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Dry event trends and frequencies in the south central United States

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DRY EVENT TRENDS AND FREQUENCIES IN THE SOUTH CENTRAL UNITED STATES

A Thesis

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Abstract

In this study, dry spells in the southern United States are analyzed. Dry spells are defined as consecutive days with no recorded rainfall. Seventy (70) weather stations are researched in Texas, Oklahoma, Louisiana, Arkansas, Mississippi, and Tennessee. Daily precipitation for each station identifies potential trends in consecutive dry days. Stations were selected for their completeness, longevity, and their proximity to one another. Only stations with five percent or less missing data were allowed. All 70 stations will be analyzed from 1950-2008. Twenty-four stations possess over 100 years of data and will be analyzed.

The best geographical indicator for consecutive dry days across this region is longitude, where dry spells have longer durations at westernmost stations. Longitude is a good indicator of changes in frequencies across the study area due to natural climatological controls. Continental tropical (cT) airmasses that exist mainly over Mexico and the southwestern United States compared to the maritime tropical (mT) airmass over the Gulf of Mexico influence precipitation in this area. Moving west from 95°W, there is a steep gradient in dryness of the selected stations. This is the point in which the maritime tropical airmasses lose its influence over the region.

Annual average dry spells are calculated. Results from this analysis illustrate more positive tendencies than negative for the years 1908-2008. Annual maximum dry spells are also determined, which show a tendency toward shorter duration events overtime (71.4% of stations). Longer annual maximum dry spells also occur in the west. These tendencies support the idea of climate change, increasing temperatures, and therefore more rain days.

Return periods for these events are also presented to further analyze the climatology of dry spells in this region for the 2-, 5-, 10-, 25-, 50-, and 100-year events. Steep gradients are discovered in the western half of the study area. From near 95°W eastward, the gradient is much less evident.

Results from this research should assist those in the agriculture industry, water resource management, and the many others who depend on high-quality forecasts of precipitation. This analysis also aims to benefit decision and policy-makers in all levels of government.

Chapter 1: Introduction and Literature Review

1.1 Introduction

Drought is a weather phenomenon that can occur anytime, across a limited or broad area, and can persist for an extensive period of time. It is probably the most persistent climatic problem experienced in the contiguous United States (Soule 1992). Droughts also have large impacts on many segments of the economy, including agriculture, industry, and water supplies (Mo et al. 1997). Predicting droughts has not yet become an exact science. Recent droughts in the southern United States have further emphasized the need for research on impacts of drought as well as its causes. Federal organizations such as the National Oceanic and Atmospheric Administration (NOAA) have continued to invest funds toward research and planning to help mitigate impacts of future droughts. However, Louisiana, Arkansas, Mississippi, and Tennessee all currently are without emergency drought plans according to the National Drought Mitigation Center which is located on the campus of the University of Nebraska in Lincoln (NDMC, http://drought.unl.edu/mitigate/status.htm). This research strives to provide valuable data and analysis to be put toward creating a drought plan for the region.

Meteorological forecasting of droughts has proven to be a complicated undertaking, especially in summer in the south central United States. Patches of convective thunderstorms are liable to pop up randomly in summer afternoons when increases in temperature and water vapor usually tend to cool the atmosphere and warm the surface, leading to amplified convection (Mitchell and Manabe 1990). It may be easier for a forecaster to predict rain for a given day and more difficult for consecutive days, especially for longer durations than a week. Also, different regions respond differently to the lack of rain. An area of the world that typically receives more rain than another will be more susceptible to large changes in normal climate activity. A city such as Baton Rouge, Louisiana, which is one of the wettest in the United States, would have a greatly different response to a lack of rain than that of El Paso, Texas. Baton Rouge averages over 60 inches of rain per year, whereas El Paso averages approximately 10 inches per year. These annual averages were obtained by the program CLIMOD made available by the Southern Regional Climate Center.

This research does not intend to be a study of drought, but rather an analysis of dryness throughout the region focusing on consecutive runs of dry days. Studies of climate change note that global temperatures on average are increasing. Increasing temperatures would lead to higher chances for daily convection and further chances for thunderstorm and otherwise rain activity. With this under consideration, this analysis intends to determine trends in dry spell (period of consecutive dry days) average lengths per year as well as annual maximum dry spell lengths. It should be noted the methods used herein have yet to be applied in an analysis of consecutive dry days.

1.2 Statement of Problem

Economic damages credited to natural disasters tripled from an estimated $40 Billion in the 1960s to $120 Billion in the 1980s (Domeisen 1995). Also according to Domeisen (1995), only one natural disaster resulted in losses of more than $1 Billion before 1987 and since then until 1995, thirteen natural disasters have cost greater than $1 Billion each. Drought is commonly excluded from these estimations because it differs from other natural hazards by its slow onset and it seldomly results in human fatalities or structural damage (Wilhite 1996). However, for the years 1963-1992, drought ranked highest among all types of natural disasters affecting one percent or more of the total global population (Wilhite 2000). Wilhite et al. (1986) found that during the droughts of the mid 1970s, particularly 1974, 1976, and 1977, the United States federal government spent more than $7 Billion on drought assistance programs. The drought of 1988 in the United States rendered estimated monetary losses of $40 Billion (Riebsame et al. 1990). The economic, social, and environmental setbacks resulting from drought are increasing considerably, however; it is complicated to measure this trend accurately due to the lack of consistent historical estimates of losses (Wilhite 2000). Conversely, the increasing trend, however difficult to quantify, may still be viewed as a way to gauge vulnerability to drought in the United States. It is important to monitor drought-like conditions and possibly predict the variability of its effects (Dai et al. 2004).

For many years, local media outlets in the United States have made light of dry conditions for their respective local areas when they occur. The Baton Rouge Advocate published an Associated Press article (12 July 2006) entitled “La. Experiencing Texas-Size Drought” discussing the dry conditions before and after Hurricanes Katrina and Rita and up until the summer of 2006 for south Louisiana. The article first implies in the title, that readers could easily relate to the meaning of a “Texas-size drought.” Is this common knowledge? Are droughts worse in Texas than anywhere else? Or is this just a play on words relating to Texas’ size in mere land mass? The title appears to be drawn from a quote in the article claiming that Louisiana’s current climate conditions at the time were compared to conditions generally found in west Texas. The article further explains how the dry period has been difficult for some people who depend on the rain, like farmers, but somewhat beneficial to others, such as the construction workers at the time repairing the roof of the Louisiana Superdome and those fixing the damaged levees, both located in the city of New Orleans. Farmers are actually said to be praying for tropical storms and hurricanes to make their way to Louisiana via the Gulf of Mexico. On the other hand, those who have fallen victim to the recent hurricanes to hit the Gulf coast might find such statements offensive, while recalling memories of the aftermath of those storms. The author later interviews a 55 year-old sugar cane farmer who explains that the sugar cane crop struggles in dry conditions because the stalks are grown on raised beds to keep them out of standing water. This in turn makes it more difficult than other crop types to retain water. The farmer asserts it would be too expensive to install an irrigation system or dig ditches to hold water. The closing of the article explains that this particular drought was unique, since for the 450,000 acres of sugar cane fields, irrigation is unprecedented and has never been necessary. This statement assumes that when the article was written, it had never been as dry as long as sugar cane has been farmed in southern Louisiana. Even though the people of south Louisiana might remember how dry it was during that summer in 2006, there is no evidence for the claim.

This raises an important question whether this claim of south Louisiana's climate is valid or not. Prior research has concluded that major droughts in the United States are cyclical and occur in a pattern which has peaks of every twenty-one years on average (Borchert 1971). Daily precipitation records will be analyzed for this project to illustrate dry trends across the southern states of Texas, Oklahoma, Louisiana, Arkansas, Mississippi, and Tennessee.

Are there any locations in this region that are enduring more dry spells between rainfalls annually over time? Where do the longest dry spells occur in the region? Is there a geographical element proving to be more of an indicator of these dry spells? Are these dry spells becoming more frequent in any parts of the selected region? How often are dry spells of different magnitudes expected to occur? These are the questions this research intends to answer.

Well documented monthly moisture and drought indices include the water budget analysis technique created by Thornthwaite and Mather (1955), Palmer Drought Severity Index (PDSI; Palmer 1965), the Rainfall Anomaly Index (RAI; van Rooy 1965), the Bhalme and Mooley Drought Index (BMDI; Bhalme and Mooley 1980), the Standardized Precipitation Index

(SPI; McKee et al. 1993, 1995), and the Reclamation Drought Index (RDI; Weghorst 1996). Additionally, several drought indices are conducted weekly or bi-weekly such as the PDSI and the Crop Moisture Index (CMI; Palmer 1968). Most measurements of drought rely upon indices such as these. However, none of them actually measure the length of dry spells, which may not qualify as drought by some definitions, but are nonetheless important climatologically.

Alley (1984) concludes that the PDSI addresses drought intensity and beginning and ending dates, but lacks confidence in the measuring of these properties. Other limitations include the PDSI loosely defines the terms severe and extreme and care should be used when referring to those drought severity classes (Alley 1984). All considered, this research intends to answer the aforementioned questions using the approach of analyzing lengths of dry spells, herein defined as consecutive days with no rain.

1.3 Objectives

The Southern Climate Impacts Planning Program (SCIPP) is a new climate research initiative whose objective is to help communities plan more effectively for weather and climate-related disasters in the southern United States (TX, OK, LA, AR, MS, and TN), mainly in the face of climate change and variability. SCIPP focuses on the high regularity of climatological events that disrupt the region including extremes in precipitation, such as droughts and floods, as well as other dangers including severe storms and hurricanes. No research has been found which calculates the annual average of consecutive dry days between rainfalls as a method of analyzing drought. Therefore, this thesis analyzes the daily precipitation record for the southern region of the United States to assess recent dry episodes in relation to the long-term climate records of each part of the region. The main objectives are:

1. Analyze a time series of the annual average length of dry days between rainfalls to

gain an alternate understanding of drought through temporal and trend analysis across the south-central United States.

2. Create a time series of the longest annual dry spells for each station to be utilized in temporal and trend analysis.
3. Test the theory that recent dry episodes have been increasing in magnitude.
4. Calculate the annual return periods of extreme dry spells for each selected station and for the region.

1.4 Background

Arguably, the most well known drought in the Unites States in the last 100 years was the period in the 1930s that mostly impacted the Great Plains states. It was a decade including a series of rain deficits known as the Dust Bowl, where above average temperatures and severe wind-driven soil erosion occurred (Baumhardt 2003). This led to the popular characterization of this region of the country as the "Dust Bowl" (Schubert et al. 2004). It affected nearly two-thirds of the United States, as well as parts of Canada and Mexico. The most affected area encompassed forty million hectares (98.8 million acres) and the most severely affected farmland was located within a 160-km radius of Liberal, Kansas, considered the center of the Dust Bowl (Baumhardt 2003). The dust storms forced once regularly-farmed soil in the Great Plains of the United States into the far reaches of New England. Poor farming techniques in addition to the weather conditions made for one of the worst environmental disasters in American history.

Studies have verified that major droughts in North America can be associated with a rhythmic fluctuation between comparatively wet and dry series of years (Borchert 1971). In an anonymously written leaflet from the Department of Agriculture, the early half of the 20th century was examined to identify these periods of wet and dry years. It was written that "once every twenty years or so", there is a dry period and identified the dry years in the 1930s as well as the 1950s. Harold Thomas reviewed the drought of the 1950s and eventually identified "four major periods of extensive drought" (Borchert 1971, p. 2). These periods of dry years were identified by their mid points which were 1892, 1912, 1934, and 1953. The average number of years between these midpoints is twenty one, suggesting other events to follow with midpoints near the years 1974, 1995, and 2016 and Borchert (1971) suggests that there was a likelihood of another great drought in the 1970s. Mitchell et al. (1979) produced verification of a 22-year cycle for drought in the western United States in the 17th century using tree rings. McCabe et al. (2004) acknowledged the 20-year patterns in their research to analyze influences by the Pacific and Atlantic Oceans on drought. Following Borchert (1971), there was a drought in 1976-1977 that Karl and Koscielny (1982) analyzed by implementing principal component (PC) analysis. That research showed that areas in the west and "east-north central" experienced very low principal component values during those years (Karl and Koscielny 1982, page 321). This showed the impact was nearly as devastating for the west and east-north central as the Dust Bowl was in the "west-north central" during the 1930s (Karl and Koscielny 1982, page 321). For the areas hit hardest by the Dust Bowl in the 1930s, the droughts of the mid 1950s and mid 1970s were mild in comparison. Wilhite (1983) also acknowledges the great losses associated with drought during the 1930s, 1950s, and 1970s. It seems the 21-year midpoint for dry years found in Borchert (1971) fits the pattern. The 1990s were no exception. Hayes et al. (1999) recognizes the drought of 1996 that struck the southern Great Plains and the southwestern United States. Agricultural losses in 1996 in Texas alone have been estimated at $2.1 Billion and the drought by and large cost the state more than $5 Billion (WGA 1996). Hong and Kalnay (2000) also analyzed the drought in Texas and Oklahoma during 1998. They found that soil moisture in their study area reached levels comparable to the Dust Bowl (Hong and Kalnay 2000). Sauchyn et al. (2003) focuses on the northern Great Plains and Piechota et al. (2004) analyzes the Upper Colorado River Basin (UCRB) in Utah, with both focused on the drought beginning in 1999 and ending in 2001. Piechota et al. (2004) states the drought in the UCRB during those years is the worse than any other in the previous 80 years. Sauchyn et al. (2003) utilized tree ring analysis at several stations with records dating back to 1884 to show that for a three-year period, 1999-2001 received less precipitation than any other three-year period on record. Also found in the study was 2001 was the driest year on record at one station and the third driest at another.

Another driving factor for this research is that defining drought has certainly proved to be difficult historically (Harding 1970; Houman 1975; W.M.O. 1975; Dey 1982). Developing an appropriate universal definition of drought events has proven to be a complex task (Yevjevich 1967; Dracup 1980). Leathers et al (2000) defines meteorological drought as a significant decrease from normal precipitation totals over a wide area for an extended period of time. The phenomenon has yet to be given a single, specific definition in scientific journals. In fact, Wilhite and Glantz (1985) constructed over 150 definitions. In that study, ten conclusions were made:

1. “The lack of a precise (and objective) definition of drought in a specific situation has been an obstacle to understanding drought, which has led to indecision and/or inaction on the part of managers, policy makers, and others;
2. There cannot (and should not) be a universal definition of drought;
3. Available definitions demonstrate a multi-disciplinary interest in drought;
4. It is useful to subdivide definitions of drought into four types on the basis of disciplinary perspective, i.e., meteorological, agricultural, hydrological, and

socioeconomic.

5. Drought is a complex phenomenon with pervasive societal ramifications;
6. Most scientific research related to drought has emphasized the physical over the societal aspects of drought;
7. Drought severity is sometimes expressed by its societal impacts, although the precise nature of those impacts is difficult to quantify;
8. Secondary and tertiary effects often extend beyond the spatially defined borders of drought;
9. Drought impacts are long lasting, at times lingering for many years; and
10. Human or social factors often aggravate the effects of drought." (Wilhite 1993).

1.5 Literature Review

This thesis focuses on meteorological drought defined by Research Paper No. 45 (1965) as, a period of more than some particular number of days with precipitation less than some specified small amount. Because this definition is vague, the standard seems simple to satisfy and adapt to regions with highly varying climate. Additional research has attempted to do so. Kamenkova (1964) concluded for European Russia, a drought is a period of ten consecutive days during which the total rainfall does not exceed 5 mm (0.2 inches). Tannehill (1947) defined drought in England as a period of fourteen consecutive days of less than 0.01 inches each (0.25 mm). Currie (1953), focused on precipitation over the Canadian Prairie Provinces and Northwest Territories and defined drought as a period of at least five days uninterrupted by rainfall of at least 0.01 inches (0.25 mm). Karl and Quayle (1981) stated drought reflects the balance between moisture demand and supply. Dey (1982) explains that criteria for identifying and classifying drought have yet to become traditional. In Dey's (1982) study, a drought was indicated when a summer (May to August) or a winter (November to March) season precipitation has recorded 50 percent or less than average across a large area of the Canadian Prairies.

According to Diaz (1983), drought occurs when three or more consecutive months measure a Palmer Drought Severity Index (PDSI) value of less than or equal to -2. Diaz (1983) analyzed what he deemed “major dry and wet periods” in the contiguous United States from 1895-1981 and concluded that interior and western areas of the United States are more likely to suffer extended episodes of dry weather. Wayne Palmer, author of Research Paper No. 45 (1965), “Meteorological Drought”, created the index in the 1960s and it applies to moisture deficits as well as surpluses. It formulates temperature and rainfall data to determine the amount of dryness for a specific area. Diaz (1983) defined a major dry episode as “six or more consecutive months of dryness.” In that study, he demonstrated the spatiotemporal distribution across the United States of moderate to extreme droughts for two different time periods, 1895-1939 and 1940-1981 for each state.

The PDSI has been considered the most widely used method of measuring drought since the mid-1960s (Alley 1984). In his paper, Alley (1984) discusses the limitations of the PDSI. The PDSI not only takes into account the deficiency of precipitation, but also evapotranspiration and soil moisture conditions. Each of these properties turns out to be causes of hydrologic drought even though the PDSI is typically referred to as an indicator of meteorlogic drought (Alley 1984). Another limitation of the index is it was originally created using climate records collected only in central Iowa and Kansas. Even with the limitations of the PDSI, Alley (1984) believes that until a more intricate and complete index is developed, the PDSI will continue to be commonly used.

Another monthly observation used is the Thornthwaite and Mather (1955) water budget analysis technique. Recently, Leathers et al. (2000), used this method to analyze growing season moisture deficits in the New England area of the United States stretching southward to West Virginia, Maryland, and Delaware. This particular method balances estimated inputs of water (precipitation) with outputs such as evaporation and evapotranspiration. Their results showed particularly dry conditions in this study area during the early 1910s and again during the 1960s. A wet period was also recognized from the 1970s to the early 1990s.

Byun and Wilhite (1999) attempted to quantify drought severity and duration. The authors describe three weaknesses to existing drought indices. Their first claim is that the current indices are not precise enough to identify the onset, end, and accrued stress of drought. The second is the indices do not consider the effects of runoff and evapotranspiration, which over time can worsen. Lastly, since current indices operate on a monthly time step, their efforts of monitoring ongoing drought are limited in their value (Byun and Wilhite 1999). The authors further state that since drought occurs with the deficiency of water, then drought indices should be calculated with the notion of "consecutive occurrences of water deficiency" (Byun and Wilhite 1999, page 2749). Most current drought indices use a month or longer time period as a component and only a few are weekly (Byun and Wilhite 1999). Another point made by Byun and Wilhite (1999) is the drought measurement must be measured in days because a single day's rainfall can return a region's drought conditions to normal. For example, if heavy rainfall were recorded on September 1 and November 31 in a given area, with no rain in between, a monthly index for September or November may not show a drought, when in fact there might be severe conditions due to the fact that rain was not recorded for sixty straight days. Also a dry episode lasting less than one month may not necessarily be insignificant. Byun and Wilhite (1999) also state that in some countries, United Kingdom for instance, a period as short as fifteen days with “little rain” has been classified as a dry spell. A daily index as opposed to monthly would be especially helpful to those in areas that receive a high amount of precipitation normally and where it is the main water source (Byun and Wilhite 1999). A monthly index is limited to being calculated only at the end of a month.

There is also a need to recognize and appreciate the spatial and temporal disparities for planning and development purposes, since the United States economy is becoming more reliant upon an abundant moisture supply (Karl and Koscielny 1982). It offers direction for research in quest of the explanation for the commencement, progress, and end of droughts in the United States (Karl and Koscielny 1982). In their study, as mentioned above, they presented monthly average precipitation for the months between January 1895 to April 1981 (1,036 months). Nine regions of the United States were determined spatially using sixty grid points across the country. However, this study found no significant cycles in their dataset, contrary to results found by Borchert (1971) and Mitchell et al (1979). Even though Karl and Koscielny (1982) disagree that such a cycle for drought exists in their twentieth century dataset, many publications as explained above have analyzed periods of drought in the twentieth century. These periods tend to be spaced roughly twenty years apart (1930s, 1950s, 1970s, and 1990s).

Groisman and Knight (2008) analyzed prolonged dry episodes during warm seasons across the conterminous United States to find any new tendencies in the 40 years prior to the study. Their results included the seven driest warm seasons over the eastern United States in the past 99 years since 1908. In order by driest, they were 1963, 1924, 1953, 2000, 1908, 1939, and 2001. Groisman and Knight (2008) also found that for the last 40 years, dry day episodes with 1-month or longer durations are increasing in occurrences per year.

Chang and Wallace (1987) studied drought and heat wave conditions in the Kansas City area. The study objectively ranked 276 months during ninety-two summers in the years from 1889 to 1980. They found that the majority of the drought months fell during the decades of the 1910s, 1930s, and 1950s.

Drought is a relative term that is geographically dependent. Depending on the study area, the criteria used to classify drought will vary. This is partly because climate conditions can be quite different across a region. For there to be drought in one part of the country, atmospheric conditions must be situated a certain way. Mo et al. (1997) states that during dry events in North America, high pressure is present throughout a vertical column in a pattern in a swathe across North America from 30° to 60° N". During wet events however, the high pressure is limited to the eastern half of the continent and low pressure existing in the western half with increased meridional winds found between the low and high pressure systems, leading to amplified moisture flow northward from the Gulf of Mexico at low levels in the atmosphere.

The weather stations used in this analysis belong to the Cooperative Observer Program (COOP). The COOP Network was initiated in the 1890s to formulate meteorological observations across the United States, mainly for agricultural purposes (Daly et al. 2007). A handful of the stations selected are taken from the United States Historical Climate Network (USHCN). The USHCN provides much of the country's official data on climate trends and variability over the past century (Karl et al. 1990; Easterling et al. 1999; Williams et al. 2004; Daly et al. 2007).

Several publications analyze weather-related trends. Temporal analysis of changes in extreme events is becoming more essential with the possibility of a global climate change (Keim and Cruise 1998). Andreadis and Lattenmaier (2006) analyzed trends in drought over the continental United States. In addition to precipitation, they also used soil moisture, runoff, wind speed, and temperature as driving factors for their study. Some interesting results were found in their study. For the majority of stations used in the six states used herein, Andreadis and Lattenmaier (2006) found increasing trends in soil moisture from 1915 to 2003. For all the stations used in Texas, they found decreasing trends in drought duration and all but one had negative trends in drought severity for those years. Andreadis and Lattenmaier (2006) used the Mann-Kendall (MK) test and a variation of it called the seasonal MK Test to calculate these results.

Groisman and Easterling (1994) analyzed trends of total precipitation and snowfall over the United States and Canada. Their study indicates a four percent (4%) increase in precipitation in the United States as whole between the years 1951 and 1990. Keim et al. (1995) studied temporal variability of long term trends of the precipitation record and runoff in Louisiana over the last 100 years. They concluded that Louisiana has experienced considerable increases in precipitation and runoff over the last century. Keim (1997) analyzed temporal patterns of heavy rainfall in the south central United States. Daily precipitation data was collected from twenty-seven stations across Alabama, Arkansas, Florida, Georgia, Louisiana, Mississippi, North Carolina, Oklahoma, South Carolina, Tennessee, and Texas. Results from that study showed that the central gulf Coast was the area with the highest frequencies of heavy rainfall and conversely, central Texas and the Appalachian Mountains received the fewest (Keim 1997). A major conclusion of this study was that a region of this size does not respond consistently regarding heavy rainfall climatologies (Keim 1997). Keim and Cruise (1998) implemented a technique to analyze trends in the frequency of extreme events. Using the Poisson Process to study Nor'easters along the east coast of the United States, the authors demonstrated the advantages of using parametric methods to test for trends of discrete, random events (Keim and Cruise 1998).

New et al. (2001) also analyzed precipitation tends in the 20th Century. They found the El-Nino Southern Oscillation (ENSO) to have a strong influence over the southern and midwestern United States. Their results showed evidence of an increase in precipitation, especially during the summer months in North America. This study area was widespread and results do not primarily reflect trends in the southern United States.

Groisman and Legates (1995) examined problems and achievements in the documentation of precipitation changes during the period of instrumental measurements. Currently, there are approximately 100,000 rain gauges worldwide and the spatial distribution of the stations that take the measurements are not uniform. More stations are located near urban areas and coastlines (Groisman and Legates 1995). They concluded that studies analyzing changes in precipitation should include a dense network of stations and careful processing of the data to avoid problems.

Keim and Muller (1992) examined heavy rainfall magnitudes by analyzing annual maximum storm series in New Orleans, LA. Keim (1999) researched the annual maxima precipitation trends for the same stations analyzed in Keim (1997). Keim (1999) set out to observe whether magnitudes of heavy rainfall events were changing through time. Utilization of the Spearman Rank test illustrated only provided the analysis with three significant trends. The dominance of positive correlations suggested a propensity towards increasing precipitation values across the study area (Keim 1999).

Cohn and Lins (2005) analyzed trends in hydroclimatological data for long-term persistence (LTP). This analysis was prompted by a problem in the overstating the statistical significance of observed trends when LTP is present. They found that there are tests available that are powerful enough to accommodate LTP, if needed.

Recently, McCabe et al. (2010) examined the variability and trends in dry day frequencies and dry event length in the southwestern United States. The authors analyze dry events with minimum thresholds of 10 and 20 consecutive days each with less than 2.54 mm (0.1 inches) of precipitation. McCabe et al (2010) focuses on the comparison of these dry events during the months October through March or “cool season” as compared to April through September, “warm season”. Twenty-two National Weather Service first-order weather stations were used and daily precipitation was extracted from 1951-2006. They found that for the cool seasons, the trends in dry event length were mostly negative. Conversely, trends were mostly positive for the same sites during the warm season. For as similar a study McCabe et al. (2010) is to this research, it is unfortunate that results will be difficult to compare. None of the states selected for McCabe et al. (2010) are used in this study. However, results from McCabe et al. (2010) are similar to those found in Andreadis and Lettenmaier (2006) which both identified significant increases in dry spell occurrences in the southwestern United States.

Two studies that are useful to this research regarding return periods were Faiers et al (1997) and Keim and Faiers (2000). Faiers et al. (1997) produced rainfall frequency maps for the six-state region of the Southern Regional Climate Center (Texas, Oklahoma, Louisiana, Arkansas, Mississippi, and Tennessee). These frequencies were determined for 3 hour-, 6 hour-, 12 hour-, and 24 hour-storms. Recurrence intervals of 2-, 5-, 10-, 25-, 50-, and 100-years were found using the Huff-Angel (Huff and Angel 1992) and SRCC methods for each of the storm durations listed above. Keim and Faiers (2000) also used the Huff-Angel and SRCC methods to produce quantile estimates of heavy rainfall in western Texas. This study area was selected for its arid and mountainous environment. Keim and Faiers (2000) compare Huff-Angel, SRCC as well as other methods to find the best fit for analysis of the data set used. The authors demonstrate that overall, the Kolmogorov-Smirnov (K-S) test found Huff-Angel to be the best technique (Keim and Faiers 2000). However, they concluded that since Huff-Angel tends to overestimate values associated with the 50- and 100-year return periods, the SRCC method was chosen as the best fit. The SRCC method had the most undisputed number one rankings of quantile estimates at each of the stations used in the study (Keim and Faiers 2000). These methods are also utilized later in this research.

Recent studies have addressed the methodology for estimating drought return periods; Fernandez and Salas (1999), Chung and Salas (2000), and Kim et al. (2003). Fernandez and Salas (1999) summarized the definitions of the return period as applied to drought events. Chung and Salas (2000) focused on drought occurrence probabilities, return periods, and risks of drought events for dependent hydrological processes. In their analysis, they studied drought based on annual streamflow of the Niger River and the south Platte River. Kim et al. (2003) utilizes a methodology for estimating the return periods of droughts using a nonparametric kernel estimator and is presented in order to examine the univariate (one variable) as well as the bivariate (two variables) behavior of droughts in the Conchos River Basin in Mexico, just south of El Paso, TX. It should be noted that neither of these publications produce return periods using the Huff Angel and SRCC methods.

Various studies have been conducted to measure and quantify drought in different parts of the world and especially the United States. Many are listed and discussed in the preceding paragraphs. However, there is little existing research which studies drought and its frequencies using the methods of this research. In the following chapters, the annual average length of consecutive days between days with measured rainfall of 0.01 inches will be calculated. The annual maximum for consecutive dry days using the same criteria will be examined. Finally, return periods of consecutive dry spells for each of the seventy stations will also be investigated. One study has been found in which the annual average length of consecutive days between recorded precipitation was used to analyze dry spells (Knoop and Walker 1985). However, the method was used to measure the average frequency of rain days and to compare seasonality between the October to December months and January to March months for 1978-1982. They conducted the study to show the interactions between the woody and herbaceous vegetation in two particular southern African savannahs. The investigators compared the results of the method listed above to another measuring the mean rainfall per day for the same months. The study showed that the rainfall in the focus areas varied between the years, both in quantity and in pattern.

Chapter 2: Methodology

2.1 Description of Study Area

The study area consists of the Southern region as defined by the National Oceanic and Atmospheric Administration (NOAA). The region is the same as assigned to the Southern Regional Climate Center (SRCC) which includes six states: Texas, Oklahoma, Louisiana, Arkansas, Mississippi, and Tennessee (Figure 2.1). The analysis examines a total of 70 stations across the region. Initially, as many as 85 stations in the Cooperative Observer Network (COOP) were chosen for their spatial distribution across the region. These 85 seemed to create enough coverage of the region with the forethought that some of the stations would not qualify the missing data requirement set forth as explained in the following sections. Preliminary analysis of the amount of missing data in the records of all 85 stations, the number was reduced by 15 to a new total of 70. The remaining 70 stations were of high-quality and continued to provide the desired spatial distribution. Methods for condensing the amount of stations will be explained in more detail later in this chapter.

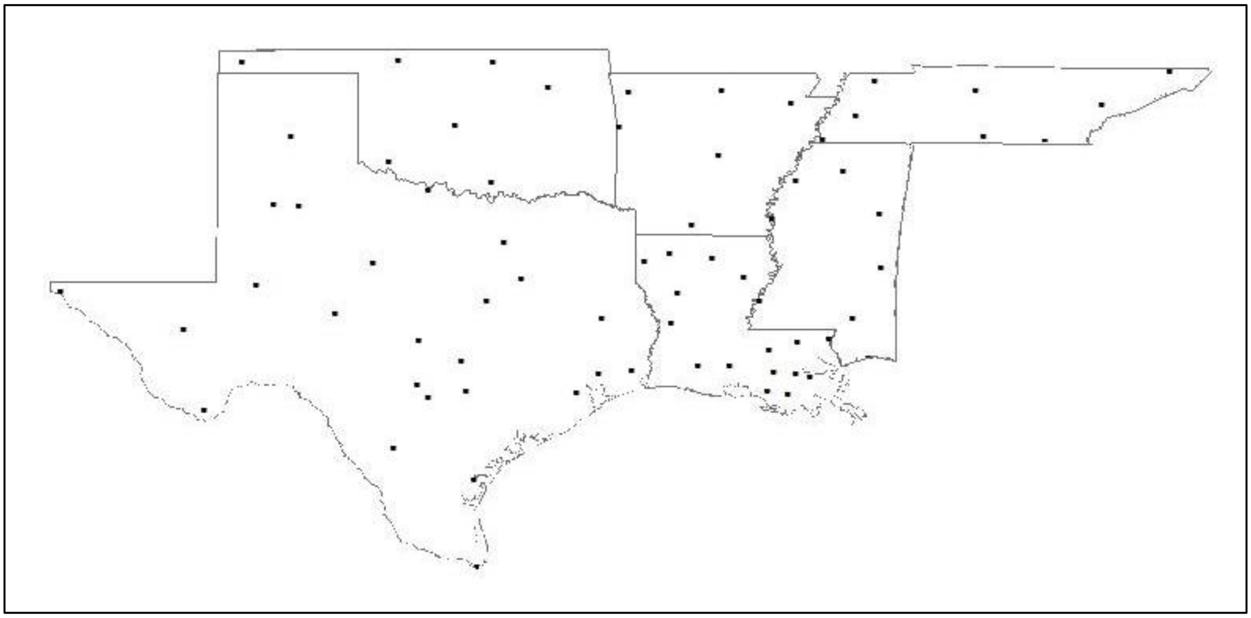

Fig. 2.1. Seventy stations chosen throughout the Southern Region for analysis of dry spells.

The latitude measurements range from 25.91° N (Brownsville, TX) to 36.76° N (Freedom, OK). The longitudes of the selected stations range from 82.53° W (Kingsport, TN) to 106.38° W (El Paso, TX). The elevations are widely ranging and are typically lower along the coast of the Gulf of Mexico and higher in the northernmost latitudes and the westernmost longitudes. The weather station with the lowest elevation is Morgan City, LA at only five feet above sea level (1.524 m). Chisos Basin, Texas located in Big Bend National Park is the highest; 5,300 feet above sea level (1,615.44 m).

This region of the United States is mostly under the same climate classification according to the updated Köppen-Geiger Climate Classification System (Peel et al. 2007), with the exception of some areas of southern and western Texas, as well as western Oklahoma. As such, most of the region falls under the Cfa classification (Figure 2.2). Cfa is described as humid subtropical, which is without a dry season and with hot summers. There is an area in south central Texas classified as BSh which is described as arid, low-latitude hot steppe climate. The area that surrounds extreme southwestern Texas near El Paso is classified as BWk. This is better known as arid, mid-latitude cold, desert climate. The area of western Texas that spreads north into the western panhandle of Oklahoma is known as BSk, or arid, mid-latitude cold, steppe climate. It is difficult to determine from simply viewing Fig 2.2, but there appears to be a small area in eastern Tennessee classified as Cfb, represented by the small, dark green circular area. Cfb is defined as temperate, without a dry season and with a warm summer.

2.2 Climate Classification

Even though most of this study area is classified as a Cfa climate, and with no dry season, there are not any areas within the region that are unsusceptible to extended dry periods. Some areas may be more vulnerable than others due to their geographical location. The areas near

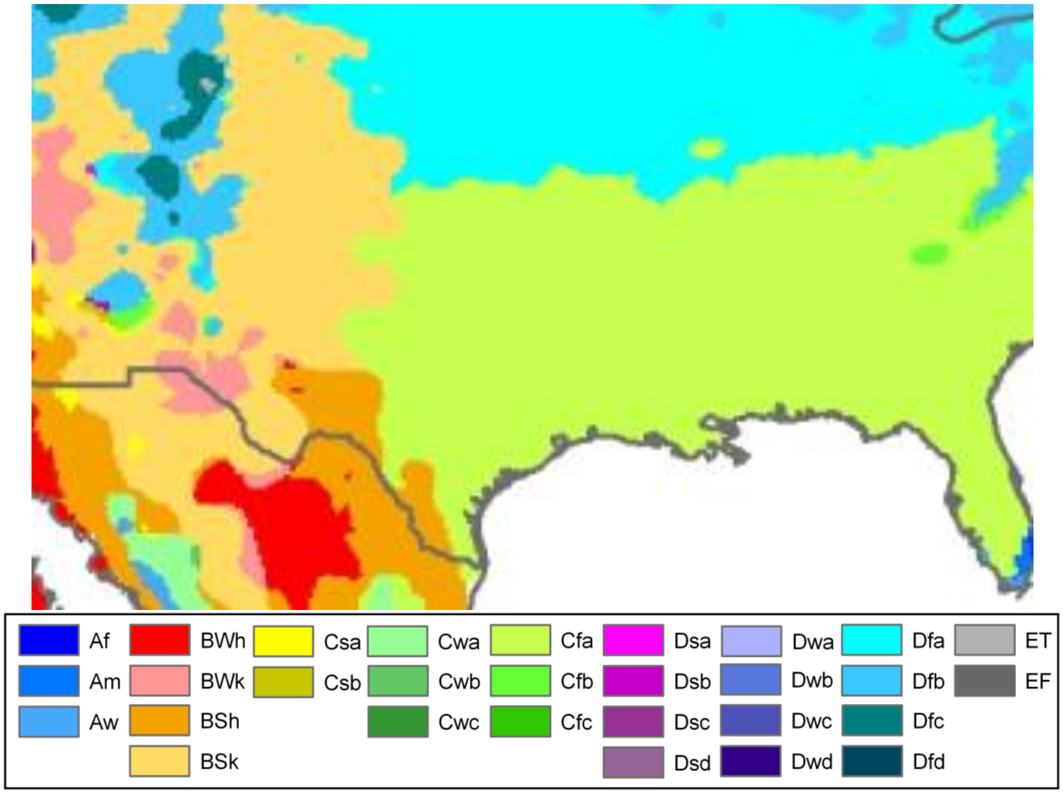

Figure 2.2. Updated world Köppen-Geiger climate classification map.
Source: Peel et al. (2007).

the Gulf of Mexico receive most of their rainfall from the moisture-laden air when the wind blows in from the south. This humid air can be further lifted by fronts and convective activity, which can generate rainfall. Additionally, the Gulf is a well known area of propagation for extratropical cyclones in the winter and tropical disturbances, tropical storms, and hurricanes in the summer and fall (Faiers 1986).

The areas in the west are typically drier due to the airflow over the Rocky Mountains. As air descends down the eastern face of the mountains, it warms adiabatically, stabilizes, and therefore limits precipitation (Neiman and Wakimoto 1999). Not until the drier air meets up with the humid Gulf air over the Great Plains, are there improved chances for rainfall. Karl and Koscielny (1982) found droughts to continue nearly twice as long in interior portions of the United States as opposed to areas closer to vast moisture sources. Therefore, it is hypothesized that the more inland from the Gulf of Mexico and further west a weather station is, the more vulnerable it may be to extended periods of no rain.

2.3 Overview of Selected Stations

Tables cataloguing each of the stations in terms of record length, completeness of record, and geographical location are listed below. Throughout this thesis, the stations will be referred to by their COOP Network station name which is the name used below. They are organized by state and are listed in alphabetical order.

2.3.1 Texas

Twenty-five weather stations were selected in Texas based on their spatial distribution across the state (Table 2.1). It is perhaps the most interesting state in the study area geographically. Station elevations range from as low as 24 feet in Brownsville to 5,300 feet at Chisos Basin located in Big Bend National Park. It is approximately 760 miles across from El Paso to the Louisiana border and over 800 miles from the northwest Oklahoma border to Brownsville. Texas is the second largest state in the United States in terms of square miles with over 268,500 square miles and none of the selected stations are more than 150 miles apart from another in a straight line. In theory, each station represents an average of 15,800 square miles. The westernmost station selected in Texas is the El Paso International Airport. Beaumont is the easternmost, Amarillo is the northernmost, and Brownsville, the southernmost, located on the southeastern border with Mexico. Seven stations had a complete enough record for over the last 100 years to be used for a study beginning in 1908. Most of the station records in Texas commenced in the 1940s and 1950s, many of them near airports where first order stations were relocated to around that time (Groisman and Easterling 1994). It was essential in this study to use these airport weather stations, due the quality of their records being located in relatively open sites. A few other stations have records dating back to the 1890s and early 1900s, but the records did not meet the completeness of record criteria, however each station selected has better than ninety-five percent complete data for its respective record that is analyzed. Ninety-five percent is herein set as the threshold of completeness for a stations data to be allowed in this analysis. This method is further explained in the following sections.

Table 2.1. Stations selected from Texas, their first year of record, latitude, longitude, elevation and completeness of record.

Cooperative Observing Network Identifier	Station Name	First Year of Record	Latitude (°N)	Longitude (°W)	Elevation	Completeness of Record
410016	Abilene	1950	32.41	99.68	1790	100.00
410211	Amarillo	1950	35.13	101.43	3604	99.99
410428	Austin Mueller AP	1950	30.32	97.76	658	99.99
410498	Balmorhea	1950	30.98	103.74	3220	95.77
410611	Beaumont	1908	30.10	94.10	20	98.03
410092	Boerne	1908	29.80	98.72	1422	99.00
411136	Brownsville, TX	1950	25.91	97.42	24	99.98
411715	Chisos Basin	1950	29.27	103.30	5300	99.95
412015	Corpus Christi	1950	27.77	97.51	44	100.00
412019	Corsicana	1908	32.09	96.47	425	99.10
412048	Cotulla La Salle AP	1950	28.46	99.22	476	99.34
412121	Crosbyton	1908	33.66	101.25	3010	98.50
412244	Dallas Love	1950	32.85	96.86	440	99.99
412797	El Paso	1950	31.81	106.38	3918	99.97
414307	Houston Hobby AP	1950	29.64	95.28	44	98.85
415196	Liberty	1908	30.05	94.80	35	98.05
415272	Llano	1908	30.75	98.69	1040	99.16
415411	Lubbock	1950	33.67	101.82	3254	100.00
415424	Lufkin	1950	31.24	94.75	288	99.90
415429	Luling	1908	29.67	97.66	398	99.69
415890	Midland	1950	31.94	102.19	2862	99.98
417943	San Angelo	1950	31.35	100.50	1916	99.97
417945	San Antonio	1950	29.53	98.47	809	100.00

Table continues

419419	Waco	1950	31.62	97.23	500	99.88
419729	Wichita Falls	1950	33.98	98.49	1017	97.85

2.3.2 Oklahoma

Seven stations were chosen from Oklahoma (Table 2.2). Oklahoma is the 20th largest state in the United States with over 69,900 square miles. Each station selected in the state represents on average 9,985 square miles in theory. Only one station has a record beginning in 1908, and the others use 1950 as the starting year. Oklahoma includes the three northernmost stations in the entire study, Freedom, Ponca City, and Boise City. Boise City, located in the panhandle is not far from the New Mexico and Colorado borders. Freedom and Ponca City are located near the Kansas border. Oklahoma City Will Rogers Airport and Union City were both chosen for their superior quality of record. However, they are only separated by sixteen miles (25.75 km). Since Union City has a longer record by thirty-four years, the Oklahoma City Will Rogers station was omitted. None of the seven stations chosen have more than 3.32 percent data missing from their respective record.

Table 2.2. Stations selected from Oklahoma, their first year of record, latitude, longitude, elevation and completeness of record.

Cooperative Observing Network Identifier	Station Name	First Year of Record	Latitude (°N)	Longitude (°W)	Elevation	Completeness of Record
340179	Altus Research Stn.	1950	34.59	99.33	1380	96.68
340292	Ardmore	1908	34.17	97.13	880	97.25
340908	Boise City	1950	36.72	102.48	4145	97.20
343358	Freedom	1950	36.76	99.11	1515	97.34
347201	Ponca City	1950	36.74	97.10	1000	99.85
348992	Tulsa	1950	36.20	95.89	650	99.99
409219	Union City	1950	35.37	97.89	1255	98.93

2.3.3 Louisiana

Sixteen stations were selected in Louisiana and they cover approximately 51,843 square miles (Table 2.3). This equals 3,240 square miles of coverage in theory for each station on average. Six of the stations had complete records beginning early enough to use 1908 as a beginning year. The remaining ten will start in 1950. In several cases, two stations with good quality records that happened to be very near each other geographically. In one instance, Louisiana Tech University in Ruston, LA was originally chosen for the 1950 study; however Calhoun Research Station is located only approximately seventeen miles to the east and has a longer and more complete record. Therefore, LA Tech was omitted from the study for Calhoun. The sixteen stations included from Louisiana range from near the coast of the Gulf of Mexico to the I-20 corridor. Additionally, all stations also provide a 95 percent or more complete record.

Table 2.3. Stations selected from Louisiana, their first year of record, latitude, longitude, elevation and completeness of record.

Cooperative Observing Network Identifier	Station Name	First Year of Record	Latitude (°N)	Longitude (°W)	Elevation	Completeness of Record
160205	Amite	1908	30.71	90.53	130	96.30
160549	Baton Rouge	1950	30.54	91.15	64	99.89
160945	Bogalusa	1950	30.78	89.86	100	98.03
161411	Calhoun Research Station	1908	32.51	92.35	180	98.50
162534	Donaldsonville	1908	30.07	91.03	30	98.80
164407	Houma	1950	29.59	90.73	15	99.59
164700	Jennings	1908	30.20	92.66	25	98.30
165026	Lafayette	1908	30.20	92.66	38	98.56
165266	Leesville	1950	31.14	93.24	28	95.10
166244	Minden	1908	32.61	93.29	185	97.13
166394	Morgan City	1908	29.68	91.18	5	99.30
166582	Natchitoches	1950	31.77	93.10	130	97.28
166665	New Orleans Audubon	1950	29.99	90.25	20	96.61

Table continues

167767	Reserve	1908	30.06	-90.58	15	98.70
168440	Shreveport Reg. AP	1950	32.45	-93.82	254	99.88
169806	Winnsboro	1950	32.10	-91.70	80	98.47

2.3.4 Arkansas

Arkansas has few stations with reliable, long records, with six stations selected for this study (Table 2.4). On the other hand, they are distributed spatially quite well. No one station is more than 120 miles from another. Arkansas ranks 29th out of the fifty states in size. It is 53,100 square miles giving each station an average of 8,850 square miles of coverage. Little Rock's Adams Field Airport has the longest record of all seventy stations in this study beginning in 1879. Unfortunately, there are forty-one years missing from 1898 to 1938. So 1950 will be used as the first year of record for Little Rock. There are two stations with records of at least 100 years, Calico Rock and Fayetteville. Each station's completeness of record is very high (Average: 99.14 percent).

Table 2.4. Stations selected from Arkansas, their first year of record, latitude, longitude, elevation and completeness of record.

Cooperative Observing Network Identifier	Station Name	First Year of Record	Latitude (°N)	Longitude (°W)	Elevation	Completeness of Record
31132	Calico Rock	1908	36.11	92.16	350	98.82
32300	El Dorado	1950	33.22	92.81	252	99.96
32444	Fayetteville, AR	1908	36.10	94.17	1270	97.90
32574	Ft. Smith	1950	35.33	94.36	449	99.96
33734	Jonesboro	1950	35.85	90.66	310	98.20
34248	Little Rock Adams AP	1950	34.73	92.24	258	99.99

2.3.5 Mississippi

Eight stations are selected from Mississippi. The state ranks 32nd in size with just over 48,400 square miles. This gives each of the eight stations roughly 6,050 square miles of coverage each on average (Table 2.5). Half of the stations have records beginning in 1908 and each is exceptionally complete. The least complete station is Biloxi at 95.7 percent and Meridian Key Field is the only station with a record beginning after 1931.

There are two records that are located near colleges in Mississippi. State University is in Starkville, the home of Mississippi State University. University is located in Oxford, near the University of Mississippi. Both stations have long and near-complete records.

Table 2.5. Stations selected from Mississippi, their first year of record, latitude, longitude, elevation and completeness of record.

Cooperative Observing Network Identifier	Station Name	First Year of Record	Latitude (°N)	Longitude (°W)	Elevation	Completeness of Record
220792	Biloxi	1950	30.39	89.00	10	95.70
221707	Clarksdale	1950	34.19	90.56	173	98.80
223605	Greenville	1908	33.36	91.06	125	97.70
223887	Hattiesburg	1908	31.25	89.34	385	98.20
225776	Meridian Key FLD	1950	32.33	88.74	294	99.95
226177	Natchez	1908	31.59	91.34	195	98.42
228374	State University	1908	33.47	88.78	185	97.20
229079	University	1950	34.38	89.54	408	98.90

2.3.6 Tennessee

Tennessee contains some of the easternmost stations in the dataset. The state ranks 36th in size with just over 42,000 square miles. Eight stations were selected in Tennessee. (Table 2.6). Kingsport is the easternmost station of all the seventy stations chosen for this study. It also has the highest elevation of the eight Tennessee stations selected which should help illustrate a correlation with elevation if one exists.

Table 2.6. Stations selected from Tennessee, their first year of record, latitude, longitude, elevation and completeness of record.

Cooperative Observing Network Identifier	Station Name	First Year of Record	Latitude (°N)	Longitude (°W)	Elevation	Completeness of Record
401145	Brownsville, TN	1908	35.59	89.26	330	98.44
401656	Chattanooga	1950	35.03	85.20	671	99.98
403074	Fayetteville, TN	1950	35.15	86.54	725	96.84
404858	Kingsport	1950	36.52	82.53	1284	97.94
404950	Knoxville AP	1908	35.82	83.99	962	97.99
405681	Martin U of TN	1950	36.34	88.86	340	99.13
405954	Memphis AP	1950	35.06	89.99	254	99.99
406402	Nashville	1950	36.12	86.69	600	99.96

2.4 Methodology

This section describes the methods used to derive the compilation of dry spells for the stations listed above. These chronological collections of events are the data sets used in the chapters to follow. It is important to understand how they are developed.

For this research, a specific data set is created of the inter-arrival periods between rainfall, defined as the number of consecutive dry days between rain events. Before this could be accomplished, the weather stations, from which precipitation data would be used, had to be selected. This south central region of the United States is a good area of study for drought due to the rich recent history of devastating drought in this area such as the Texas drought in the 1950's, the drought of 1988, which caused billions in economic impact nation-wide, the drought of 1999-2000, and the "Texas-Sized" drought of 2006 in Louisiana as referenced in chapter one. For the most part, historical precipitation records in these states reach back well into the early 20th century and in some cases, the late 19th century. There are many weather stations in this region that were available for analysis, however a station selection for this study was based on certain criteria. Three conditions were established:

1) The station must possess a record of daily precipitation data beginning at least on or prior to January 1, 1950.
2) The station must not be within a 50 mile (80.47 km) proximity to another selected station.
3) The station must have a data record that is at least ninety-five percent complete (five percent or less missing data).

Using the COOP Network of weather stations, maps of the region, and analysis of the station history, the stations were selected. The first step in station selection was based on geographical location. The seventy stations selected ultimately provide for sufficient coverage of the study area including a wide variety of elevation heights. In many of these cases however there was a lack of complete data. In this instance, a nearby station was chosen and then analyzed for data completion. This manual process continued until the seventy stations used in this study were selected.

Of these seventy stations, twenty-four were found to have a data record greater than ninety-five percent complete since 1908. A handful of other stations have records dating back to 1908 or before, but had too much missing data for analysis. Choi and Meentemeyer (2002) aimed to calculate simple statistics for daily precipitation in a long period of record (POR) and the computation of runs of anomalous days necessitates records that are of high quality and uninterrupted. It is also suggested that there are issues with the interpretation of precipitation time series. With this in mind, the investigation continued with confidence in the data being of high quality. Keim et al. (1995) indicate that such problems arise from large interannual and spatial variability, which establishes “noise” and greatly hinders the examination of temporal trends. To satisfy this statement, it would be necessary for the studies conducted in this research to use consistent starting dates. In doing so, results will be easily comparable between stations.

Ninety-five percent complete records are used as the standard in this study. This decision as partly based on Quiring (2009) who used weather stations located in Texas to examine drought, and he used station records with less than five percent missing data. In this study, the percentage of missing data for each station was calculated by simply dividing the number of days with missing records by the total number of days used for that specific station.

Furthermore, for the remaining forty-six stations without clean records since January 1, 1908, the year 1950 was selected as the first year to keep a consistency throughout the results. In addition, most of the stations without records dating back to 1930 began recording precipitation daily in the 1940s. For that reason, the analysis herein for those stations without complete records dating back to 1908 will begin January 1, 1950. Due to data limitations, a starting year of 1950 was selected. This allows for a fifty-nine year study period, which should allow for a reliable climatological analysis.

The justification for averaging the length of dry spells is such that this study of drought will be conducted on a daily basis rather than monthly like many other drought studies. Some popular monthly moisture and drought indices are the Palmer Drought Severity Index (PDSI; Palmer 1965), the Rainfall Anomaly Index (RAI; van Rooy 1965), the Bhalme and Mooley Drought Index (BMDI; Bhalme and Mooley 1980), the Standardized Precipitation Index (SPI; McKee et al. 1993, 1995), and the Reclamation Drought Index (RDI; Weghorst 1996).

Additionally, several drought indices are conducted weekly or bi-weekly such as the PDSI and the Crop Moisture Index (CMI; Palmer 1968).

A monthly study in particular might not index environmental conditions up to 30 consecutive days from July 1 to July 31, without rain if a heavy rainstorm occurred on July 1. A given storm might be enough rain to give the month a near-average amount of rain, when in fact, there were 30 days in a row without rain. This same rationale goes for two consecutive months. If it rains heavily on the first and last day of a sixty day period, a monthly index would not indicate the 58-day dry run in between with no recorded rainfall, and the associated impacts. This daily study may prove helpful towards creating a more detailed and accurate account of the dryness of an area at any given time.

In Chapter Three, for each year of record, the inter-arrival periods between recorded rainfalls are determined at each station. The length of each set of dry days for that year is averaged using the “R” computer program (Hubbard et al. 2004). A program was written to automatically calculate the average number of dry days between days with recorded rainfall for each year. Recorded rainfall of 0.01 inches is the smallest amount that can end a dry run. Once 0.01 inches of rain is recorded, the amount of days counting back from that day to the last recorded rain day is found. The length of this dry run is averaged with the other dry runs for that year to get an annual average length of dry spells.

In Chapter Four, manual calculations were used to find the annual maximum dry spells for each year on record at each station. Rather than sifting through the all the raw data manually, the Climate Information for Management and Operational Decisions (CLIMOD) was used to gather all the dry spells exceeding a certain truncation level at each location. The CLIMOD system provides users with web-based access to a vast amount of data and information powered by the Applied Climate Information System (ACIS) developed by the NOAA Regional Climate Centers (Hubbard et al. 2004). The Southern Regional Climate Center's (SRCC) website provides access to CLIMOD. The truncation level was set as such to ensure that in this group of dry spells, at least one was found for each year. At this point it became a matter of finding the longest event in a smaller list from each year. This method was sufficient enough to complete the analysis in a reasonable time-frame. Moreover, this process allowed for a thorough manual analysis of the longer dry spells that occurred, even if they were not all the longest in a given year. For instance, a station might show fifteen days as the longest dry spell for that year. This may seem short and therefore suspicious on the surface, but with this manual method, an investigator may discover that there were six other 15-day events and with other 14-day events, etc. Simply put, even though a station's longest dry spell for a given year is short, it may not directly relate to an above average year for precipitation.

In Chapter Five, return periods will be calculated for the selected sites. To do so, the longest dry spells are extracted from each data set. Each station in the study area varies in the true total length of record with some extending back over 100 years, and others not beginning until the 1940s. For this analysis, the number of extreme dry spells for each station will equal the number of years in the data set. This produces a new data set referred to as a partial duration series (PDS) which are frequently implemented in analyses of extreme values (Hershfield, 1961; Dunne & Leopold, 1978; Keim & Faiers, 2000). In using these datasets, I will determine the 100-, 50-, 25-, 10-, 5-, and 2-year events for dry spells. The Weibull Plotting Position Formula will be used to determine the Annual Exceedence Probability for each dry spell in the PDS. Two regression methods will be used in the distributions of the results. They are Huff-Angel (H-A) developed by Huff & Angel (1992) and the Southern Regional Climate Center method (SRCC) developed by Faiers et al. (1997). I will then use a goodness of fit test implemented by Keim & Faiers (2000). These resulting return periods may prove useful to emergency managers and planners who work specifically with drought-like conditions in the areas represented in the study area. For emergency management methods directly tied to natural disaster-type emergencies, it is important to begin with understanding the climatologies of that location.

2.5 Preview of Following Chapters

In the next three chapters, the analysis conducted will be explained and portrayed graphically. Each chapter will discuss a separate type of analysis performed with the same overall dataset for the study area. The methods mentioned above (Section 2.4) will be used and underlying trends in the occurrence of dry spells over time at each station will be revealed. In the closing chapter, a summary will be made in addition to the concluding remarks in relation to the results of the analysis.

Chapter 3: Annual Average Dry Spells

3.1 Introduction

There are several published methods of measuring drought in various ways. The Rainfall Anomaly Index (RAI), the Bhalme and Mooley Drought Index (BMDI), Standard Precipitation Index (SPI), and the Reclamation Drought Index (RDI) each incorporate several factors and take measures on a monthly scale. The Palmer Drought Severity Index (PDSI) and Crop Moisture Index (CMI) are both indices of the relative dryness or wetness which affects water-sensitive economies. Furthermore, the PDSI is a bi-weekly index and the CMI is conducted weekly. Although the PDSI is considered widely used and respected as a measurement of drought, there is not one single index that might be considered as the most accurate and useful in all situations. This study focuses on dry spells, defined as lengths of consecutive days with no recorded rainfall. Rather than measure dry days from weekly, monthly, or longer durations, this analysis will consist of determining the inter-arrival times between each precipitation event, and then averaging these lengths of dry runs throughout each year for each station included in the analysis. No other weather-related elements or factors will be involved in this study other than days with less than 0.01 inches recorded precipitation. This should provide a unique dataset suitable for further analysis. From the lack of a true definition of drought and no single agreed upon measurement, the inspiration to conduct this study arose. The objectives of this chapter are as follows:

1. Create a time series displaying temporal variability for the annual average dry spells at the selected stations in the study area.
2. Test for trends of annual average dry spells at each station for durations of 58 years and 101 years.
3. Examine spatial variability of annual average dry spells across the study area.

3.2 Literature Review

This chapter examines the annual average dry spells at each of the 70 station in the study area. Temporal variability will examined by using time series for each location by analyzing daily precipitation data for the year 1950-2008 and 1909-2008. Quiring (2009) used five percent as the benchmark for amount of missing data. Recently, two studies analyzed dry spells using similar methods as those used herein. They are Nasri and Modarres (2008) and McCabe et al. (2010). Conducting a trend analysis is a method that has been widely used by various studies for identifying trends. Such studies include Howells (1981), Walsh et al. (1982), Yu and Neil (1993), Keim and Muller (1993), Keim et al. (1995), Keim (1997), Keim and Cruise (1998), Shankman et al. (2005), and Groisman et al. (2005). The Spearman Rank Test is used to determine the relationship between the average annual length of consecutive dry days and the year in which they take place. To generate a valid trend, the test must find a statistically significant association between the data and the year. The Spearman test is also used by Hanson et al. (1989) to find trends in annual rainfall in the United States, by Yin (1993) to detect trends in PDSI values, by Keim et al. (1995) for trends in annual precipitation and runoff in Louisiana, by Keim (1997) to find trends in heavy rainfall across the southeastern United States, by Keim (1999) to find trends in the annual maximum precipitation in the southeastern United States, and by Groisman et al. (2005) to detect trends in intense precipitation in many locations globally.

3.3 Methods

Daily precipitation values are analyzed for this study at seventy stations across the Southern region of the United States. For this chapter, six of these stations will provide the focus needed to examine the data sets used in the analysis in detail. One station from each of the six states was chosen for their long duration and high quality record of 101 years. This will allow for a focus of longer duration on the study area. To do so for all 70 stations may be a bit overwhelming for a reader to comprehend. However, all 70 stations will be utilized for the trends analysis later in the chapter. The six stations with century-long records selected are Luling, Texas, Ardmore, Oklahoma, Morgan City, Louisiana, Calico Rock, Arkansas, Natchez, Mississippi, and Brownsville, Tennessee (Figure 3.1).

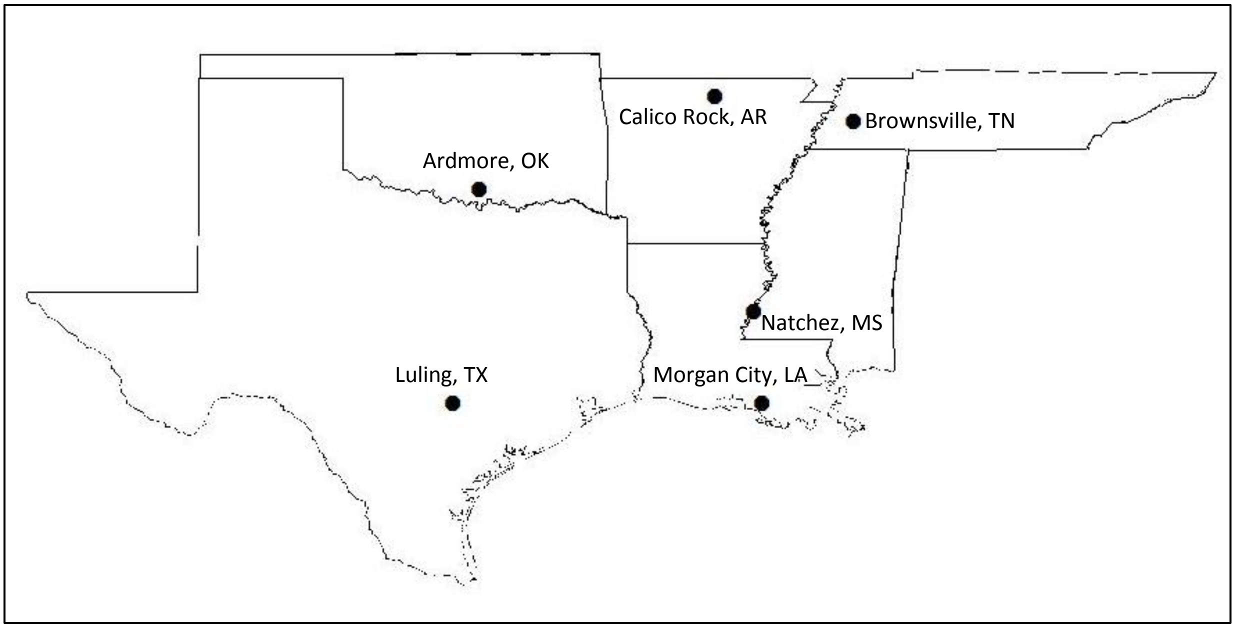

Figure 3.1. One station chosen from each state for their long duration and high quality record of 101 years.

In the following paragraphs, these stations are analyzed separately. For each station, precipitation days from January 1, 1908 to December 31, 2008 are displayed graphically. A precipitation day is defined as any day that records a measured precipitation of 0.01 (0.25 mm) inches or more. Traces of precipitation are considered dry days. In each of these graphs, the blue color indicates a precipitation day. The gray color shows a day with no rain and white is used to show days in which data are missing. The clusters of gray, or dry spells, shown in these graphs are the driving force behind this study i.e., (Fig. 3.2). In Fig. 3.2 and other similar figures, day 1 is January 1^{st} for every year and day at the top of the graph is December 31^{st}. By displaying the daily precipitation in this manner, it is easier to visualize long runs of dry days that exist at these stations throughout their entire record.

The Spearman Rank Test is used to identify trends in the data sets for each location in the study area. The correlation coefficients (ρ) produced by the test will determine if a station's trend is negative or positive. If the value (ρ) is less than or equal to 0.10, it is a significant trend at the 90% confidence level. This is done for the 70 stations for the years 1950-2008 and for the 24 stations during the period of 1908-2008.

A time series is created displaying all 70 stations' annual average dry spells. Each stations annual average dry spell values for the years 1950-2008 are averaged and then shown in a single time series to identify spatial variability.

3.4 Interannual Variability

A data set of protracted periods of dry weather is an important component of a location's climatology that has yet to be studied thoroughly. For this chapter, daily precipitation was examined for all seventy stations listed in Chapter 2 from 1950 to 2008. These data were obtained through the program CLIMOD available on the Southern Regional Climate Center's website (www.srcc.lsu.edu). The year 1950 was chosen as a starting point for this study due to the majority of the weather stations' precipitation records began in a variety of different years in the 1930s through 1940s. Therefore, to keep the study consistent, 1950 was selected as a common starting point. However, twenty-four stations consisted of precipitation records dating back to at least 1908. For those stations, a 101-year study was done with the intent of showing an extension of any underlying trends found in the shorter study. In addition, with a large scale study area, I hoped to find significant similarities in these trends of dry spells throughout the region. This analysis is not only aimed at finding these trends, but also to examine the annual average consecutive day dry spells. Each run of days with no recorded rainfall on record for each station was averaged annually. A time series was created for each station to show the annual variability associated with the dry spells. One station is chosen from each state in the study area to display the interannual variability, with a more comprehensive study to follow in this chapter.

3.4.1 Morgan City, Louisiana

The station at Morgan City possesses one of the longest and most complete records in the entire study area. From 1908 to 2008, only 0.7% of the data are missing. This means that out of 36,891 days in those 101 years, only 273 days are missing precipitation data, which is outstanding in relation to stations across the overall study area. Located at 29.68° N, 91.18° W, the station at Morgan City, LA is very near the Gulf Coast of southern Louisiana and coincidently has the lowest elevation of all stations in the entire study area, at 5 feet (1.524 meters) above sea level. Figure 3.2 below shows the daily precipitation for Morgan City for the years 1908-2008.

A prevalent signal beginning late summer through late September identifies the time of year that convective thunderstorms are more likely (Fig. 3.2). This explains the cluster of precipitation days that seems to appear nearly every year during that time.

Figure 3.3 is the time series created for the annual average dry spell lengths at the station in Morgan City, Louisiana. On the surface, there is certainly some temporal variability in the graph above with peaks of longer average dry spells in the late 1910s, late 1920s, mid 1940s, mid 1950s, early 1970s, and late 1990s, but it is difficult to tell if there is an overall trend associated with this station.

A negative trend would indicate that the annual average dry spell lengths are shortening in length over time and the days with measured rainfall are occurring more often. The longest

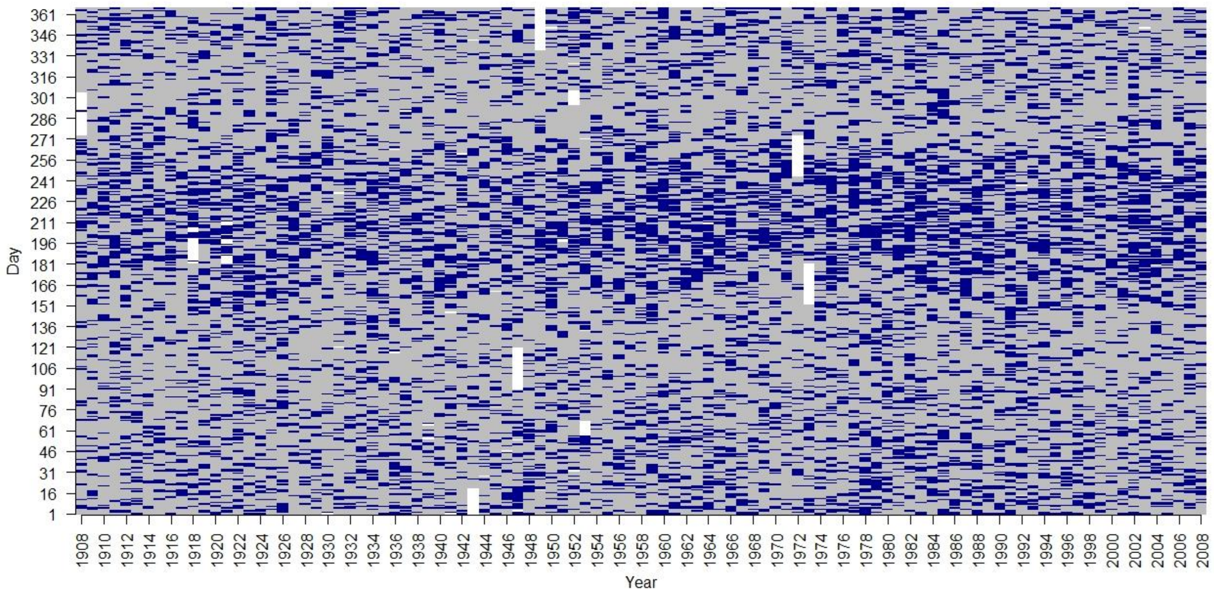

Figure 3.2. Daily Precipitation for Morgan City, Louisiana.

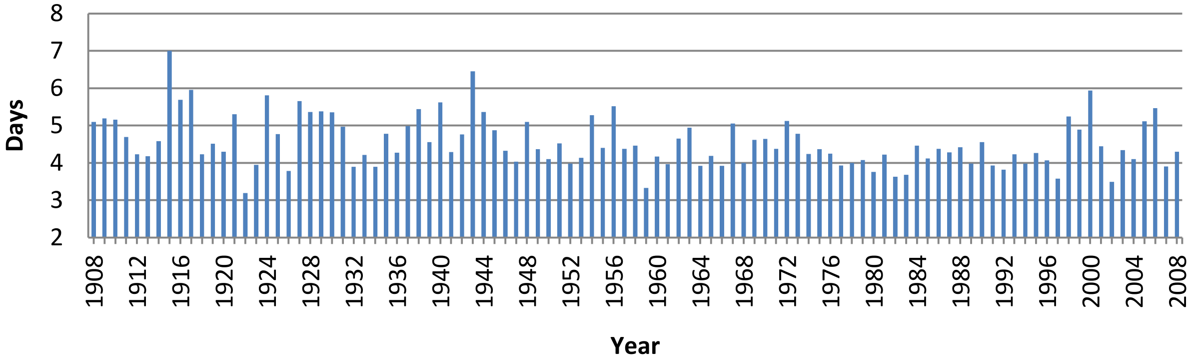

Figure 3.3. Annual average dry spell time series for Morgan City, LA

annual average dry spell is 7.0 days in 1915. The shortest annual average dry spell is 3.19 which occurred only 7 years later in 1922 indicating interarrival times in 1915 were twice the length of those in 1922. The total annual precipitation for 1915 was 43.06 inches (70% of normal) and more than 1.5 times more in 1922 with 66.43 inches (108% of normal). In addition, there were

78 precipitation days in 1915 and 132 precipitation days in 1922, nearly double. It is important to note that the average amount of precipitation per precipitation day is nearly the same for both years; 0.55 inches in 1915 and 0.50 inches in 1922.

3.4.2 Luling, Texas

Luling, TX is located at 29.67° N, 97.66° W, approximately 60 miles east of San Antonio, TX and has an elevation of 398 feet (121.31 meters). The precipitation record for Luling dates back to 1908 and is only missing 0.31% of the data (116 days (157 days less than at Morgan City, LA)) (Figure 3.4). It is necessary to note that the summer convective pattern illustrated at Morgan City, LA (Figure 3.2) is not evident for Luling, TX. This is most likely because Morgan City is closer to the moisture-laden air near the Gulf of Mexico. Luling, TX may be just to the west of the area that receives more moisture in the air from the southerly winds from the Gulf.

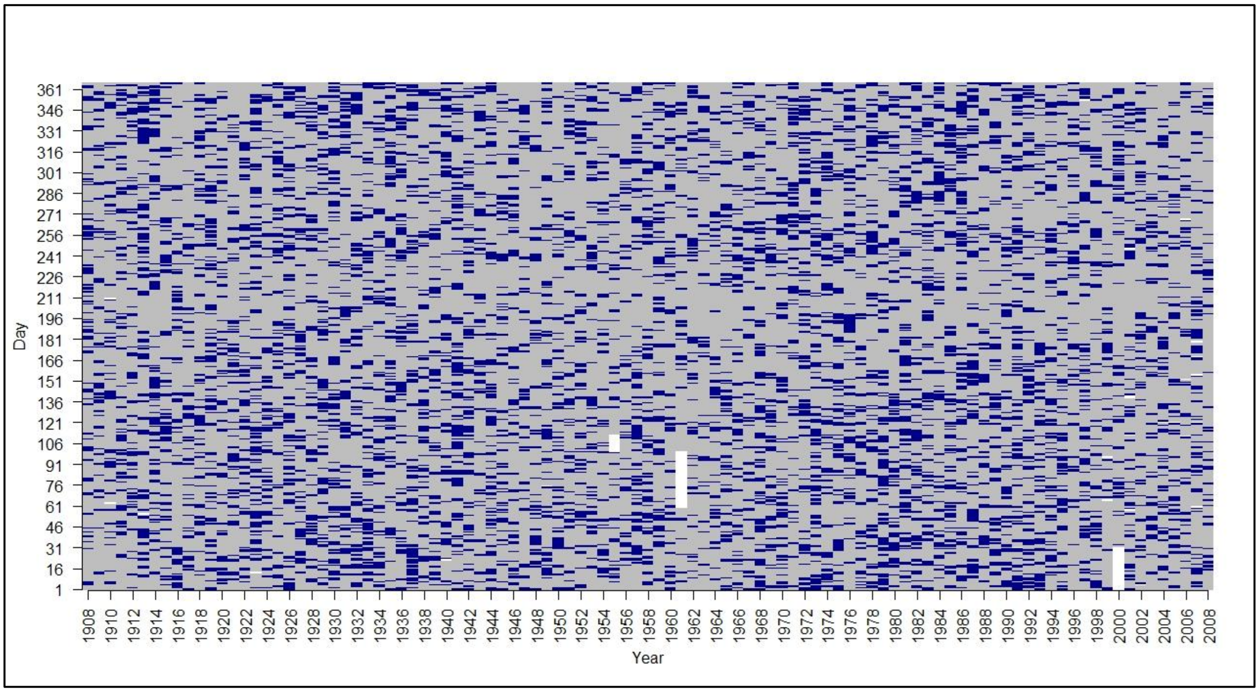

Figure 3.4. Daily Precipitation for Luling, Texas.

Figure 3.5 also shows variability in the annual average dry spell lengths and shares some of the longest values in the same years with Morgan City. However, each of these values are substantially higher than those at Morgan City. The highest annual average dry spell is 9.39 days in 1947 and the lowest 4.06 days in 1923. Similar to Morgan City, interarrival times are more than twice the length in 1947 as compared to 1923. For 1947, annual precipitation totaled 26.0 inches (75% of normal). There were 58 precipitation days with an average amount of precipitation of 0.45 inches per precipitation day. For 1923, annual precipitation was 45.44 inches (132% of normal) with 116 precipitation days and an average of 0.39 inches per precipitation day. There were half as many precipitation days in 1947 compared to 1923 and nearly 1.75 times more total rainfall in 1923. The year 1923 did not have the highest annual precipitation, nor was 1947 the lowest, but this analysis of the precipitation certainly supports the pattern that the years with longer average annual dry spells fall within years with lower than normal annual precipitation. It should be noted that the years with the lowest annual average dry spell lengths for Morgan City, LA (1922) and Luling, TX (1923) are only one year apart.

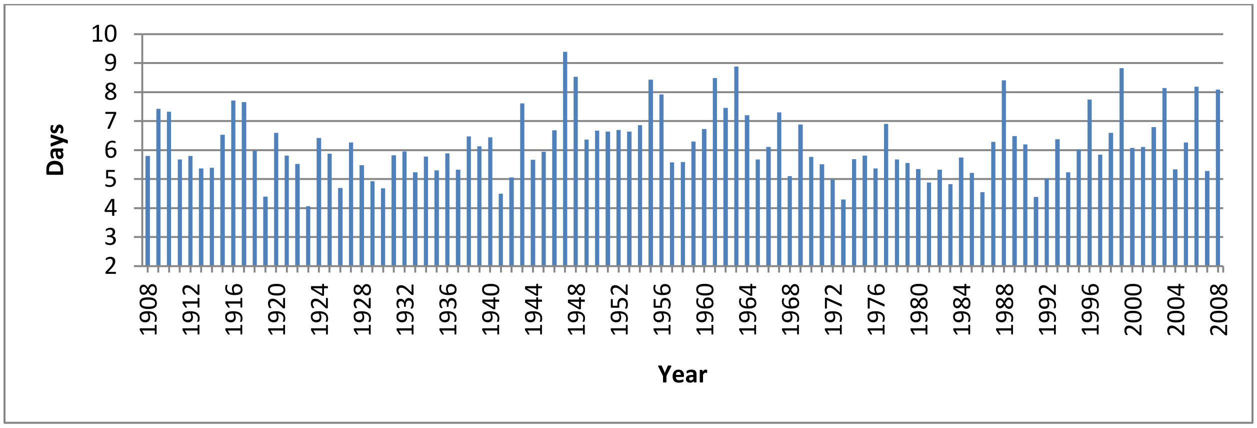

Figure 3.5. Annual average dry spell time series for Luling, TX.

3.4.3 Brownsville, Tennessee

For Brownsville, Tennessee's record from 1908 to 2008, only 1.56% of the days are missing data (577 days). The station is located at 35.59° N, 89.26° W, approximately 60 miles northeast of Memphis, TN. Even though it is much farther north than Luling, TX, the elevation at Brownsville is lower at 330 feet (100.58 meters). Figure 3.6 illustrates the daily precipitation data collected for Brownsville. There is a pattern of many precipitation days earlier in the years and more dry days in the latter part of each year. In the year 1953, there was a run of 82 days with no recorded rainfall between August 6 and October 26. This is the longest dry spell at Brownsville in the period of record. Figure 3.6 illustrates a clear, uninterrupted band of gray from day 218 to day 299 in the year 1953.

Brownsville is another station that shows quite a bit of variability, but no trend appears evident. Below is the annual average dry spell time series for Brownsville (Figure 3.7). Several peaks are shown starting with the first few years in the data set (1908-1911), also the mid-1950s, mid-1960s, late 1970s, late 1980s, late 1990s, and around 2007. The highest annual average dry spell length is 6.12 days in 1908 and the shortest is 3.34 days in 1937. This gives Brownsville an annual average dry spell length range of 2.78 days, lower than both Morgan City and Luling.

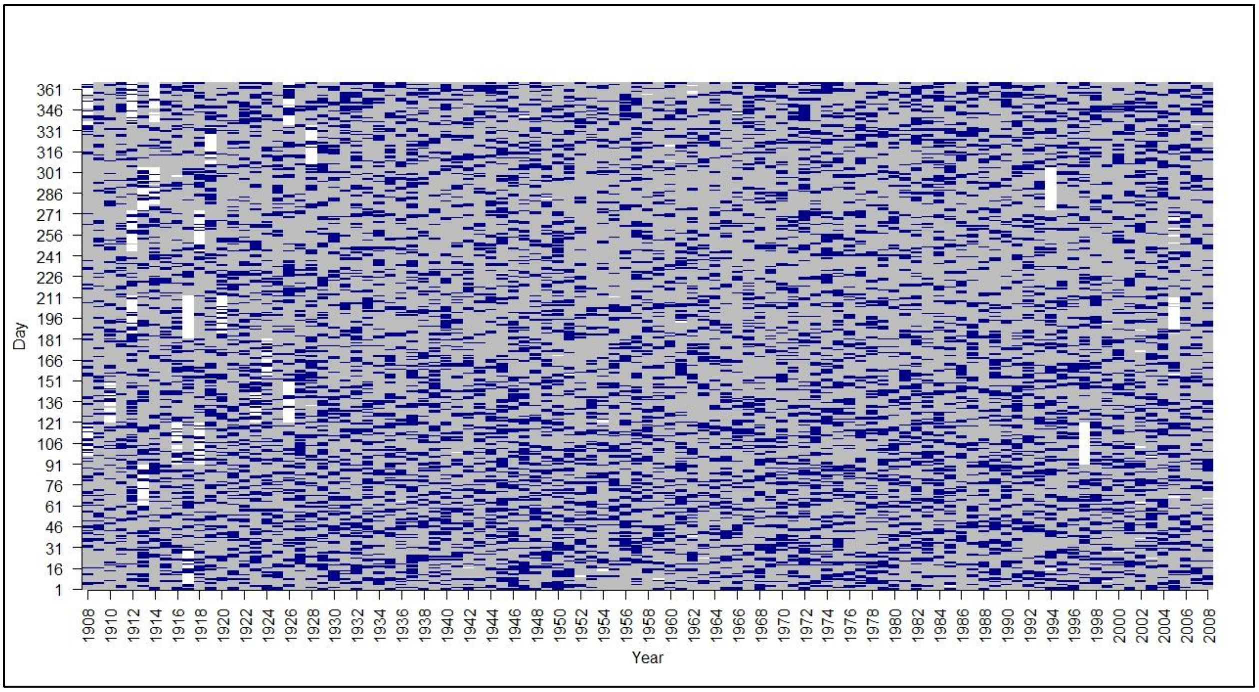

Figure 3.6. Daily Precipitation for Brownsville, Tennessee.

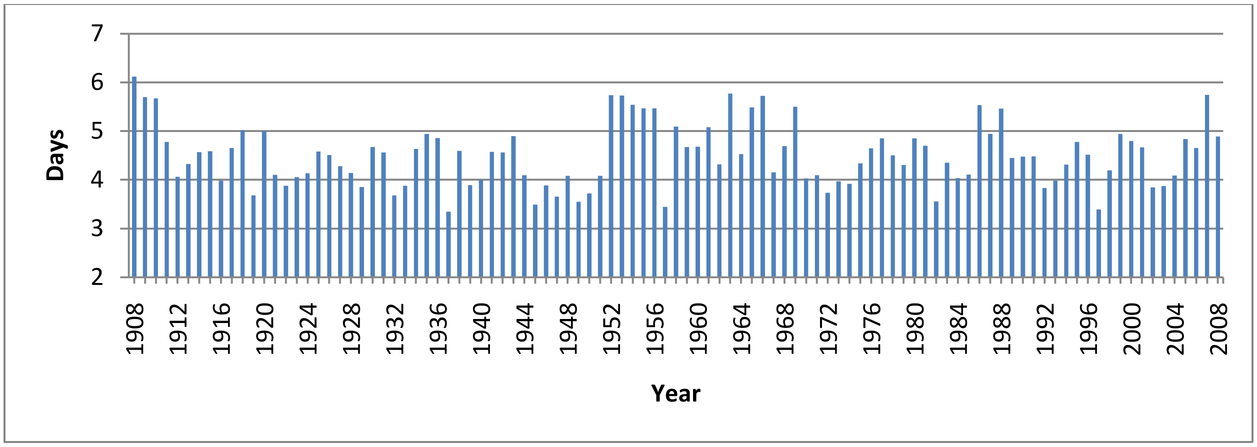

Figure 3.7. Annual average dry spell time series for Brownsville, TN

The annual precipitation for 1908 is 43.79 inches (85% of normal) and 67.12 inches for 1937 (130% of normal). The number of precipitation days for 1908 are 72 with an average precipitation per rain day of 0.61 inches. In 1937, the number of precipitation days are 133, with an average of 0.50 inches of precipitation per precipitation day.

3.4.4 Ardmore, Oklahoma

Ardmore, Oklahoma is the only station selected from Oklahoma that has a complete enough record for this study dating back to January 1, 1908. The station is located at 34.17 N°, 97.13 W°. The elevation is 880 feet (268.2 meters) and the precipitation record is missing only 2.75 percent of the data which is 1,016 days out of the total 36,891 used in the analysis (Fig. 3.8). A similar signal to Morgan City (Fig. 3.1) is shown, but less prevalent, at Ardmore earlier in the year. There seems to be a heightened seasonality in precipitation days with clusters of blue illustrated through the spring season (Figure 3.8).

Figure 3.9 shows the interannual variability of the annual average dry spells for Ardmore, OK. A major flaw with the data from Ardmore exists however. For the years 1947, 1957, and 1981, there is a large percentage of data missing. These years are highlighted in red for Figure 3.8.

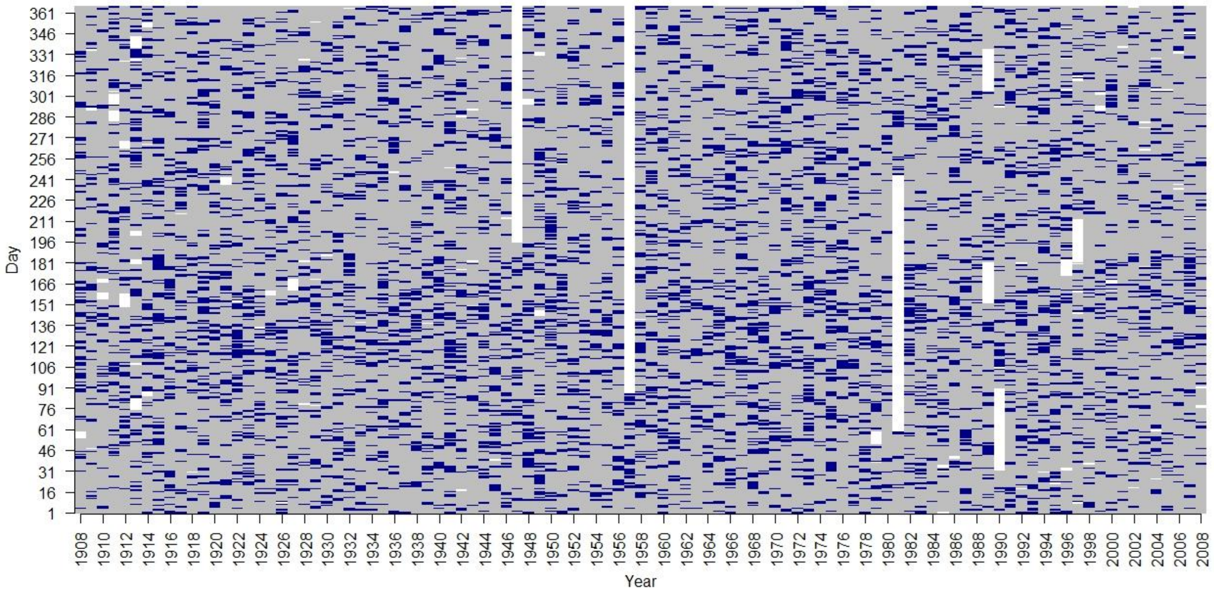

Figure 3.8. Daily Precipitation for Ardmore, Oklahoma.

There are 170 days missing in 1947, 279 days in 1957, and 184 days missing in 1981. There are 58 days of no recorded precipitation between November 4 and December 31 in 1950. This dry run is also clearly noticeable in Figure 3.8. This amounts to 633 days and 62 percent of all the missing data for Ardmore from 1908-2008. Therefore, these three years were removed from the time series. By removing these years, the new data set becomes 99.0 percent complete. In the original time series, these years showed were some of the shortest annual average dry spell lengths on the graph. By removing them, one might get a clearer sense of the true interannual variability of the data set for Ardmore.

There certainly seems to be more of a variable pattern in the latter half of the data set as opposed to the first half in which a few more anomalies are present. Unchanged by omitting the three years, was the longest annual average dry spell of 10.79 days in 1954. The shortest annual average dry spell is 4.47 days in 1941. The total precipitation for 1954 was 32.03 inches (91% of normal) and in 1941, it was 46.64 inches (132% of normal). Interestingly, the total number of

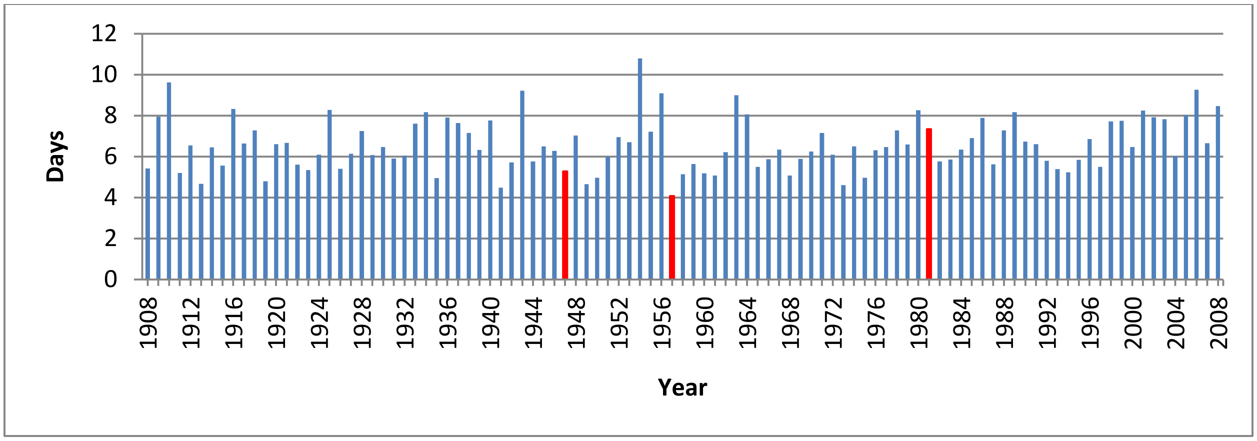

Figure 3.9. Annual average dry spell time series for Ardmore, OK. (Red columns denote years of high amounts of missing data)

precipitation days are 50 for 1954 and twice that (100) in 1941. The average precipitation for 1954 is 0.64 inches per precipitation day and 0.47 inches per precipitation day in 1941. Prior to, 1957 was the year with the shortest annual average dry spell of only 4.07 days. The 279 days that are missing in 1957 begin on January 1st and therefore skip over what is typically the dry season for Ardmore. This is a great example of how delicate these data sets can be regarding missing data. With the automatic calculation of the data sets, missing data is treated the same as a precipitation day because a day with missing data also ends a dry spell.

3.4.5 Calico Rock, Arkansas

Calico Rock, AR is located in extreme north central Arkansas at 36.11° N, 92.16 W. Located on the Upper White River in the Ozark Mountains, the station is 350 feet above sea level (106.68 meters), but one of the northernmost stations in the study area. Missing data makes up only 1.12 percent of the total data set and is temporally irregular unlike Ardmore, OK in which three years contained more than half of the missing data (Figure 3.10).

The longest annual average dry spell at Calico Rock, AR is 7.92 days in 1912 and the shortest is 3.56 days in 1944 (Figure 3.11). The total annual precipitation for 1912 was 38.86

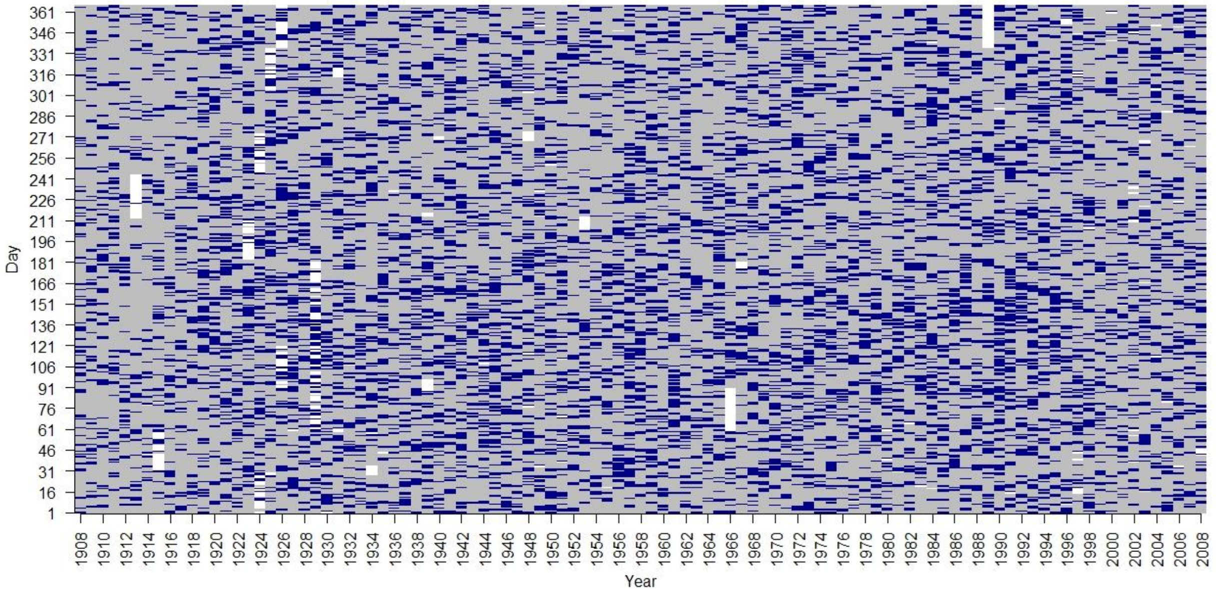

Figure 3.10. Daily Precipitation for Calico Rock, Arkansas.

inches (86% of normal) compared to 42.54 inches in 1944 (94% of normal). Also, the number of precipitation days for 1912 was 63 with a 0.61 inch average and 109 precipitation days were found in 1944 with a 0.39 inch average per precipitation day.

The interannual variability is indeed muted when compared to the other stations previously examined. There is a cluster in the beginning of the time series from 1910 to 1918 that are some of the longest annual average dry spells on record for this station. While this seems suspicious, there are only 54 days of missing data from 1910 to 1918 which only encompasses 1.6 percent of the 3,287 days during those years. These missing days can be seen in Figure 3.10, but do not seem to interfere with the results enough to create the illusion that these early years on record were drier than they really were. After 1918, there seems to be a drop followed by a period of stability until a spike in 1934 and another in 1936. Following those two years, a more variable pattern begins to present itself. Another group of dry years are

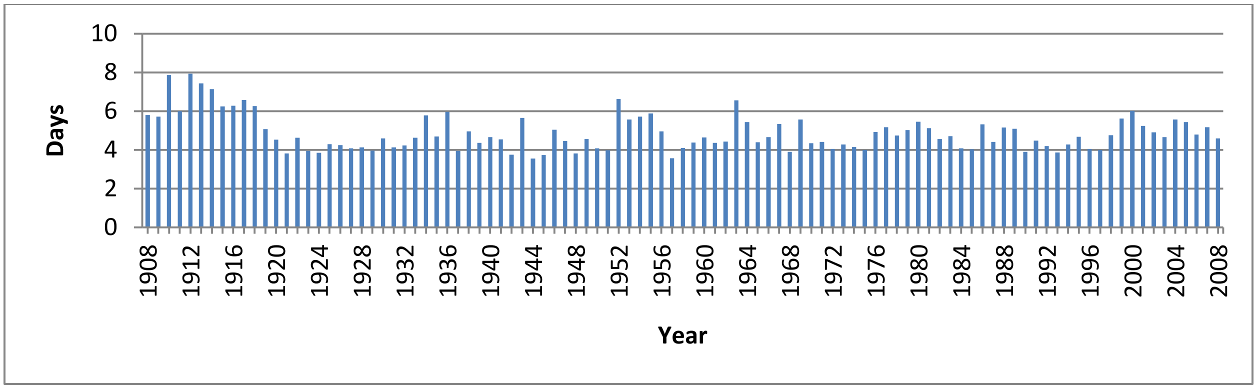

Figure 3.11. Annual average dry spell time series for Calico Rock, AR.

evident from 1952 to 1956 with another spike following in 1963, then the cyclical pattern dominates for the remainder of the time series.

3.4.6 Natchez, Mississippi

Natchez, Mississippi is located along the Mississippi River in the southwest portion of the state. The station is located at 31.59°N, 91.34° W with an elevation of 195 feet above sea level (59.44 meters). The missing daily precipitation data from 1908 to 2008 only amounts to 1.58 percent of the total data set (Figure 3.12). There are strings of missing data in certain years, but that does not seem to affect the graph as it did for Ardmore, OK. In 1964, there are 62 days missing in a row from May 31 to July 31. The annual average dry spell length for 1964 is 5.23 days, only 0.22 days higher than the average of 5.01 days (Fig. 3.12).

In figure 3.13, 1924 is clearly an anomaly as the longest annual average dry spell at 8.07 days and has no missing data. The shortest annual average dry spell is 3.6 days in 1987. The annual precipitation in 1924 was 34.24 inches (60% of normal) compared to 54.39 inches in 1987 (96% of normal). The number precipitation days was less than half in 1924 (50) than in 1987 (107). The average amount of precipitation per precipitation day was 0.68 inches in 1924 and 0.51 inches in 1987. It is also important to note that the six longest annual average dry spells for

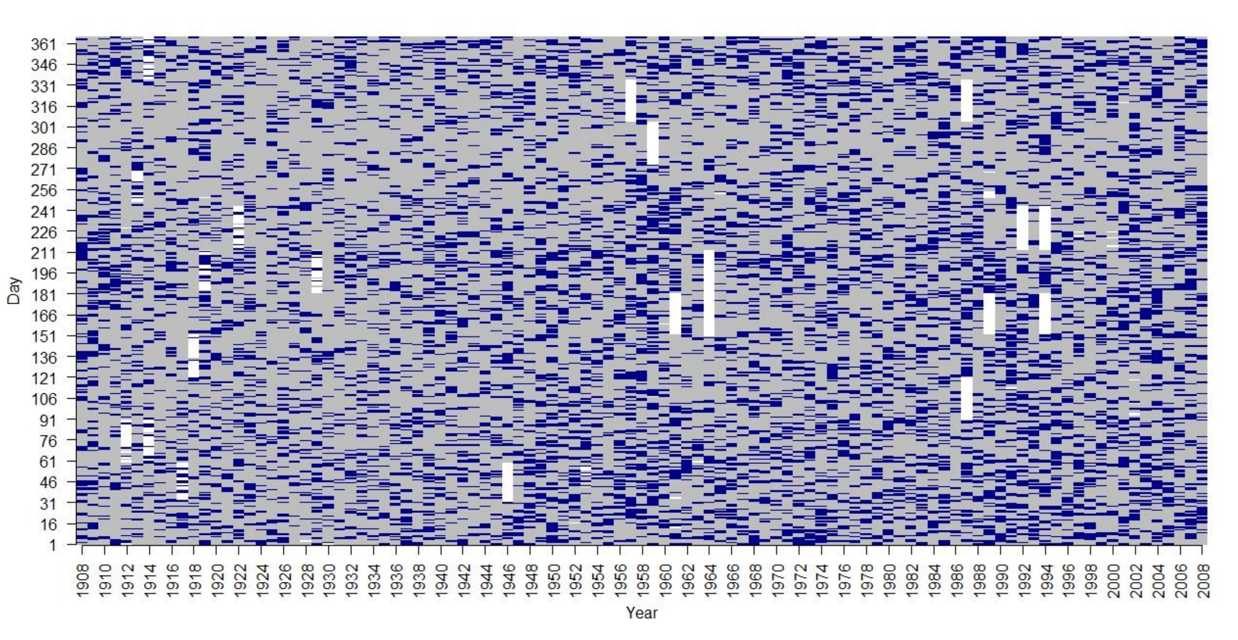

Figure 3.12. Daily Precipitation for Natchez, Mississippi.

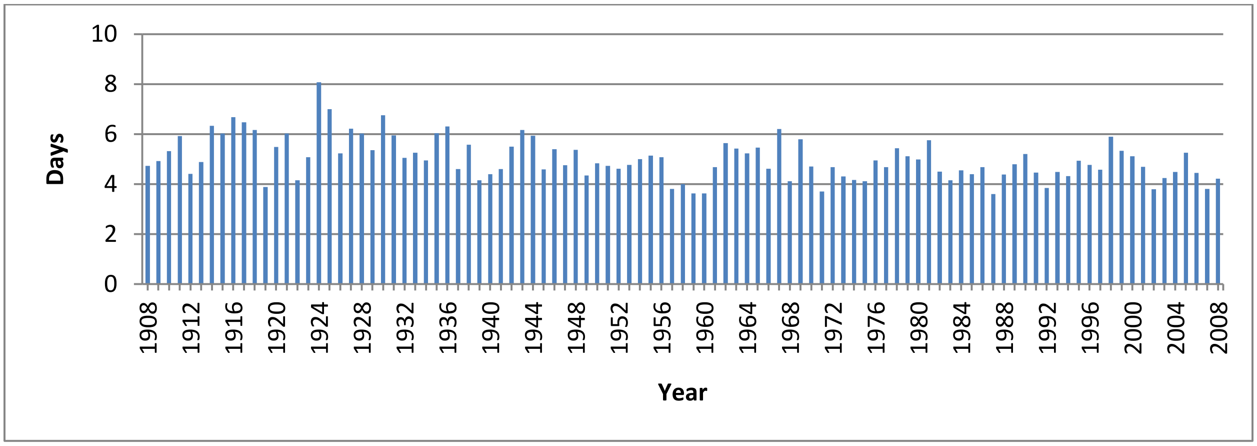

Figure 3.13. Annual average dry spell time series for Natchez, MS.

Natchez all occur before 1931 and nine of the ten longest occur before 1940. Since 1940, there seems to be a leveling off with occasional spikes thereafter.

An interesting observation is at each of the six stations analyzed above, during the years with the longest annual average dry spells, the precipitation days were significantly less (nearly half) than in the years with the shortest annual average dry spells. However, for the years with the longest annual average dry spells and less precipitation days, the average precipitation per precipitation day is more than that per precipitation day in the wet years. This suggests that for years with longer annual average dry spells, higher magnitude precipitation amounts per rain day may be expected.

3.5 Trend Analysis of Annual Average Dry Spells

Region-wide trends are observed for the annual average dry spell lengths. Other studies have used similar methods of examining trends in various weather-related frequencies. Table 3.1 lists the correlation coefficients for the annual average dry spells at the 70 stations as a result of the Spearman Rank Test.

Table 3.1. Correlation coefficients for annual average dry spells at the 70 stations in the study area. (1950-2008)

Station	**ρ**	**P-Value**	**Station**	**ρ**	**P-Value**
El Paso, TX	0.2597	0.0492	Minden, LA	-0.3622	0.0054
Balmorhea, TX	0.1995	0.1314	Leesville, LA	-0.5181	0.0000
Chisos Basin, TX	0.0342	0.8185	Natchitoches, LA	-0.3467	0.0077
Boise City, OK	0.2377	0.0700	El Dorado, AR	-0.2461	0.0611
Midland, TX	-0.1294	0.3280	Jennings, LA	-0.5241	0.0000
Lubbock, TX	0.1427	0.2849	Calhoun Research Station, LA	0.3004	0.0205
Amarillo, TX	0.1370	0.3027	Little Rock Adams AP, AR	-0.1179	0.3828
Crosbyton, TX	-0.1949	0.1412	Calico Rock, AR	0.0551	0.6613
San Angelo, TX	0.2606	0.0732	Lafayette, LA	-0.2580	0.0499
Abilene, TX	0.1482	0.2689	Winnsboro, LA	0.1281	0.3254
Altus Research Stn, OK	-0.3250	0.0124	Natchez, MS	-0.1326	0.3234
Cotulla La Salle AP, TX	-0.4375	0.0006	Morgan City, LA	-0.0608	0.6514
Freedom, OK	0.1836	0.1657	Baton Rouge, LA	-0.1952	0.1387

Table continues

Boerne, TX	-0.2205	0.0938	Greenville, MS	0.2165	0.0989
Llano, TX	-0.3243	0.0126	Donaldsonville, LA	-0.5276	0.0000
Wichita Falls, TX	-0.3252	0.0131	Houma, LA	-0.1195	0.3724
San Antonio, TX	0.1650	0.2198	Jonesboro, AR	0.1823	0.1810
Union City, OK	-0.5476	0.0000	Reserve, LA	0.0247	0.8512
Austin Mueller AP, TX	0.3034	0.0209	Clarksdale, MS	-0.2264	0.0862
Luling, TX	-0.1310	0.3219	Amite, LA	0.1137	0.3908
Corpus Christi, TX	0.2295	0.0815	New Orleans Audubon, LA	-0.1639	0.2121
Brownsville, TX	0.3377	0.0093	Memphis AP, TN	-0.0039	0.6942
Waco, TX	-0.2947	0.0235	Bogalusa, LA	-0.0041	0.3958
Ardmore, OK	0.2863	0.0477	University, MS	-0.0787	0.5590
Ponca City, OK	0.0603	0.6536	Hattiesburg, MS	0.0098	0.9198
Dallas Love, TX	0.1852	0.1702	Brownsville, TN	-0.1759	0.1824
Corsicana, TX	-0.2418	0.0683	Biloxi, MS	-0.3153	0.0161
Tulsa, OK	-0.1150	0.3972	Martin U of Tenn, TN	0.3754	0.0036
Houston Hobby AP, TX	0.2103	0.1141	State University, MS	-0.0581	0.6613
Liberty, TX	-0.2877	0.0277	Meridian Key FLD, MS	0.2653	0.0437
Lufkin Angelina Co AP, TX	0.2111	0.1098	Nashville, TN	0.0460	0.5989
Ft. Smith, TX	0.1374	0.3033	Fayetteville, TN	-0.3781	0.0040
Fayetteville, AR	-0.1561	0.2428	Chattanooga, TN	-0.1965	0.1400
Beaumont, TX	-0.4242	0.0009	Knoxville AP, TN	0.0205	0.8658
Shreveport Reg AP, LA	-0.2000	0.1338	Kingsport, TN	-0.0282	0.8316

Figure 3.14 shows results from the Spearman Rank Test after correlating the annual average dry spell lengths and the year in which they occurred. This test was first conducted for all stations beginning in 1950. Thirty-eight of the seventy stations have negative Spearman Rank

coefficients, suggesting decreasing tendencies (Figure 3.14). Three of these are significant at α levels of ≤ .05 (Memphis, Bogalusa, and Kingsport) and three others have trends of statistical significance of ≤ .10 (Morgan City, University (Oxford, MS), and State University (Starkville, MS)). Of the remaining thirty-two stations with positive trends, six are significant at α levels of ≤ .05 (Chisos Basin, Calico Rock, Reserve, Hattiesburg, Nashville, and Knoxville). Ponca City possesses a positive trend of statistical significance of ≤ .10. It should be noted that positive trends in the annual average dry spells indicate that dry spells are increasing in length, hence rainfall events are becoming spaced further apart temporally and are occurring less often over time at these locations. The opposite applies to negative trends.

There is little evidence of an overall cohesive spatial pattern across the study area. However there are some sub-regional patterns within the region. For instance, and with the exception of Midland, most of western Texas and western Oklahoma have positive trends. Conversely, along the I-10 corridor from Beaumont to Biloxi, most trends are negative. Reserve is certainly an anomaly amongst that group of negative trends since it is a statistically significant positive trend. Similarly, along the northern border of Tennessee, there are three stations with positive trends, two of which are statistically significant. However, Knoxville is negative with high significance. Keim (1997) observed a significant positive trend in heavy rainfall for Covington in southern Louisiana. Keim et al. (1995) results showed a positive trend in state- wide average precipitation for Louisiana. This evidence certainly seems to support results of this study at Louisiana stations. Twelve of the sixteen stations in Louisiana depict a negative trend in annual average dry spells. However, for this study, more important than heavy or average precipitation is how often the precipitation falls.

A potential explanation for the observed pattern in southern Louisiana might be an increase in convective activity in the warm season. The higher the chance for rain each day, the more likely these annual average dry spells trends might be negative. This should be evident in the study of seasonal variability in Chapter 5. Results therein may show a clear signal that indicates more rain during the convective season for stations in southern Louisiana and others near the Gulf of Mexico that experience convective thunderstorms more often than others in the study area.

The same analysis as above was done for the twenty-four stations with records dating back to 1908. Forty three years were added to the beginning of the previous analysis and it certainly produced some interesting results. Table 3.2 lists the correlation coefficients for the annual average dry spells at the 24 stations as a result of the Spearman Rank Test.

Conversely to the 1950 – 2008 analysis, Fig. 3.15 shows that only eight of the twenty-four stations have negative trends from 1908-2008, four of them significant (Luling, TX, Fayetteville, AR, Brownsville, TN, and Amite). The remaining sixteen stations are positive with two being significant (Donaldsonville and Knoxville).

Adding 1908-1949 to these stations is certainly helpful in broadening the perspective of the climatology of these annual average dry spells. It seems obvious that somewhere between 1908 and 2008, there may have been a shift in the length of annual average dry spells for these stations. When comparing the two sets of results, many cases are found of a station with a negative trend from 1950-2008, but a positive trend when the length of record is expanded to 1908-2008. Such cases exist at Boerne, TX, Llano, TX, Corsicana, TX, Liberty, TX, Beaumont, TX, Minden, LA, Jennings, LA, State University, MS, Morgan City, LA, and Donaldsonville, LA. Coincidently, five of these ten cases are located in Texas.

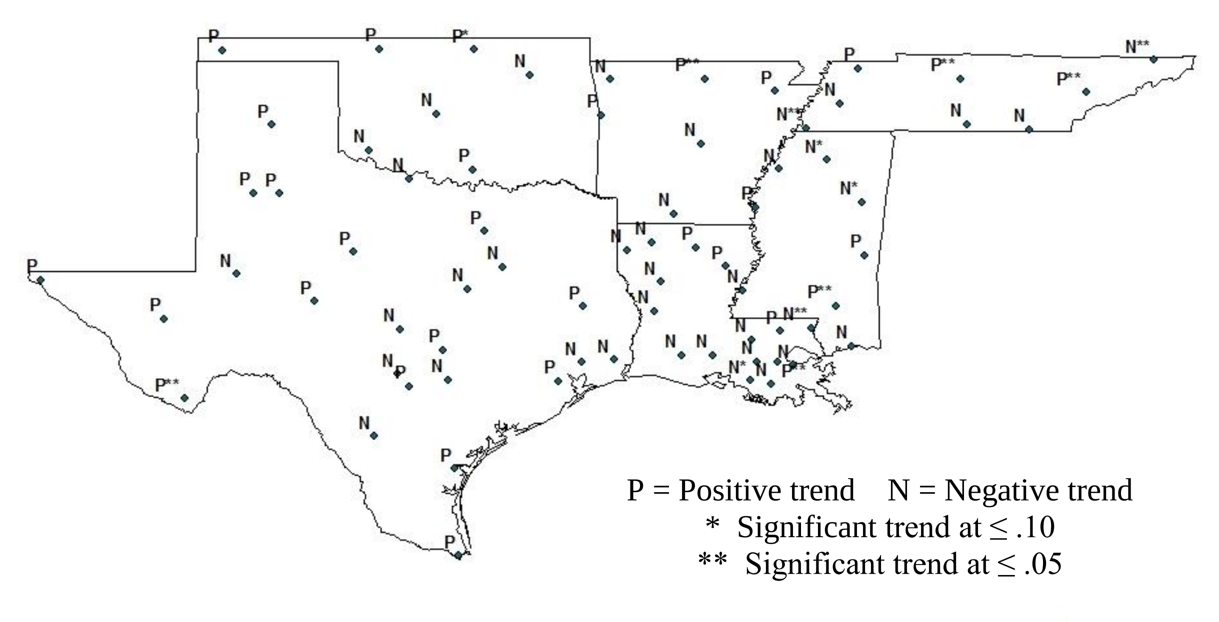

Figure 3.14. Spatial distribution of the correlations of annual average dry spells and year (1950-2008).

Table 3.2. Correlation coefficients for annual average dry spells at the 70 stations in the study area. (1908-2008)

Station	ρ	P-Value	Station	ρ	P-Value
Crosbyton, TX	0.2558	0.0102	Calico Rock, AR	0.1070	0.2932
Boerne, TX	0.2586	0.0096	Lafayette, LA	-0.1068	0.2801
Llano, TX	0.1417	0.1620	Natchez, MS	0.4508	0.0000
Luling, TX	-0.0608	0.5336	Morgan City, LA	0.3212	0.0012
Ardmore, OK	-0.1754	0.1749	Greenville, MS	-0.1653	0.0977
Corsicana, TX	0.4858	0.0000	Donaldsonville, LA	0.0883	0.4682
Liberty, TX	0.3706	0.0002	Reserve, LA	0.2351	0.0187
Fayetteville, AR	-0.0851	0.5736	Amite, LA	-0.0259	0.7934
Beaumont, TX	0.3322	0.0007	Hattiesburg, MS	0.2844	0.0046
Minden, LA	0.1328	0.1887	Brownsville, TN	-0.0261	0.7938
Jennings, LA	0.4238	0.0000	State University, MS	0.3879	0.0001
Calhoun Research Station, LA	0.1671	0.0960	Knoxville AP, TN	-0.0188	0.7901

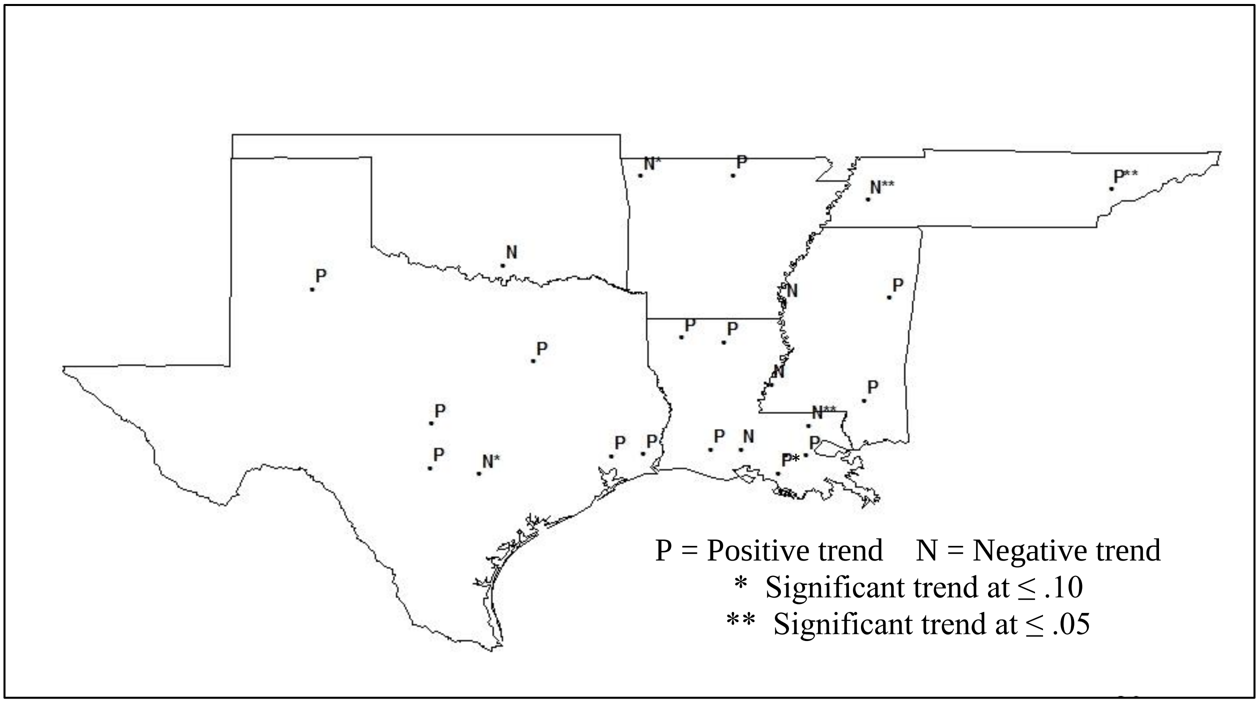

Figure 3.15. Spatial distribution of the correlations of annual average dry spells and year (1908-2008).

Interestingly, the negative trend in Donaldsonville during 1950-2008, gives way to a significantly positive trend at the 90% confidence level during 1908-2008. This may prove that the dry spells at Donaldsonville are becoming shorter, but that there was a period before 1950 when the dry spells were even shorter as to create a significantly positive trend beginning in 1908.

On the other hand, there are three cases of trends that are positive during 1950-2008 and negative from 1908-2008. This occurs at Ardmore, Greenville, and Amite. Amite stands out due to a positive trend from 1950-2008 and a highly significant negative trend (95% confidence level) from 1908-2008. In addition, there are three stations that have trends that remain the same but become significant when the time period of analysis is expanded. Brownsville, TN's negative trend becomes significant at the 95% confidence level. Luling, TX and Fayetteville, AR trends are negative from 1950-2008 and significantly negative at the 90% confidence level from 1908-2008. There is a possibility that the dry spells are becoming longer since a study of only the last 59 years lacks significance compared to the study of the entire 101 year data set. This would mean that precipitation is falling more often (in days) at these stations from 1950-2008 compared to records beginning in 1908.

Of the remaining eight stations with 101 year records, four of them reserved their positive trends (Lafayette, Natchez, Crosbyton, and Calhoun Research Station). Three saw a weakening in the significance of positive trends. Calico Rock, Reserve, and Hattiesburg all possess a significant positive trend (95% confidence) from 1950-2008 and positive trends that are not significant from 1908-2008. Of all the twenty-four stations in this particular analysis, only one station with a significant trend from 1950-2008 remained the same after adding data from 1908-1949. Knoxville's significant positive trend (95% confidence) from 1950-2008 is the same for 1908-2008.

3.6 Spatial Variability

In the graph below (Figure 3.16), all of the annual average dry spell measurements were averaged annually for each station and are displayed. These stations are listed by longitude from west to east.

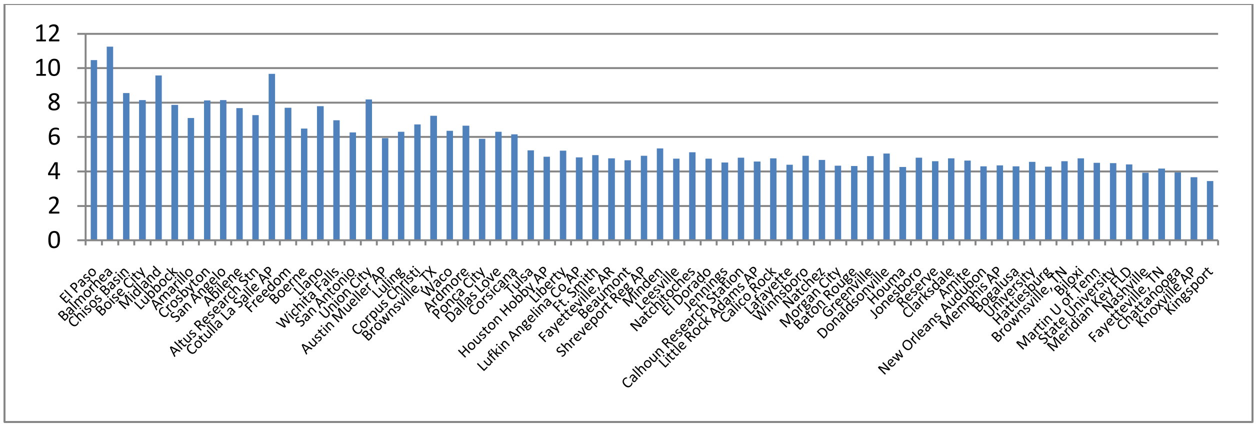

Figure 3.16. Spatial variability of annual average dry spell length averages (1950-2008). Stations are aligned from west to east.

It is curious how the graph shows a definite negative slope meaning the stations in the west average longer dry spells than those in the east portions of the study area. The left side of the geographic continuum clearly shows an overall decrease in the interarrival time length from west to east, however, near the midpoint of the study area, the averages seem to level off for the remainder of the stations in the east, beginning with stations in east Texas and Oklahoma extending eastward. It is important to remember that this graph shows each station's rainfall interarrival time averaged from 1950-2008. It does not take into account the intra-annual variability within each station's annual average dry spell lengths.

3.7 Summary and Conclusions

In conclusion, for each of the six stations chosen for closer analysis in this chapter, the year with the longest annual average dry spells had less annual precipitation and less total precipitation days than the year with the shortest interarrival time. Interestingly, the average precipitation per precipitation day was higher for those years with the longest annual average dry spells at each station. This suggests that for drier years, precipitation days are less in number, but precipitation is more intense on average for those years. Karl and Knight (1998) found that 1-day precipitation events are increasing in intensity for heavy and extreme precipitation days across the contiguous United States from 1910-1995. If those heavy and extreme precipitation days occurred during dry years, it would certainly support the results made in this chapter.

It was quite helpful to include the years 1908-1949 for the stations in which data were available and of high quality. These results may prove useful in discussions of climatological changes in the southern United States over the last century. For fourteen of the twenty-four stations used from 1908-2008, there was a changeover in the trend during that time when the period of analysis was essentially cut in half for a separate study. Two of the trends were strengthened, three weakened, and five remained consistent.

Andreadis and Lettenmaier (2006) results showed that all seven stations they analyzed in Texas had increasing trends in drought duration. In addition, all of the stations in Arkansas and Mississippi experienced positive trends. Each of these findings is predominantly consistent with the results found in this study from 1908 to 2008. Figure 3.15 illustrates that six of the seven stations experienced positive trends in the annual average dry spell lengths in for those 101 years. It should be noted that the station in Luling, Texas had a negative trend in annual average dry spell length and it was significant. However, the overall widespread spatial pattern is consistent with the results found in Andreadis and Lettenmaier (2006).

At the majority of the stations in this trends analysis, the results are not significant and thereby inconclusive. Confidence in a correlation coefficient at a given station without a significant trend is less than the pre-designated 90%. These results do not signify a strong enough confidence to be considered a trend. For all stations without a significant trend for either of the two time periods, the results will hereby be allocated as tendencies rather than trends. Therefore, for the majority of the stations (57: 1950-2008; 18: 1908-2008) the positive or negative shown on the figures above (3.14 and 3.15) as a “P” or “N” without an asterisk, depict a station in which there is only a tendency for that station’s annual average dry spells to be leaning one way or the other.   Regarding the trend analysis, more stations possess negative tendencies (54%) than positive, however it is nearly even. The trends analysis with all seventy stations from 1950-2008 seems to be more useful than the 24-station study from 1908-2008 simply because of the spatial coverage and more information can be disseminated from the 1950-2008 study.

Chapter 4: Annual Maximum Dry Spells

4.1 Introduction

Extreme weather events in a dynamic climate have become an increasing concern in recent years (Chagnon et al., 1997). The south central United States is certainly an area of the country that experiences these extremes in various forms such as hurricanes, flooding, tornadoes, and severe thunderstorms. Drought is a type of extreme weather event that because of its slow onset is often overlooked until it is too late. Furthermore, it is important to realize that drought has the potential to be as destructive as other natural disasters. The economic, social, and environmental setbacks resulting from drought are increasing considerably, however; it is complicated to measure this trend accurately because of the lack of consistent historical estimates of losses (Wilhite 2000). Wilhite (2000) also found that for the years 1963-1992, drought ranked highest among all types of natural disasters affecting one percent or more of the total population. The drought of 1988 in the United States rendered estimated monetary impacts of $40 Billion (Riebsame et al. 1991). The Federal Emergency Management Agency estimates that annual losses in the United States as a result of drought are between $6-8 Billion (Andreadis and Lattenmaier 2006). Furthermore, there is great concern over changes in the severity of drought associated with dryness during the summer projected by some climate models over the next one hundred years (Wetherald and Manabe 1995).

This chapter will analyze the same daily precipitation data used in Chapter 3, however the data sets analyzed are the longest dry spell per year for each of the datasets. This study focuses on the annual maximum dry spells, defined as the length of consecutive days with no recorded rainfall. Trends of the annual maximums are also examined. Rather than measure dry days from weekly, monthly, or longer durations, this analysis will consist of determining the longest dry spell of each year for each station included in the analysis. No other weather-related elements or factors are involved in this analysis other than days with less than 0.01 inches recorded precipitation. This should provide a unique dataset suitable for further analysis. The objectives for this chapter are as follows:

1. Create time series displaying temporal variability for the annual maximum dry spells at the selected stations in the south central United States.
2. Test for trends of annual maximum dry spells at each station.
3. Examine spatial variability of annual maximum dry spells across the study area.

4.2 Background

In reviewing the literature for publications that used similar methods as those in this chapter, examples were limited. Past studies which conducted analysis of annual maximum series were researched (Hershfield 1961; Keim and Muller 1992). Nasri and Modarres (2008) used a similar method to identify annual maximum dry spells for the Isfahan Province, Iran. To test for trend, the Spearman Rank test is used. The same test was also conducted by Hanson et al. (1989) to find trends in annual rainfall in the United States, by Yin (1993) to detect trends in PDSI values, by Keim et al. (1995) for trends in annual precipitation and runoff in Louisiana, by Keim (1997) to find trends in heavy rainfall across the southeastern United States, by Keim (1999) to find trends in the annual maximum precipitation in the southeastern United States, and by Groisman et al. (2005) to detect trends in intense precipitation in many locations globally.

4.3 Methods

Daily precipitation values are analyzed at seventy stations across the study area. For this chapter, six of these stations, one from each of the six states, were chosen for additional analysis because of their high quality record and duration of 101 years. The stations are Luling, Texas, Ardmore, Oklahoma, Morgan City, Louisiana, Calico Rock, Arkansas, Natchez, Mississippi, and Brownsville, Tennessee (Figure 4.1).

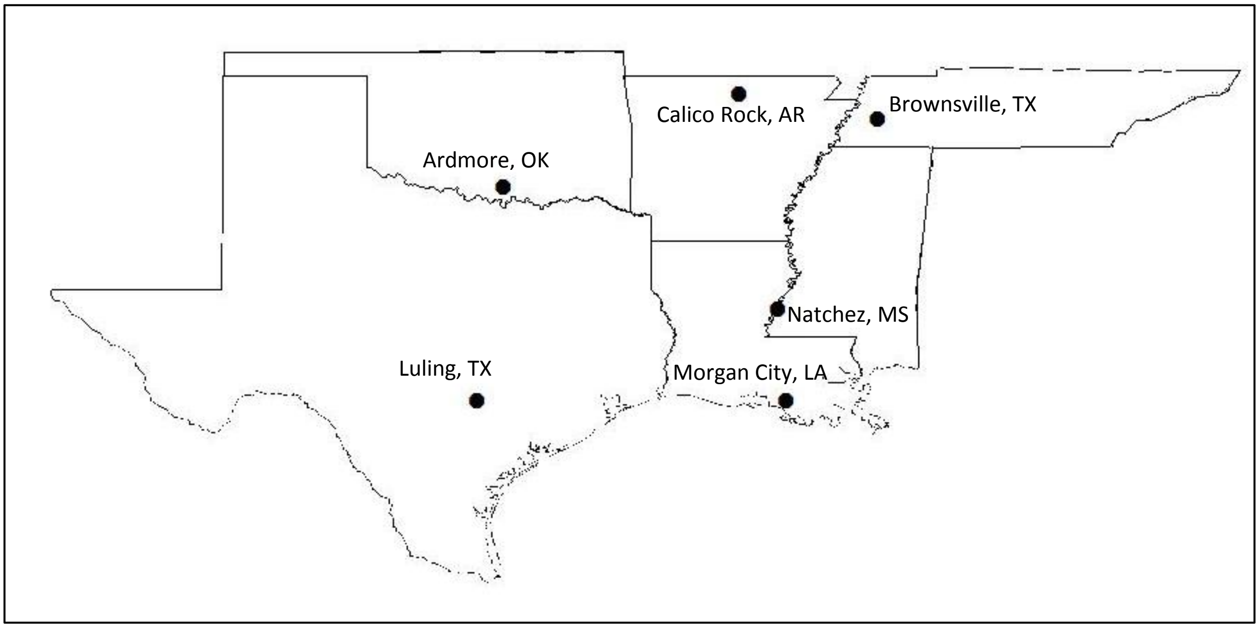

Figure 4.1. One station chosen from each state for their long duration and high quality record of 101 years.

Below, these stations are analyzed separately. For each station, precipitation days from January 1, 1908 to December 31, 2008 are displayed on a graph. A precipitation day is defined as any day that records a measured precipitation of 0.01 (0.25 mm) inches or more. Traces of precipitation are considered dry days. In each of these graphs, the blue color indicates a precipitation day. The gray color shows a day of no precipitation and white is used to show days in which data are missing. The clusters of gray, or dry spells, shown in these graphs are the driving force behind this study. By displaying the daily precipitation in this manner, it is easy to visualize long runs of dry days that exist at these stations throughout their entire record. The longer clusters of gray shown in these graphs are the driving force behind this study. Displaying the daily precipitation in this manner, it is clear to see longer runs of dry days that exist at these stations throughout their entire record.

The Spearman Rank Test is used to identify trends in the data sets for each location in the study area. The correlation coefficients (ρ) produced by the test will determine if a station's trend is negative or positive. If the value (ρ) is less than or equal to 0.10, it is a significant trend at the 90% confidence level. This is done for the 70 stations for the years 1950-2008 and for the 24 stations during the period of 1908-2008.

A time series is created displaying all 70 stations' annual maximum dry spells. Each stations annual maximum dry spell values for the years 1950-2008 are averaged and then shown in a single time series to identify spatial variability.

4.4 Interannual Variability

A data set of protracted periods of dry weather is an important component of a location's climatology that has yet to be studied thoroughly. For this chapter, daily precipitation was examined for all seventy stations listed in Chapter 2 from 1950 to 2008. The data was collected through the program CLIMOD, available on the SRCC's website (www.srcc.lsu.edu). The year 1950 was chosen as a starting point for this analysis due to the majority of the weather stations' precipitation records began in a variety of different years in the 1930s through 1940s. Therefore, to keep the study consistent, 1950 was selected as the common starting point. However, twenty-four stations consisted of precipitation records dating back to at least 1908. For those stations, a 101-year analysis was conducted with the intent of showing an extension of any underlying trends found in the study of shorter duration. In addition, with a large scale study area, there was potential to find significant similarities in these trends of dry spells throughout the region. This analysis is not only aimed at finding these trends, but also to examine the annual maximum dry spell at each station for the period of record. All strings of consecutive days with no precipitation were examined for each year and manually analyzed to determine the annual maximum dry spell. If a dry spell ran over December 31 for one year and into the next year, it was broken up into two dry spells, the first ending on December 31 and the next one starting on January 1 for the following year. This method was utilized to keep the study consistent as an annual analysis. Each maximum dry spell must be contained entirely in one year. However, it is important to note that for a handful of stations, their longest dry spell on record ran over December 31 and into the next year. They were Balmorhea, TX (195 days, 1999-2000), Boise City, OK (79 days, 2000-2001), Amarillo, TX (75 days, 1956-1957), Crosbyton, TX (127 days, 1903-1904), San Angelo, TX (116 days, 1966-1967), Altus Research Station, OK (97 days, 1950-1951), Freedom, OK (116 days, 1955-1956), Llano, TX (102 days, 1950-1951), Wichita Falls, TX (75 days, 1913-1914), Ponca City, OK (62 days, 1977-1978), and Shreveport, LA (44 days, 1955-1956). These dry spells are impressive in length, but to use them in their entirety would have been counterproductive for this annual maximum analysis. Only if an overlapping dry spell occurred during the period of record chosen for the study and was still the longest for the either year after being cut off at December 31, then that dry spell was used in the analysis. In addition, if a dry spell contained one day in which data were missing, it was omitted from the analysis. Only dry spells without missing data were used. In the following paragraphs, the six stations highlighted for this study will be further scrutinized regarding the annual maximum dry spells for the years 1908 to 2008.

4.4.1 Morgan City, Louisiana

Located at 29.68° N, 91.18° W, the station at Morgan City, LA is very near the Gulf Coast of southern Louisiana and coincidently has the lowest elevation of the entire study area, at 5 feet (1.524 meters) above sea level. The station at Morgan City possesses one of the longest and most complete records in the entire study area. From 1908 to 2008, only 0.7% of the data are missing (Figure 4.2). This means that out of 36,891 days in those 101 years, only 273 days are missing precipitation data, which is outstanding in relation to stations across the overall study area.

A prevalent signal beginning late summer through late September identifies the time of year that convective thunderstorms are more likely. This explains the cluster of precipitation days that seems to appear nearly every year during that time. In the similar graphs that follow, it

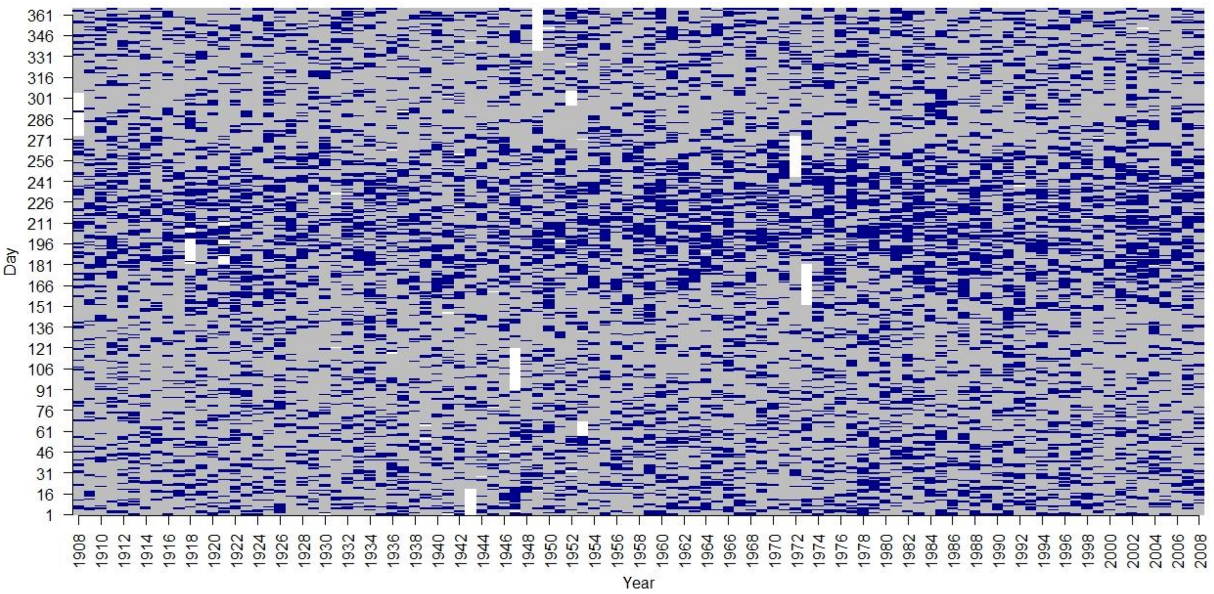

Figure 4.2. Daily Precipitation for Morgan City, Louisiana.

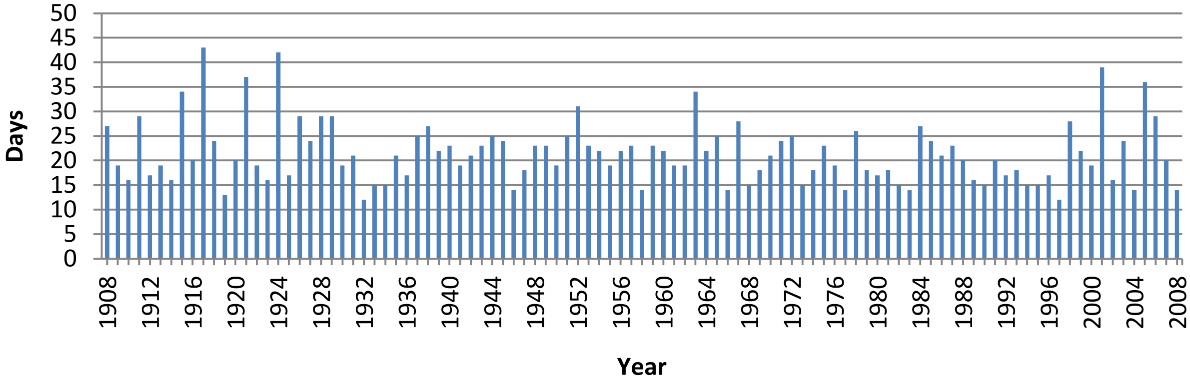

Figure 4.3. Annual maximum dry spell time series for Morgan City, LA.

is clear to see the longer dry spells illustrated by long runs of gray.

The average annual maximum dry spell for Morgan City over the 101 year record is 21.49 days (Fig. 4.3). The longest annual maximum dry spell occurred in 1917 and was 43 days long from May 14 to June 25. The second longest dry spell occurred only a few years later in 1924 and was 42 days from October 10 to November 20. The shortest annual maximum was 12 days which transpired in two different years; 1932, from January 31 to February 11 and in 1997 from May 4 to May 15. For 1917, the year with the longest annual maximum dry spell, the annual precipitation totaled 38.11 inches (62% of normal) compared to 70.67 inches in 1932 (115% of normal), the year with the shortest annual maximum dry spell. In 1917, there were a total of 79 precipitation days (days with measurements of at least 0.01 inches of precipitation) and an average of 0.48 inches per precipitation day. In 1932, there were 112 precipitation days with an average of 0.63 inches per precipitation day.

4.4.2 Luling, Texas

Luling, TX is located at 29.67° N, 97.66° W, approximately 60 miles east of San Antonio, TX and has an elevation of 398 feet (121.31 meters). The precipitation record for Luling dates back to 1908 and is only missing 0.31% of the data (116 days (157 days less than at Morgan City)) (Figure 4.4).

It is necessary to note that the apparent summer convective pattern illustrated at Morgan City, LA (Figure 4.2) is not evident for Luling, TX. Little evidence of any seasonal patterns is apparent. However, as explained for Morgan City, long periods of no rain are clearly discernible. Figure 4.5 illustrates the annual maximum dry spells for Luling from 1908 to 2008. The longest annual maximum dry spell occurred in 1916 and was 60 days long from February 1 to March 31. The shortest annual maximum lasted was 13 days in 1973, which actually occurred three separate times that year (May 13-May 25, July 18-July 30, and August 16-August 28). This is common for the years containing the shortest annual maximum. Shorter annual maximum dry spells are more common in general and therefore tend to occur multiple times in a single year.

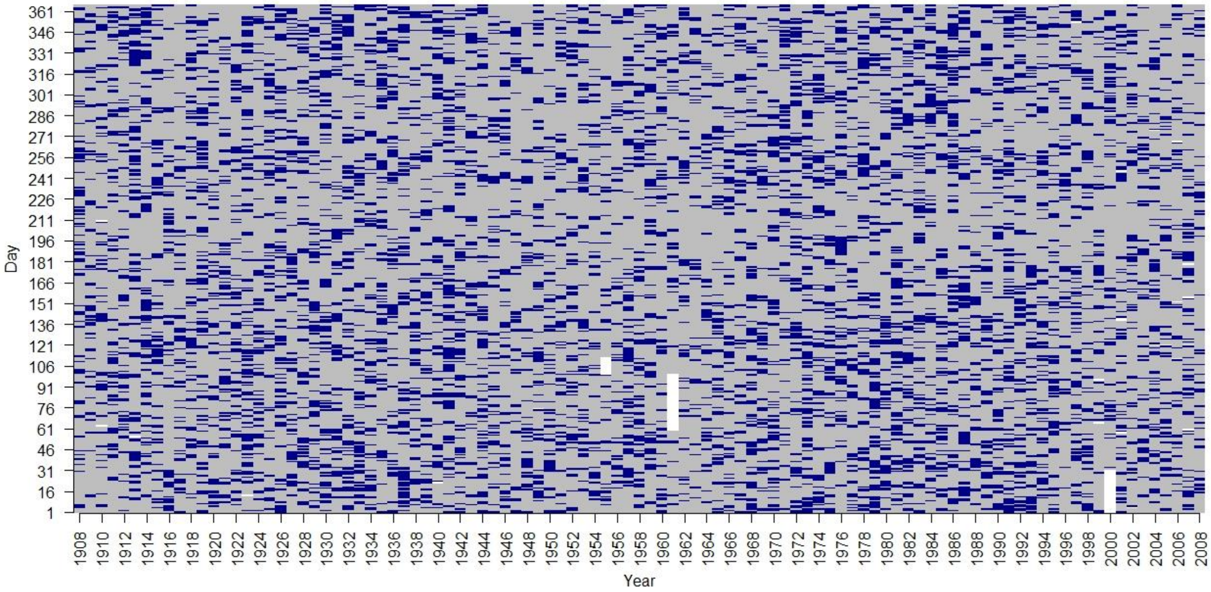

Figure 4.4. Daily Precipitation for Luling, Texas.

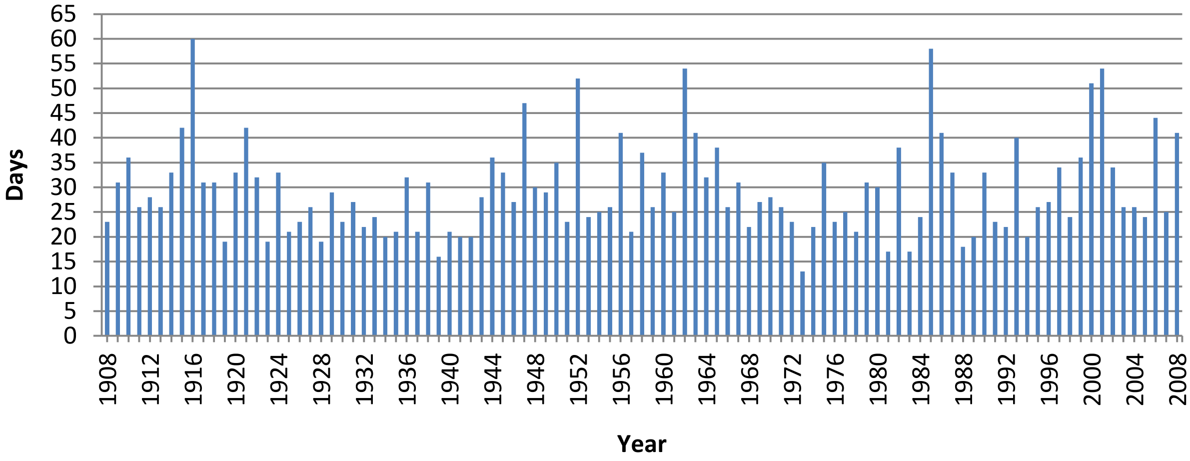

Figure 4.5. Annual maximum dry spell time series for Luling, TX.

The annual precipitation for Luling in 1916 was 23.86 inches (69% of normal) compared to 51.13 inches in 1973 (149% of normal). There were a total of 72 precipitation days in 1916 with an average of 0.33 inches per rain day. In 1973, precipitation days totaled 115 days with an average of 0.44 inches per precipitation day. Similar to Morgan City, the year with the longest annual maximum had a lower annual precipitation total, less precipitation days, and a lower average of precipitation per rain day.

4.4.3 Brownsville, Tennessee

For Brownsville, Tennessee's record from 1908 to 2008, only 1.56% of the days are missing data (577 days) (Figure 4.6). The station is located at 35.59° N, 89.26° W, approximately 60 miles northeast of Memphis, TN. Even though it is much further north than Luling, TX, the elevation at Brownsville is lower at 330 feet (100.58 meters).

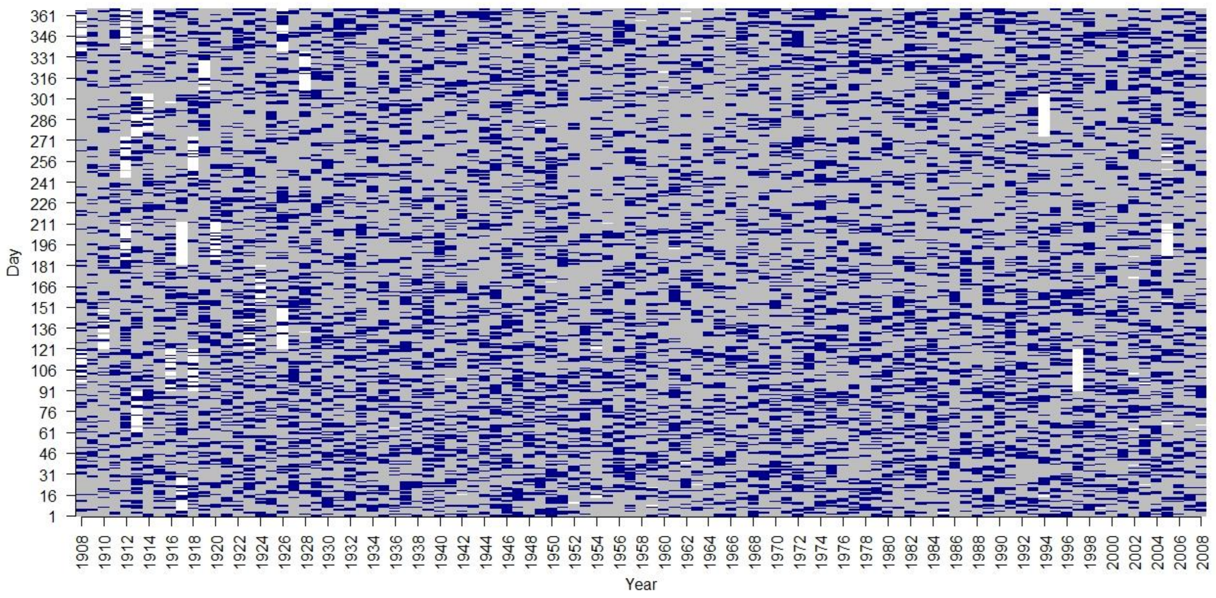

Figure 4.6. Daily Precipitation for Brownsville, Tennessee.

In the year 1953, there was a run of 82 days with no recorded rainfall between August 6 and October 26. This is the longest dry spell at Brownsville in the period of record. Figure 4.6

illustrates a clear, uninterrupted band of gray from day 218 to day 299 in the year 1953 and the dry spell is easily noticeable in Figure 4.7. This anomaly is nearly double that of the next highest annual maximum of 48 days in 1963. Analyzing the year 1953 closer for Brownsville, the day before the dry spell begins, there was a 0.36 inch precipitation event and for thirteen days prior, there was no recorded precipitation. If not for that 0.36 inches of precipitation, this dry spell could have been 96 days. During that year, there is only one day in which data are missing. However, that day is not contained in the 82 days, nor the 96 days as mentioned above.

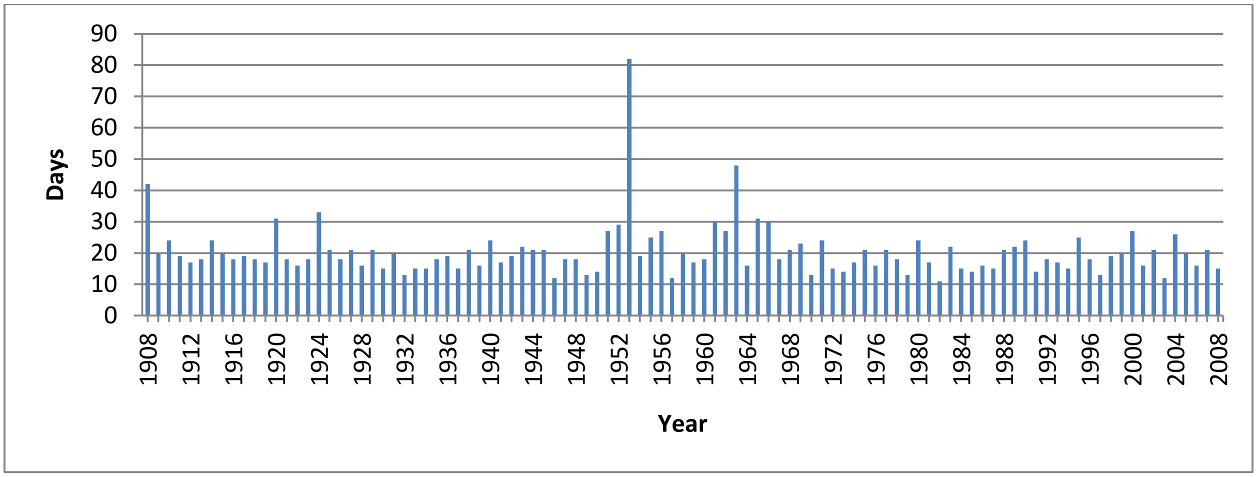

Figure 4.7. Annual maximum dry spell time series for Brownsville, TN.

In an effort to justify such an extreme outlier from the remainder of the data set, nearby stations were examined for the year 1953 around the same time that year. In Memphis, TN, the station with the closest proximity to Brownsville, 1953 was not the year with the longest annual maximum. At 24 days, neither was it in the top five longest for all of Memphis' annual maximum dry spells. This was disconcerting until the data was examined closer for 1953 in Memphis. The 24-day annual maximum begins on July 24 and for 95 days until October 26, only 6 precipitation days are observed totaling 0.72 inches (18.29 mm) for an average of only 0.12 inches (3.05 mm) of rain per rain day. Jonesboro, AR has an annual maximum of 35 days in 1953, the 2nd longest on record. The 35-day annual maximum is included in a 79-day stretch beginning August 10, in which 5 precipitation days scattered throughout were observed with an average of 0.33 (8.38 mm) inches per rain day. Chattanooga's 30 day annual maximum in 1953 was the highest at that station, but it should be noted that it occurred later in the year (September 28 – October 27) than Brownsville's 82 days. However, beginning on August 6, for 84 days there were fourteen precipitation days distributed throughout totaling 5.63 inches (143 mm), averaging 0.40 inches per rain day. Nashville had a 30 day annual maximum in 1953 during the same time as the Brownsville dry spell which was its 2nd longest. In Nashville, a 74-day run including the 30-day annual maximum was observed, with only 8 days of recorded rainfall scattered throughout totaling 1.18 inches (29.97 mm) for an average of 0.15 inches (3.81 mm) per rain day. Clarksdale, MS experienced one of its longest annual maximum dry spells in 1953 with 35 days. This annual maximum came much earlier in the year (May 21 – June 24) than Brownsville's 82-day event. However, for 96 days in 1953 from July 24 to October 27, there were only 10 days with recorded rainfall at Clarksdale totaling 2.88 inches (73.15 mm) for an average of 0.28 inches (7.11 mm) per rain day. Fayetteville, TN experienced a 31-day annual maximum in 1935 from September 27 to October 27. This was Fayetteville's 2nd longest annual maximum on record. During the same time frame as Brownsville's 82-day dry spell, Fayetteville experienced 110 days with only seven precipitation days evenly distributed during those days. However, during those 101 days for Fayetteville, the seven precipitation days totaled 6.05 inches averaging 0.86 inches. Those rain events in Fayetteville during that time in 1953 were not meager rainfall amounts compared to some of the other stations nearby Brownsville, TN. The year 1953 was certainly a dry one for this area and it is difficult to explain what occurred at Brownsville without further analyzing the synoptic characteristics in 1953 for Brownville. There was no missing data for Brownsville in 1953 and it should be noted that for the time frames analyzed above in comparison to Brownsville's 82-day annual maximum, there were also no missing days. Nearby stations to Brownsville, TN not only had some of their longest annual maximum dry spells on their respective records in 1953, that time of year was not only dry at Brownsville, but also for the stations surrounding it. The evidence explained above is hereby considered sufficient to accept the 82 days at Brownsville, TN in 1953, albeit an extreme outlier for that station.

The shortest annual maximum dry spell is 11 days which occurred twice in 1982 (July 10-July 20 and September 26-October 6). The total annual precipitation for 1953 was 46.56 inches (90% of normal) compared to 56.40 inches in 1982 (109% of normal). In 1953, there were 86 precipitation days with an average of 0.54 inches of precipitation per rain day. For 1982, there were a total of 131 precipitation days with an average of 0.43 inches per rain day. At Brownsville the year with the highest annual maximum dry spell had less total precipitation and precipitation days that the year with the shortest annual maximum. However, 1953 had a higher average measurement of precipitation per rain day than 1982. This statistic is opposite of Morgan City and Luling.

4.4.4 Ardmore, Oklahoma

Ardmore, Oklahoma is the only station selected from Oklahoma that has a complete enough record for this study dating back to January 1, 1908. The station is located at 34.17 N°, 97.13 W°. The elevation is 880 feet (268.2 meters) and the precipitation record is missing only 2.75 percent of the data which is 1,016 days out of the total 36,891 used in the analysis. A similar signal to Morgan City (Fig. 4.2) is shown, but less prevalent, at Ardmore earlier in the year. There seems to be a heightened seasonality in precipitation days with clusters of blue illustrated through the spring season (Figure 4.8).

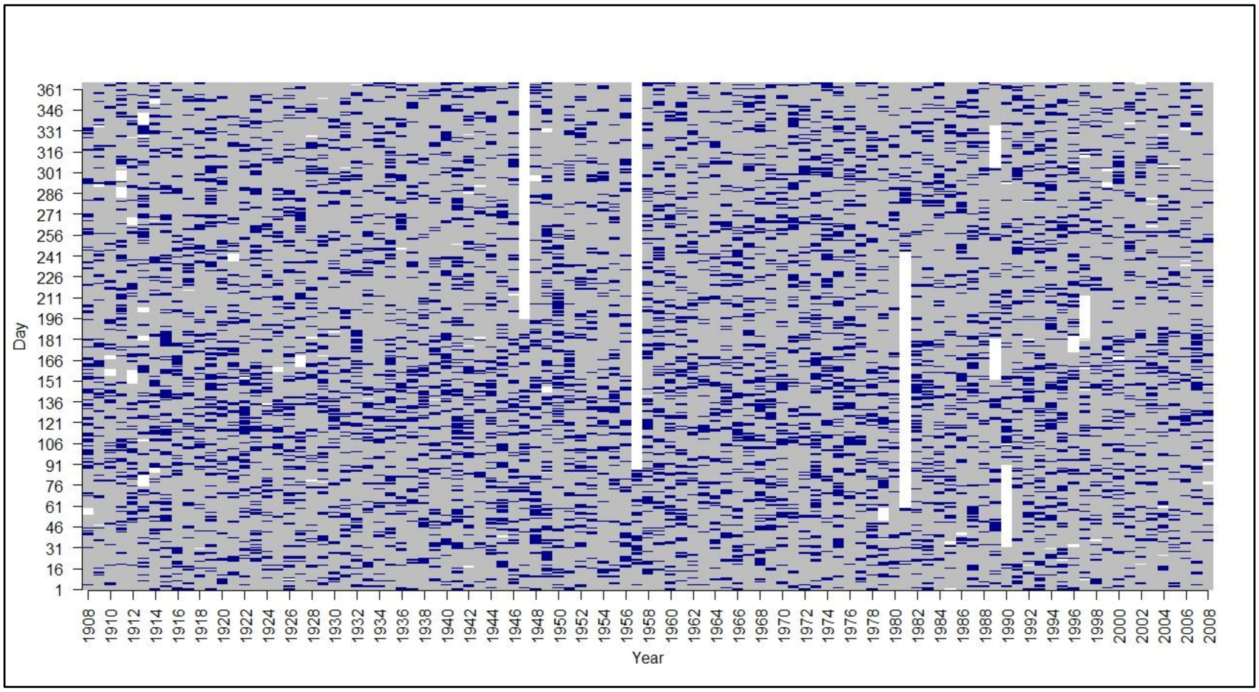

Figure 4.8. Daily Precipitation for Ardmore, Oklahoma.

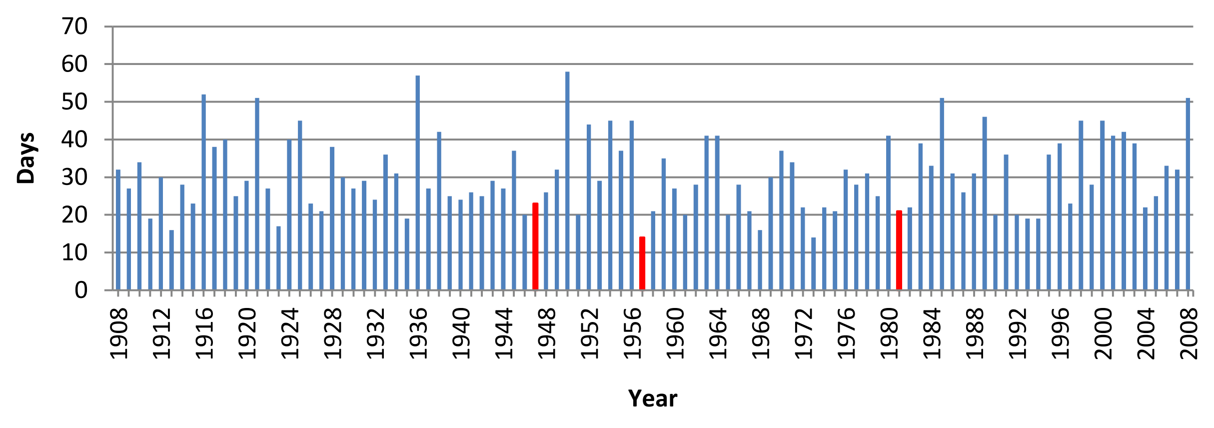

Figure 4.9. Annual maximum dry spell time series for Ardmore, OK.

Similar to Chapter 3, the values for the years 1947, 1957, and 1981 are colored in red due to their high amount of missing data (Figure 4.9). The annual maximum analysis is not affected as much as Chapter 3's analysis because neither of these years possesses a relatively long annual maximum dry spell. In fact, 1957's annual maximum dry spell is 14, which is the shortest on record. The year 1973 has the next shortest annual maximum with 15 days (two occurrences: August 17-August 31 and December 4-December 18). Since there is so much missing data for 1957, 1973 will be used as the year with the shortest annual maximum dry spell. The year with the longest annual maximum is 1950 with 58 days from November 4 to December 31. This happens to be a case where the dry spell was cut off at December 31. However, even if the spell had not been stopped due to the fact that it would continue into the next year, December 31, 1950 would still be the last day of the spell because 0.04 inches of precipitation was recorded on January 1, 1951.

In 1950, there was a total of 41.82 inches of precipitation recorded (118% of normal) compared to 55.01 inches in 1973 (155% of normal). The total number of precipitation days is 103 days in 1973 and 74 days in 1950. The average inches of precipitation per precipitation day are close for the two years; 0.56 inches in 1950 and 0.53 inches in 1973.

4.4.5 Calico Rock, Arkansas

Calico Rock, AR is located in extreme north central Arkansas at 36.11° N, 92.16 W. Located on the Upper White River in the Ozark Mountains, the stations is 350 feet above sea level (106.68 meters), but one of the northernmost stations in the study area. Missing data makes up only 1.12 percent of the total data set and is temporally irregular unlike Ardmore, OK in which three years contained more than half of the missing data. Figure 4.9 shows the daily precipitation amounts recorded for Calico Rock from 1908 to 2008.

The longest annual maximum dry spell was 46 days which occurred twice in the time series (Figure 4.11). The first was in 1913 from May 7 to June 21. The second occurrence was in 1934 from June 12 to July 27. It is important to note that there are 31 days of missing data in 1913 and 9 days missing in 1934. However, none of the missing days are during these annual

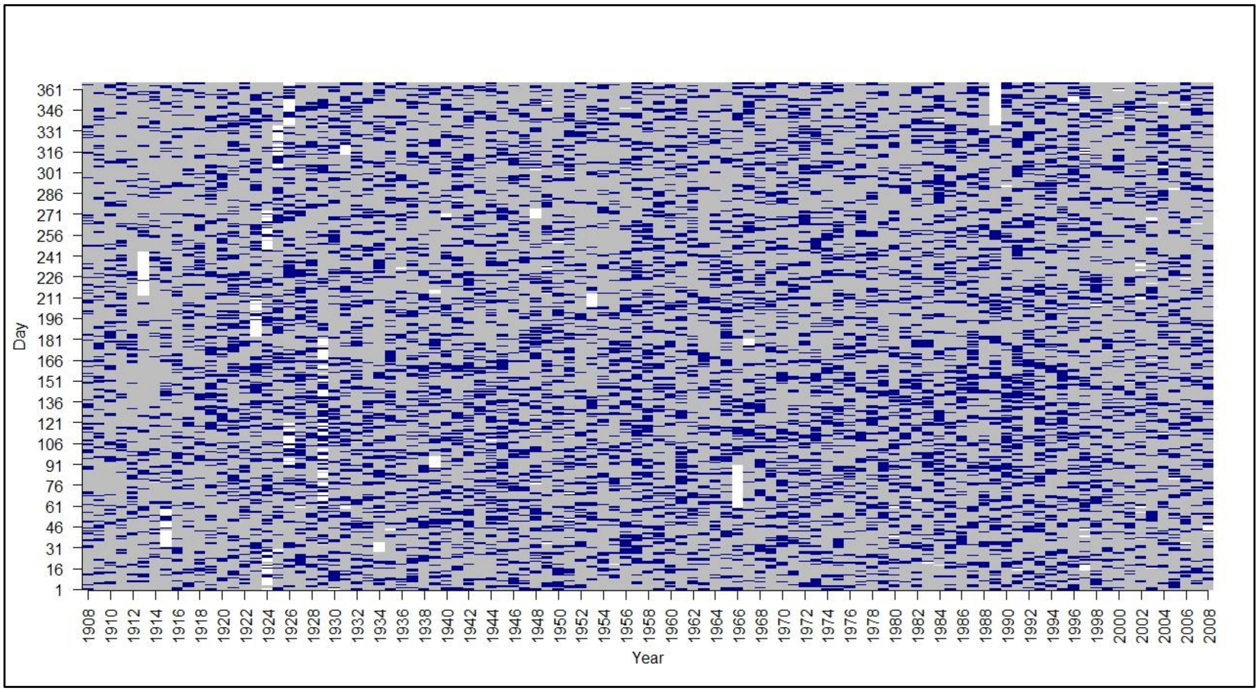

Figure 4.10. Daily Precipitation for Calico Rock, Arkansas.

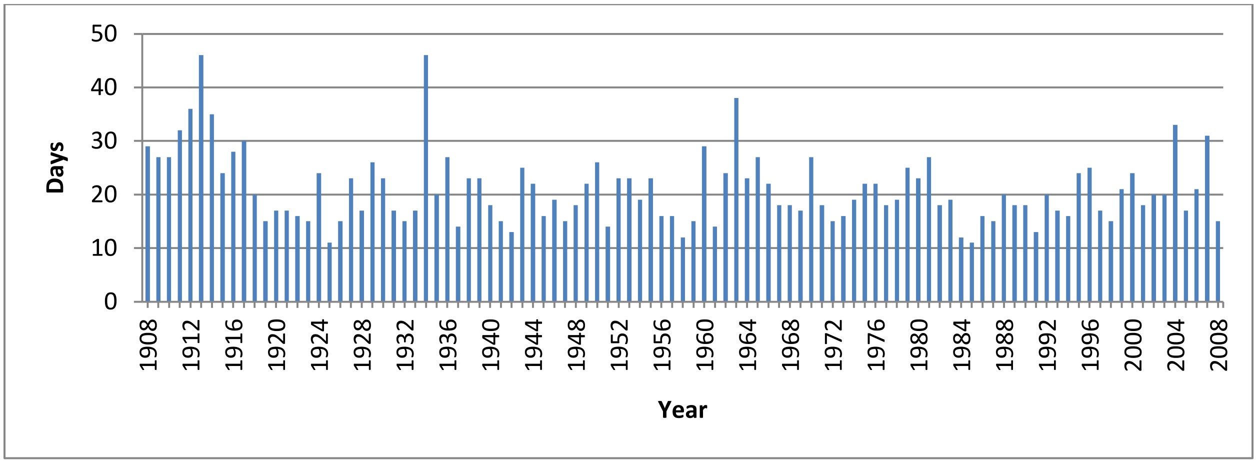

Figure 4.11. Annual maximum dry spell time series for Calico Rock, AR.

maximum dry spells. The shortest annual maximum of 11 days also occurred in two separate years; in 1925 (February 10-February 20) and in 1985 (July 5-July 15). There are 21 days of missing data in 1925 and no missing data in 1985. There are no missing days in the 11-day AM dry spells for these years.

The annual precipitation for each year is 44.58 inches in 1913 (99% of normal), 33.06 inches in 1934 (73% of normal), 41.55 inches in 1925 (92% of normal), and 51.49 inches in 1985 (114% of normal). Precipitation days total 54 in 1913 (avg. 0.82”), 90 in 1934 (avg. 0.36), 102 days in 1925 (avg. 0.41”), and 110 days in 1985 (avg. 0.46”). For Ardmore, it is interesting that one year (1913) with the longest AM has more annual precipitation than a year (1925) with the shortest annual maximum. The average precipitation per rain day in 1913 is also high at 0.86 inches. It is obvious that 1913 was not necessarily a dry year so it is deemed just a coincidence for that year to have one of the longest annual maximum dry spells on record from 1908 to 2008.

4.4.6 Natchez, Mississippi

Natchez, MS is located along the Mississippi River in the southwest portion of the state. The station is located at 31.59°N, 91.34° W with an elevation of 195 feet above sea level (59.44 meters). The missing daily precipitation data from 1908 to 2008 only amounts to 1.58 percent of the total data set (Figure 4.12). There are strings of missing data in certain years, but that does not seem to affect the analysis as it did for Ardmore, OK. In 1964, there are 62 days missing in a row from May 31 to July 31. Figure 4.12 displays the annual maximum dry spells at the station in Natchez.

The longest annual maximum dry spell at Natchez was 65 days in 1924 (September 23-November 26) (Figure 4.13). It should be noted that there was also a 50-day run (July 23-August 11) of consecutive dry days in 1924. For that year, the total precipitation recorded was34.24 inches (60% of normal). There were a total of 50 days in which at least 0.01 inches of precipitation was recorded. Therefore, the average amount of precipitation per rain day was

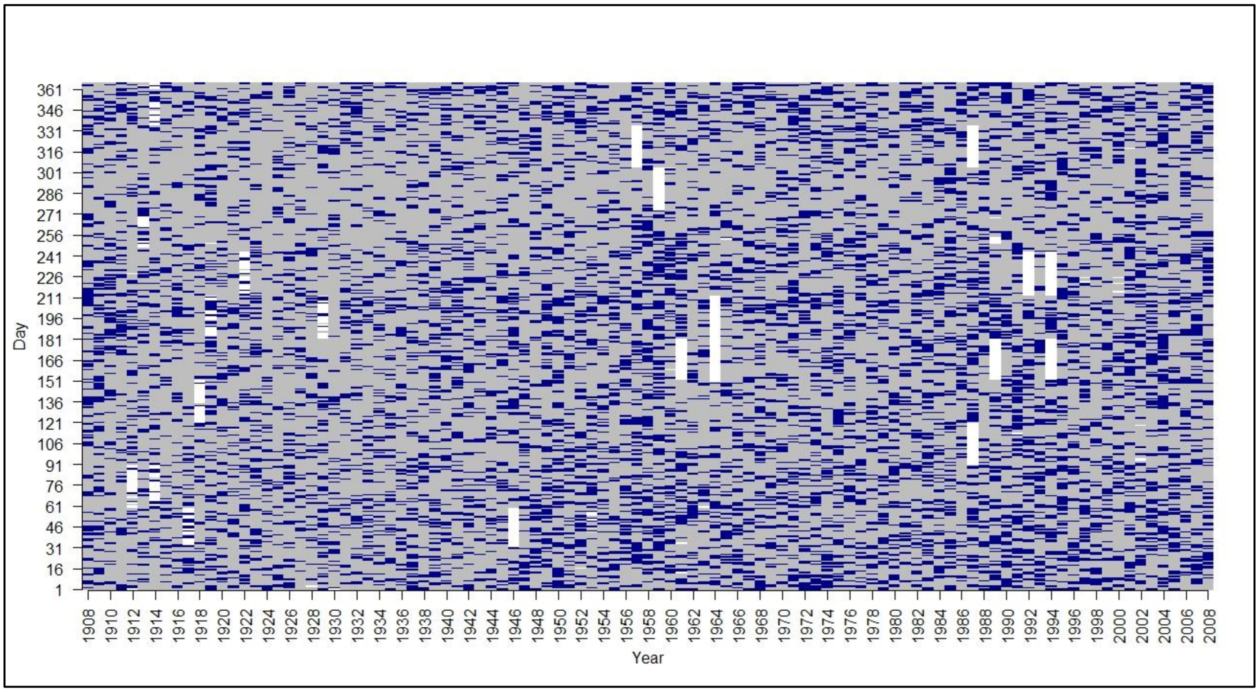

Figure 4.12. Daily Precipitation for Natchez, Mississippi.

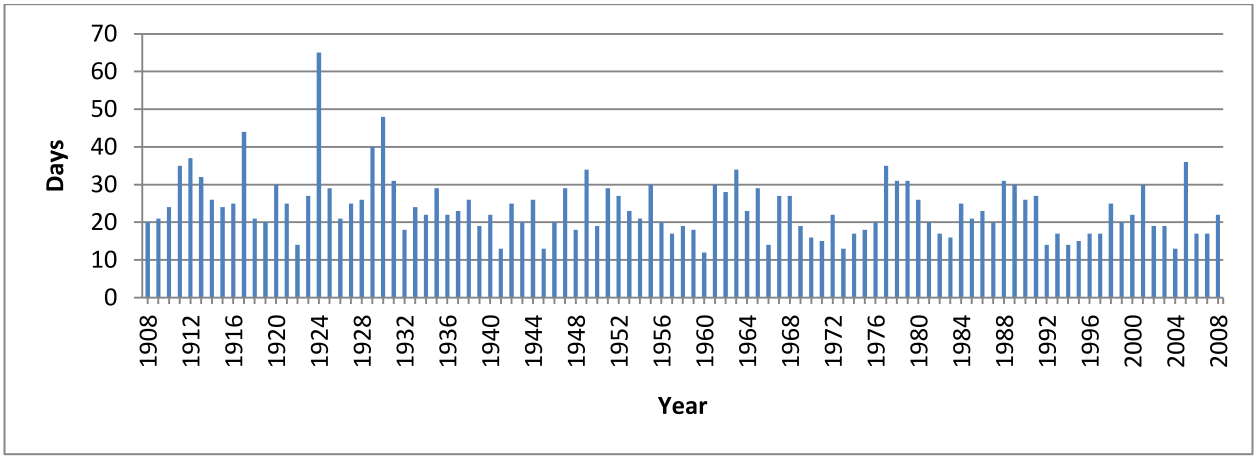

Figure 4.13. Annual maximum dry spell time series for Natchez, MS.

0.68 inches. The year 1924 was also the year with the longest annual average dry spell as found in chapter 3. The year with the shortest annual maximum dry spell was 1960 with 12 days (two occurrences: September 11-September 22 and October 7-October 18). In that year, total precipitation amounted to 39.27 inches (69% of normal), only 5.03 inches more than in 1924. However, there were 112 precipitation days that year for average of 0.35 inches per rain day. Even though the total precipitation in 1960 was relatively low for a year with the shortest annual maximum, there were more than twice as many precipitation days as in 1924. The year 1960 was not a wet year compared to other years on record. Natchez averaged 56.76 inches (annually from 1908-2008. Nevertheless, in 1960, the higher number of precipitation days (112) found kept the annual maximum dry spell short.

For these six stations, the longest annual maximum dry spells tend to fall early in their respective records. Morgan City's longest was 1917 (second longest was 1924), Luling's was 1916, Brownsville's was 1953, Ardmore's was 1950, Calico Rock's was 1913 and 1934, and Natchez's was 1924. Furthermore, each of the station's shortest annual maximum dry spells occurred predominantly in the latter half of their records. Morgan City's shortest annual maximum was in 1997 and 1932, Luling's and Ardmore's were both in 1973, Brownsville's was 1982, Calico Rock's was 1985 and 1925, and Natchez's was in 1960. The next section of this chapter examines if there are any underlying trends in the occurrences of these annual maximum dry spells. A trends analysis will show if these annual maximum dry spells are becoming more or less frequent.

Consistent with the analysis conducted in Chapter 3, at each of the six stations analyzed above, during the years with the longest annual maximum dry spells, the precipitation days were less than in the years with the shortest annual maximum dry spells. However, for the years with the longest annual maximum dry spells and less precipitation days, the average precipitation per rain day is more than that of the precipitation days in the wet years at four of the six stations.

The only exceptions were Morgan City, LA and Luling, TX. This suggests that for years with longer annual maximum dry spells, higher magnitude rainfall amounts per rain day are common.

4.5 Trend Analysis of Annual Maximum Dry Spells

Region-wide trends are examined for the annual maximum dry spell at each station. For this analysis, as in chapter 3, The Spearman Rank Test is used to determine the relationship between the annual maximum length of consecutive dry days and the year in which they take place. To generate a valid trend, the test must find a statistically significant association between the data and the year (α levels of at least ≤ .10). Below are the correlation coefficients (ρ) for the annual maximum dry spells at each of the 70 stations (Table 4.1).

Table 4.1. Correlation coefficients for annual maximum dry spells at the 70 stations in the study area. (1950-2008)

Station	ρ	P-Value	Station	ρ	P-Value
El Paso, TX	-0.1144	0.3874	Minden, LA	-0.1227	0.3534
Balmorhea, TX	0.2392	0.6810	Leesville, LA	-0.3148	0.0155
Chisos Basin, TX	-0.0581	0.6613	Natchitoches, LA	-0.1422	0.2817
Boise City, OK	0.0988	0.4557	El Dorado, AR	0.0829	0.4109
Midland, TX	0.1957	0.1372	Jennings, LA	-0.3003	0.0212
Lubbock, TX	-0.0771	0.5604	Calhoun Research Station, LA	0.1864	0.1569
Amarillo, TX	-0.1606	0.2238	Little Rock Adams AP, AR	-0.0873	0.1542
Crosbyton, TX	-0.0736	0.5787	Calico Rock, AR	-0.0262	0.8433
San Angelo, TX	-0.1020	0.9387	Lafayette, LA	-0.0991	0.4541
Abilene, TX	-0.0765	0.5634	Winnsboro, LA	0.0372	0.7787
Altus Research Stn, OK	-0.1693	0.1995	Natchez, MS	-0.1420	0.2825
Cotulla La Salle AP, TX	-0.0554	0.6758	Morgan City, LA	-0.1691	0.1998
Freedom, OK	-0.2315	0.0777	Baton Rouge, LA	-0.1891	0.1512
Boerne, TX	-0.1580	0.2314	Greenville, MS	0.0785	0.5533
Llano, TX	-0.1156	0.3823	Donaldsonville, LA	-0.2433	0.0635
Wichita Falls, TX	-0.0384	0.7723	Houma, LA	-0.0032	0.9808
San Antonio, TX	0.0733	0.5800	Jonesboro, AR	0.0846	0.2919
Union City, OK	-0.3340	0.0100	Reserve, LA	0.1010	0.4456
Austin Mueller AP, TX	-0.1236	0.3500	Clarksdale, MS	-0.1241	0.3479
Luling, TX	0.0358	0.7872	Amite, LA	0.0980	0.4589

Table continues

Corpus Christi, TX	-0.3000	0.0213	New Orleans Audubon, LA	-0.2247	0.0872
Brownsville, TX	-0.0245	0.8533	Memphis AP, TN	-0.1154	0.3832
Waco, TX	-0.2360	0.0721	Bogalusa, LA	-0.0947	0.4744
Ardmore, OK	0.1059	0.4214	University, MS	-0.0154	0.9079
Ponca City, OK	-0.1241	0.3482	Hattiesburg, MS	0.0602	0.6495
Dallas Love, TX	-0.0575	0.6645	Brownsville, TN	-0.1046	0.0468
Corsicana, TX	-0.1800	0.1721	Biloxi, MS	-0.1880	0.1572
Tulsa, OK	0.0528	0.6903	Martin U of Tenn, TN	-0.0522	0.6939
Houston Hobby AP, TX	-0.0453	0.7324	State University, MS	0.0076	0.9545
Liberty, TX	0.0181	0.8911	Meridian Key FLD, MS	-0.2666	0.0415
Lufkin Angelina Co AP, TX	-0.1414	0.2845	Nashville, TN	-0.0998	0.4511
Ft. Smith, TX	0.0065	0.4771	Fayetteville, TN	-0.0295	0.1227
Fayetteville, AR	-0.1164	0.3791	Chattanooga, TN	0.0262	0.2318
Beaumont, TX	-0.1837	0.1634	Knoxville AP, TN	-0.0758	0.5673
Shreveport Reg AP, LA	0.0480	0.7172	Kingsport, TN	-0.1160	0.3806

Figure 4.14 shows trends resulting from the Spearman Rank Test in the annual maximum dry spells at each of the seventy stations. Fifty stations out of the seventy in this study area (71.4%) possess a negative trend regarding annual maximums since for the years 1950-2008. This is a much wider division than the study in chapter three (54% were negative). Twenty of these trends are found in Texas, eleven are in Louisiana, four in Oklahoma, three in Arkansas, five in Mississippi, and seven in Tennessee. Of those fifty stations, eleven have negative trends that are significant at the 90% confidence level (Chisos Basin, Lubbock, Crosbyton, Abilene, Cotulla La Salle, Little Rock, Lafayette, Bogalusa, Martin U of TN, Nashville, and Knoxville). Eight are significant at the 95% confidence level (San Angelo, Wichita Falls, Brownsville (TX), Houston, Calico Rock, Houma, University, and Fayatteville (AR)). Simply stated, over time these stations are experiencing a decreasing length of the longest annual dry spell. Of the remaining twenty stations with positive trends, fifteen of them are significant. Eight are

significant at the 90% confidence level (Boise City, San Antonio, Tulsa, El Dorado, Greenville, Jonesboro, Amite, and Hattiesburg). Seven have positive trends that are statistically significant

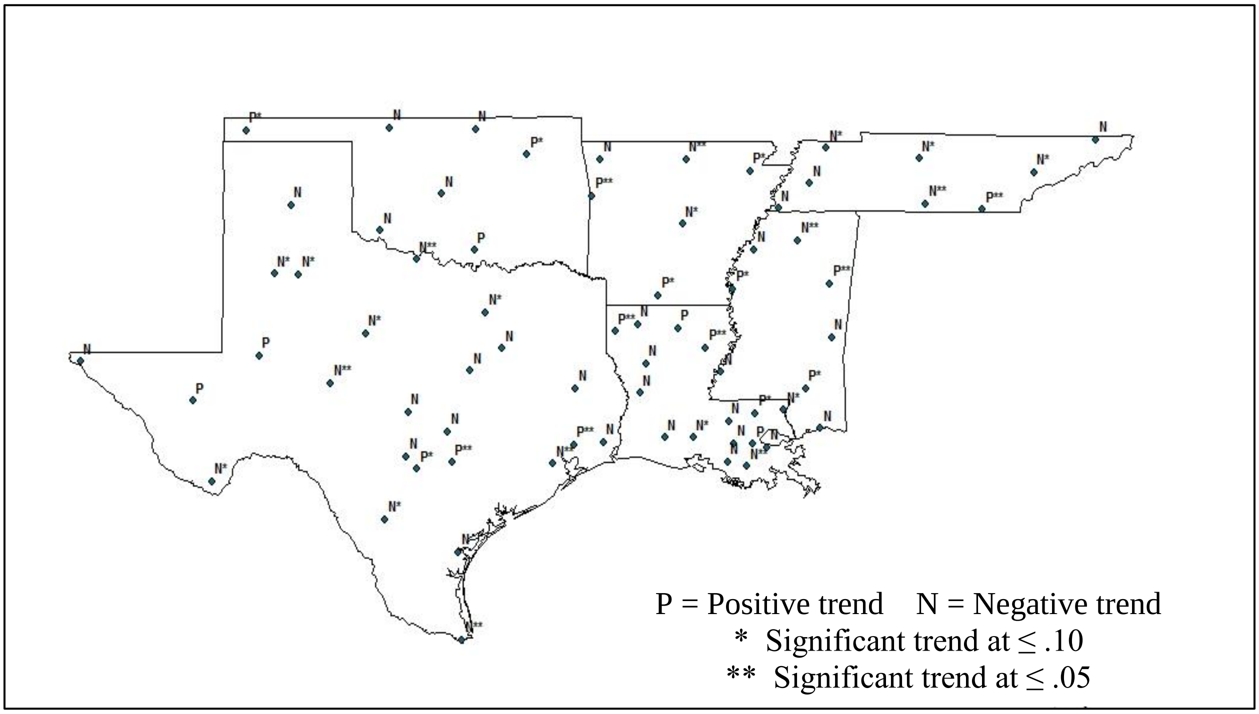

Figure 4.14. Spatial distribution of the correlations of annual maximum dry spells and year (1950-2008).

at the 95% confidence level (Luling, Liberty, Ft. Smith, Shreveport, Winnsboro, State University, and Chattanooga. These stations are showing increasing trends in the length of annual maximum dry spells.

Regardless of the high percentage of negative trends, few spatial patterns exist with any of the trends (Fig. 4.14). One small pattern should be noted however. Each of the stations along the coast of the Gulf of Mexico (9) all have negative trends in the annual maximums, with three of them significant. Therefore, it is suggested that the region as a whole may have a slight tendancy toward decreasing annual maximum dry spell lengths, since 50 of the 70 stations have negative trends with nineteen significantly increasing trends.

The Spearman Rank test was also conducted to test trends for the twenty-four stations with records from 1908-2008. Table 4.2 lists the correlation coefficients for the stations used from 1908-2008.

Table 4.2. Correlation coefficients for annual maximum dry spells at the 70 stations in the study area. (1908-2008)

Station	**ρ**	**P-Value**	**Station**	**ρ**	**P-Value**
Crosbyton, TX	-0.1372	0.1711	Calico Rock, AR	-0.1732	0.0832
Boerne, TX	-0.1086	0.2793	Lafayette, LA	0.1214	0.2263
Llano, TX	-0.1171	0.2432	Natchez, MS	-0.3033	0.0021
Luling, TX	0.0632	0.5293	Morgan City, LA	-0.1631	0.1032
Ardmore, OK	0.0640	0.5234	Greenville, MS	0.0102	0.9194
Corsicana, TX	-0.1415	0.1578	Donaldsonville, LA	0.0359	0.7209
Liberty, TX	-0.1853	0.0636	Reserve, LA	-0.1453	0.1468
Fayetteville, AR	-0.0949	0.3447	Amite, LA	0.0163	0.8710
Beaumont, TX	-0.2121	0.0334	Hattiesburg, MS	-0.0724	0.4712
Minden, LA	-0.0199	0.8435	Brownsville, TN	-0.1123	0.2632
Jennings, LA	-0.2137	0.0321	State University, MS	-0.3765	0.0001
Calhoun Research Station, LA	-0.2456	0.0135	Knoxville AP, TN	-0.0015	0.8208

Consistent with the trend analysis above for the years 1950-2008, this 101-year analysis results in 18 of the 24 stations (75%) with negative trends (Fig. 4.15). Two stations (Fayetteville (AR) and Hattiesburg) have negative trends of significance at the 90% confidence level. Two other stations (Minden and Knoxville) are negative trends significant at the 95% confidence level. Hattiesburg, MS stands out since in the study beginning in 1950, it had a significant positive trend, but when adding the forty three years to the front end of the record, it results in a significant negative trend. An explanation may be that the average annual maximum for Hattiesburg from 1950 to 2008 was 21.41 days. There are seventeen years between 1908 and 1949 that have annual maximums higher than that average and for those years, the average annual maximum is 22.02 days. When these years are added to the study, they may have caused the change in the trend between studies. The trend at Knoxville remains negative and highly significant between the two analyse. Overall, these results indicate that annual maximum dry spells are getting shorter in duration with time.

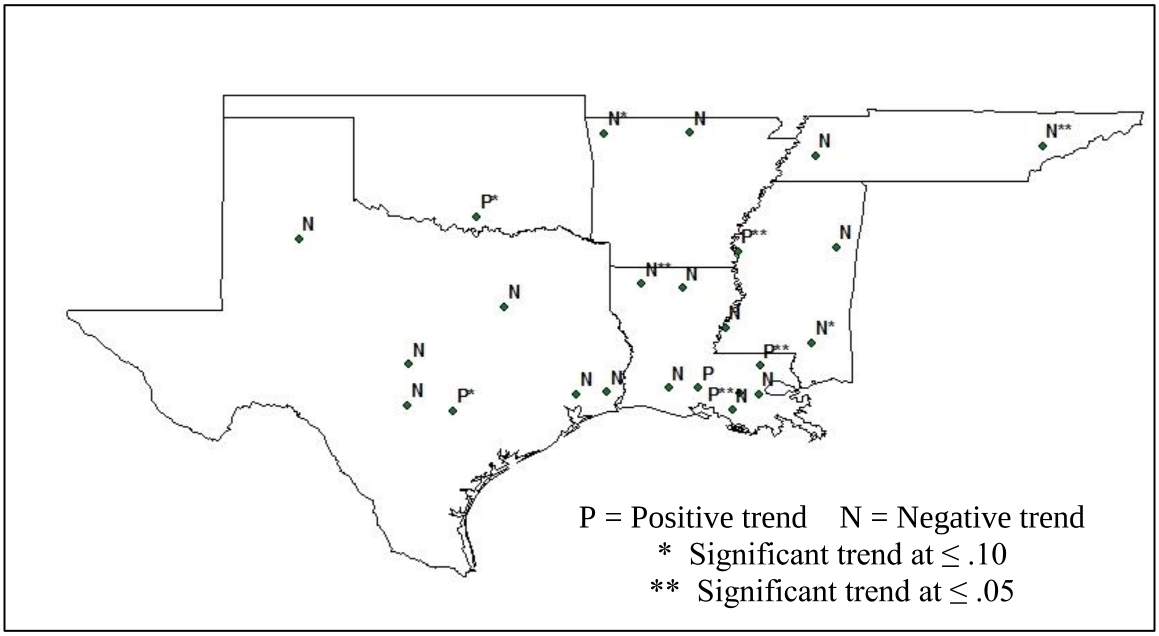

Figure 4.15. Spatial distribution of the correlations of annual maximum dry spells and year (1908-2008).

Of the remaining six stations with positive trends, Ardmore and Luling have significant positive trends at the 90% confidence level. Donaldsonville, Greenville, and Amite are significant positive trends at the 95% confidence level. Trends at both Luling and Amite remain positive and significant between the two studies. In addition, similar to the 1950-2008 analysis, little spatial cohesion exists with this study as well.

4.6 Spatial Variability

In the graph below (Fig. 4.16) each of the annual maximum dry spell lengths for each station are averaged for the years 1950-2008. This allows each station's annual maximum record to be displayed on a single graph. Similar to Fig 3.15, the stations are arranged from west to east. Also similar is the definitive negative slope from the westernmost stations to the easternmost until about the Louisiana – Texas and Oklahoma – Arkansas borders. Eastward from that point (starting with Tulsa), the annual maximum averages seem to stabilize around the 20-25 day mark. The exception being the five easternmost stations in Tennessee which are less than twenty days.

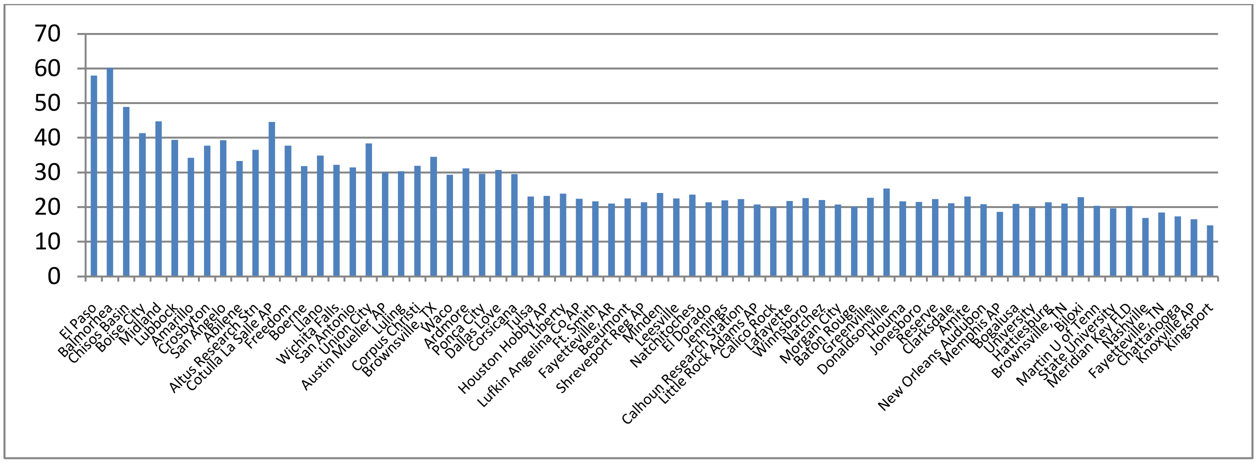

Figure 4.16. Spatial variability of annual maximum dry spell averages (1950-2008).

4.7 Longest Annual Maximum Dry Spells

A glance at each station's longest annual maximum on record follows similar west to east characteristics as Fig. 4.16 above. The drier annual maximum dry spells are in southwestern Texas with the driest having occurred in Brownsville, TX (142 days) from January, 3 – May 24, 1901 (Figure 4.17). The shorter annual maximum dry spells are in eastern Tennessee and in south western Arkansas. Even though patterns found in the longest annual maximum dry spells on record for each station (Fig. 4.17) seem consistent with other graphs produced herein, it should be noted that these are single events only and should not be used to judge the overall climatology of any given place.

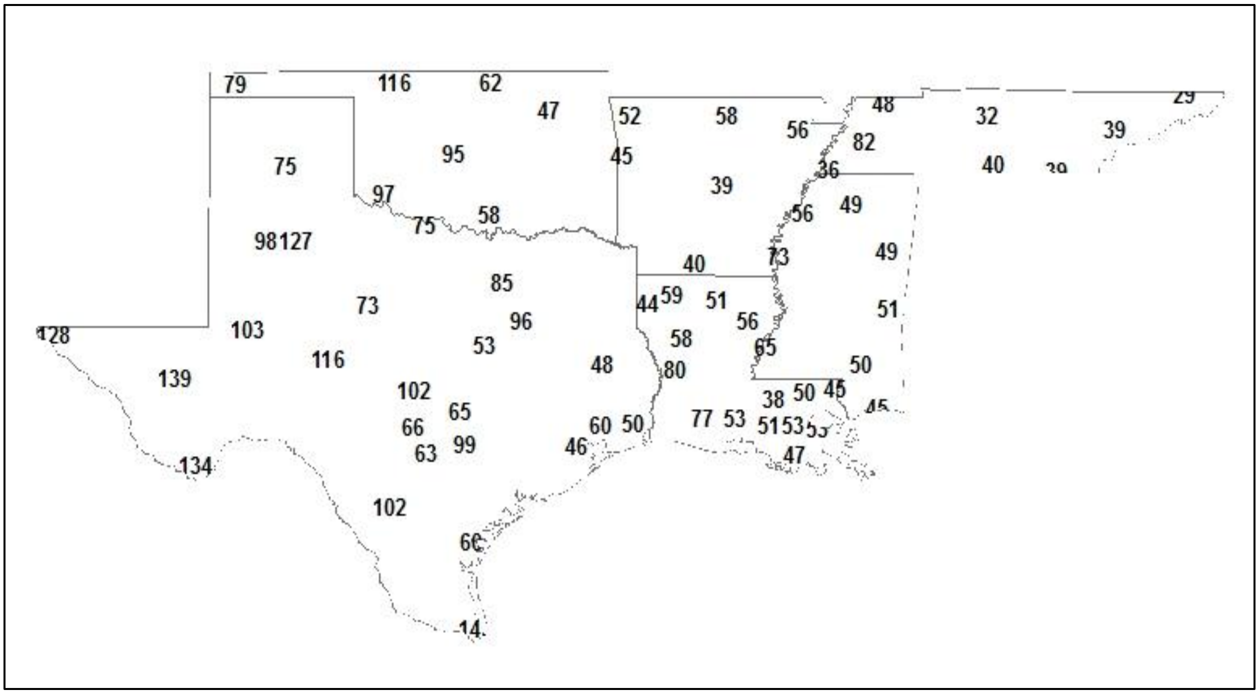

Figure 4.17. The longest annual maximum dry spell on each station's precipitation record.

4.8 Summary and Conclusions

These results were difficult to compare to the drought severity study conducted by Andreadis and Lettenmaier (2006) since their drought severity analysis included multiple components including soil moisture, runoff, and other drought characheristics. Their results illustrate most of the stations in the southeastern United States experieinced incresing trends in drought severity during the 20th Century. In this study of annual maximum dry spells, most of the stations experieinced negative trends during a similar time period. However, as previously noted, this study only takes daily precipitation into account.

At the majority of the stations in this trends analysis, the results are not significant and thereby inconclusive. Confidence in a correlation coefficient at a given station without a significant trend is less than the pre-designated 90%. These results do not signify a strong enough confidence to be considered a trend. For all stations without a significant trend for either of the two time periods, the results will hereby be allocated as tendencies rather than trends. Therefore, for the majority of the stations (35: 1950-2008; 15: 1908-2008) the positive or negative shown on the figures above (4.14 and 4.15) as a “P” or “N” without an asterisk, depict a station in which there is only a tendency for that station’s annual average dry spells to be leaning one way or the other.

In comparison of the two trend studies conducted in Chapter 3 and Chapter 4, there are a few intersting results that should be noted. University, Hattiesburg, and Bogalusa are the only stations that possess significant negative trends in the 1950-2008 trend analysis for annual maximums (Chapter 4) as well as for interarrival times (Chapter 3). However, as noted above, Hattiesburg’s trend in annual maximums differs when 1908-1949 is added to the period of record. Interestingly, Knoxville (1908-2008), Calico Rock (1950-2008), Chisos Basin (1950-2008), and Nashville (1950-2008) each have positive significant trends in the length between precipitation arrival times, indicating an increase in frequency, but significant decreasing trends in annual maximums, indicating a decrease in extreme intensity. With fifty of the seventy stations in this study resulting in negative trends associated with annual maximum dry spells since 1950, the evidence indicates that the annual maximum dry spells are decreasing in length with time. Since 1908, eighteen of the twenty-four stations have negative tendencies (four have significant trends). Over time, and for the majority of the this region, the longest annual dry spell is seems to be decreasing in length.

Chapter 5: Return Periods for Dry Spells

5.1 Introduction

The purpose of the analysis in this chapter is to determine the return periods for dry spells across the study area to complement the results found in Chapters 3 and 4. As with the occurrences of other weather-related phenomena, it is deemed equally important to understand how often long dry spells can be expected for a given location. This information would benefit local, state, and federal decision makers who would be knowledgeable of the chances annually of experiencing a dry spell of a particular length. Results found in this analysis may assist in mitigation efforts against drought-related conditions. This information might also help those in the agricultural industry and others, who need to plan accordingly for the possible chances of not receiving rain for an extended period of time. The objectives for this chapter are as follows:

1. Calculate return periods for all stations for the 2-, 5-, 10-, 25-, 50-, and 100-year recurrence intervals.
2. Identify spatial patterns in the return periods.

5.2 Literature Review

Partial Duration Series are determined for each of the 70 stations in the study area. The partial duration series are determined by collecting the longest dry spells from a station's record and using the same number of top events as the number of years in the dataset (Hershfield, 1961; Dunne & Leopold, 1978; Keim & Faiers, 2000). Two studies utilized for this research regarding return periods were Faiers et al (1997) and Keim and Faiers (2000). Faiers et al. (1997) produced rainfall frequency maps for the six-state region of the SRCC (Texas, Oklahoma, Louisiana, Arkansas, Mississippi, and Tennessee). These frequencies were found for 3 hour-, 6 hour-, 12 hour-, and 24 hour-storms. Recurrence intervals of 2-, 5-, 10-, 25-, 50-, and 100-years were found using the Huff-Angel and SRCC methods for each of the storm durations listed above. Keim and Faiers (2000) also used the Huff-Angel and SRCC methods to produce quantile estimates of heavy rainfall in western Texas. This study area was selected for its arid and mountainous environment. The main purpose of Keim and Faiers (2000) was to compare Huff-Angel, SRCC as well as other methods to find the best fit probability distribution or technique for analysis of the data set. The authors found Huff-Angel to be the best technique (Keim and Faiers 2000). However, they concluded that since Huff-Angel tends to overestimate values associated with the 50- and 100-year return periods, the SRCC method was chosen as the best fit. SRCC had the most undisputed number one rankings of quantile estimates at each of the stations used in the study (Keim and Faiers 2000). These methods are also utilized later in this research. In recent years, a few studies have been published addressing the methodology for estimating drought return periods (Fernandez and Salas (1999), Chung and Salas (2000), and Kim et al. (2003). Fernandez and Salas (1999) summarized the definitions of the return period as applied to drought events. Chung and Salas (2000) focused on drought occurrence probabilities, return periods, and risks of drought events for dependent hydrologic processes. Kim et al. (2003) utilizes a methodology for estimating the return periods of droughts using a nonparametric kernel estimator and is presented to examine the univariate (one variable) as well as the bivariate (two variables) behavior of droughts in the Conchos River Basin in Mexico, just south of El Paso, TX.

5.3 Methods

For this analysis, a partial duration series (PDS) of dry spells for each of the 70 weather stations selected is used to determine return periods for dry spell lengths in the south central United States. The partial duration series are determined by collecting the longest dry spells from a station's record and implementing the longest dry spells, with the retained number of events equal to the number of years in the dataset (Hershfield, 1961; Dunne & Leopold, 1978; Keim & Faiers, 2000). For the 24 stations with 101-year data sets between 1908 and 2008, the longest 101 dry spells are determined. The remaining 46 stations in the study area have 59-year data sets from 1950 to 2008. For those 46 stations, the longest fifty nine dry spells are determined. The PDS is selected over the Annual Series (AS) because the data used in the PDS generates more precise results for this study. The AS includes only the longest dry spell per year, while the PDS contains the longest dry spell regardless of the year in which they occur. Some years have multiple extreme events that would not be included in an AS.

In this analysis, there is no annual cutoff for a dry spell. In previous chapters, dry spells were analyzed annually and December 31 would mark the end of a spell and January 1 would begin a new one. This analysis simply utilizes the longest dry spells at each station regardless of the beginning and ending date. For all the dry spells used in this study, there are no missing days. If it was discovered a dry spell had one or more missing days within its record, the spell was discarded and the next longest spell was chosen. Following the determination of the partial duration series, the exceedence probability was found by using the formula: P=R / (n+1), where P = probability, R = rank of the dry spell (where the longest dry spell = 1), and n = the number of dry spells in the series (which is based on length of record). For the data sets with 101 years, the annual exceedence probability values range from 0.001 for the longest dry spell and 0.990 for the shortest. For the stations with 59-year data sets, annual exceedence probabilities ranged from 0.0167 for the longest dry spell and 0.983 for the shortest. The exceedence probabilities were the applied to calculate the return periods using the equation, "1 / Exceedence Probability." The 101-year data sets produced return periods of 102 years for the longest dry spells and 1.001 years for the lowest rank dry spell. The 59-year data sets produced return periods of 59.001 years for highest ranked dry spell and 1.017 years for the lowest ranked. The longer the dry spell, the less likely it should occur each year statistically.

Two methods of deriving quantile estimates for dry spells are examined. Return periods at each station are established by employing the Huff-Angel and the SRCC regression methods. The Huff-Angel method was created and first used in Huff and Angel (1992). That publication studied the rainfall frequency of the midwestern United States. The method is a log-log method that produces a graph of the longest dry spells on the y-axis and the corresponding return period values on the x-axis (Fig. 5.1). This is an example of Huff-Angel method as conducted for Morgan City, LA.

Geospatial Information System technology was utilized to create maps displaying the 2-, 5-, 10-, 25-, 50-, and 100-year patterns for dry spell return periods across the study area. These maps are displayed later in the chapter.

5.4 Calculating Return Periods for Dry Spells

The Huff-Angel and SRCC methods were applied to determine quantile estimates for dry spells. The Huff-Angel method is a log-log method that produces a graph of the longest dry spells on the y-axis and the corresponding return period values on the x-axis. Fig 5.1 is an example of Huff-Angel method as conducted for Morgan City, LA. The SRCC method was developed by Faiers et al. (1997). It uses a log-linear regression to determine the relationship between the return period values and magnitudes of the longest dry spells in the partial duration series. Figure 5.2 below illustrates an example of the SRCC method as used for Morgan City, LA. When using both the Huff-Angel and the SRCC methods, it is important to determine which is the best fit regarding the return periods. Faiers et al. (1997) implemented the SRCC method

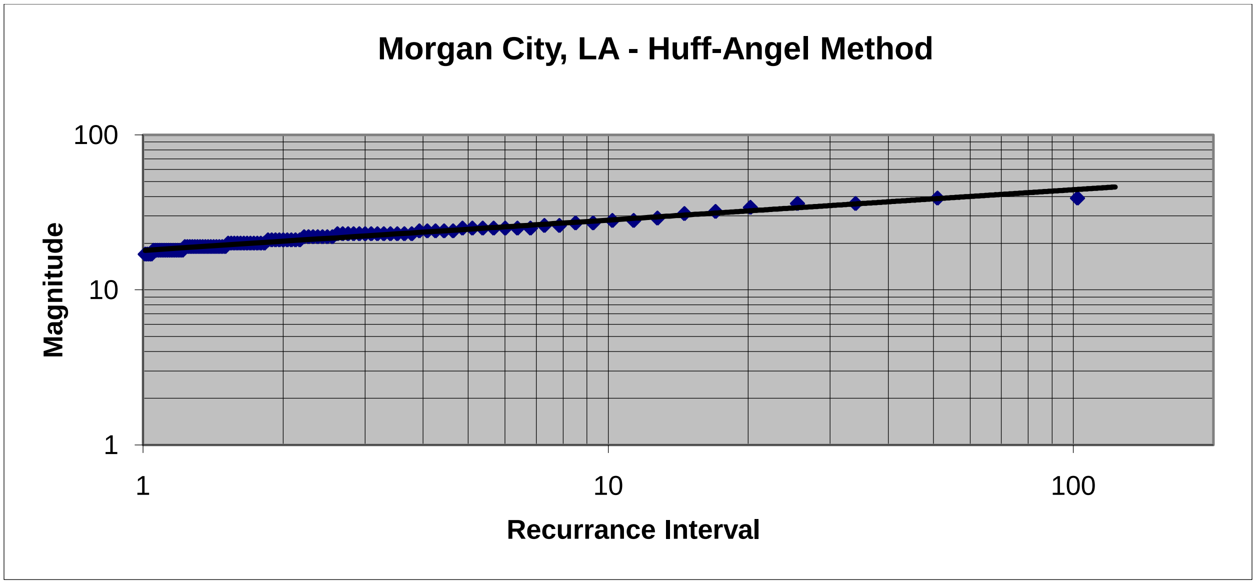

Figure 5.1. Huff-Angel method for determining return periods at Morgan City, LA.

to decrease the 100-year and 50-year return periods to more climatically appropriate rainfall values.

The Huff-Angel method was found to sufficiently approximate the 2-, 5-, 10-, and 25-year dry spells at most sites, but for stations with extreme outliers, this method produced

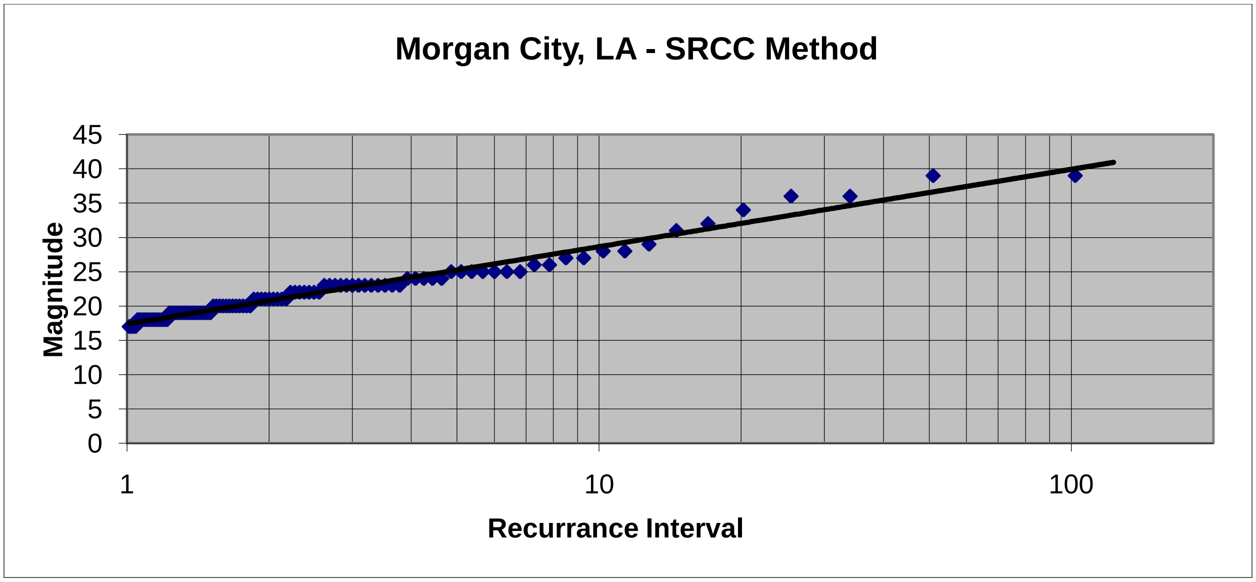

Fig. 5.2. SRCC method for determining return periods at Morgan City, LA.

100-year and 50-year quantile estimates that seem excessively large. For example, the Huff-Angel method produced a 100-year quantile estimate of 236 days in Balmorhea, TX. The longest dry spell in the record of Balmorhea was 195 days from September 19, 1999 to May 31, 2000. Coincidentally, the 195-day spell is the longest of any in the entire study area. The overestimation by Huff-Angel in this instance by forty-one days over the longest dry spell on record was enough to raise concerns.

5.5 Test for Best Fit

Keim and Faiers (2000) incorporated the Kolmogorov-Smirnov (K-S) Test to determine the method that provides the "best fit" to the distribution of dry spells in each partial duration series. The K-S test is a non-parametric process that weighs the return period or quantile estimate output of the various techniques against a hypothetical distribution (Keim and Faiers 2000). The K-S test was conducted for each of the seventy stations to find the best fit between the two methods used, Huff-Angel and SRCC. Once the two methods are conducted to find the return period values, the expected number of events is calculated for each return period (100-, 50-, 25-, 10-, 5-, and 2-year). Based on the Huff-Angel and SRCC estimates, the partial duration series is analyzed to determine how many of the actual events occurred relative to how many would be expected.

Table 5.1. The return periods (in days) for Huff-Angel and SRCC, expected events (in number), and actual events (in number) at Morgan City, LA (101 years). (Act.=Actual)

Return Period	H-A	SRCC	Expected	H-A Act.	SRCC Act.
100	44.29	39.93	1.01	0	0
50	38.67	36.54	2.02	2	2
25	33.76	33.14	4.04	5	5
10	28.22	28.66	10.1	8	8
5	24.64	25.26	20.02	21	14
2	20.59	20.77	50.5	55	55

It is those numbers of actual events that occur over/under the estimates that are analyzed by the K-S test. A value produced by the test named the "two-tailed K-S statistic" is found and the lower value between the Huff-Angel and SRCC methods is deemed the best fit (Table 5.2). Of the seventy stations, the SRCC method was the best fit for thirty-six stations. Huff-Angel was the best fit for twenty and for the remaining fourteen stations, there was a tie between the two methods. Since the SRCC method was the best fit for the majority of the 70 stations, the SRCC values for each station will be used to depict the spatial variability in quantile estimates of dry spells.

In this case, for Morgan City, the Huff-Angel method was deemed the best fit by the K-S test. The Huff-Angel method produced a two-tailed K-S statistic of 0.02, while SRCC produced a value of 0.07. The lower of the two values recognizes the method with the best fit. This process was conducted for all seventy stations. Table 5.2 below illustrates the results of the K-S test at each station.

Table 5.2. The Kolmogorov-Smirnov test for the seventy stations. **Bold** indicates the lowest value and therefore the best fit of that station between the Huff-Angel and SRCC methods.

Station	H-A Value	SRCC Value	Station	H-A Value	SRCC Value
El Paso	0.03	**0.02**	Minden	0.04	**0.02**
Balmorhea	**0.01**	0.04	Leesville	**0.02**	0.05
Chisos Basin	0.04	**0.02**	Natchitoches	**0.01**	0.02
Boise City	0.06	**0.04**	El Dorado	0.05	**0.03**
Midland	0.04	**0.02**	Jennings	0.03	**0.02**
Lubbock	0.06	**0.04**	Calhoun Research Station	0.06	0.06
Amarillo	0.05	0.05	Little Rock Adams AP	0.07	0.07
Crosbyton	**0.04**	0.07	Calico Rock	0.05	**0.02**
San Angelo	**0.01**	0.04	Lafayette	0.06	**0.05**
Abilene	**0.03**	0.04	Winnsboro	0.07	**0.04**
Altus Research Stn	0.03	0.03	Natchez	**0.04**	0.05
Cotulla La Salle AP	0.03	**0.02**	Morgan City	**0.02**	0.07
Freedom	0.05	**0.04**	Baton Rouge	0.07	**0.05**
Boerne	0.06	**0.03**	Greenville	0.02	0.02

Table continues

Llano	**0.01**	0.04	Donaldsonville	0.06	**0.04**
Wichita Falls	0.04	**0.03**	Houma	0.04	0.04
San Antonio	**0.04**	0.06	Jonesboro	**0.02**	0.08
Union City	0.03	**0.02**	Reserve	0.03	**0.02**
Austin Mueller AP	0.04	**0.03**	Clarksdale	0.04	**0.03**
Luling	**0.02**	0.06	Amite	0.02	0.02
Corpus Christi	0.05	**0.04**	New Orleans Audubon	**0.04**	0.05
Brownsville, TX	**0.07**	0.15	Memphis AP	**0.04**	0.06
Waco	0.06	0.06	Bogalusa	0.04	**0.02**
Ardmore	0.05	**0.03**	University	0.04	**0.02**
Ponca City	0.05	**0.03**	Hattiesburg	0.04	**0.03**
Dallas Love	0.04	0.04	Brownsville, TN	**0.05**	0.13
Corsicana	0.06	0.06	Biloxi	0.06	**0.05**
Tulsa	0.02	0.02	Martin U of Tenn	**0.04**	0.05
Houston Hobby AP	0.02	0.02	State University	0.04	**0.02**
Liberty	0.05	**0.02**	Meridian Key FLD	0.04	**0.02**
Lufkin Angelina Co AP	**0.02**	0.03	Nashville	0.05	**0.04**
Ft. Smith	**0.04**	0.06	Fayetteville, TN	0.04	**0.01**
Fayetteville, AR	**0.04**	0.06	Chattanooga	0.09	0.09
Beaumont	0.04	**0.02**	Knoxville AP	0.06	**0.05**
Shreveport Reg AP	0.04	**0.03**	Kingsport	0.04	0.04

5.6 Results

Since the SRCC method was clearly the best fit for the majority of the stations (51%), the return periods produced by the SRCC method are used to depict the spatial variability in quantile estimates of dry spells. Below are the six maps illustrating the 2-. 5-, 10-, 25-, 50-, and 100-year return period values calculated using the SRCC method (Figs. 5.3 - 5.8).

The main features of these maps remain consistent with the general idea that these dry spells vary spatially by longitude. This is especially evident in Texas and Oklahoma. While there are only a few contours across Tennessee, Mississippi, Louisiana, and Arkansas, there are multiple contours, hence a steep gradient of change, across Oklahoma and Texas. This reveals that there are striking differences in the return periods of the western portion of the study area

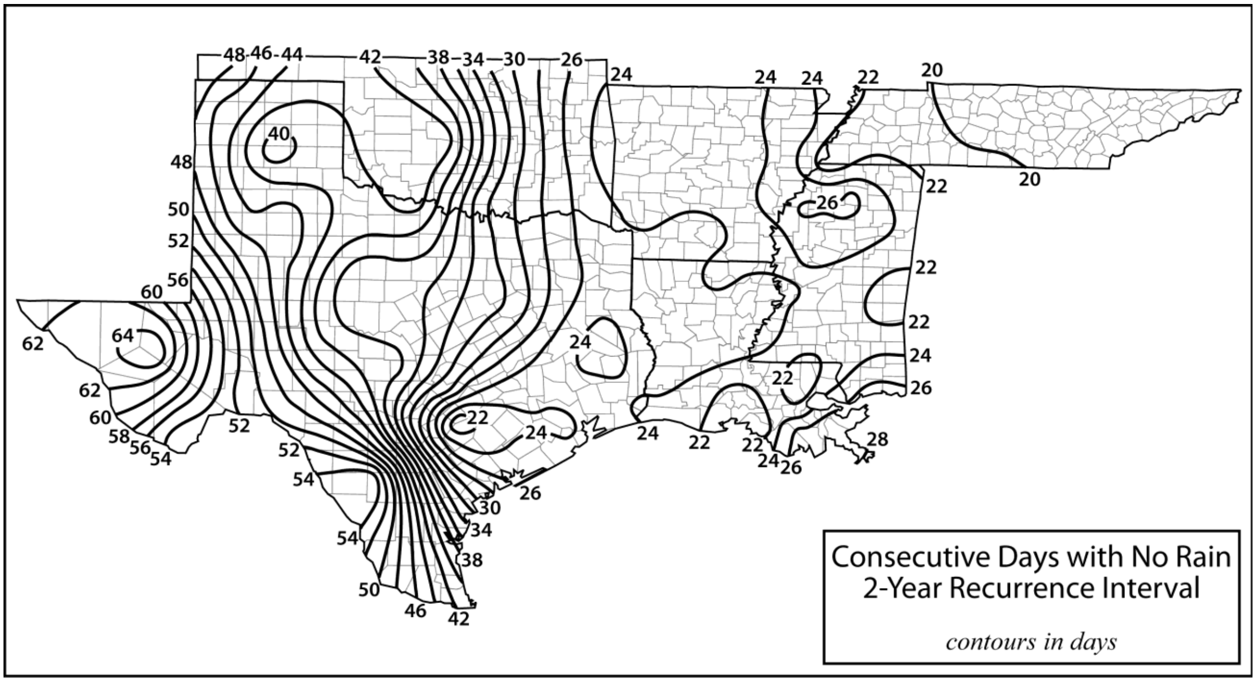

Fig. 5.3. 2-year dry spell pattern using the SRCC method.

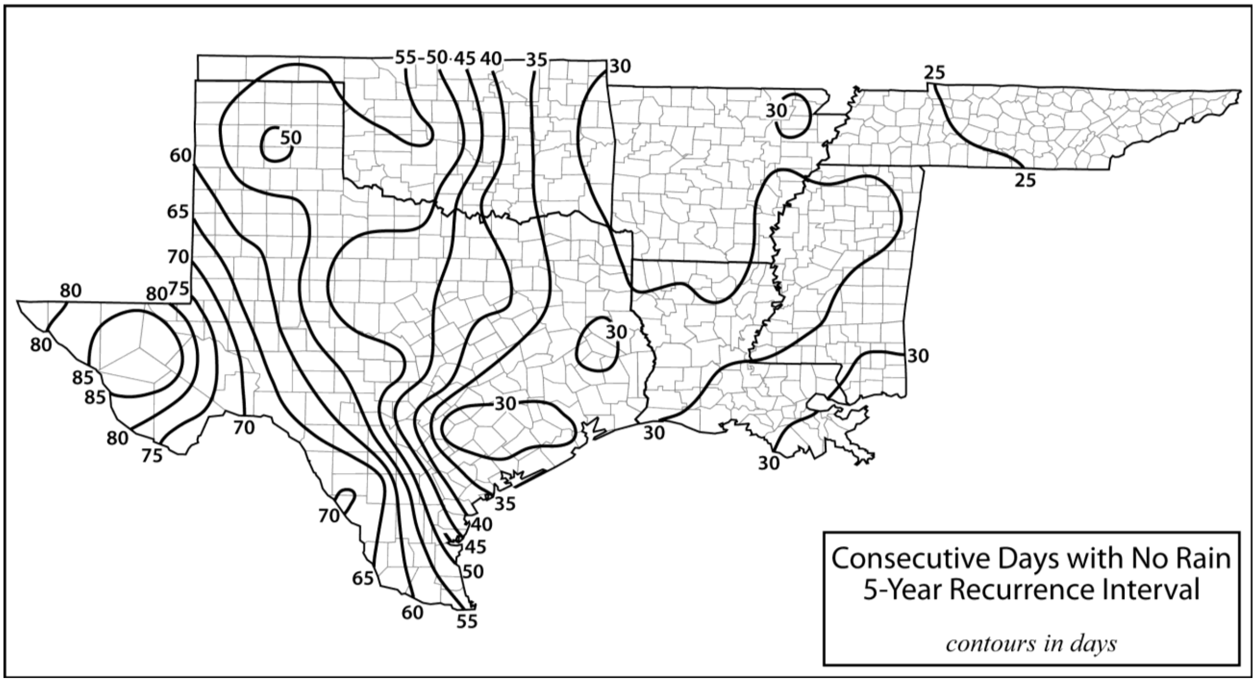

Fig. 5.4. 5-year dry spell pattern using the SRCC method.

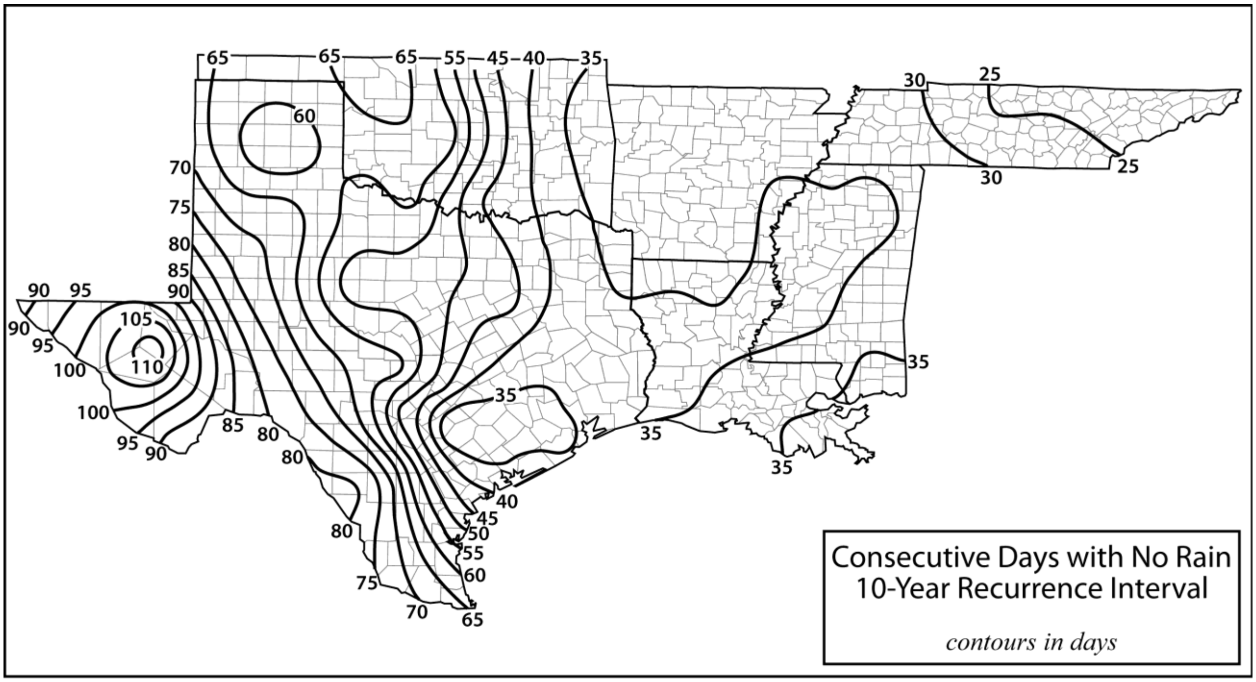

Fig. 5.5. 10-year dry spell pattern using the SRCC method.

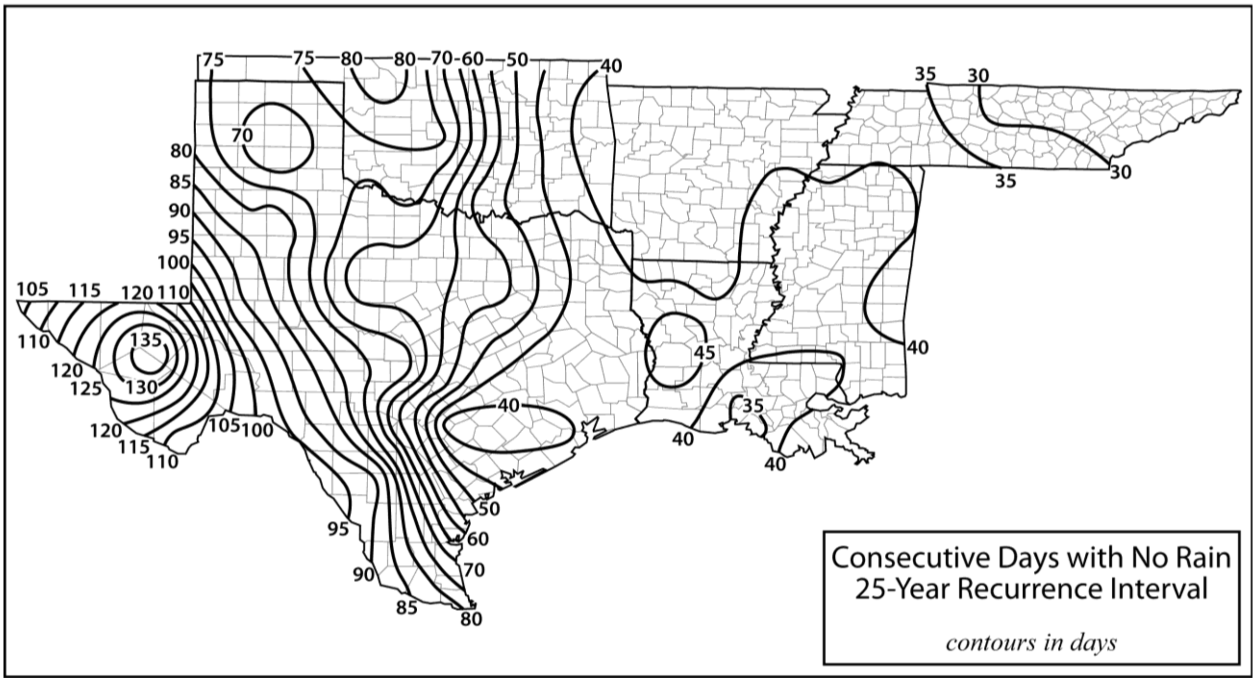

Fig. 5.6. 25-year dry spell pattern using the SRCC method.

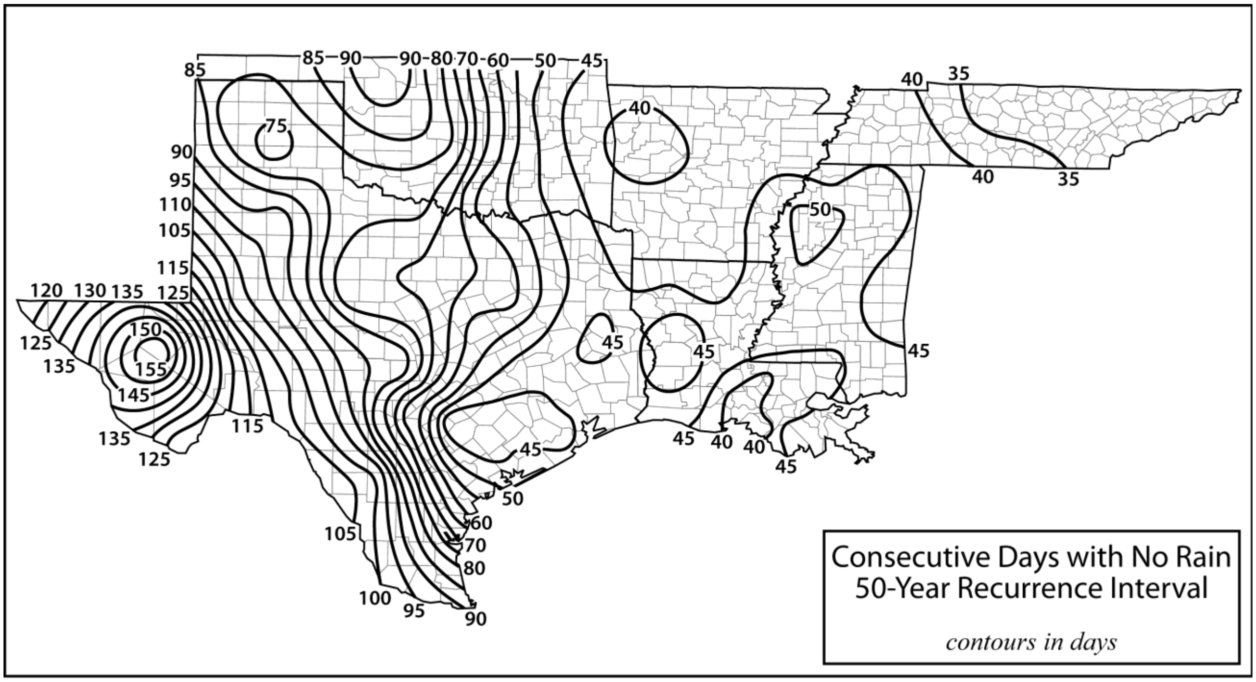

Fig. 5.7. 50-year dry spell pattern using the SRCC method.

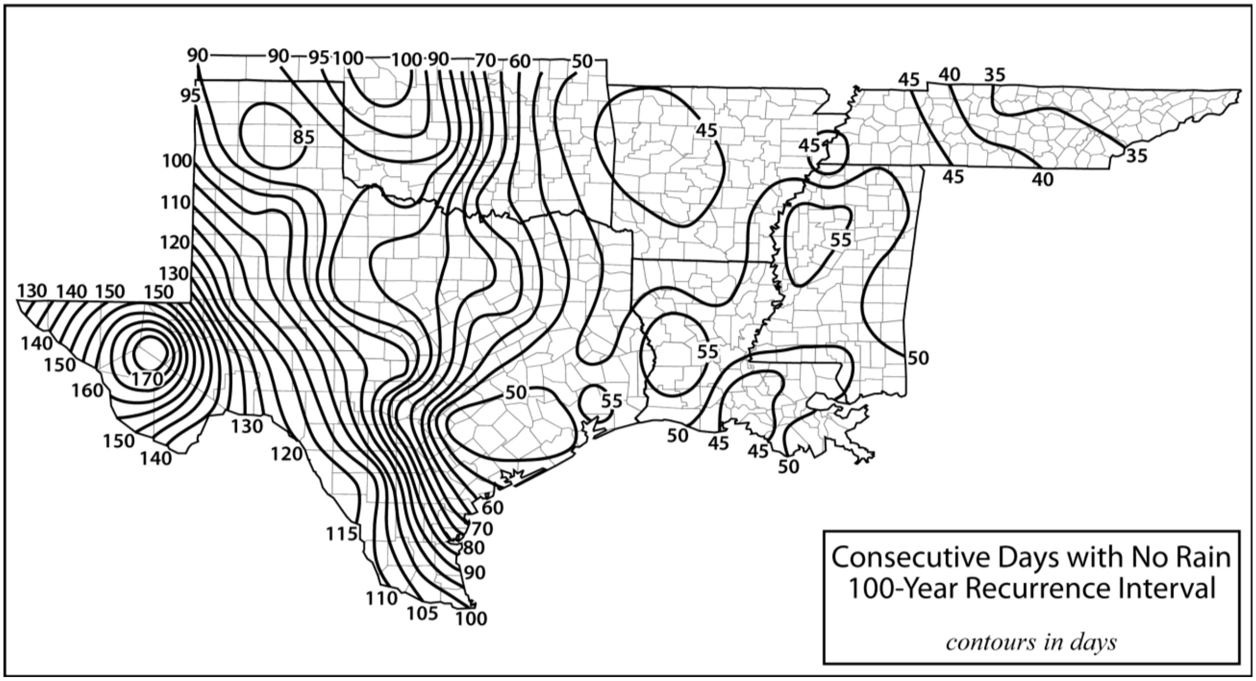

Fig. 5.8. 100-year dry spell pattern using the SRCC method.

as opposed to the eastern portion. Even the differences in the western portion to the stations in the central areas are substantial. As previously mentioned, longitude is a good indicator of changes in frequencies across the study area due to the natural climatological controls. The continental tropical (cT) airmass that exists mainly over Mexico and the southwestern United States compared to the maritime tropical (mT) airmass over the Gulf of Mexico seem to be the main influences on the precipitation in this area. Moving west from 95°W, there tends to be a steep gradient in the dryness of the selected stations. This seems to be the point in which the maritime tropical loses its influence over the region.

Another prominent and common feature in these maps is a bulls-eye centered on Balmorhea, TX. Some of the longest dry spells in the region have occurred there, which explains why the return periods are higher for that station. A third common feature in the maps is a southwest to northeast area beginning near the Houston area continuing northeastward through central Louisiana and into western and northern Mississippi. Return periods for the areas located within this area are shorter than those in the surrounding area. Additional research may be conducted to determine the reason for this feature, but one might assume that this area is more susceptible to frequent convective thunderstorms than the areas farther north and more distance away from the Gulf of Mexico and those conditions which cause these frequent storms. Another assumption might be fronts tend to stall in this area at certain time s of the year. Yaukey and Powell (2008) found that forty percent (40) of the cold fronts that make their way to this region in fall and spring stall before or after passage through New Orleans, LA. With cold fronts stalling in these areas, it can be speculated that there may be a higher chance for precipitation of a longer duration than if the front were to move through after producing one day of recorded rainfall.

5.7 Summary and Conclusions

Similar contour maps for the same study area as this research were created by Faiers et al. (1997), however theirs were of recurrence intervals for precipitation accumulation. Their results show a high gradient along the entire Gulf Coast. This illustrates that more rain falls in these areas near the Gulf and helps to explain why the contours in this analysis (Figs. 5.3 – 5.8) are more expansive near the Gulf. Conversely, Faiers et al. (1997) show few gradients over the large area of Texas and Oklahoma which are much lower values than those near the Gulf in southeastern Texas, southern Louisiana and southern Mississippi. Consistent with this research, areas near the Gulf have higher return periods for rainfall accumulation (Faiers et al. 1997) and lower return periods for dry spells. The areas in the western portion of the region have lower return periods for rainfall accumulations (Faiers et al. 1997) and higher return periods for dry spells. The greatest number of days for a given return period for dry spells are located in southern and southwestern Texas.

The quantile estimates found using the SRCC method illustrate clearly that there is not much diversity in return periods from the easternmost station, Kingsport, TN, westward to a line of longitude near the middle of the study area (approximately 95° W). The estimates for the eastern half of the study area range from only 4 days in the 2-year pattern (Figure 5.3) and 15 days in the 100-year pattern (Figure 5.8). On the other hand, from eastern Texas and Oklahoma westward, the gradient is much steeper and estimates range from 40 days in the 2-year pattern (Figure 5.3) to 130 days in the 100-year pattern (Figure 5.8). It should be noted that not only is the gradient in the western half of the region steeper, the contours show more of a longitudinal signal, much more so than the eastern half of the region.

These results certainly could benefit many in this region of the United States such as those in the agriculture industry and others who manage water resources. Policy makers might also find the information useful when laws are considered to manage mater usage similar to the summer of 2009 in Texas, for example. Seventy-seven of the state’s 254 counties were in extreme or exceptional drought at that time (The Advocate, 2009). Two hundred-thirty Texas public water systems were under mandatory water restrictions by the end of July that year (The Advocate 2009). It is quite possible that this response to the dry conditions was reactive. Decision makers may have waited until the conditions warranted a full-scale restriction in water usage. If this assumption is correct, results found in this chapter would benefit these decision makers and more gradual actions could have been put in place earlier so these areas would not be hit as hard with water restrictions and harsh cutbacks.

Chapter 6: Summary and Conclusions

Drought in the south central region of the United States has been a destructive force in the last century. As economic losses associated with drought are reported, concerns are raised that these conditions are getting worse over time (The Advocate 2006). For that reason, dry spells in this region are examined temporally and spatially to gain a better understanding of their magnitudes and how often they occur. This chapter provides a concise summary of the objectives as well as the conclusions of the thesis. All objectives are evaluated along with the results and conclusions of analysis. Possible future research topics are also discussed within the chapter.

6.1 Review: Objectives, Methods, and Study Area

Many areas all over the world experiences periods of time with little to no rainfall. The south central United States has a history of repeated high magnitude events that have cost billions of dollars in agricultural and economic damages. Many studies have been conducted to dissect drought in various ways. This study takes a different approach to measuring drought and examines the climatology of dry spells in the region over the past 100 years. The main objectives of this research are:

1. Produce a time series of the annual average length of consecutive dry days between rainfalls to gain an alternate understanding of drought through temporal and trend analysis.
2. Create a time series of the longest annual dry spells for each station to be utilized in temporal and trend analysis.
3. Test the theory that recent dry episodes have been increasing in magnitude.
4. Calculate the annual return periods of extreme dry spells for each selected station.

The scope of this analysis extends throughout six states in the south central United States and focuses on seventy weather stations selected for their location and completeness of climate record. Daily precipitation data was collected from January 1, 1908 to December 31, 2008 for twenty four stations and from January 1, 1950 to December 31, 2008 for the remaining forty-six stations. Dry spells are identified within the data and are defined as consecutive days with no recorded rainfall. Only 0.01 inches (0.25 mm) of precipitation recorded for one day is needed to end a dry spell. Unlike other drought indices (i.e. PDSI; Palmer 1965) that are dependent on the magnitudes of the precipitation, this study only takes into account if precipitation was received or not for any given day. For example, a tropical storm producing more than 5 inches (127 mm) of rain at a location is not distinguished between a summer convective shower dropping 0.1 inches (2.54 mm) at the same location. Therefore, a running measurement of soil moisture and other drought variables are not considered. This unique data set is necessary to complete the objectives set forth for this thesis. Based on these dry spell measurements, temporal analysis, trend analysis, and return periods are produced and calculated for each selected station in the region.

6.2 Objective One - Time Series and Analysis of Annual Average Dry Spells

The first objective in this study was to produce a time series of the average annual lengths of dry days between recorded rainfall amounts at seventy stations in the six-state region of the SRCC. Fortunately, twenty four of the selected stations possessed climate records of at least 100 years and with at least ninety-five percent (95%) complete. Therefore, stations with more than five percent (5%) missing data were not used in this study. For these twenty-four stations, daily precipitation data was collected for each station from 1908 to 2008. For those forty six stations without a complete record dating back to 1908, 1950 was used as the first year of record.

However, the same requirements of record completion were put in place for those forty-six stations.

Following the data collection process, the “R” computer program was utilized to calculate the annual average dry spell length. For each year, the lengths for each set of consecutive dry days throughout the year were averaged. At each station, these values for each year were set into a time series. The distribution of these values offers insight into the years with longer protracted periods of no rainfall. One station from each state with high completeness of record dating back to 1908 was selected for in-depth examination.

Trend analysis showed that there was not much of a cohesive pattern for all seventy stations from 1950-2008. However, most of western Texas and Oklahoma resulted in positive trends meaning dry spell length averages are getting longer over time for those fifty-nine years. Along the northern border of the study area, there are eight stations with positive trends, four of which are significant. On the contrary, along the I-10 corridor from Beaumont, TX to Biloxi, MS, most trends are negative. In fact, twelve of the sixteen stations in Louisiana show negative trends. Thirty eight of the seventy stations portrayed negative trends. It should be noted that due to the lack of a sufficient amount of stations with significant trends, the overall conclusion is that only tendencies should be used to define what is occurring overtime for the study area as a whole.

For the twenty-four stations with records from 1908 to 2008, the same trend analysis is conducted. Results were quite different. Only eight of the twenty-four stations have negative trends from 1908-2008, four of them significant (Luling, TX, Fayetteville, AR, Brownsville, TN, and Amite, LA). The remaining sixteen stations are positive with two being significant

(Donaldsonville, LA and Knoxville, TN). Adding 1908-1949 to these stations is certainly helpful in broadening the perspective of the climatology of these annual average dry spells.

In further analysis, the years with the highest and lowest average dry spells are extracted to compare with the annual rainfall in the same years. Consistently, at each of these six stations, the annual precipitation was lower for the year with the longest dry spell length average. In that same year, the number of precipitation days was considerably less. However, the average precipitation per rain day was more for the years with the longest dry spell length average at each of the six stations. This suggests that for drier years, precipitation days occur less frequently, but precipitation is more intense on average for those years. Karl and Knight (1998) found that 1-day precipitation events are increasing in intensity for heavy and extreme precipitation days from 1910-1995. If those heavy and extreme precipitation days occurred during dry years, it would certainly support the results made in this chapter.

Results of the trend analysis from 1908 to 2008 are consistent with results found in Andreadis and Lettenmaier (2006). Figure 3.15 illustrates that six of the seven stations experienced positive trends in the annual average dry spell lengths in for those 101 years. It should be noted that the one station in Texas (Luling) that had a negative trend in annual average dry spell length, the trend was significant. However, the overall widespread spatial pattern is consistent with the results found in Andreadis and Lettenmaier (2006).

6.3 Objective Two - Time Series and Analysis of Annual Maximum Dry Spells

The second objective was to create a time series at each station for analysis focusing on the longest dry spell for each year. The same daily precipitation data previously collected for the seventy stations was used for this time series. Every year on record for every station was examined and the longest dry spell for each year was found manually. These annual maximum dry spells were placed into a time series for each station. The same six stations previously selected for further analysis were also applied here.

Similar to the previous study, the years with the longest and shortest annual maximum dry spells are extracted to compare with the total annual precipitation for those same years. Also, consistent with the previous study, at each of the six stations, the years with the longer annual maximum dry spell recorded less total precipitation and had less total precipitation days than the years with the shortest annual maximum dry spells. Four of the six stations had a higher average of precipitation per rain day for the years with the longest annual maximum dry spell compared to the years with the shorter annual maximum. The two that did not were Morgan City, LA and Luling, TX. This suggests that for years with longer annual maximum dry spells, higher magnitude rainfall amounts per rain day are common.

The trend analysis produced results similar to the previous study in that most of the stations produced negative trends when analyzed from 1950-2008. In fact, for this study, fifty of the seventy stations have negative trends, with eleven of the stations possessing significant trends. For the most part, the annual maximum dry spell lengths are becoming shorter. Of the remaining twenty stations with positive trends, fifteen of them were significant. Again, few spatial patterns were evident. One small pattern should be noted however. Each of the stations along the coast of the Gulf of Mexico (9) all have negative trends in the annual maximums, with three of them significant.

In the trend analysis for the years 1908 to 2008, eighteen of the twenty-four stations (75%) showed negative trends, with only four being significant. Therefore, it is suggested that the region as a whole may have a slight tendancy toward decreasing annual maximum dry spell lengths, since most of stations in each analysis have negative tendencies. As in the annual average dry spell analysis, due to the lack of a sufficient amount of stations with significant trends, the overall conclusion is that only tendencies should be used to define what is occurring overtime for the study area as a whole.

These findings are particularly interesting since they seem to be aligned with the popular beliefs behind climate change. With a climate change and increasing temperatures, free convection is more likely, therefore precipitation has the opportunity to become more frequent. The results of the annual maximum dry spell analysis show that there are negative tendencies in the data set. Meaning, the annual maximum dry spells seem to decreasing over time. If studies show that precipitation is falling more often over time, the results found in this analysis would certainly support those findings.

Results from this study did not concur with those found by Groisman and Knight (2008). Their results showed and increase in the occurences of dry day episodes of 1-month or longer durations or longer during warm seasons over the past 40 years in the eastern United States. One reason for this disagreement may be that this research included entire years and did not make distinctions between seasons.

These results were an inconsistent comparison to the drought severity study conducted by Andreadis and Lettenmaier (2006) since their drought severity analysis included multiple components including soil moisture, runoff, and other drought characheristics. Their results illustrate most of the stations in the southeastern United States experieinced incresing trends in drought severity during the 20th Century. In this study of annual maximum dry spells, most of the stations experieinced negative trends during a similar time period. However, as previously noted, this study only takes daily precipitation into account.

6.4 Objective Three - Test the Theory of Increasing Magnitude in Dry Spells

Objective number three was to test this theory that the magnitudes of recent dry spells are increasing over time. Results from the analysis conducted in chapters two and three are the main components for testing this theory. The trend analysis in Chapter Three showed that for a little more than half (54%) of the selected stations from 1950-2008, the annual average length of dry spells are trending negatively. And when the length of record is expanded to 1908-2008, only eight of the twenty-four stations resulted in negative trends. For the study of annual average dry spell lengths, the length of record determines the answer to the question. Since 1950, at most of the stations, these values are decreasing over time. However, since 1908, the values are increasing essentially.

For the study of the annual maximum dry spells conducted in Chapter Four, results are more conclusive. Since 1950, fifty of the seventy stations resulted in negative trends. Since 1908, eighteen of the twenty-four stations have negative trends. These results are substantial in answering the question. Over time, and for the majority of the this region, the longest annual dry spell is decreasing in length.

6.5 Objective Four - Calculate Return Periods

The fourth objective was to calculate the return periods for dry spells at each of the seventy stations in the study area. Partial duration series were created for each station based on their longest dry spells and length of record. The Weibull Plotting Position Formula was used to determine the Annual Exceedence Probability for each dry spell in the PDS. The Huff-Angel and SRCC methods were utilized to calculate the recurrance intervals for the 2-, 5-, 10-, 25-, 50-, and 100-year dry spells. As mentioned in previous publications, the Huff-Angel method tended to overestimate the 50- and 100-year events. Once the K-S test was conducted for each station, it was found that the SRCC method had the best fit overall for the study area. Thirty-six stations favored SRCC, twenty supported Huff-Angel and the remaining fourteen were ties.

The SRCC values for each recurrance interval at each station were plotted on a map to illustrate the variability across the region. For the most part, this study remained consistent in that the higher magnitude quantile estimates exist in the western portion of the study area for each recurrance interval with the highest being in southwest Texas. For the 2-year pattern, the lowest quantile estimates are 20 days in eastern Tennessee and the highest are 64 around Balmorhea, TX. For the 100-year pattern, the results are similar, but higher in magnitude. The lowest estimates are 35 in eastern Tennessee and the highest are 180 near Balmorhea, TX. These results may certainly prove valuable to those who rely on long-term forecasts of drought such as farmers and water resource managers.

6.6 Future Research

Results from this research illustrate that there is quite a difference between the western and eastern halves of the study area. However, the update of the Köppen-Geiger climate classifications by Peel et al. (2007) show that approximately three quarters of the region enjoys the same climate (Cfa) Cfa is described as humid subtropical, which is without a dry season and with hot summers. With the results found in this analysis, the climate classification system could possibly be revisited if it is deemed that portions of the areas classified as Cfa actually posess a regular dry season.

Research on droughts and other climatological phenomena can be conducted with each passing year or season. Weather systems can arrive quickly and depart just as fast. Some however, and regarding drought, can linger for weeks, months, or years. After the next widespread dry episode more data may be collected and added to this and other previously conducted research projects. Continued research on this topic is necessary to increase standards in emergency preparedness and planning.

A specific focus on the causes for certain years to experience much longer than average dry spells is an essential research topic. If the approximate twenty-year cycle of extended periods of drought is correct, then it is important that we understand what might be causing the episodes. This would improve planning and help mitigate economic and agricultural losses.

Further research could include an analysis of prolonged periods of dry days with a minimal amount of recorded rain. An example might be analysis of 30-day events or longer in duration with less that 0.1 inches (2.54 mm) of recorded rainfall. This would allow for longer periods of dry conditions to be studied even with rainfall. A low amount of rainfall such as 0.1 inches over 30 days is not a significant amount of precipitation for most locations in this particular study area of the south central United States.

Another possible topic would be to determine if for all years with longer average dry spell lengths, the total annual precipitation is less than average, the number of precipitation days are more, and the average precipitation per rain day is higher as found in chapters three and four. If it is true, it would be helpful to know if for every above averge dry year overall, when it does finally rain, it is of high magnitudes.

These same methods could also be utilized to examine drought in other parts of the United States or around the world. Any research that adds to the understanding of protracted periods of no precipitation would be advantageous to scientists as well as people who live in the affected areas.

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Vita

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Following three years of employment in the sales industry, he entered graduate school at Louisiana State University in the Department of Geography and Anthropology in June 2007. While pursuing his Master of Science degree, he served a year as a graduate research assistant in the Southern Regional Climate Center before accepting employment with the East Baton Rouge Parish Mayor's Office of Homeland Security and Emergency Preparedness in August 2009. He is expected to receive his Master of Science degree in geography in August 2010.