INVESTIGATING TRENDS IN LOWER TROPOSPHERIC HEAT CONTENT AND HEAT WAVES OVER THE CENTRAL USA USING EQUIVALENT TEMPERATURE (1951-2011)

by

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MAJOR PROFESSOR: Dr. Justin T. Schoof

ABSTRACT

Equivalent temperature (T_E) is an atmospheric variable that combines both dry static energy (associated with temperature) and moist static energy (associated with moisture). Changes in T_E therefore reflect changes in total surface energy content. This research is concerned with quantifying trends in T_E and its subcomponents at 8 National Weather Service (NWS) 1st Order stations in the central USA. Data quality control was conducted and time series and time-varying percentile trends of maximum and minimum T_E and its subcomponents were developed for each of the stations on the daily scale; along with a heat wave trend analysis. It was found that there is an overall positive trend in lower tropospheric heat content over the last 60 years—driven primarily by increases in low-level moisture. The largest changes in T_E occurred during spring and fall, with some of these trends as large as $5°C/50$ years. Furthermore, it was found that there is an increase in the number of high humidity heat wave events and that these types of events are more frequent than low humidity events; which saw a slight decrease in frequency. Interestingly, one station (Nashville, TN) exhibited a slight negative trend in T_E maxima, which may be due to synoptic-scale influence such as the Great Plains low-level jet. The results demonstrate that T_E provides a different perspective than temperature for assessing regional climate change.

DEDICATION

I would like to dedicate this thesis to God—who gave me both the opportunity and capability to complete this work; my wife, Theresa, and my children, Leah and Ezekiel who without; this thesis would not have been possible. I would also like to dedicate this thesis to my parents, Ron and Janet who instilled good values during my childhood and gave me a desire to pursue an education. Lastly, I would like to thank my brother, Phillip. Thank you all for your love, support, and encouragement.

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CHAPTER 1

INTRODUCTION

1.1 Background

Near surface air temperature is the most commonly used metric to assess climate change and lower tropospheric heat-content. However, recent research suggests that observed air temperature alone provides an incomplete representation of near surface (lower tropospheric) heat content (Pielke et al., 2004). Therefore, in order to more thoroughly investigate changes in total near surface energy content, one should employ a variable known as *equivalent temperature* *(T_E)*. T_E combines terms representing both the sensible heat (dry static energy) and latent heat (moist static energy) components of near surface air, making it a more comprehensive metric for assessing total surface energy content as well as investigating the contribution of humidity to human heat stress during heat waves.

Heat waves have different impacts depending on their moisture characteristics. The 1995 Chicago Heat Wave, the summer of 1980, and the Dust Bowl of the 1930s exemplify ways in which summer temperature and humidity profoundly impact humans and agriculture. The 1995 Chicago Heat Wave, for example, resulted in the death of more than 500 people after two consecutive days of daytime and nighttime apparent temperatures > $45℃$ and $31.6℃$, respectively. These apparent temperatures were driven by very high dew point temperatures ($\geq 26℃$) (Karl and Knight, 1997). The summer drought of 1980 created $16 billion in economic losses (Karl and Quayle, 1981). When high temperatures are coupled with elevated specific humidity, humans are vulnerable to physiological heat stress and discomfort. Furthermore, the presence of low-level moisture—especially during late spring and early summer—creates instability in the troposphere and can potentially lead to severe weather outbreaks. Conversely, when high temperatures are coupled with low humidity, drought generally persists and crops and ecosystems suffer as a result. Moreover, drier conditions create a favorable situation for the genesis of forest fires. Further research is needed to investigate changes in specific combinations of temperature and humidity, especially at the regional scale. There have been numerous studies that have quantified trends in heat waves and the temperature-moisture relationship (Fall et al., 2010; Rogers et al., 2007; Pielke et al., 2004; Souch and Grimmond, 2004; Davis et al., 2002; Durre et al., 2000; Gaffen and Ross, 1999; Gaffen and Ross, 1998; Karl and Knight, 1997). However, these studies lack heat wave event analysis with emphasis on moisture characteristics. Therefore, trends in heat wave regimes (high humidity vs. low humidity heat waves) and heat wave length (multi-day events) have yet to be addressed—particularly within the context of T_E.

1.2 Problem Statement

There is a need to quantify historical changes in total surface energy content and trends in heat wave length, intensity, and frequency within the context of T_E. Furthermore, studies that have investigated T_E on a broader scale lack thorough *in-situ* data quality control. Studies that have performed thorough in-situ data quality control (Rogers et al., 2007) only investigated trends in T_E for a single station. For this study, a network of 8 National Weather Service 1st order stations were selected across the central USA to produce a T_E dataset that is both *relatively* homogenized and broad enough to investigate trends in total surface energy content and heat waves on a regional scale. Furthermore, this network of stations encompasses an area of the USA known as the 20th Century Midwest Warming Hole (Pan, 2004). The Warming Hole is an area of the Midwest USA that was characterized by a flat trend in annual *maximum temperature* (T_{max}) over the last half of the 20th century (Meehl et al., 2012). Recent research suggests that winter cold-air advection and summer low-level moisture convergence result in the Warming Hole during those seasons (Meehl, et al., 2012). Therefore, the results from this study are important—given that low-level moisture has been shown to be a key contributor to the flat trends in annual T_{max} over this study area.

1.3 Research Questions

Since regions are affected differently by global climate change, each region can be characterized by trends that are different from the global trend (Robinson, 2001). Although relative humidity (RH) will remain somewhat constant globally (as dew point temperature tends to increase in concert with temperature), the dew point-temperature relationship will be characterized differently on the regional scale—caused by variations in regional- or synoptic-scale circulation (Allen and Ingram, 2002). This study quantifies T_E at a regional scale and therefore cannot be representative of T_E on larger spatial scales. This study seeks to answer the following questions:

1. *Is there a coherent regional historical trend in* T_E *and its subcomponents over the central USA*? It is already known that there are positive trends in low-level moisture and nighttime temperature minima over much of the eastern USA (Robeson, 2004; Davis et al., 2002; Gaffen and Ross, 1999), but until recently, T_E has not been used as the metric of assessment. Lastly, the study area's inclusion of the 20th century Midwestern Warming Hole will allow T_E to shine-forth

light on whether or not the flat trend in summertime maximum temperature translates into a flat or negative trend in total surface energy content over the Midwestern USA.

2. *Are there significant historical changes in heat wave length, frequency, and intensity over the central USA?* The answer to this question will inform fellow scientists and policy-makers about whether or not we are seeing more frequent, longer lasting, and more intense high humidity heat waves or whether we are seeing more summers characterized by hot and dry conditions—favorable for drought (such as the summer of 2012). Moreover, this question seeks to answer whether or not we are seeing increases in both types of regimes; since increases in the frequency of both regimes is also possible.

3. *Does T_E provide a different perspective than temperature for understanding regional climate change?* The literature shows that T_E is a more robust metric than T for assessing total energy content of the climate system. Since this study only focuses on the central USA, it will serve as a framework for future studies that may consider different or larger regions, or even create a future climate change projection to investigate the effects of increasing atmospheric greenhouse gases (GHGs) on total surface energy content. This study seeks to determine the legitimacy of the argument that T_E is the best metric for assessing warming of the climate system.

1.4 Formal Definition of T_E

Equivalent temperature is a quantity whose terms are observed air temperature and moist static energy. It accounts for total surface energy content (Fall et al., 2007; Rogers et al., 2007;

Pielke et al., 2004). Fall et al., (2010) provides the following formula for the computation of isobaric T_E (℃):

$$T_E = T + \frac{L_v q}{C_p},$$

where T is the observed air temperature (℃), L_v is the latent heat of vaporization in units of Joules per kilogram (J kg^{-1}), q is the specific humidity (g/kg), and C_p is the specific heat of air at constant pressure in units of Joules per kilogram per degree Celsius (1005 J kg^{-1} ℃$^{-1}$). The component on the right-hand side of the addition sign is the moisture term whose subcomponents are $L_v q$ and C_p. This moisture term is referred to as moist static energy, and presented as L_q, in this study. Latent heat of vaporization is the amount of energy required to evaporate 1 kg of water. Specific humidity is the mass of water vapor per unit mass of atmosphere. The specific heat of air at constant pressure represents the amount of energy required to heat 1 kg of atmosphere by 1℃. T_E is further detailed in Chapter 2.

Chapter 2 contains a thorough literature review of the following: 1) T_E and its forces of influence 2) the importance of in-situ quality control and the most commonly used methods to achieve data homogenization 3) a description of some of the methods employed by this study. Chapter 3 expands upon the methods of this study and the source of the data. Chapter 4 details the analysis—outlining the data quality control procedures and trend analyses. Chapter 5 discusses the results from the analysis and provides conclusions based on those results. Lastly, correspondence and figures that were not included in the body of this thesis are provided in the Appendix section.

CHAPTER 2

LITERATURE REVIEW

2.1 Definition of a Heat Wave

It is difficult to define the term *heat wave*. However, without a tangible definition, it is difficult to assess heat waves (Robinson, 2001). These difficulties are due to factors such as individual physiological, social, and cultural adaptations that are somewhat governed by geographic region (Robinson, 2001). A *one-size-fits-all* approach to defining a heat wave may not be plausible. The NWS has certain criteria that must be achieved for an anomalous weather event to be considered a heat wave. According to the NWS, a heat wave is defined as a period where daytime maximum and nighttime minimum temperatures do not fall below 105°F or 80°F for a period of at least 48 hours, respectively (Robinson, 2001). Various definitions of heat waves are present in the literature and many of them lack consistency (Souch and Grimmond, 2004). One example is over-generalized and defines a heat wave as a period of several consecutive days with 'very warm' daytime and nighttime temperatures with no relief (Meehl and Tebaldi, 2004). Another is more specific and defines a heat wave as a 3-day period where daily maximum temperatures are above the 97.5^{th} percentile, with the average daily temperature above the 97.5^{th} percentile over the entire period, and a daily maximum temperature above the 81^{st} percentile for every day of the entire period (Meehl and Tebaldi, 2004). Frequently, heat waves are investigated through an applied climatological perspective—underscored by the profound impacts heat waves have on human health and mortality. Therefore, heat waves cannot be evaluated without reference to human impacts (Souch and Grimmond, 2004).

As a result of the convoluted nature of defining heat waves, heat index development has been a focal point in research that seeks to better evaluate ways in which society is impacted by weather. One such index known as the *heat stress index (HSI)* (Watts and Kalkstein, 2004) is seen as an improvement over the *weather stress index (WSI)* and the criteria that are commonly used by the NWS to issue heat stress warnings. The HSI possesses benefits over previous indices because of its consideration of relative human stress and adaptation that are governed by spatial and temporal conditions (Watts and Kalkstein, 2004). The HSI takes into account maximum and minimum *apparent temperature* (T_A), cloud cover, cooling degree-days, and total successive days of extreme heat (Watts and Kalkstein, 2004). Paradigms such as the HSI add clarity and consistency to the definition of a heat wave. However, given the complexity of the calculation of T_A (which consists of many factors such as wind and clothing); indices such as the HSI are cumbersome. Nonetheless, moisture is a key consideration when defining heat waves, as the amount of low-level moisture present during these events makes a profound difference in the amount of human heat and/or vegetative stress caused by the event.

2.2 Impacts of Low-level Moisture and Drought Conditions

In the previous section (section 2.1), differences in the temperature-dew point relationship between the global and regional scale were briefly mentioned. These regional variations are shown to be a result of regional- and/or synoptic-scale circulation as well as local antecedent moisture conditions (Fall et al., 2010; Pielke et al., 2004; Durre et al., 2000; Karl and Quayle, 1981). Karl and Quayle (1981) bring the 1980 summer heat wave and drought into a historical perspective by analyzing temperature and precipitation data over the USA from the period 1895-1980. In their analysis, the investigators determined that the most anomalous areas in the USA preceded two decades of rather cool summers. Furthermore, they suggested the 1980 summer drought would have been substantially worse than it was if antecedent weather had not been as favorable. Abundant precipitation during the spring months of 1980 occurred over a majority of the study area that later experienced summer drought conditions (Karl and Quayle, 1981). The abundant precipitation during those spring months prevented the summer drought from being as intense. The 1930s Dust Bowl is another example of a major historical drought that had profound impacts on humans and the environment. One study (Schubert et al., 2004) investigated the mechanisms held responsible for the Dust Bowl and compared the anomalies present during the Dust Bowl to climate proxy records and will be discussed in the following section.

Another example of how low-level moisture can negatively impact humans besides heat waves is via enhanced convection that leads to thunderstorm activity (Bonner, 1966; Pitchford and London, 1962). The presence of the LLJ contributes significantly to the occurrence of nocturnal thunderstorms in the Midwestern USA (Pitchford and London, 1966). Bonner (1966) performed a case study relative to the LLJ and confirmed the influence of the LLJ on a period of severe thunderstorm activity that occurred over the Great Plains on May 16-17th, 1961. These two early studies demonstrate how the impacts of increased (decreased) low-level moisture can be manifest not only in heat wave or drought conditions, but also in severe weather. Therefore, increasing amounts of low-level moisture not only contributes to heat waves but also increases severe weather occurrence and/or intensity during the spring and early summer across the Midwestern USA. Trends in the amount of low-level moisture are addressed in the following section.

2.3 Historical and Future Trends

There has been a cornucopia of studies that have looked at historical and future trends in summer temperature and moisture (precipitation and humidity). It has been found that the annual frequency of days exceeding locally-defined thresholds has increased for most of the USA (Gaffen and Ross, 1998). Daily-minimum T_A and the total number of heat-stress nights have increased by as much as 25% (Gaffen and Ross, 1998). When considering the regional frequencies, it has been found that daily-maximum T_A is markedly less than frequencies for extreme daily minima (Gaffen and Ross, 1998). Over all, between 1949 to 1995, there is approximately a 20% increase in the number of heat waves across the USA, with many of these increases manifest in the Midwestern and eastern portions of the USA (Robinson, 2001; Gaffen and Ross, 1998; Degaetano and Allen, 2002), with the exception of one study that also found increases in heat wave intensity across the southeastern USA (Meehl and Tebaldi, 2004). It has also been found during the last half of the 20th century that positive trends in specific humidity and temperature across a majority of the USA exist for every season, but to a lesser extent in the fall (Robeson, 2004; Gaffen and Ross, 1999). The most pronounced positive trends were manifest in nighttime weather conditions (Meehl and Tebaldi, 2004; Degaetano and Allen, 2002; Frich et al., 2002; Gaffen and Ross, 1999). Lastly, it has been determined that areas that are already experiencing strong heat waves such as the southwest, Midwest, and southeastern USA could be characterized by increasingly more intense heat waves in the future (Meehl and Tebaldi, 2004). Despite the aforementioned findings, trends in heat wave mortality for the eastern USA have not been found to be unprecedented during the last half of the 20th century (Davis et al., 2002). Therefore, concerns over increasing heat-related mortality rates for eastern portions of the USA as a result of anthropogenic activities are somewhat tenuous (Davis et al., 2002). Given seasonal variations in temperature and moisture, it is necessary for future studies to consider an entire year when investigating trends in temperature or related variables instead of focusing on an individual season (Robeson, 2004).

As mentioned earlier, there are studies that have compared the Dust Bowl to other historical droughts. When compared to proxy climate records, the Dust Bowl was less severe than droughts that occurred in the late 13th and 16th centuries (Schubert et al., 2004). Furthermore, climate records indicate that droughts as severe as the Dust Bowl have occurred in the Great Plains region of the USA once or twice per century over the past 400 years (Schubert et al., 2004). Therefore, although droughts such as the Dust Bowl are relatively rare in occurrence, they are not unprecedented and equal or worse droughts have occurred centuries ago.

Although historical trends in temperature, moisture, and climate impacts on human health are important, future trends are also important. It has been found that the USA climate will be characterized by increasing temperatures, a transformed hydrologic cycle, and increased variability in temperature and precipitation (Patz et al, 2000). Furthermore, models of weather-mortality relationships show that populations in Midwestern and northeastern USA cities will have the greatest amount of vulnerability to heat-related death and illness as a result of changes in summer temperature (Patz et. al., 2000). Aside from the human physiological stress induced by the combination of elevated temperature and humidity, vector-borne diseases may also be intensified and spread spatially as a result of warmer and more humid atmospheric conditions (Tol, 2002). Furthermore, as a result of climate change, it has already been found that relative mortality has increased uniformly when analyzed on the global scale (Tol, 2002). Therefore, the need for more research investigating temperature and moisture is evident in the literature as well as the need for a more comprehensive variable (T_E) that quantifies changes in total surface energy content as well as human and environmental impacts.

2.4 Equivalent Temperature

Studies have explored the contribution of temperature and moisture to the magnitude of T_E (Fall et al., 2010). It has been found that identical temporal patterns between the two terms exist, with larger values of T_E (Fall et al., 2010). Furthermore, the differences between the two variables are small during the winter and spring months when humidity is low (Fall et al., 2010). Intuitively, as atmospheric humidity increases from late spring to early fall, the differences between T and T_E increase—more markedly during the summer months (Fall et al., 2010). Also, temperature contributes to most of the magnitude of T_E with the specific humidity contributing a smaller portion. It was found that specific humidity's maximum contribution to T_E occurs in July (approximately 11.01% of the total magnitude) (Fall et al., 2010).

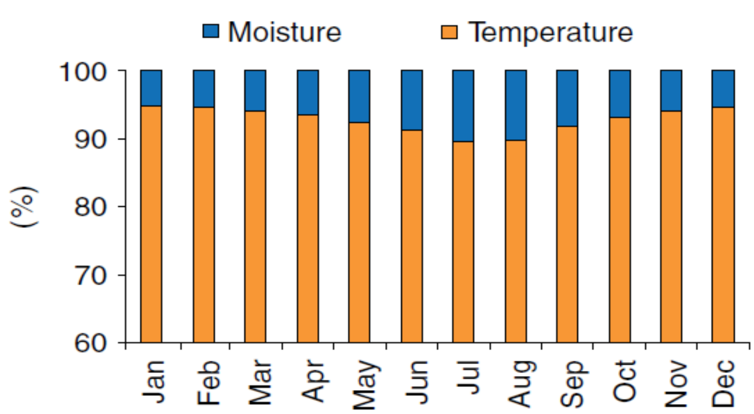


Figure 2.1 The proportion (%) of mean monthly temperature (level: 2m) and moisture (%) contributing to the overall magnitude of equivalent temperature for the USA (1979-2005) (Fall *et al.* 2010).

A marked contrast between the eastern and western halves of the USA exists in regards to the mean differences in T and T_E in the lower levels of the troposphere (<850 mb level) (Fall et al., 2010). Moreover, these largest differences are manifest over the Midwest and along the coastal Carolinas by as much as 8°C. An evaluation of the long-term historical variability in summer total surface energy content and variability occurring in surface temperatures, precipitation, and soil moisture has been conducted (Rogers et al., 2007). It has been found that for at least one station in the Midwest with a long time series record, mean T and moist static energy anomalies have opposite signs when summers are stratified into highest and lowest quintiles of soil moisture conditions and summer precipitation (Rogers et al., 2007); stressing the importance of antecedent moisture conditions on summer temperature and moisture. Given that T_E effectively quantifies energy and the temperature-moisture relationship, it is evident that T_E is ideal for assessing climate change and human/environmental impacts.

2.5 Assessing Climate Change and Human/Environmental Impacts Using Equivalent Temperature

Recent studies (Fall et al., 2010; Pielke et al., 2004) have suggested using surface heat content (manifest in T_E) rather than observed air temperature in order to more comprehensively assess climate change. Furthermore, T_E more comprehensively assesses both human and environmental impacts related to anomalous heat and/or humidity. Comparisons between T_E and T_A can be explored through a review of a study conducted by Steadman (1979). T_A is a measure of *sultriness* or how it *feels* outside to mammals. Exposure to such factors as air temperature, humidity, wind, *extra* radiation, and the dampness of one's skin—all factor into the computation of T_A Steadman (1979). Therefore, unlike T_E—that is composed of only components of observed air temperature and moist enthalpy—T_A is a combination of multiple factors. Therefore, current quantities used to assess climate change (i.e., T and T_A) are incomplete. In light of this, T_E is unique because of its ability to address climate change, human comfort, and environmental impacts all in one variable. It is for these reasons that future research addressing climate change and the effects of temperature and moisture on humans and the environment should focus on the use of T_E as the primary metric.

2.6 The Need for Research

Given the lack of consistency in the definition of a heat wave, T_E can be used to improve the definition of a heat wave. There is an explicit need for more research focusing on such methods as changes in the surface energy budget, soil moisture fluctuations, the effects of atmospheric circulation on the variability of specific humidity, and therefore T_E (Fall et al., 2010; Pielke et al., 2004). Furthermore, future studies' aim should be to quantify the contribution of anthropogenic activities on the magnitude and variability of T_E (Fall et al., 2010). In reviewing the literature expressing the need for further research considering heat waves, it is evident that understanding synoptic mechanisms, antecedent moisture conditions, and determining trends in summer equivalent temperature is also necessary. The latter is the impetus of this study.

2.7 Synoptic Controls on Summer Temperature and Moisture

Before considering the individual synoptic-scale mechanisms that control summer temperature and moisture over the eastern USA, it is important to note that multiple mechanisms generally work in concert to produce anomalous temperature and moisture conditions. Aside from global climate change impacting local temperature and moisture conditions, synoptic scale atmospheric processes also influence temperature and moisture regionally (Karl and Trenberth, 2003). Meridional wind anomalies forced by cyclones and anticyclones have an effect on both soil moisture and the LLJ (Mo et al., 1997). Furthermore, a northward shift in the *Intertropical Convergence Zone (ITCZ)* can result in weak synoptic-scale eddy activity and the subsidence of the enhanced Hadley cell that weakens the LLJ—resulting in less moisture transport into the USA (Mo et al., 1997). Synoptic-scale circulation patterns coupled with drivers such as soil moisture and vegetative health also play a significant role in high dew point temperature events (Bentley and Stallins, 2008). It is not that any single mechanism such as cyclones or anticyclones produce high T_E. Rather, it is a combination of mechanisms working in concert that produce elevated dew points. Therefore, although some mechanisms may contribute to anomalous temperature and moisture more than others, it is often multiple mechanisms working in concert that produce anomalous conditions.

General warming of the global climate system manifests itself differently on the regional scale. Since general warming has occurred mostly as a result of anthropogenic activities, changes in extreme temperature and precipitation are likely (Karl and Trenberth, 2003). Regional climate change is unique because every region is affected differently by general warming of the global climate system. Aside from the smaller or synoptic-scale atmospheric phenomena, this general warming influences T_E and will likely continue to create changes in temperature and moisture in the future (Karl and Trenberth, 2003). An example of the complexity of the climate system is the 20th Century Midwest Warming Hole. The lack of warming over the area of the Warming Hole has been attributed to small-scale circulation-precipitation coupling that is likely the result of enhanced greenhouse gas (EGHG) concentrations (Pan et al., 2004). Although trends in temperatures over the Midwest have been flat over the last century, there has been a positive trend in specific humidity over the eastern USA (Gaffen and Ross, 1999). Therefore, despite the presence of less energy in the form of sensible heat, it does not indicate that the total surface energy content over the Midwest has been decreasing because there has been an increase in moist static energy (latent heat) over the region.

Synoptic-scale forcing such as air-masses also profoundly affect temperature and moisture. Using *spatial synoptic classification (SSC)* to develop an air-mass climatology, it is evident that 6 of the most common summer air-masses over the eastern USA are *dry polar (DP), dry temperate (DM), dry tropical (DT), moist polar (MP), moist temperate (MM), and moist tropical (MT)* (Green and Kalkstein 1996). DP is the least frequently occurring air-mass during the summer over the eastern USA. The other two dry air masses (DM and DT) have a more dominant presence during the summer months (Green and Kalkstein, 1996). The low frequency of DP is likely due to a minimum in the tropospheric height gradient that limits the areal extent of the prevailing Westerlies (Green and Kalkstein, 1996). MP is rare in summer and most of the days associated with frontal conditions are characterized by MM air-masses (Green and Kalkstein, 1996). Though, MM is not predominant in summer either. The most common air-mass over the eastern USA during the summer is MT. The frequency of MT over the eastern USA during summer is concomitant with a pattern that is characterized by the interaction between the surface pressure gradient manifest between the Bermuda high and a low pressure located over the southwestern USA (Green and Kalkstein, 1996). This type of pattern generally results in MT movement northward into the Midwest from the Gulf of Mexico. Lastly, there are different regional responses to air-masses created by the characteristics of the surface over which they traverse (Green and Kalkstein, 1996). Therefore, although there is a lower frequency of transient systems over the summer in the eastern USA, transient air-masses play an integral role in regional weather conditions. If air-masses traverse over drier areas, the masses will generally be dry. If air-masses pass over highly-vegetated areas or areas with high soil moisture, they have the proclivity to be moist air-masses. Air-mass source regions also play a key role in an air-mass type. An air-mass moving from the Gulf of Mexico, for example, will be characterized by high moisture and warmer temperatures. Contrastingly, an air-mass originating from Alberta, Canada will be characterized by cooler, drier air.

The Gulf of Mexico is also highly influential on the location, duration, and extent of drought conditions in North America—specifically over eastern North America (Oglesby 1991). In fact, if it were not for the frequent presence of Gulf of Mexico moisture advection, central USA summers would be consistently dry (Oglesby, 1991). Northward moisture advection from the Gulf of Mexico (manifested in MT) is common in the eastern USA during summer (Green and Kalkstein, 1996). Other studies have underscored the key role moisture advection via the Gulf plays in eastern USA climatology. For example, it has been found that the Gulf of Mexico played a central role in both the Drought of 1988 and the Flood of 1993 (Dirmeyer and Brubaker, 1999). Southern areas of the eastern USA derive more moisture directly from the Gulf, whereas, the northern areas receive more of their moisture indirectly (Dirmeyer and Brubaker, 1999). An example of this indirect moisture transport is manifest over most of the Mississippi River basin, as this area does not receive moisture directly from the Gulf. Rather, moisture from the Gulf is transported northward in steps (Dirmeyer and Brubaker, 1999). The moisture falls over the Lower Mississippi basin, evaporates, falls again further to the north, re-evaporates, and so on in this type of cycle. During the Flood of 1993, the Gulf was a major source of moisture, whereas, the Drought of 1988 was characterized by a more terrestrial moisture transport regime. Therefore, it was determined that over-dominance of terrestrial moisture versus marine moisture transport—especially during the spring and summer months—leads to drought conditions (Dirmeyer and Brubaker, 1999). Contrastingly, over-dominance of marine sources generally leads to flooding (such as the case of 1993). Lastly, moisture from remote subtropical/tropical marine sources such as the Gulf and the Caribbean Sea is highly variable and can become quite marked at times (Dirmeyer and Brubaker, 1999). However, there are other mechanisms that are closely-related and contribute to Gulf of Mexico moisture transport such as the Great Plains LLJ (Helfand and Schubert, 1995).

There is a strong flux convergence in the lowest 100-mb of the atmosphere in regards to water vapor transport over North America (Rasmusson, 1967). Furthermore, there are systematic diurnal variations in flux (Rasmusson, 1967). The LLJ is characterized by maximum frequency alignment along the Gulf Coast of Texas and Mexico northward through central Texas toward Iowa and Minnesota (Helfand and Schubert, 1995). The LLJ is integral in transporting moisture onto the USA mainland from the Gulf of Mexico (Helfand and Schubert, 1995). Moreover, the east Mexican portion of the LLJ is representative of the westward inundation of the subtropical Atlantic anti-cyclone known as the Bermuda high (Helfand and Schubert, 1995). Lastly, below approximately 850-mb, the lower atmosphere is the main source (over half of the total influx) of moisture over the continental USA and there are marked diurnal variations in the LLJ (Helfand

and Schubert, 1995). Other studies have considered the influence of the Great Plains LLJ on summertime precipitation and moisture transport over central portions of the USA. One such study found that the LLJ plays a significant role in the genesis of summertime precipitation over the USA during meteorological summer (JJA) (Higgins et al., 1997). Their findings are also commensurate with previous studies in that 25% more precipitation falls during the night than during the day over portions of the Great Plains. Furthermore, the largest influx of moisture onto the continental USA ensues over the summer months with most of this moisture originating from the Gulf (Higgins et al., 1997). Lastly, synoptic-scale cyclonic and anti-cyclonic centers evolve from an east-west orientation in moisture transport during May to a north-south orientation during August (Higgins et al., 1997).

It is well-established that the Bermuda high plays a significant role in summer conditions over the eastern USA. Depending on the position and extent of the Bermuda high, the eastern USA can be characterized by dry or moist conditions. Anomalies in the western fringes of the Bermuda high are associated with sea-level pressure (SLP) and rainfall anomalies over the southeastern USA (Stahle and Cleaveland, 1992). Furthermore, during dry extremes, the western edge of the Bermuda high is characterized by strong ridging westward of its usual position—spilling over into the southeastern USA (Stahle and Cleaveland, 1992). Contrastingly, when the high is shifted east of its mean position (markedly offshore); wet extremes occur (Stahle and Cleaveland, 1992). In fact, it was the west-ward extent of the Bermuda high that prevented the supply of moisture from entering the continental USA via the Gulf of Mexico during the 1930s Dust Bowl (Schubert et al., 2004). Therefore, a west-ward expansion of the Bermuda high during the summer produces hot and dry conditions over the continent east of the Rocky Mountains and a more truncated Bermuda high allows for more moisture transport onto the continent—

producing wetter conditions.

Atlantic Ocean forcings besides the Bermuda high also influence temperature and precipitation over the eastern USA. Teleconnections such as the Atlantic Multi-decadal Oscillation (AMO) are also key drivers in summertime climate of North America and Europe (Sutton and Hodson, 2005). The study by Sutton and Hodson (2005) considered SLP, precipitation, and surface air temperature data between the warm phase of the AMO (1931-1960) and the proceeding 30 years from 1961-90 that were dominated by the cool phase of the AMO. In their examination of the results from an ensemble of 6 atmospheric general circulation model (AGCM) simulations, the investigators found that the AMO produced marked changes in regional atmospheric circulation and was associated with precipitation and surface temperature anomalies over the USA. Therefore, there is strong evidence suggesting that the frequency of USA droughts and Europe heat waves are both influenced by Atlantic sea surface temperatures (SSTs) that is consistent with finding in the Schubert et al., (2004) study. Lastly, given the temporal characteristics of the AMO phases, the authors suggest that we would now be entering a warm phase of the AMO (the manuscript was published in 2004). Warm Atlantic SSTs generally produce anomalous upper-level anti-cyclones on either side of the equator that can extend into the Gulf of Mexico and southern USA (Schubert et al., 2004). For example, this type of pattern was present during the 1930s Dust Bowl.

One more study considered the future behavior of heat waves and found that 500-hPa height anomalies contribute substantially to surface conditions characteristic of heat waves (Meehl and Tebaldi, 2004). Under semi-stationary 500-hPa positive height anomalies, dynamically produced subsidence, clear skies, light winds, warm-air advection, and persistent hot conditions at the surface are generally present (Meehl and Tebaldi, 2004). Moreover, this type of regime was present during the 1995 Chicago Heat Wave (Meehl and Tebaldi, 2004). Therefore, upper-level ridging is common over the USA during heat waves. It is for this reason that analysis of 500-hPa geopotential height anomalies may be important in future studies of summertime temperature and humidity of the USA. Lastly, as described in section 2.2, aside from the effects of circulation on the regional temperature-moisture relationship, antecedent moisture conditions are also important to consider.

2.8 Antecedent Conditions

Several studies have considered the effects of antecedent conditions on summer temperature and moisture (Fall et al., 2010; Durre et al., 2000; Findell and Eltahir, 1997; Oglesby, 1991; Madden and Williams, 1978). Madden and Williams (1978) considered the correlation between temperature and precipitation in the USA and Europe. Using 72 stations across North America, the investigators found that during the winter season, a negative correlation between temperature and precipitation is manifest over the Central Plains states. Cold winters in this part of the country are generally wet winters and vice versa (Madden and Williams, 1978). However, a significant positive correlation between temperature and precipitation over the Pacific Northwest and a regional band—extending from the Northeast south and westward into the lower Mississippi Valley is also present (Madden and Williams, 1978). Nevertheless, most areas of North America are characterized by negatively-correlated summer temperature and precipitation and this type of pattern occurs on all time scales (Madden and Williams, 1978).

Mid-to-late spring soil moisture anomalies can potentially impact summer climate by encouraging drought conditions (Findell and Eltahir, 1997; Oglesby, 1991). Moreover, the timing of spring soil moisture anomalies is critical as anomalies very early in the spring may not have as much of an impact as drought later in the spring or in early summer. Soil moisture is an important aspect of regional climate manifest in its effects on surface albedo (α) and the Bowen ratio (β) (Findell and Eltahir, 1997). Therefore, knowledge of antecedent soil moisture conditions can help predict years that are characterized by droughts or floods (Findell and Eltahir, 1997). It is quite possible that synoptic-scale circulation contributes to the summertime daily maximum and temperature-soil moisture relationship (Durre et al., 2000). This contribution seems to be most pronounced across the southeastern USA (Durre et al., 2000). If a certain synoptic regime creates a persistence of dry soil, the proceeding days may tend to be sunnier that would in-turn lead to a greater sensible heat flux and warmer daytime temperatures (Durre et al., 2000). Cloud cover between days with low soil moisture anomalies and other days is not a main driver in the relationship between soil moisture anomalies and high daily maximum temperatures (Durre et al., 2000). Moreover, maximum daily temperatures are not simply dictated by the previous day's meteorological conditions but it is dependent on antecedent soil moisture conditions—suggesting a *memory* effect (Durre et al., 2000). Lastly, daily soil moisture time series generally provide greater insight into the relationships between meteorological and land surface conditions than monthly soil moisture time series (Durre et al., 2000).

Vegetative properties (which are affected by soil moisture conditions) also influence T and T_E because of their effects on the surface energy budget via evapotranspiration (Fall et al., 2010). The influence of land cover types on moisture availability and temperature in the lower troposphere is significant (Fall et al., 2010). T_E has been found to be greater in areas with large evapotranspiration rates (i.e., the eastern USA); areas characterized by deciduous broadleaf forests and croplands.

Since long-term data is idealistic for assessing changes in the temperature-moisture relationship, one cannot discount the need for high quality data—especially given that in-situ data are susceptible to inhomogeneities. The following section (section 2.9) discusses the importance of data quality and the associated methods of quality control.

2.9 Data Quality

In any study, data homogeneity is integral. Any inconsistencies with a dataset must be considered before performing the analysis. Various techniques, approaches, and philosophies have been employed to address inhomogeneities in in-situ climate data. Factors affecting data homogeneity include station re-locations, instrument changes, changes in observing practices, formulae used to calculate atmospheric variable means, and the surrounding environment (i.e., urbanization) (Peterson et al., 1998). Station metadata (history) are important for determining when inhomogeneities occur and various techniques whose aim is to minimize any potential inhomogeneities in time series are necessary (Peterson et al., 1998). There is a relationship between data homogeneity and domain size. As the domain size increases, data inhomogeneity is somewhat balanced as adjusted and unadjusted trends have a proclivity to cancel out one another (Peterson et al., 1998). Studies (Changnon and Kunkel, 2006; Gaffen and Ross, 1999) have investigated how changes in instrumentation and site affect historical weather records. Although it is recommended that data homogeneity be performed for all weather stations on a case-by-case basis, some studies have found effects such as station re-locations and the surrounding environment (i.e., urbanization and station relocations greater than 1 mile) to be negligible

(Changnon and Kunkel, 2006; Gaffen and Ross, 1999).

It has been found that water vapor emissions from fossil fuel consumption produced effects that were negligible in regards to the positive trend in surface humidity (Gaffen and Ross, 1999). However, water vapor emissions created by the aviation industry and irrigation could have an effect on variable trends, that is something one must consider when using data from stations located at or near airports or agricultural areas (Gaffen and Ross, 1999). Close proximity to agricultural areas utilizing irrigation is especially important to consider for stations located in more arid climates (Gaffen and Ross, 1999). For stations in the conterminous USA, poor siting has been further refuted as an inflator of average temperature trends. In fact, by comparing adjusted to unadjusted data, there is a slight maximum temperature cool bias in unadjusted poorly sited data (Menne et al., 2010). The warm bias is only manifest in the minimum temperatures, but to a lesser extent than the maximum temperature trend (Menne et al., 2010). Nonetheless, all of the 1^{st} order weather stations across the USA exhibit at least one or several potential biases or inconsistencies as many of them are located in urban areas and near airports. Most agree, however, that the 1^{st} order stations possess some of the highest quality in-situ atmospheric data available.

It is rather difficult to characterize the nature of 20^{th} century trends across the USA (whether or not they are the result of a bias or inconsistency) in cold and warm extremes on a national or regional scale (DeGaetano and Allen, 2002). Numerous studies show that the strongest positive trends in minimum temperature extremes are manifest in the 1951-89 time period (Meehl and Tebaldi, 2004; Degaetano and Allen, 2002; Frich et al., 2002; Gaffen and Ross, 1999). Given the warmer observed nighttime temperatures, the mean temperatures display the same characteristic across all stations in the USA. Also, the percentage of increasing warm minimum temperatures is significantly higher at urban stations compared to rural or suburban sites (DeGaetano and Allen, 2002). During the 1960-96 time period, it has been found that urbanization exerts a strong influence on trends of warm temperature extremes (DeGaetano and Allen, 2002). When these urban stations are composited, the warm minimum temperature exceedences have a slope that is nearly 3 times greater than for rural composite series (DeGaetano and Allen, 2002); though there is some inconsistency across studies (Peterson, 2003) in the findings of the effects of urbanization on temperature. Lastly, the rate of extreme temperature warming is greatest in the eastern USA and least in the central region and is related to the spatial distribution of urban stations (DeGaetano and Allen, 2002).

Easterling and Peterson (1995) considered the effects of artificial discontinuities on contemporary trends in minimum and maximum air temperatures. Their study stresses the importance of identifying and addressing inhomogeneities because of the significant effect they can have on perceived trends in temperature minima and maxima. Despite inevitable inhomogeneities manifest in station climate data, trends in temperature minima and maxima are not because of extensive changes in instrumentation, but are indeed because of actual changes in climate (Easterling and Peterson, 1995). Further research has been undertaken by Easterling that considers trends and the effects of artificial discontinuities on perceived maximum and minimum temperatures. Easterling et al., (2000) highlight that one of the main issues with analyzing extreme climate events (at least from a global perspective) is the paucity of high quality, long-term climate data that are characterized by an appropriate time resolution. These issues along with instrument and site changes must be considered when performing quality control. Somewhat contrary to the findings of DeGaetano and Allen (2002), Peterson (2003) found no significant difference between urban and rural in-situ surface temperature data. Urban heat islands (UHIs) therefore may not contaminate surface temperature data for urban stations. Micro- and local-scale impacts on in-situ climate data overshadow the mesoscale UHI (Peterson, 2003). Also, for the majority of the time, meteorological observations are taken within cool park islands rather than industrial areas (Peterson, 2003). Therefore, the frequent argument that the UHI creates a warm bias in surface temperature trends is significantly discredited by the study conducted by Peterson (2003).

Various techniques used to homogenize atmospheric time series data exist. Such techniques include side-by-side instrument comparisons, statistical studies of instrument changes, identifying change points in time series via nonparametric statistical tests, data modification, using more than only 1 station, development of reference time series, both subjective and objective decision-making, the standard normal homogeneity test (SNHT), multiple linear and two-phase regression, and the rank-order change-point and Craddock tests; to name a few (Lanzante et al., 2003; Peterson et al., 1998). Furthermore, methods of homogenizing time series are country and/or region specific (Lanzante et al., 2003; Peterson et al., 1998). There are two statistical tests currently employed by the NCDC as part of their quality control procedures. These two tests are the *white noise test* (also known as the *cross-correlation test*) and the *lag 1 (1-day) autocorrelation test* (Menne and Duchon, 2001). Since these tests are applied to 1st order station data, data from those stations have already undergone some quality control. This is important because analyses are erroneous if data quality assurance is not achieved.

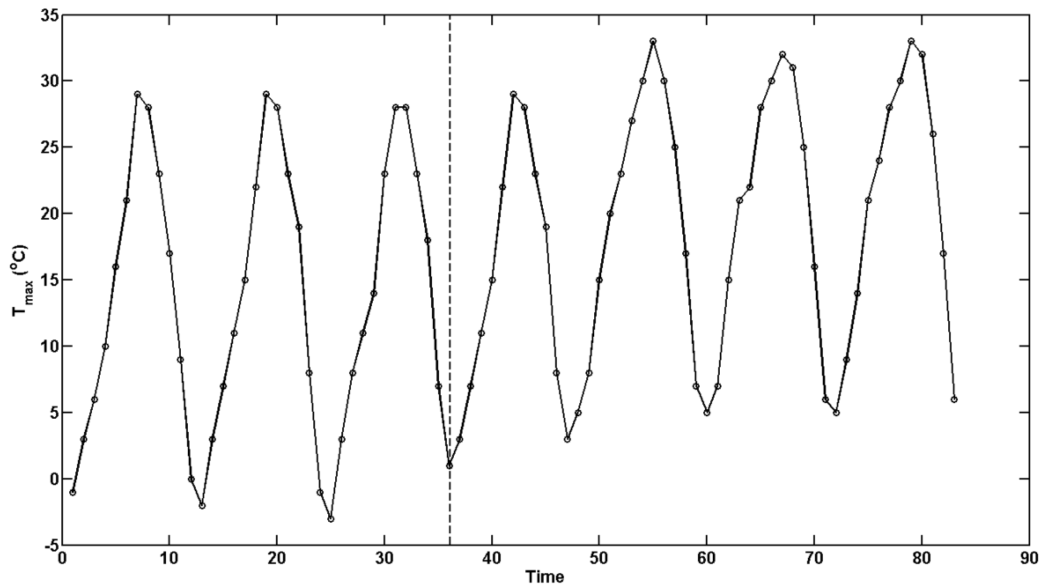


Figure 2.2 Time series of synthetic monthly data used to show the appearance of a step-like change. The change-point occurs at the dashed reference line.

As previously mentioned, observation times may be another factor that introduces bias in daily temperature statistics (Janis, 2002). These observation-time-dependent biases manifest themselves more frequently during winter than summer (Janis, 2002). One 1st order station's observation time change is important to identify because it can produce an artificial step-change (Figure 2.2) in its historical temperature time series (Janis, 2002). Therefore, two neighboring stations possessing different observation times may possess disparate temperature records because of simple observation time differences (Janis, 2002). Although observation-time bias is seemingly a temporal homogeneity matter, it also expresses spatial aspects when one considers the differences in temperature records between neighboring stations as a result of changes in observation time (Janis, 2002). Therefore, one can easily consider observation-time bias as being manifest in both temporal and spatial inhomogeneities. Therefore, observation time change may significantly reduce an investigator's ability to make substantial inferences about climatic change and variability.

Given that inhomogeneities in climate data are inevitable, finding robust techniques to manage them is integral. In order for statistical tests performed on time series of climate data to be substantiated, homogeneity or *relative homogeneity* must be present (Lanzante, 1996; Easterling and Peterson, 1995). One of the techniques identified in Lanzante (1996) is designed to identify change-points in time series data without relying on reference series from neighboring stations. Once change-points are identified, a review of station metadata can be performed in order to confirm a change or attempt to identify what has caused the change (i.e., is it artificial or natural) (Lanzante, 1996). The proposed procedure is a type of iterative design that searches for multiple change-points in a time series. This procedure applies a *Wilcoxon-Mann-Whitney* nonparametric test that is followed by an *adjustment step* iteratively until a test statistic is non-significant (Lanzante, 1996). This procedure may be viewed as a relatively simpler way of identifying change-points because it is not contingent on reference time series from neighboring stations. One more recent homogeneity test known as the MAC-D procedure (Reinzner and Gandolfi, 2013) is an algorithm designed to detect change-points in daily temperature series. Although the MAC-D approach is useful for studies using daily temperature data, it is more complex than many of the other homogeneity procedures, such as the Lanzante (1996) change-point detection method and the SNHT. Additionally, it shares the same shortcoming as the vast majority of homogeneity procedures; it does not provide a clear method of eliminating known inhomogeneities.

2.10 Summary

Heat waves are poorly defined. Therefore, when investigating the evolution of heat waves over time (i.e., their intensity, frequency, and duration) it is important how one defines a heat wave event. The potential impacts of heat waves and droughts on society are numerous. Therefore, further study in the trends or evolution of temperature, moisture, and specific combinations of the two over time and space are a necessity. Various regional- and synoptic-scale mechanisms profoundly influence temperature and moisture—particularly over the eastern USA during summer. Understanding temperature and moisture from the perspective of climate change is important in future research. The commonly used metric for assessing climate change (T) may not be ideal. Rather, a more robust metric (T_E) may be needed in order to fully capture both the sensible and latent heat components of total near-surface energy content. Given the contentiousness of climate change results produced from data derived from in-situ measurements, quality control addressing potential inhomogeneities caused by artificial changes (i.e., station re-locations, instrument changes, and changes in observation practices) is necessary for further research investigating changes in total surface energy content; especially on the regional-scale.

This study produces a high quality in-situ dataset and determines trends and changes in near surface temperature and humidity from a historical perspective. Furthermore, this study identifies historical changes in intensity, frequency, and duration of heat waves on a regional scale and underscores the implications these changes have on society. Lastly, this study further promulgates the use of T_E as the ideal metric for assessing climate change on any temporal or spatial scale.

CHAPTER 3

METHODOLOGY

3.1 Study Design

This study was designed to gain a better understanding of trends in temperature and moisture over the central USA from a historical perspective. The scope of this study was to determine if the central USA is seeing an evolution of temperature and humidity into a hotter/ cooler and wetter/ drier regime, or if there was an increase in the frequency of both regime types. Also, this study sought to determine seasons of the year that are experiencing warming/cooling and wetter/drier conditions. Furthermore, the goal of this study was to determine the overall trends in temperature and humidity and whether these trends are coherent across the 8 stations within the study area. Lastly, this study was designed to determine whether the central USA is experiencing changes in heat wave intensity, frequency, and duration; defined by multi-day events that exceed the locally-defined July-August 90th percentile of T_E; or if the region is experiencing more hot and dry spells (defined as multi-day events where T_{max}exceeds its July-August 90th percentile and L_{qmax} is below its July-August 50th percentile)

3.2 Study Area

The study area has been defined as the central USA encompassing portions of the Midwestern and southern USA. It includes the following states: Arkansas, Illinois, Indiana, Iowa, Missouri, and Tennessee. The 8 NWS 1st order weather stations contained within the aforementioned states are located in the following cities: Des Moines, Indianapolis, Little Rock, Memphis, Moline, Nashville, Springfield, and St. Louis (Figure 3.1). This area was chosen for two reasons: 1) It encompasses the Midwest Warming Hole 2) This area is prone to frequent summer heat waves.

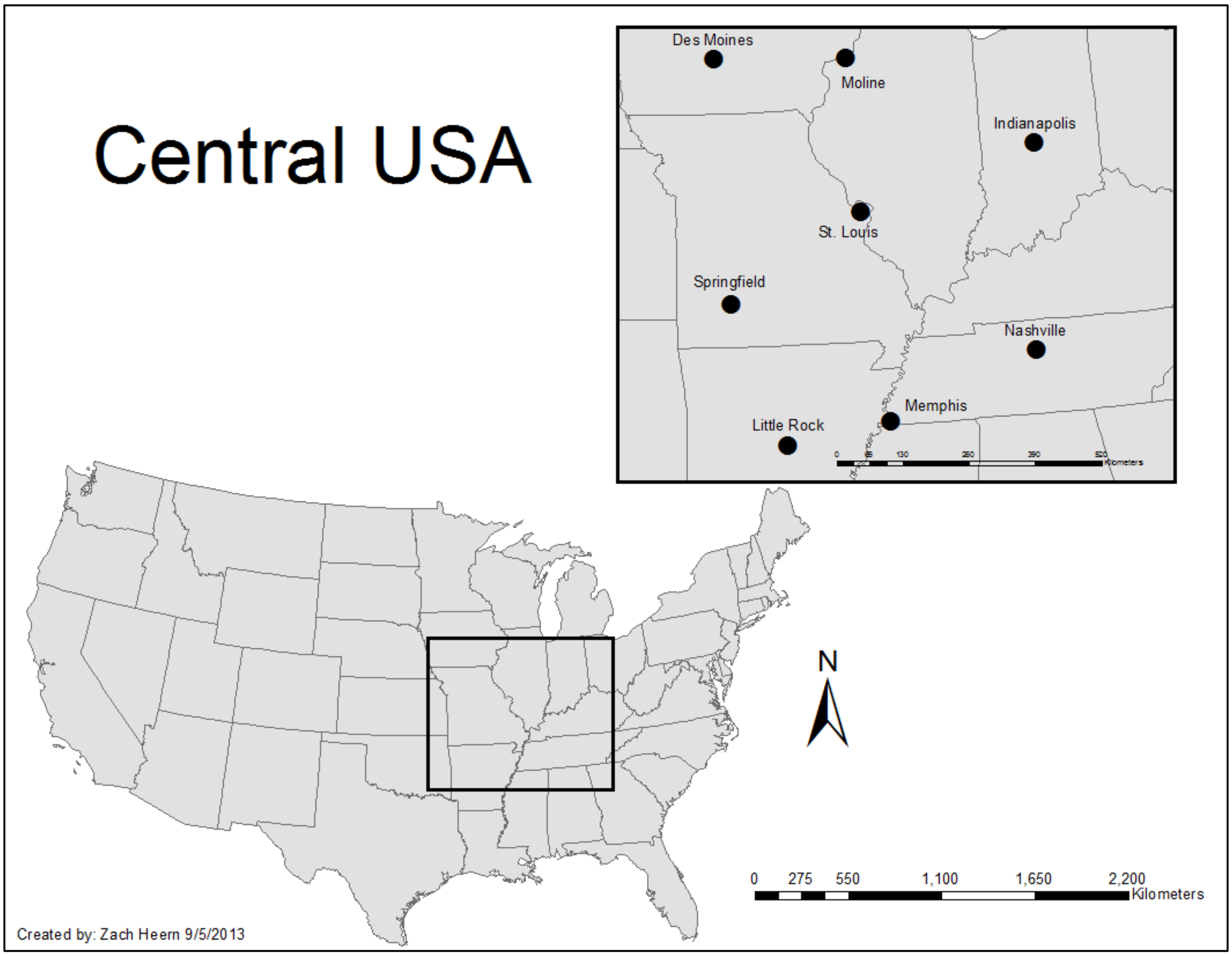


Figure 3.1. Map of the study area; it encompasses the central USA. The region roughly corresponds to the 'warming hole' presented by Meehl et al., (2012). Station locations are represented with black dot symbols. Map was produced using ArcMap 10.

3.3 Data

This study utilized hourly observational data extracted from NOAA's NCDC Integrated Surface Database (ISD) for the 8 aforementioned stations. Aside from the standard quality control performed by NCDC (procedures of which were outlined in Chapter 2), these data underwent quality control to achieve the greatest amount of relative homogeneity possible. Metadata for each station were gathered from NCDC and underwent thorough review. In order to first determine the distance (km and/or m) of station moves outlined in the metadata, the *Haversine* formula was used since the metadata only provide changes in latitude and longitude (decimal degrees) of the station locations over time. The Haversine formula is defined as follows:

$$a = sin^2\left(\frac{\Delta\varphi}{2}\right) + \cos(\varphi_1)\cos(\varphi_2)sin^2\left(\frac{\Delta\lambda}{2}\right)$$

$$c = 2atan2(\sqrt{a}, \sqrt{(1-a)}\ )$$

$$d = Rc,$$

where φ is the latitude, λ is the longitude, and R is the radius of the earth (6,371 km) (Sinnott, 1984). The angles are in radians. The distance yielded by this formula is an approximation since the formula assumes a spherical earth (the earth is slightly ellipsoidal). Nonetheless, given the short distances of the station moves, the errors caused by the underlying assumptions are negligible. The formula provides the distance the stations were re-located across the ground and the direction they were moved from their previous location. Also, the Haversine formula does not take into account changes in topography (that can affect the actual distance). However, all of the stations in this study are located at airports where topography is relatively flat. Therefore, for the purposes of this study, only approximations were necessary. The main concern was to identify if stations were moved substantial distances, namely, from one side of a city to another. If the magnitudes of the distances are relatively small (that is the case for the stations in this study), then that is sufficient. The distances and changes for Des Moines, Iowa are shown in the following table (Table 3.1). The metadata tables for the other stations are located in Appendix B.

Table 3.1. Metadata with elevation, station location, and calculated station re-location distances for Des Moines, Iowa (1928-2011).

Period	Site Ground Elevation (m)	Barometric Height Above Ground (m)	Lat/Long (decimal degrees)	Comments
1928-36	Unverifiable	Unverifiable	41.51667/-93.63333	Located at Des Moines International Airport
1936-44	284.24	9.09	41.53333/-93.65	Location change--moved 2.315 km northwest of 1928-36 position
1944-52	284.24	8.48	41.53333/-93.65	Barometric height change
1952-60	284.24	8.48	41.53333/-93.65	No verifiable changes
1960-68	284.24	8.48	41.53333/-93.65	No verifiable changes
1968-76	284.24	8.48	41.53333/-93.65	No verifiable changes
1976-84	284.24	8.48	41.53333/-93.65	No verifiable changes
1984-92	284.24	8.48	41.53333/-93.65	No verifiable changes
1992-2000	290.00	2.73	41.53333/-93.65	Site ground elevation and barometric height change
2000-08	290.00	2.73	41.53333/-93.65	Dew Point instrument (DTS1) change: 5/8/2006
2008-Present	290.00	2.73	41.5338/-93.653	Location change--moved 1 km east of 1936-44 position

After identifying changes in the stations' metadata, the raw hourly data from NCDC had to be formatted, processed, and analyzed. This formatting, processing, and analysis was done using FORTRAN and MATLAB. In order to extract the necessary time information and variables from the data files to complete this study, FORTRAN was used. The program in FORTRAN extracted year, month, day, hour, minute, T, dew point (T_d), and station pressure (STP). Although 1st order stations generally provide 1-h observations, the observations are not always taken at the same time within the hour and there are periods in the record where 3-h observations are taken. Furthermore, some hours may be missing from a 24-h period. In order to remedy these issues, the data were *cleaned* using MATLAB. The program produced in MATLAB assigned the observations that were not on the hour to the nearest hour. If the closest observation to the hour was missing or had some type of other error; the program searched in the neighborhood (30 minutes on each side of the hour) for the next closest, useable observation. Assignment to a particular hour was determined by traditional rounding principles. For example, if an observation was at 0134, then it was assigned to 0200. If an observation was at 0127, then it was assigned to 0100. The data were then converted to daily data by finding the daily maximum and minimum T and their corresponding T_d and STP. Once the data were converted to daily data, T_E was calculated using T, T_d, and STP. The new daily dataset contained year, month, day, T_{max}, maximum moist static energy (L_{qmax}), T_{Emax}, T_{min}, L_{qmin}, and T_{Emin}. These daily data were then converted to monthly, seasonal, and annual data. The monthly data are an average of the daily values. The seasonal is an average of the monthly values in 3-month increments and expressed according to standard meteorological season partitioning (DJF, MAM, JJA, SON). The annual is the average of the monthly values. In order for the daily values to be calculated, each day had to contain at least 2 hourly observations in a 3-h block. With eight 3-hour blocks in a 24 hour period, each block had to have at least 2 values in it, or that block was not counted. If one block was missing from a day, the entire day was not counted. In order for the monthly averages to be calculated, each month had to contain at least 90% of its values or it was not counted. In order for a season to be calculated, it had to contain all 3 months in each seasonal block. In order for the annual average to be calculated, the year had to contain all 12 months or that year was not counted.

Two different methods were employed to ensure the data were relatively homogenous. Many of the current methods for data homogenization cannot be utilized with a one-size-fits-all approach. Furthermore, many of them may be somewhat effective, but not very simplistic. This study sought after a method that was both effective and simplistic. The two methods used in this study were completed in order as follows:

1. *Gross Inspection:* A visual inspection of each time series for each station for all variables was completed. This somewhat subjective, qualitative method followed a particular framework. 4-year periods on each side of a known station change (whether it was a change in NWS 1st order stations on the national level or a change at the local level) were analyzed along with the year in between the 4-year period that possibly contained the known change. Since the temporal resolution of the station metadata is relatively coarse (Appendix B), each year within the 8-to 9-year period of a known change had to be stepped-through with a 4-year period on each side of the year in question. For example, if a station-change occurred sometime from 1928-36, one would look at the period from 1924-28 to 1929-33 and so forth until each year within 1928-36 was included with its previous and subsequent 4 years. This visual inspection is very similar to the method employed by Gaffen and Ross (1999). When looking at these time periods containing

a known station change, the objective was to identify any step-like changes present. The presence of a step-change could indicate a potential inhomogeneity related to a station-change.

2. *Pairwise Differences:* Following the gross inspection, a more objective, quantitative method was employed. The annual time series data of T_{max}, L_{qmax}, T_{min}, and L_{qmin} for each station were paired. Initially, the entire record of each dataset was used (1920-2011). However, due to a great deal of missing data prior to 1951, the time series were truncated to 1951-2011 for all stations. The pairwise differences were calculated between station combinations according to each station's proximity to one another. Then, the pairwise differences were plotted in a time series and these differences were inspected for change-points. A step-like change or a statistically significant trend in the time series for the pairwise differences could be indicative of a potential inhomogeneity. Therefore, each time series of the pairwise differences for each pair combination was visually inspected for step-like changes and tested for a significant trend ($H_{\theta}: \beta = 0$).

3.4 Objective

In order to answer the following research questions, various methods were employed. Beginning with the first research question:

1. *Is there a coherent regional historical trend in T_E and its subcomponents over the central USA*?

A frequency distribution for maximum and minimum T_E, T, and L_q was developed for the monthly data. This study employed a very similar method as Robeson (2004); but instead of looking at T maxima and minima, trends in time-varying percentiles for T_E and its subcomponents were determined. In order to achieve this, 5-95th percentiles for each month of every year (1951-2011) were calculated. This yielded an array containing the year, month, and percentile (5-95th) for maximum and minimum T_E and its terms (each variable had its own array) for each station. Then, this array was converted into another array that had the percentiles as the rows and the months as the columns, with each cell containing the °C trend or change for each percentile. The array contained the percentile trends for each month. The percentile trends were calculated using a resistant regression method known as *Median of Pairwise Slopes (MPWS)* regression from Lanzante (1996). MPWS regression was chosen over OLS because of its resistance to outliers—providing a more conservative, unbiased trend estimate. This array was then represented graphically using a contour plot to show the percentiles that are experiencing warming/cooling and the months or seasons that are experiencing the most warming/cooling and the °C change (trend) associated with each percentile and month. The contour plot is a method of graphically representing the 3-dimensional percentile trend array data in 2 dimensions.

The model for MPWS regression used to calculate the percentile trends is defined as follows:

$$b_k = (y_i - y_j)/(x_i - x_j)$$

$$res_i = y_i - (b\, x_i)$$

$$y_i = a + (bx_i)\ ,$$

where b_k is the slope between each possible pair of points (x_i, y_i) and (x_j, y_j), b is the final slope estimate (the median value of the b_k's), res_i is the residuals for all n points, a is the intercept estimate (median of these residuals) and $y_i = a + (bx_i)$ is the regression equation (Lanzante, 1996). MPWS calculates the slope between every possible pair combination of points in the data and calculates the median of those values. Therefore, since this type of linear regression method utilizes the median statistic, it is resistant. Additionally, MPWS does not require constant variance.

In order to expand upon whether overall trends in T_E and its subcomponents were coherent across the study area, time series analysis on the *annual* data for each station was performed and the slopes of the data in the series were determined using the MPWS regression method. The slopes were tested for significance (H_θ: $\beta = 0$) at the 95% confidence level using the *corr* function in the MATLAB statistics package.

2. *Are there significant historical changes in heat wave length, frequency, and intensity over the central USA?*

In order to answer this question, the analysis was broken down into 5 parts: 1) Extreme equivalent temperature days; defined as days exceeding the July-August 90th percentile (P_{90}) equivalent temperature 2) Extreme moisture days; defined as days where moist static energy maxima exceeded their July-August P_{90} value 3) Extreme temperature days; defined as days where temperature minima exceeded their July-August P_{90} value 4) High humidity heat wave events; defined as multi-day events where both $T_{max} >$ P_{90} July-August value and L_{qmax} > 50th percentile (P_{50}) July-August value 5) Low humidity heat wave events; defined as multi-day events where T_{max} > P_{90} July-August value and L_{qmax} < P_{50} July-August percentile value. The total number of events that met the criteria of the aforementioned thresholds (steps 1-3 above) were counted for each year for each station and plotted in time series. Trend analyses were then performed on these plots again using MPWS regression. The trends were tested for a significant slope at the 95% confidence level. In order to quantify changes in the moisture characteristics of heat waves (steps 4-5 above), two different trend analyses were employed: 1) Trends in the proportion of annual hot days characterized by high humidity 2) Trends in the frequency distribution of multi-day events characterized by elevated temperature and high/low humidity. The first method is characterized by a quantitative approach and the second is characterized by a more qualitative approach. A different threshold was used for T_{max} between the two analyses. For the former method, the July-August 75th percentile (P_{75}) T_{max} was locally-defined for each station. For days of the year meeting this T_{max} threshold, the proportion of the total days for every year characterized by days where $L_{qmax} > P_{50}$ July-August (high heat and high humidity days) value was calculated. These calculations yielded annual time series that were the proportion of the total number of hot days ($T_{max} > P_{75}$) characterized by high humidity ($L_{qmax} > P_{50}$). A MPWS trend analysis was then conducted on these times series and tested for significance. For the latter method, the T_{max} threshold was set at the July-August 90th percentile value. Event frequency (per year) for 1-day through 8-day events for each regime (i.e., high humidity heat waves, and low humidity heat waves) was then calculated. After this overall frequency was calculated, the 61-year period was partitioned into two 30-year periods (1951-1980 and 1981-2010) and the differences between the distributions for these periods were calculated for each regime in order to determine trends in these multi-day events. The last year of the entire period (2011) was discarded so the periods were of even length.

3. *Does T_E provide a different perspective than temperature for understanding regional climate change?*

The 3rd research question is a consummation of the first 2 research questions. Namely, did the results from the first 2 questions provide a different perspective than temperature for understanding regional climate change? The behavior (trends and variability) of T and L_q helped address this question. Since T_E accounts for latent heat energy, as opposed to T (which only accounts for sensible heat energy), the influence of L_q on total surface energy content considered in this study helps answer this question—considering there has been an overall flat trend in annual T_{max} over the central USA during the last-half of the 20th century.

CHAPTER 4

RESULTS

4.1 Introduction of Results

Prior to conducting analysis, data quality control was performed. This quality control served as an integral component of this study. In Chapter 3, two parts of this quality control were identified: (1) Gross inspection (2) Pairwise differences. The gross inspection did not yield any concerns as no inhomogeneities were identified. Additionally, time series plots of the pairwise differences (Figure 4.2) did not yield any concerns as no change-points were identified. There was one significant slope for all variables for the Nashville-Memphis station combination. However, when Nashville was paired with Indianapolis, no significant trend was found. Therefore, as the rest of the results will demonstrate, the slight negative trends in moisture for Nashville (and to a lesser extent Indianapolis) may not be the result of an inhomogeneity. Rather, they may be caused by a change or variation in a synoptic-scale influence such as the Great Plains LLJ—given their location in the eastern extent of the study area. This issue is further addressed in the following sections and in Chapter 5. Therefore, the data were deemed to be relatively homogenous upon completion of these 2 steps and analysis ensued.

In Chapters 1 and 3, three research questions were posed: (1) Is there a coherent regional historical trend in T_E and its subcomponents over the central USA? (2) Are there significant historical changes in heat wave length, frequency, and intensity over the central USA? (3) Does T_E provide a different perspective than temperature for understanding regional climate change? The answers to these questions are addressed in the results and conclusions (Chapter 5).

4.2 Data Homogenization Results

4.2.1 Gross Inspection

The goal of the gross inspection was to identify change points in the monthly data that coincided with a known station change. The procedures of this inspection outlined in Chapter 3 were performed by plotting monthly time series for each variable for each station. This gross inspection was originally completed before the data were truncated (1951-2011) during the analysis of the pairwise differences and so the period 1920-2011 was analyzed in this step. Given that only the largest change-points are necessary for consideration (Peterson et al., 1998), small change-points were ignored. Nonetheless, there were no change-points for any of the variables for any of the stations that were questionably large. Furthermore, given that the data after 1951 are of much greater quality, the data were relatively homogenous during this step—especially after 1951 where little to no missing data are present. One example graphic of the plotted monthly data is shown on the following page (Figure 4.1).

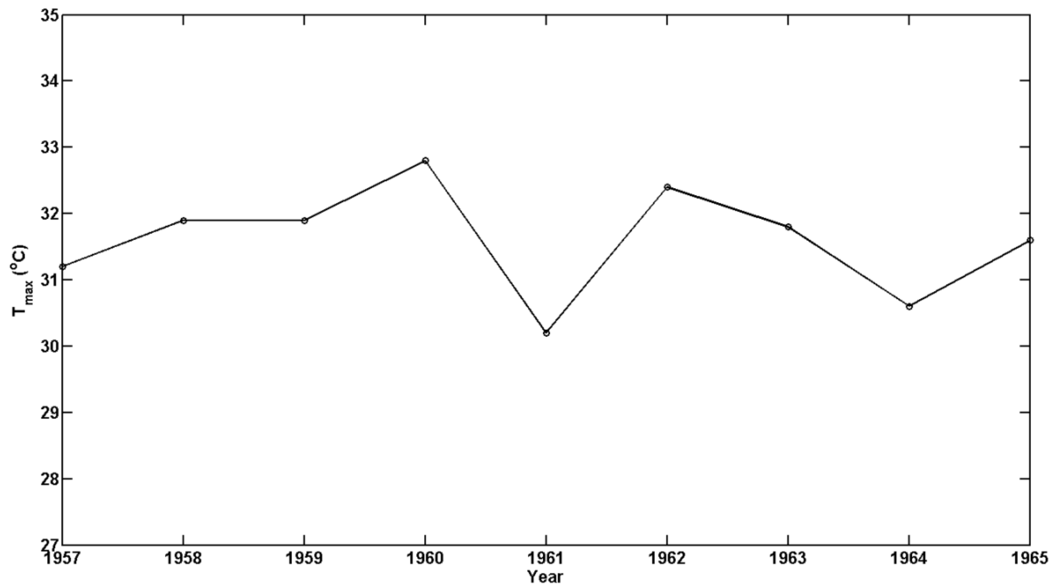


Figure 4.1. Time series of August T_{max} (°C) for Memphis (1957-65). This time series plot is an example of a data sample that was visually inspected for change-points. Each 9-10 year sample contained one of the years within the period of a known station change. This figure, for example, was inspected for a known station change that might have occurred between 1961 and 1970.

4.2.2 Pairwise Differences

The time series of the pairwise differences were truncated to the period 1951-2011. This yielded a time series dataset that possessed little to no missing data. The 6 individual pair combinations were as follows: (1) St. Louis and Springfield (2) Nashville and Memphis (3) Memphis and Little Rock (4) Des Moines and Moline (5) Indianapolis and St. Louis (6) Nashville and Indianapolis. These pairwise differences were calculated for each variable. These differences were then plotted in individual time series, inspected for change-points and tested for a significant trend ($H_\theta: \beta = 0$) at the 95% confidence level. As outlined in chapter 3, a change-point or significant slope in these data would suggest a potential inhomogeneity. However, none of the data reflected suspect change-points and for the station combination that exhibited a significant trend (Nashville-Memphis), the drift was attributed to a natural change or variation in climate instead of an inhomogeneity due to the non-significant trend in the pair combination of Nashville-Indianapolis. The possible influence of a synoptic-scale influence such as the LLJ is further exemplified in the results presented in the following sections of this chapter. It is possible that a synoptic-scale influence is responsible for the slight negative trend in moist static energy in Nashville (and to a lesser extent, Indianapolis). An example of the time series plots for the pairwise differences is shown below (Figure 4.2).

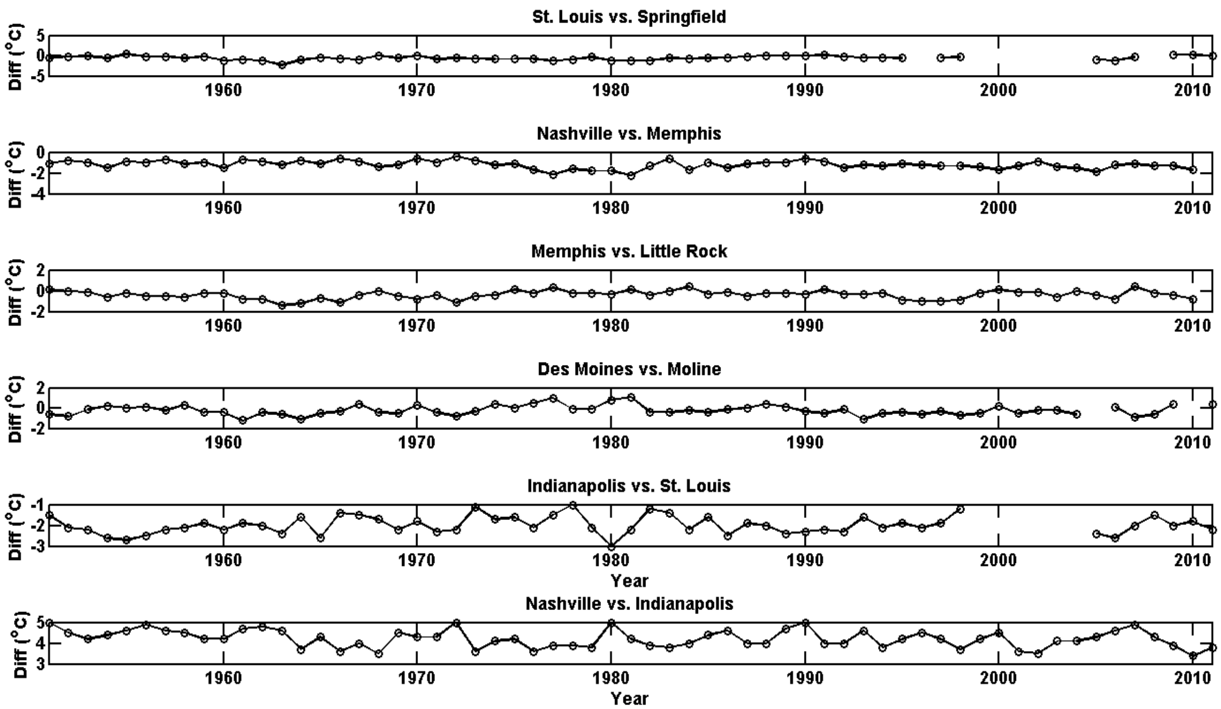


Figure 4.2. Annual time series plots of pairwise differences for each station pair for L_{qmax} (1951-2011). The pairwise differences are in ℃ and the gaps in the plots are due to missing data as a result of the data quality control via formatting and pre-processing outlined in Chapter 3. Change-points or trends in these data could be indicative of an inhomogeneity.

4.2.3 Conclusion

The gross inspection and pairwise difference steps were both designed to identify step-like changes; the latter was also designed to identify a statistically significant slope. A step-like change or significant slope could be indicative of an inhomogeneity—especially if the change corresponded to a station change recorded in station metadata. For both inspections, no suspect change-points were identified. Although a significant slope was identified for the Nashville-Memphis pairwise difference, when Nashville was compared to Indianapolis, no significant slope was found. Since Indianapolis and Nashville are the most eastern located stations in the study area—it is possible that their trends in moist static energy are due to a synoptic-scale influence rather than an inhomogeneity. The following results further promulgate this hypothesis and are further addressed in Chapter 5. Therefore, the in-situ station data for this study were deemed relatively homogenous and sufficient for analysis.

4.3 Trend Analysis

4.3.1 Time Series Trend Analysis

Prior to performing the time-varying percentile trend analysis, a trend analysis of annual time series of T, L_q, and T_E for all stations was performed using MPWS regression. The results for the median trends (℃/50 years) (Table 4.1) and example time series of annual T_E maxima (minima) (Figure 4.3) are shown below. Time series for the other stations are located in Appendix D.

Table 4.1. Shows the median trend ℃/50 years (1951-2011) for the annual maximum and minimum values of T_E and its subcomponents. '*' denotes significant ($0.05 \geq$ p-value > 0.01) and '**' denotes highly significant (p-value ≤ 0.01) trends.

Station	T (Max)	L_q(Max)	T_E (Max)	T (Min)	L_q (Min)	T_E (Min)
Des Moines	***0.88**	****0.84**	****1.63**	****1.15**	****0.72**	****1.94**
Indianapolis	0.62	0.50	0.85	****1.18**	***0.7**	****2.00**
Little Rock	0.43	****1.09**	****1.10**	***0.65**	****0.84**	****1.67**
Memphis	0.60	0.50	*0.86	****1.43**	***0.49**	****2.30**
Moline	***0.67**	***0.84**	****1.35**	***0.67**	***0.58**	***1.25**
Nashville	0.33	-0.53	-0.50	****0.75**	-0.39	0.77
Springfield	0.33	***0.76**	***1.11**	****0.79**	****0.80**	****1.67**
St. Louis	0.56	***0.96**	***1.25**	****1.54**	****0.93**	****2.50**

(a)

(b)

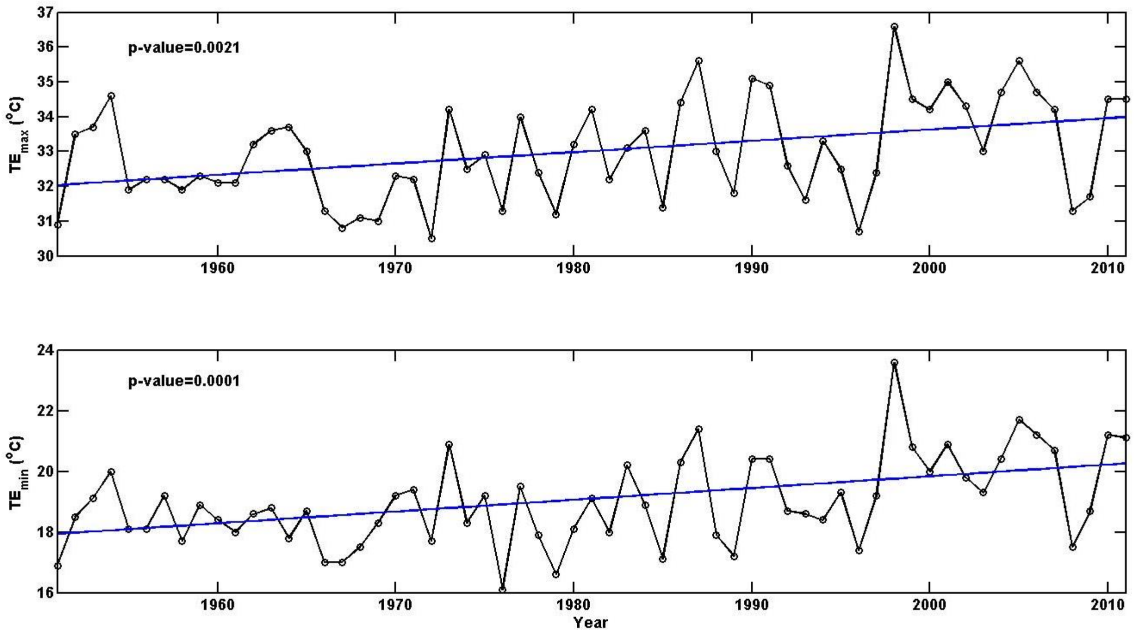


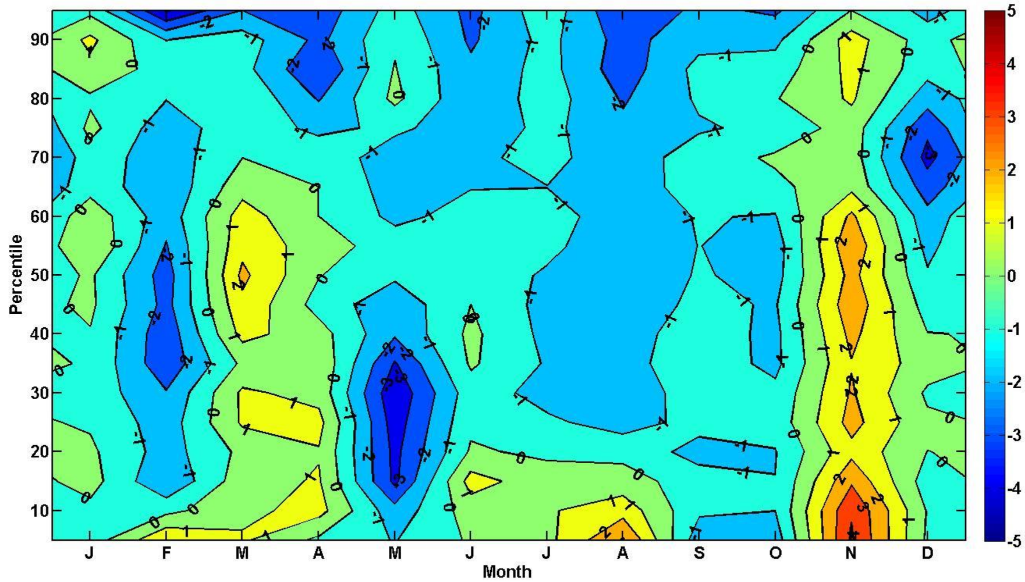
Figure 4.3. Annual time series of T_{Emax} (a) and T_{Emin} (b) for Des Moines (1951-2011). Both trends (shown in blue) are highly significant ($\alpha = 0.05$). The p-values for $H_{\theta}: \beta = 0$ are shown in the time series.

All stations in the study area (with the exception of Indianapolis and Nashville) experienced significant positive trends in both maximum and minimum T_E ; though Indianapolis did experience a highly significant positive trend in T_{Emin} at the 95% confidence level (Table 4.1). Indianapolis, Memphis, and St. Louis had the largest trends in T_{Emin} (> 2℃$/50$years) (Table 4.1). From a regional perspective, there is a significant, positive trend in T_E during the period 1951-2011. The only station that exhibited slightly negative trends in T_{Emax}, L_{qmax}, and L_{qmin} was Nashville. However, the negative trends were non-significant (Table 4.1). Lastly, it was evident from the time series that L_q was a major driver in the overall trend in T_E. The driving force of L_q was further exemplified in the time-varying percentile trend analysis (Section 4.3.2.).

4.3.2 Time-varying Percentile Trend Analysis

The time-varying percentile trend analysis yielded interesting results (Figures 4.4-4.5 and Appendix C). All of the stations except for Nashville exhibited positive percentile trends in T_E (as great as $3\text{-}5℃/50$ years) from 1951-2011 (Appendix C). St. Louis exhibited the largest positive trends (throughout all seasons for T_{Emin}) in T_E (Figure 4.5), but stations such as Des Moines also exhibited large trends. All of the stations exhibited the greatest warming during the spring and fall months—ranging from $2\text{-}5℃/50$ years, with most of this peak warming centered between the 10-90th percentiles (Appendix C). Out of the 8 total stations, 6 of them (Indianapolis, Little Rock, Memphis, Moline, Springfield, and St. Louis) did, however, also exhibit strong positive percentile trends in T_E during mid- to late-summer—especially marked in T_{Emin} (Appendix C). Many of the trends in T_{max} were relatively flat, but because of the strong positive trends in moist static energy, positive trends in T_E resulted (Appendix C). Although warming was mostly manifest during spring, summer, and fall, two of the stations in the northern portion of the study area (Des Moines and Moline) exhibited warming during the winter—particularly in the lower and middle percentiles of the distribution for T and T_E maxima and minima (Appendix C). However, slight cooling ($1℃/50$ years) in the middle percentiles for the remainder of the stations during winter was typical. Despite an overall similar sign in the trends across the stations, there was some evident variability in the magnitude of the trends (Appendix C). Lastly, minima of T_E and its subcomponents exhibited the greatest amount of warming across the stations.

(a)



(b)

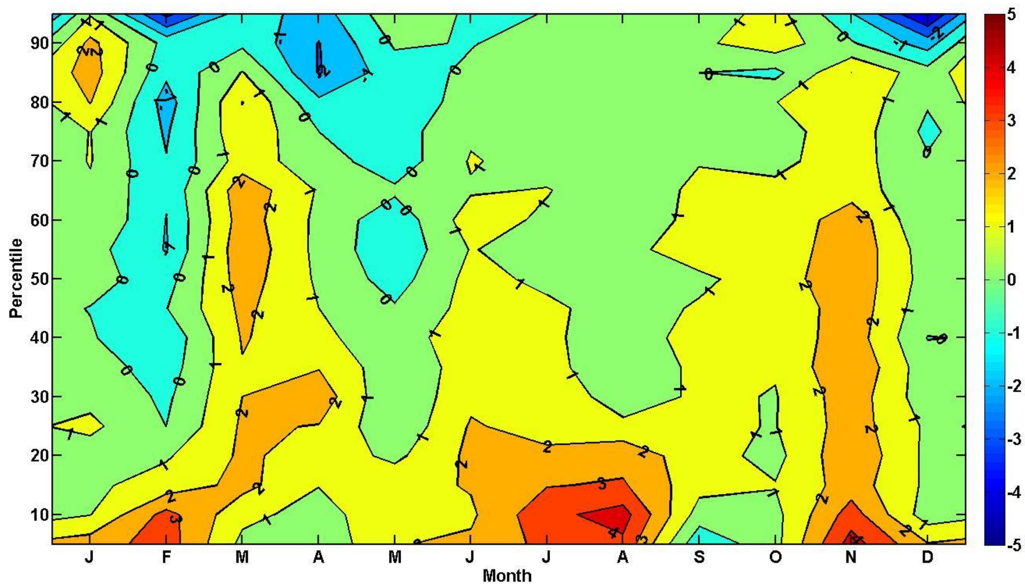
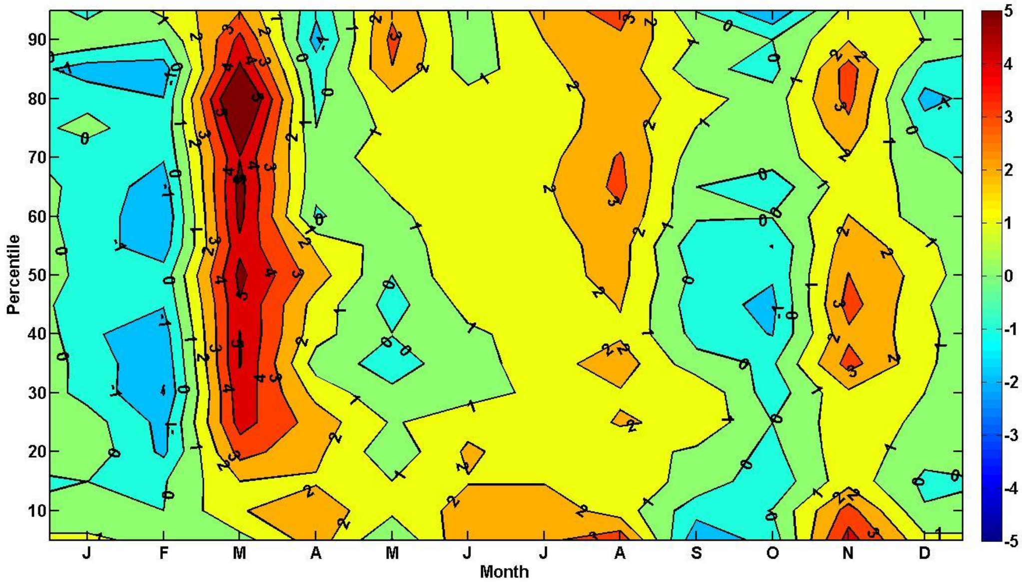


Figure 4.4. Time-varying percentile trends for T_{Emax} (a) and T_{Emin}(b) for Nashville (1951-2011). The values on the contour lines represent the trend (℃/50 years). Months are plotted along the horizontal axis and percentiles are plotted along the vertical axis. Nashville is an outlier (due to slight negative trends) in comparison to the other stations. Contour plots for the other stations are located in Appendix C.

(a)



(b)

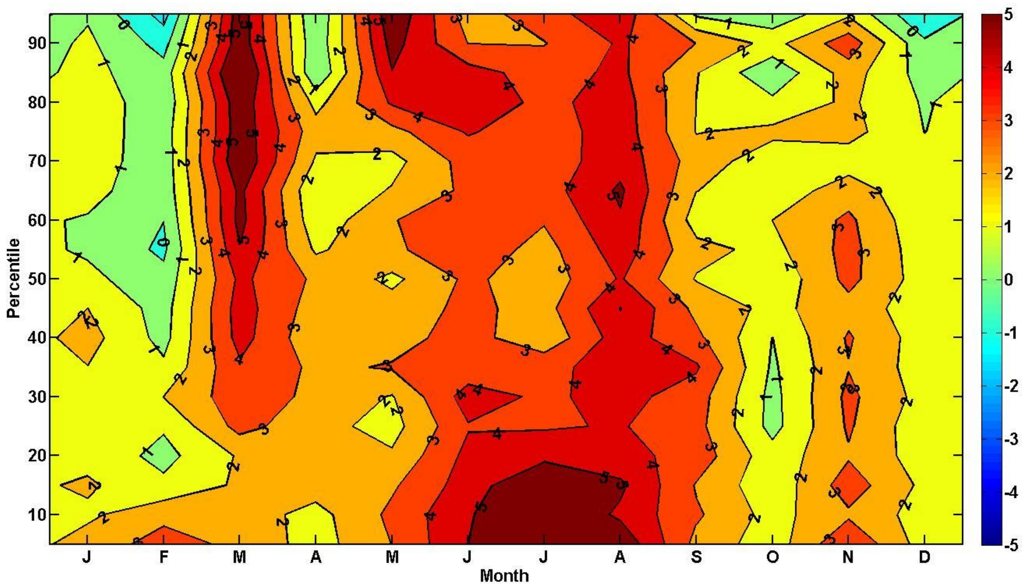


Figure 4.5. Time-varying percentile trends for T_{Emax} (a) and T_{Emin}(b) for St. Louis (1951-2011). The values on the contour lines represent the trend ($°C/50$ years). Months are plotted along the horizontal axis and percentiles are plotted along the vertical axis. Compared to the other stations, St. Louis exhibited the largest positive trends in T_E. Contour plots for the other stations are located in Appendix C.

4.4 Heat Wave Trend Analysis Results

4.4.1 Overall Trends

In this study, the *high/low humidity* heat wave trend analyses were partitioned into two parts: 1) Trends in the proportion of annual hot days characterized by high humidity 2) Trends in the frequency distribution of multi-day events characterized by elevated temperature and high/low humidity. Thresholds for the former were defined as days where T_{max} > P_{75}. The proportion of days per year meeting this threshold that were also characterized by days where $L_{qmax} > P_{50}$ July-August values was calculated and plotted in annual time series. The latter was also divided into high humidity and low humidity regimes. The high humidity regimes were defined as multi-day events where both T_{max} exceeded its July-August 90th percentile and L_{qmax} exceeded its July-August 50th percentile. Conversely, *low humidity* regimes were defined as multi-day events where T_{max} exceeded its July-August 90th percentile value and L_{qmax} was less than its July-August 50th percentile value. The first method is a quantitative approach and the second method is more of a qualitative approach. Different thresholds for T_{max} were chosen because a higher frequency of days was needed in order to do an effective MPWS trend analysis for the proportional data as opposed to the number of days necessary for the trends in the frequency distributions of multi-day events. Unlike the trend analysis of the proportions, when the T_{max} threshold was lowered to the 75th percentile, there still were not enough values for the trend analysis of the frequency distribution to perform a statistical Chi-squared test. Since the objective of the heat wave analysis was to focus on very high temperature events ($T_{max} > P_{90}$), this threshold was held for the frequency distribution analysis. However, the lower threshold ($T_{max} > P_{75}$) for the trend analysis of the proportions is still representative of the moisture characteristics of the hottest days of the year, and if a higher threshold would have been used, there would not have been a sufficient amount of data to perform a robust trend analysis on the proportion data.

First, in order to assess overall trends, the frequency of 90th percentile exceedences for maximum and minimum T_E and its subcomponents for each station were calculated for each year and trends were estimated using MPWS regression (Appendix E). The results for Des Moines are shown below (Figure 4.6). The significance of these trends was then estimated. The p-values for each trend for each station are also shown on the following page (Table 4.2).

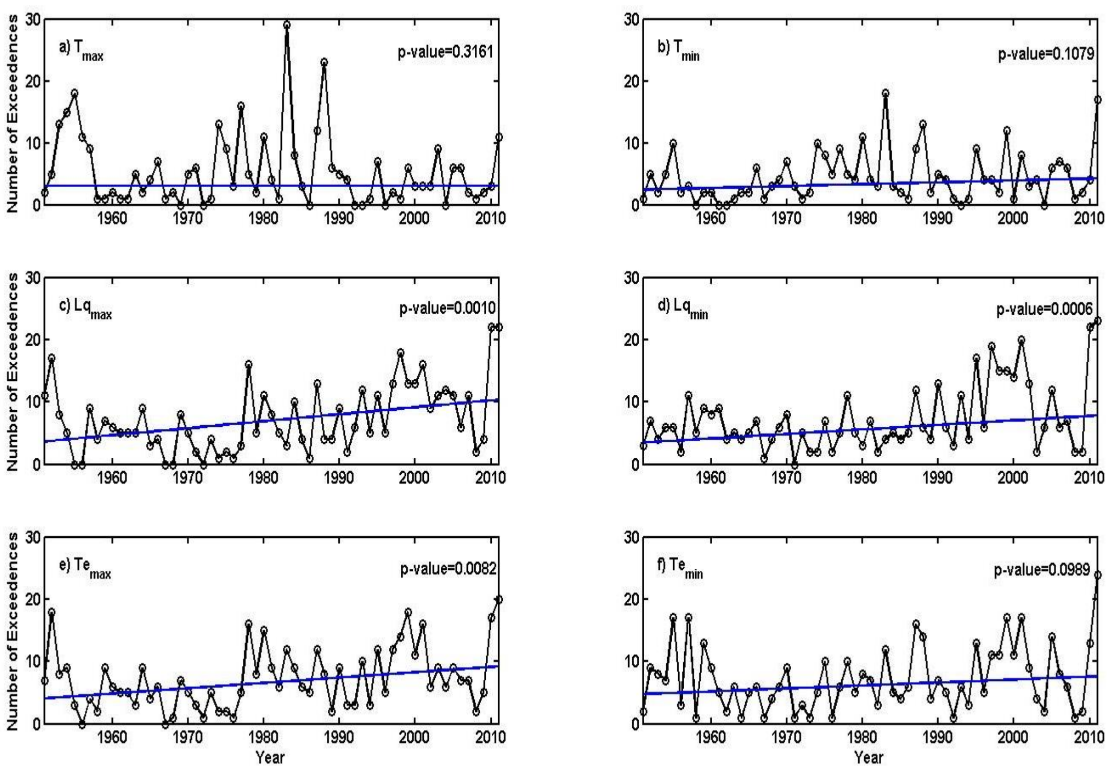


Figure 4.6. Frequency of days per year where T, L_q, and T_E maxima (minima) exceeded the 90th percentile for Des Moines (1951-2011). Percentiles are based on July-August values. The trend was calculated (shown by the blue line) and the significance of the slope was calculated ($\alpha = 0.05$). The trends for the other stations are shown in Appendix E.

Table 4.2. The estimated p-values ($H_\theta: \beta = 0$) for the trends in the frequency of days per year (1951-2011) where T_E maxima (minima) and their subcomponents exceeded their respective 90th percentiles. All significant trends ($\alpha = 0.05$) were positive and are bolded. None of the stations experienced significant trends in T_{max}.

Station	T (Max)	L_q (Max)	T_E (Max)	T (Min)	L_q(Min)	T_E(Min)
Des Moines	0.3161	****0.001**	****0.0082**	0.1079	****0.0006**	0.0989
Indianapolis	0.7327	0.1998	0.1665	***0.0426**	0.1414	***0.0327**
Little Rock	0.7542	0.0894	0.0641	***0.0185**	***0.0133**	****0.003**
Memphis	0.7869	0.06749	0.4656	***0.0163**	0.2073	****0.00151**
Moline	0.4268	****<0.0001**	****0.0045**	0.3393	****0.0093**	0.1105
Nashville	0.3356	0.3752	0.4016	0.2358	0.456	0.4482
Springfield	0.7932	0.1317	0.1813	***0.0231**	***0.0184**	****0.0002**
St. Louis	0.7479	***0.0258**	***0.013**	****0.0001**	****0.0007**	****<0.0001**

Only 3 of the stations exhibited significant positive trends in the frequency of annual T_{Emax} 90th percentile exceedences (Table 4.2 and Figure 4.7). For the 3 stations that had significant positive trends in T_{Emax}, it was because L_{qmax} was characterized by significant positive trends—with non-significant trends in T_{max} (Appendix E). Moreover, Moline actually exhibited a slightly negative trend in T_{max} 90th percentile exceedences (though non-significant), but still had a significant positive trend in T_{Emax} because of the significant positive trend in L_{qmax}. With the exception of Nashville (that had slight negative trends in both T_{max} and L_{qmax}), moisture was the main source of an increase in the number of T_E 90th percentile exceedences. In Nashville, negative trends in moisture resulted in decreases in the number of T_E 90th percentile exceedences (Appendix E).

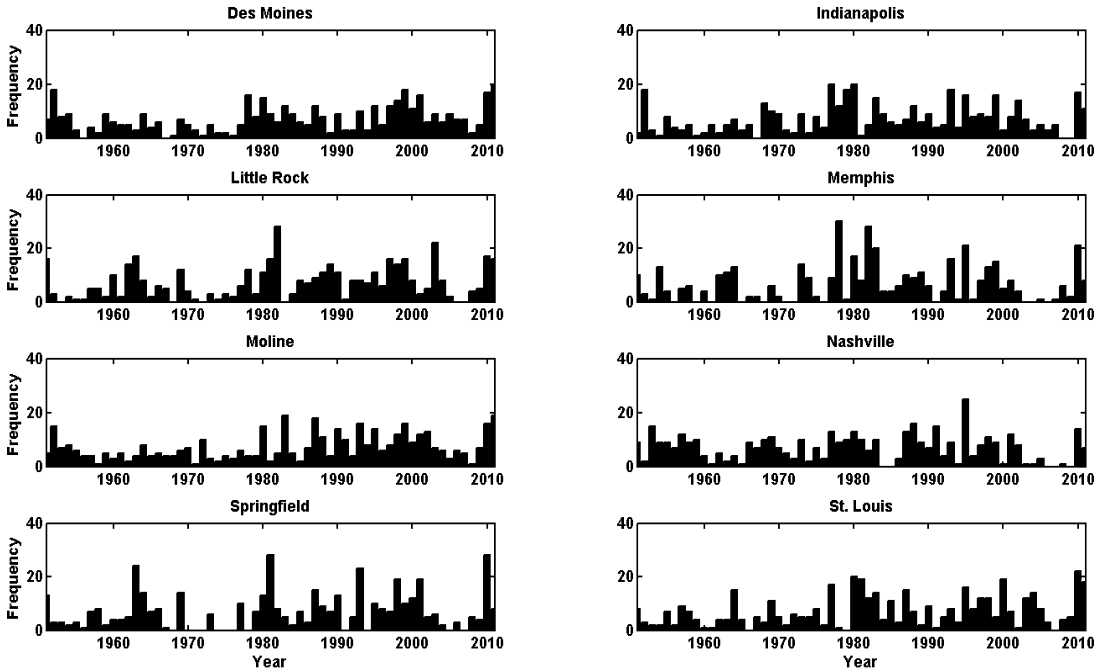


Figure 4.7. The number of days per year where T_{Emax} exceeded its locally-defined July-August 90th percentile value for all stations (1951-2011).

4.4.2 High Humidity Heat Waves

High humidity heat waves (HHHW) are heat wave events that are characterized by high levels of humidity and are locally-defined with 2 different thresholds: 1) As a proportion of days where $L_{qmax} > P_{50}$ for days where $T_{max} > P_{75}$ 2) $T_{max} > P_{90}$ and $L_{qmax} > P_{50}$ July-August values. Low humidity heat waves (LHHW) are further addressed in the following section (section 4.4.3) and are locally-defined with 2 different thresholds: 1) As a proportion of days where $L_{qmax} < P_{50}$ for days where $T_{max} > P_{75}$ 2) $T_{max} > P_{90}$ and $L_{qmax} < P_{50}$ July-August values. After performing the first portion of the HHHW trend analysis, 4 stations exhibited significant positive trends in the proportion of hot days ($T_{max} > P_{75}$) characterized by high humidity ($L_{qmax} > P_{50}$) (Figure 4.9 and Appendix G). These 4 stations include: Des Moines, Moline, Springfield, and St. Louis. Trends for 3 of the 4 stations were highly significant (Des Moines, Moline, and St. Louis) at $\alpha = 0.05$ (Appendix G). However, even with the stations that did not have statistically significant trends, when the data were interpreted collectively, they expressed an overall tendency of positive trends in the proportion of hot days characterized by high humidity. For the second portion of the analysis—looking at trends in the overall pattern in HHHW frequency—it was characterized by specific years where there was a great number of T_{max} > P_{90} and $L_{qmax} > P_{50}$ exceedences (i.e. 30-40); with most years averaging around a total of 3-10 events per year (Figure 4.8). From a regional perspective, the early 1950s, mid-1980s, and early 1990s exhibited the greatest number of exceedences per year (Figure 4.8). However, there was not a statistically significant overall increase or decrease in the number of exceedences ($T_{max} > P_{90}$ and $L_{qmax} > P_{50}$) from a historical perspective.

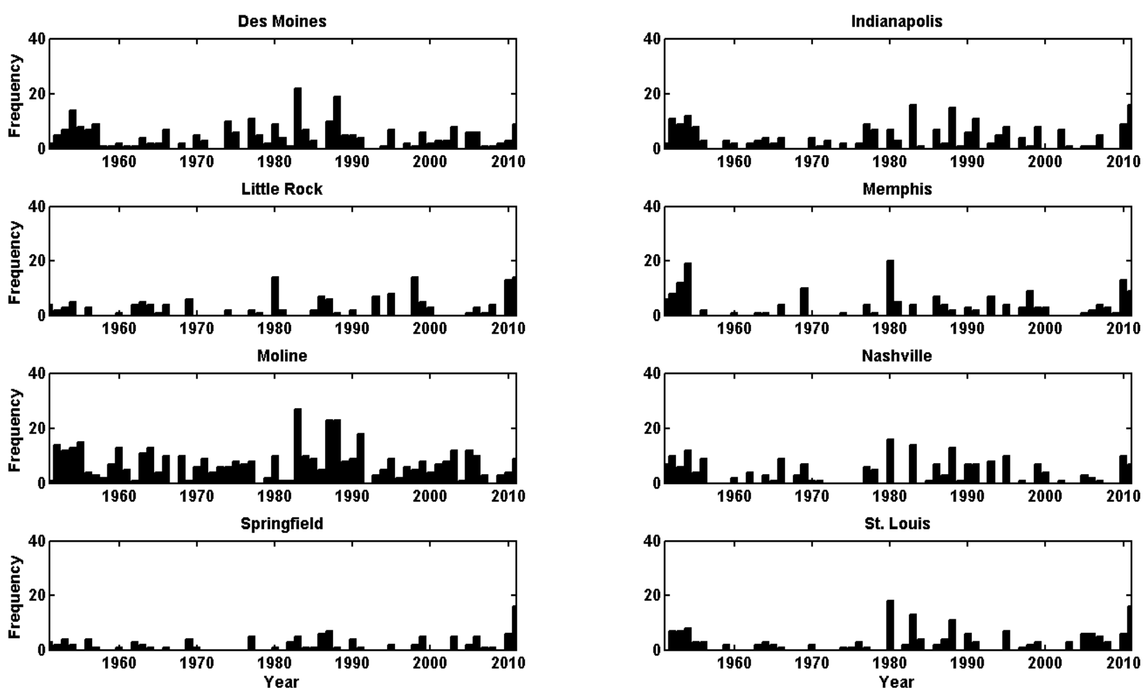


Figure 4.8. The number of days per year where HHHW ($T_{max} > P_{90}$ and $L_{qmax} > P_{50}$ thresholds) regimes occurred for all stations (1951-2011).

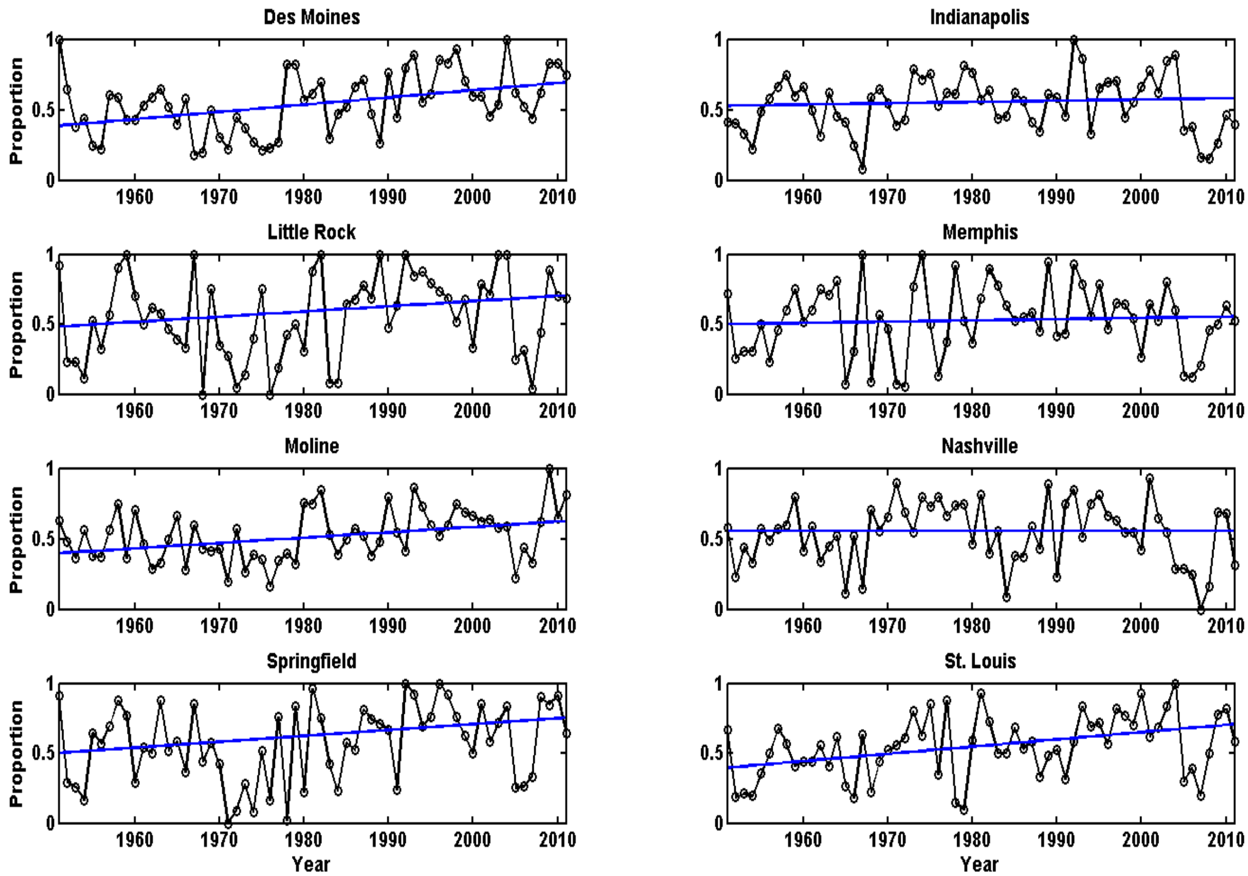


Figure 4.9. Time series of the proportion of days (per year) where $L_{qmax} > P_{50}$ July-August value for days when $T_{max} > P_{75}$ July-August value. The MPWS trend line is shown in blue. The dry proportion is above the blue line, whereas the wet proportion is below. P-values for the significance of the slope ($H_\theta: \beta = 0$) are provided in Appendix G.

Event length (1-day to 8-day) frequency distributions were developed for days characterized by this regime (Figure 4.10). In order to estimate changes in the frequency of these events over time, the study period was partitioned into two 30-year periods (1951-1980 and 1981-2010); omitting the last year in the total period in order to prevent bias (Figure 4.11).

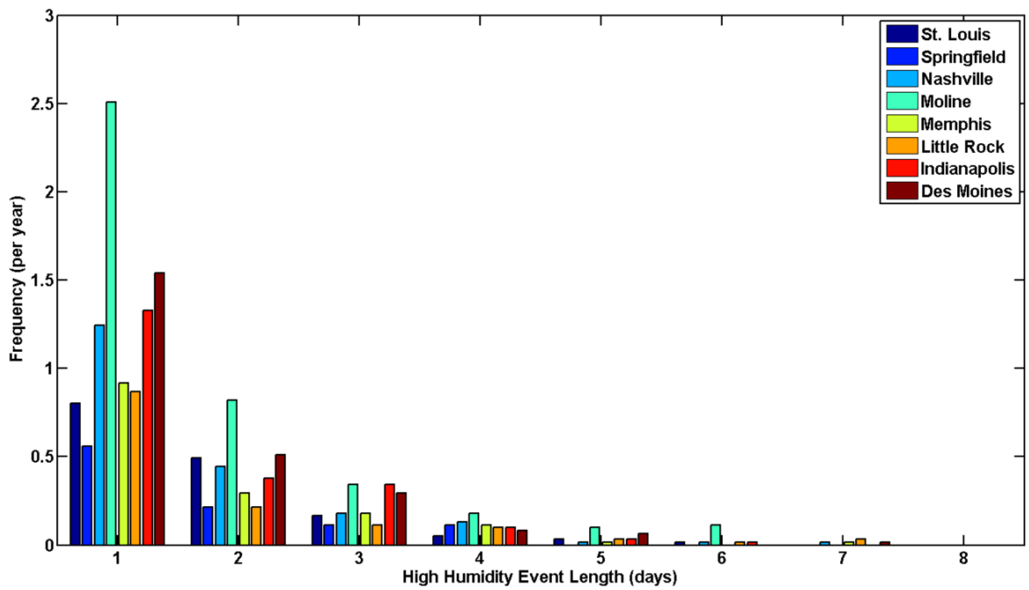


Figure 4.10 The overall frequency (days per year) of High Humidity Regime events ($T_{max} > P_{90}$ and $L_{qmax} > P_{50}$ thresholds) for 1-8-day event lengths for all stations (1951-2010).

The two frequency distributions were then compared in order to deduce changes in frequency from a historical perspective (Figure 4.11). Given the infrequency of these events, a statistical test such as a chi-squared test to compare the distributions was not possible. Therefore, a more qualitative analysis was deemed appropriate. A few of the stations saw a slight increase in the frequency of 1-day events, with most of the stations seeing highly variable (but slight) changes in multi-day events (length ≥ 2 days) (Figure 4.11). Generally, 2-day events were as infrequent as 1 every 2 years (Figure 4.10). Frequency decreased proportionally to the length of the event (Figure 4.10).

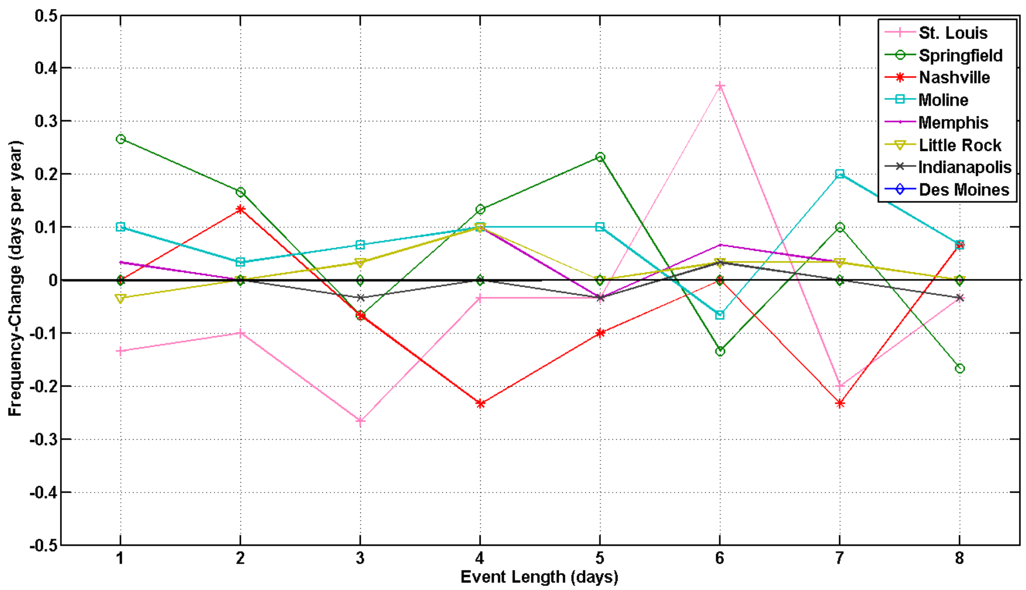


Figure 4.11. The change-in frequency of events (per year) between the first 30-year period (1951-1980) and the second 30-year period (1981-2010) for HHHW ($T_{max} > P_{90}$ and $L_{qmax} > P_{50}$ thresholds) events for all of the stations. Stations above the reference line (y = 0) saw slight increases in the frequency of events between 1981-2010.

4.4.3 Low Humidity Heat Waves

LHHW are infrequent (Figure 4.12) in the eastern-half of the USA—where the study area is located. Consistent with the HHHW analysis, trend and event length frequency analyses were performed to determine trends in LHHW events (Figures 4.12-4.14).

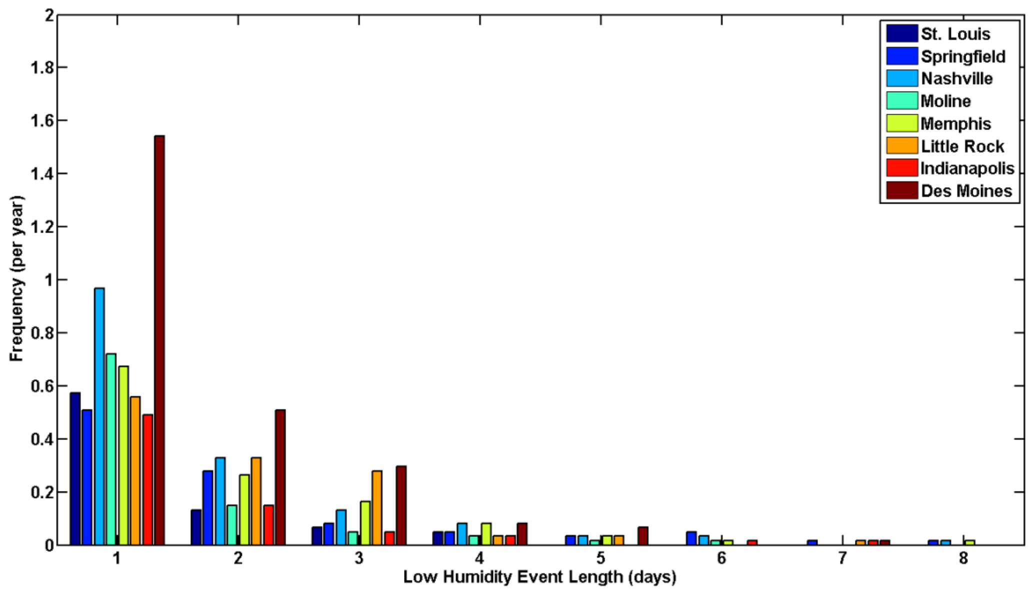


Figure 4.12. The overall frequency (days per year) for LHHW ($T_{max} > P_{90}$ and $L_{qmax} < P_{50}$ thresholds) events for 1-8-day event lengths for all stations (1951-2010). As one can see, Des Moines expresses some of the highest frequencies for the majority of event lengths.

Regionally, HHHW regimes were more frequent than LHHW regimes (Figures 4.7-4.13), but there were no statistically significant ($\alpha = 0.05$) trends in the annual frequency of days characterized by this regime (Fig 4.11 and Appendix F) There was, however, 1 significant negative trend for LHHW regimes (for St. Louis) (Appendix F) where the $T_{max} > P_{90}$ and $L_{qmax} < P_{50}$ thresholds were met. Many of the stations exhibited approximately only 1-3 days per year characterized by this regime; albeit there were some years in the early 1950s where this regime occurred ≥ 20 days (Figure 4.13). Overall, frequencies of this type of event were rare and much less frequent than HHHW events. Therefore, similar to the HHHW analysis, a more quantitative means of comparing the frequency distributions of the event lengths for the two 30-year periods such as a chi-squared test was not plausible due to the low-frequency of these types of events—making a more qualitative analysis more appropriate.

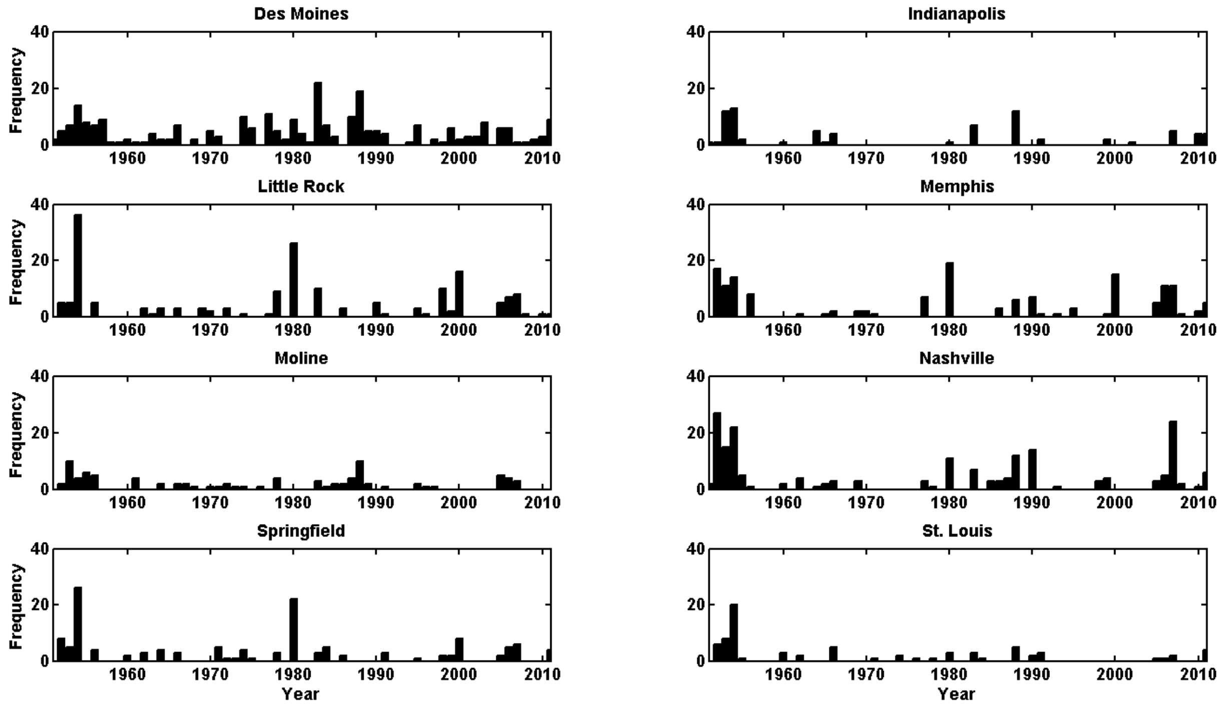


Figure 4.13. The number of days per year where LHHW ($T_{max} > P_{90}$ and $L_{qmax} < P_{50}$ thresholds) regimes occurred for all stations (1951-2011).

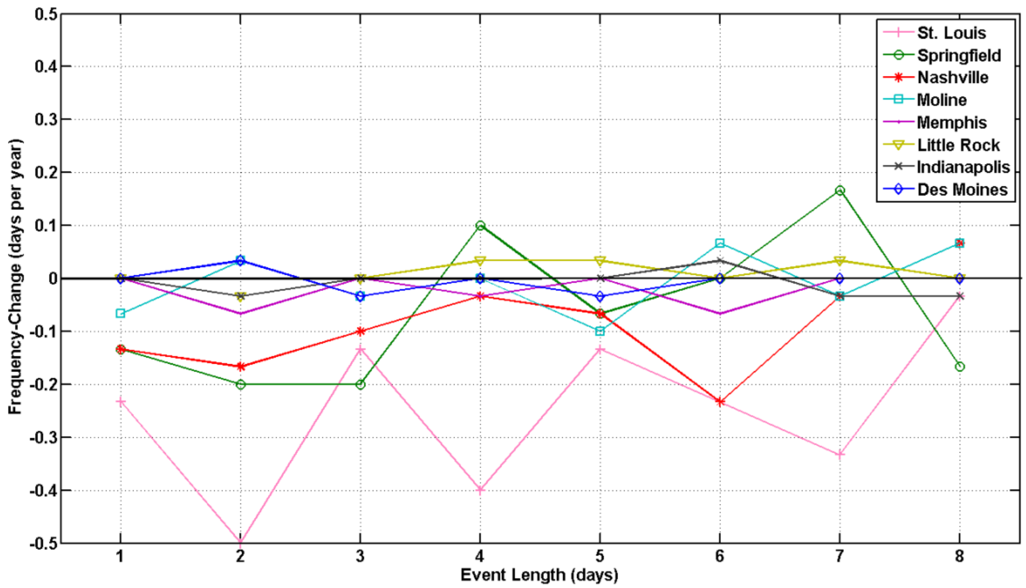


Figure 4.14. The change-in frequency of events (per year) between the first 30-year period (1951-1980) and the second 30-year period (1981-2010) for LHHW ($T_{max} > P_{90}$ and $L_{qmax} < P_{50}$ thresholds) events for all of the stations. Stations below the reference line (y = 0) saw slight decreases in the frequency of events from 1981-2010.

Overall, there was a slight decline in the frequency of multi-day events for LHHW events when comparing the frequency distributions of the two 30-year periods (Figure 4.14) with an overall increase in the frequency of HHHW (($T_{max} > P_{90}$ and $L_{qmax} > P_{50}$ thresholds) events (Figure 4.11).

4.4.4. Conclusion

The heat wave analysis was partitioned into 5 parts: 1) Extreme equivalent temperature days; defined as days exceeding the July-August 90th percentile equivalent temperature 2) Extreme moisture days; defined as days where moist static energy maxima exceeded their July-August 90th percentile value 3) Extreme temperature days; defined as days where temperature minima exceeded their July-August 90th percentile value 4) High humidity heat wave events; defined as: a) Proportion of days that $T_{max} > P_{75}$ that were characterized by high humidity ($L_{qmax} > P_{50}$) b) Multi-day events where both $T_{max} > P_{90}$ July-August value and $L_{qmax} > P_{50}$ July-August value 5) Low humidity heat wave events; defined as multi-day events where $T_{max} > P_{90}$ July-August value and $L_{qmax} < P_{50}$ July-August value. The total number of events that met the criteria of the aforementioned thresholds (parts 1-3) were counted for each year for each station and plotted in time series. Additionally, the proportion of the days where $T_{max} > P_{75}$ that were characterized by high humidity was plotted in time series. Trend analysis was then performed on these plots again using MPWS regression. Event frequency (per year) for 1-day through 8-day events for each regime (i.e., HHHW and LHHW) was then calculated based on $T_{max} > P_{90} \mid L_{qmax} > P_{50}$ and $T_{max} > P_{90} \mid L_{qmax} < P_{50}$ thresholds, respectively. After this overall frequency was calculated (for the $T_{max} > P_{90}$ and $L_{qmax} > P_{50}$ threshold), the 61-year period was partitioned into two 30-year periods (1951-1980 and 1981-2010) and the differences between the distributions for these periods were calculated for each regime in order to determine trends in these multi-day events. The last year of the entire period (2011) was discarded so the periods were of even length.

For the annual frequency of 90th percentile exceedences of T_E and its subcomponents, only 3 of the stations exhibited significant positive trends in the frequency of annual T_{Emax} exceedences (Table 4.2 and Figure 4.7). The significant positive trends were driven by significant trends in L_{qmax}, despite non-significant trends in T_{max} (Appendix E). Moreover, Moline actually exhibited a slightly negative trend in T_{max} 90th percentile exceedences (though non-significant), but still had a significant positive trend in T_{Emax} because of the significant positive trend in L_{qmax}. With the exception of Nashville (that had slight negative trends in both T_{max} and L_{qmax}); moisture was the main source (as opposed to temperature) in driving an increase in the number of T_E 90th percentile exceedences (Appendix E). In Nashville, negative trends in moisture resulted in decreases in the number of T_E 90th percentile exceedences (Appendix E). Therefore, trends in moisture show to be integral in driving increases in the number of T_E 90th percentile exceedences.

For the annual frequency of HHHW and LHHW regimes, it was found that such events are rare and only one statistically ($\alpha = 0.05$) significant trend for LHHW ($T_{max} > P_{90}$ and $L_{qmax} < P_{50}$ thresholds) was exhibited (for St. Louis) (Figures 4.8-4.14 and Appendices F and G). However, there were 4 significant positive trends (3 of which were highly significant) in the proportion of days per year where $T_{max} > P_{75}$ that were characterized by high humidity ($L_{qmax} > P_{50}$). Despite the low frequency of HHHW events, LHHW events are even less frequent (Figures 4.8-4.14). Although there was slight variability between the stations, when each regime type was partitioned into two 30-year periods and the differences between the periods were calculated, it was found that there was a slight increase in the number of HHHW events (again with variability in magnitude and sign across stations) with a slight decrease in the number of LHHW events (Figures 4.11 and 4.14). These trends were further confirmed in the proportion analysis, where half of the stations exhibited a higher proportion of hot and humid days per year as opposed to hot and dry days (Figure 4.9 and Appendix G). Furthermore, there was a slight increase in the frequency of multi-day HHHW events and a slight decrease in the number of multi-day LHHW events (again with slight variability between the stations) (Figures 4.11 and 4.14). In conclusion, although heat wave occurrence was low in frequency, HHHW events were more frequent than LHHW events, and there was an overall increase in the number of high humidity events and their lengths with an overall decrease in the number of low humidity events and their length over the last 30 years; with slight variability between the stations. It is evident that increases in low-level moisture were the contributing factor to these trends.

CHAPTER 5

DISCUSSION AND CONCLUSION

The main objective of this study was to determine whether or not the central USA is experiencing changes in lower tropospheric heat content and if there have been changes in heat wave frequency, intensity, and duration from a historical perspective. Raw T, T_d, and STP data were collected from NOAA's NCDC Integrated Surface Database (ISD) for 8 1st Order stations across the central USA for the period 1951-2011. Quality control in the form of processing, formatting, and homogeneity evaluation was completed via the following steps: 1) Omitting days, months, seasons, and years characterized by a significant amount of missing data or suspect values 2) Performing a thorough visual inspection of monthly time series data for years surrounding known stations changes for all stations (Figure 4.1) 3) Performing change-point identification and trend analyses on time series of pairwise differences (Figure 4.2). The results from the homogeneity testing show that the dataset used in this study is relatively homogenous. Although a significant slope was identified in the Nashville-Memphis pairwise differences time series during the homogenization step, when Nashville was compared with Indianapolis, no significant trend was identified. The results from the time-varying percentile trend and heat wave analyses suggest that the slight negative trend in moist static energy for Nashville is due to variability and/or change in some synoptic-scale phenomenon such as the LLJ. Although Indianapolis did not exhibit as strong of a negative trend in moist static energy as Nashville, both of these stations exhibited the smallest trends in moist static energy (Appendix C). This is further addressed in the following paragraphs. The purpose of this study was to use a relatively homogenous in-situ atmospheric data set to sufficiently promulgate a better understanding of regional climate variability and change over the central USA and answer the following questions:

1. *Is there a coherent regional historical trend in* T_E *and its subcomponents over the central USA?*

The analysis confirms what previous studies have found; increases in temperature minima and low-level moisture over the central USA, with peak increases manifest during the spring months (Appendix C) (Gaffen and Ross, 1998; Gaffen and Ross, 1999; Patz et al., 2000 Degaetano and Allen, 2002; Frich et al., 2002; Meehl and Tebaldi, 2004; Robeson, 2004). Although there is a general positive trend in maximum and minimum T_E across the stations in this study area, there is still slight variability in the magnitude of these trends. Also, the results for Nashville somewhat undermine the relative coherency of these trends; as evident in both the annual time-series (Appendix D) and time-varying percentile trend analyses (Appendix C). Furthermore, an increase in latent heat energy is a key driver in these trends (Table 4.1 and Appendix C). Despite flat trends in T_{max} across the study area and even slightly negative percentile trends at some stations (with the exception of Nashville); there is a significant positive trend in lower tropospheric energy content over the central USA over the last 60 years (Appendices C and D). Nashville was an outlier in regards to T_{Emax}. Negative trends in moist static energy were the driver of the negative trends in total surface energy maxima over Nashville (Appendix C). However, although Nashville had negative trends in L_q, it possessed some of the largest trends in T_{max} compared to the other stations. Therefore, energy in Nashville is being expressed more as dry static energy as opposed to moist static energy when compared to the other stations in the study area. Variability and change in synoptic-scale circulation is a great explanation of these negative moisture trends. Moisture advection into the central USA is horizontally confined (Bonner 1966). The LLJ is much less frequent over Nashville and Indianapolis than the rest of the stations due to its common trajectory (Bonner 1966). An urbanization signal is likely not the cause of this trend because of the following: 1) Like the other stations, Nashville's weather station is located on the outer margins of the city 2) Although Indianapolis did not exhibit as dramatic of a negative trend in moist static energy as Nashville, it still exhibited some of the weakest positive trends in comparison to the other stations—signaling the possible influence of the Great Plains LLJ on moisture advection into the eastern portion of the study area (Appendix C). The LLJ frequencies presented by Bonner (1966) show that the LLJ has a north-northeast trajectory that precipitously veers eastward asymptotically north of the Ohio River Valley. Therefore, despite Indianapolis' similar longitude, it is characterized by slightly more moisture advection than Nashville, which lies on the outer-margins of the area of higher LLJ frequency (Bonner, 1968). Given the variability of the LLJ and its lack of east-ward extent due to the frequent expansion of the Bermuda High, it explains why Nashville is an outlier in regards to trends in moisture when grouped with the other stations. Further research investigating changes in circulation over the eastern USA would provide more explanation as to the cause of the slight negative moisture trends in Nashville.

2. *Are there significant historical changes in heat wave length, frequency, and intensity over the central USA?*

Several of the stations exhibited significant positive trends in the frequency of annual T_E 90^{th} percentile exceedences from a historical perspective. Only one station (Nashville) exhibited a slight negative trend in T_E (Figure 4.4 and Appendix C). However, the trend was not statistically significant. Although HHHW and LHHW events are infrequent, this study area is seeing a greater proportion of HHHW events (with slight variability between stations); driven by the significant positive trends in moist static energy.

Historically, event length for LHHW regimes is slightly less frequent; with slight increases present in the frequency of multi-day events for HHHW regimes (again with slight variability between stations) (Figures 4.11 and 4.14). Changes in events greater than 2 days in length, however, are somewhat negligible (Figure 4.11). Due to the infrequency of these types of events, quantifying changes and variability in these regimes over time is somewhat difficult (even when the threshold was set to $T_{max} > P_{75}$). Therefore, a more qualitative interpretation of the results was appropriate.

3. *Does T_E provide a different perspective than temperature for understanding regional climate change?*

Given the overall increases in lower-tropospheric energy content despite flat trends in T_{max} (Appendices C and D), it is evident that T_E provides a different perspective than temperature for understanding climate change—more specifically, an increase in the total near surface energy content of the climate system. It is evident that moist static energy is an important consideration when investigating trends in total surface energy—a facet of which T_E effectively captures as opposed to only using T.

Therefore, although maximum temperature trends have been flat over the central USA over the last century, this portion of the country is getting warmer from a total surface energy perspective—with slight station variability in the magnitude of this trend. Also, this trend is mainly driven by significant increases in low-level moisture (Appendices C and D). Furthermore, although temperature maxima trends have been flat, temperature minima show positive trends over the study period (Appendices C and D). The spring and fall months are experiencing the greatest amount of warming—with the peak warming occurring during the months of March and November. Some of the monthly percentile warming trends in T_E were as great as $5°\text{C}/50$ years (Appendix C). Lastly, there is an overall positive trend in the annual frequency of T_E 90$^{\text{th}}$ percentile exceedences (again with variation in magnitude and significance by station) during the study period and given the trends in low-level moisture, HHHWs are the more dominant regime compared to LHHWs (Figures 4.7-4.14). Trends in the proportions of days characterized by elevated heat and humidity are both positive and significant for 4 of the stations (Figure 4.9 and Appendix G). However, even for stations which did not possess statistically significant trends in their proportions, when they data were viewed collectively, they expressed a tendency towards positive trends. Changes in the frequency of HHHWs and LHHWs and their lengths are rather difficult to assess quantitatively due to their rarity, however, the number of events characterized by LHHW types of regimes has seen a slight decline over the last 30 years (Figure 4.14). There has been an increase in the proportion of hot days characterized by high humidity for half of the study area (Figure 4.9 and Appendix G), as well as an increase in the number of HHHW events over the last 30 years however (Figure 4.11). Since this study shows an overall increase in total surface energy over the last 60 years (with the exception of one station)—driven by increases in low-level moisture—and since the majority of the warming occurs during the transitional seasons (MAM and SON), the following is concluded: 1) Despite slight negative trends in temperature maxima, the central USA is getting warmer in regards to total available energy at the surface 2) The central USA could potentially see an increase in the frequency and intensity of severe weather during the spring and fall 3) HHHWs and LHHWs are both rare in occurrence, but HHHWs are the dominant regime, as half of the study area has experienced a higher proportion and slightly higher frequency of HHHWs and less LHHWs 4) Equivalent temperature provides a different perspective than temperature for understanding regional climate change because it also accounts for latent energy.

The findings of this study are significant for many reasons. First, since the amount of energy available at the surface has been increasing over the central USA, it suggests that the climate in this region is seeing an increase in total surface energy content. Although this warming is not expressed significantly from a sensible heat-perspective in temperature maxima, it is expressed greatly from this perspective in temperature minima. Furthermore, increasing available energy in the troposphere (manifest in significant increases in low-level moisture) leads to increased convection—creating conditions favorable for thunderstorm activity—especially since the largest increases are manifest during the transitional months and are marked during the month of March. Second, increases in low-level moisture and HHHW events will lead to more human heat stress if these trends continue. Lastly, this study serves as a framework for future climate change studies (both historical and future projections) to investigate global trends in total surface energy and the temperature-moisture relationship. This study along with previous studies (Fall et al., 2010; Rogers et al., 2007 Pielke et al., 2004) demonstrates that T_E should be the primary metric of assessment when investigating warming of the climate system as opposed to using only temperature.

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APPENDIX A – CORRESPONDENCE

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APPENDIX B

This appendix shows metadata with elevation, station location, and calculated station re-location distances for all stations. This is the metadata for Indianapolis, Indiana (1931-2011).

Period	Site Ground Elevation (m)	Barometric Height Above Ground (m)	Lat/Long (decimal degress)	Comments
1931-38	244.55	0.00	39.73333/-86.26667	Located at Indianapolis International Airport
1938-45	245.45	0.00	39.73333/-86.26667	Change in site ground elevation
1945-52	245.45	0.00	39.73333/-86.26667	No verifiable changes
1952-59	245.45	0.00	39.73333/-86.26667	No verifiable changes
1959-66	240	5.45	39.73333/-86.28333	Site change--1.425 km west; change in site ground elevation
1966-73	240	5.45	39.73333/-86.28333	No verifiable changes
1973-80	240	13.64	39.73333/-86.26667	Site change--1.425 km east; Barometric height change
1980-87	240	13.64	39.73333/-86.26667	No verifiable changes
1987-94	240	13.64	39.73333/-86.26667	No verifiable changes
1994-2001	239.39	2.13	39.73167/-86.27889	Site change--1.061 km west-southwest; site ground elevation and barometric height change
2001-08	239.39	2.13	39.7318/-86.2788	Site change--16.38 m northeast; Dew Point instrument change: 6/3/2005
2008-Present	239.39	2.13	39.7318/-86.2788	No verifiable changes

APPENDIX B

Little Rock, Arkansas (1930-2011)

Period	Site Ground Elevation (m)	Barometric Height Above Ground (m)	Lat/Long (decimal degrees)	Comments
1930-37	Unverifiable	Unverifiable	34.7273/-92.2389	Located at Little Rock Adams Field Airport
1937-44	Unverifiable	Unverifiable	34.7273/-92.2389	No verifiable changes
1944-51	83.64	0.00	34.7273/-92.2389	No verifiable changes
1951-58	83.64	0.00	34.7273/-92.2389	No verifiable changes
1958-65	83.64	0.00	34.7273/-92.2389	No verifiable changes
1965-72	83.64	0.00	34.7273/-92.2389	No verifiable changes
1972-79	77.88	6.06	34.7273/-92.2389	Site ground elevation and barometric height change
1979-86	77.88	6.06	34.7273/-92.2389	No verifiable changes
1986-93	77.88	6.06	34.7273/-92.2389	No verifiable changes
1993-2000	78.18	5.76	34.7273/-92.2389	Site ground elevation and barometric height change
2000-07	78.18	5.76	34.7273/-92.2389	Dew Point instrument (DTS1) change: 8/5/2004
2007-Present	78.18	5.76	34.7273/-92.2389	No verfiable changes

APPENDIX B

Memphis, Tennessee (1930-2011)

Period	Site Ground Elevation (m)	Barometric Height Above Ground (m)	Lat/Long (decimal degrees)	Comments
1930-37	Unverified	Unverified	35.05/-89.98333	Located on Memphis International Airport
1937-44	Unverified	Unverified	35.05/-89.98333	No changes
1944-51	78.18	7.27	35.05/-89.98333	No verifiable changes
1951-58	78.18	7.27	35.05/-89.98333	No changes
1958-65	78.18	7.27	35.05/-89.98333	No changes
1965-72	78.18	7.27	35.05/-89.98333	No changes
1972-79	78.18	8.49	35.05/-90.00	Site change--1.517 km west; barometric height change
1979-86	78.18	3.94	35.05/-90.00	Barometric height change; negligible site re-location
1986-93	80.30	1.82	35.05/-90.00	Site ground elevation change
1993-2000	80.30	1.82	35.05/-90.00	No verifiable changes
2000-2007	76.97	5.15	35.0564/-89.98333	Site change--1.420 km northeast; site ground elevation change; Dew Point instrument change 12/15/2003.
2007-Present	76.97	5.15	35.0564/-89.9865	Site change--288.5 m west

APPENDIX B

Moline, Illinois (1928-2011)

Period	Site Ground Elevation (m)	Barometric Height Above Ground (m)	Lat/Long (decimal degrees)	Comments
1928-36	180	0.00	41.45/-90.51667	Location at Moline Quad City Airport
1936-44	176.06	6.97	41.45/-90.51667	Change in site ground elevation and barometric height above ground
1944-52	176.36	6.97	41.45/-90.50	Site change--moved 1.389 km east; slight site ground elevation change
1952-60	176.36	6.97	41.45/-90.50	No changes
1960-68	176.36	6.97	41.45/-90.50	No changes
1968-76	176.36	6.97	41.45/-90.50	No changes
1976-84	176.36	6.97	41.45/-90.50	No changes
1984-92	175.76	0.60	41.45/-90.50	Slight site ground elevation and barometric height above ground change
1992-2000	179.39	4.55	41.46528/-90.52333	Site change--moved 2.582 km northwest; site ground elevation and barometric height change
2000-08	179.39	4.55	41.46528/-90.52333	Dew Point instrument change 6/3/2005
2008-Present	179.39	4.55	41.46528/-90.52333	No changes

APPENDIX B

Nashville, Tennessee (1928-2011)

Period	Site Ground Elevation (m)	Barometric Height Above Ground (m)	Lat/Long (decimal degrees)	Comments
1928-36	Unverified	Unverified	36.11667/-86.68333	Located at Nashville International Airport
1936-44	Unverified	Unverified	36.11667/-86.68333	No changes
1944-52	176.06	5.76	36.11667/-86.68333	Site ground elevation and barometric height verified
1952-60	176.06	5.76	36.11667/-86.68333	No changes
1960-68	181.82	0.00	36.11667/-86.68333	Site Ground elevation change
1968-76	178.79	1.21	36.11667/-86.68333	Site ground elevation and barometric height change
1976-84	178.79	1.21	36.11667/-86.68333	No changes
1984-92	178.79	0.91	36.11667/-86.68333	Barometric height change
1992-2000	175.76	3.94	36.11667/-86.68333	Site ground elevation change; barometric height change due to ground elevation change
2000-08	181.82	Unverified	36.11667/-86.68333	Site ground elevation change; Dew Point instrument change: 9/11/2003
2008-Present	181.82	Unverified	36.1188/-86.6891	Station moved approximately 570 m west-northwest

APPENDIX B

Springfield, Missouri (1945-2011)

Period	Site Ground Elevation (m)	Barometric Height Above Ground (m)	Lat/Long (decimal degrees)	Comments
1945-51	383.33	6.06	37.23333/-93.38333	Located at Springfield Regional Airport
1951-57	383.33	6.06	37.23333/-93.38333	No verifiable changes
1957-63	384.24	1.21	37.23333/-93.38333	Change in site ground elevation and barometric height above ground
1963-69	384.24	1.21	37.23333/-93.38333	No verifiable changes
1969-75	384.24	1.21	37.23333/-93.38333	No verifiable changes
1975-81	384.24	1.21	37.23333/-93.38333	No verifiable changes
1981-87	384.24	1.21	37.23333/-93.38333	No verifiable changes
1987-93	384.24	1.21	37.23333/-93.38333	No verifiable changes
1993-99	381.52	3.94	37.23972/-93.38972	Location change--moved 908.2 m northwest; site ground elevation change and barometric height change
1999-2005	381.52	3.94	37.23972/-93.38972	No verifiable changes; Dew Point instrument (DTS1) change: 6/22/2004
2005-11	381.52	3.94	37.2397/-93.3897	Slight location change--moved approximately 3 m southwest

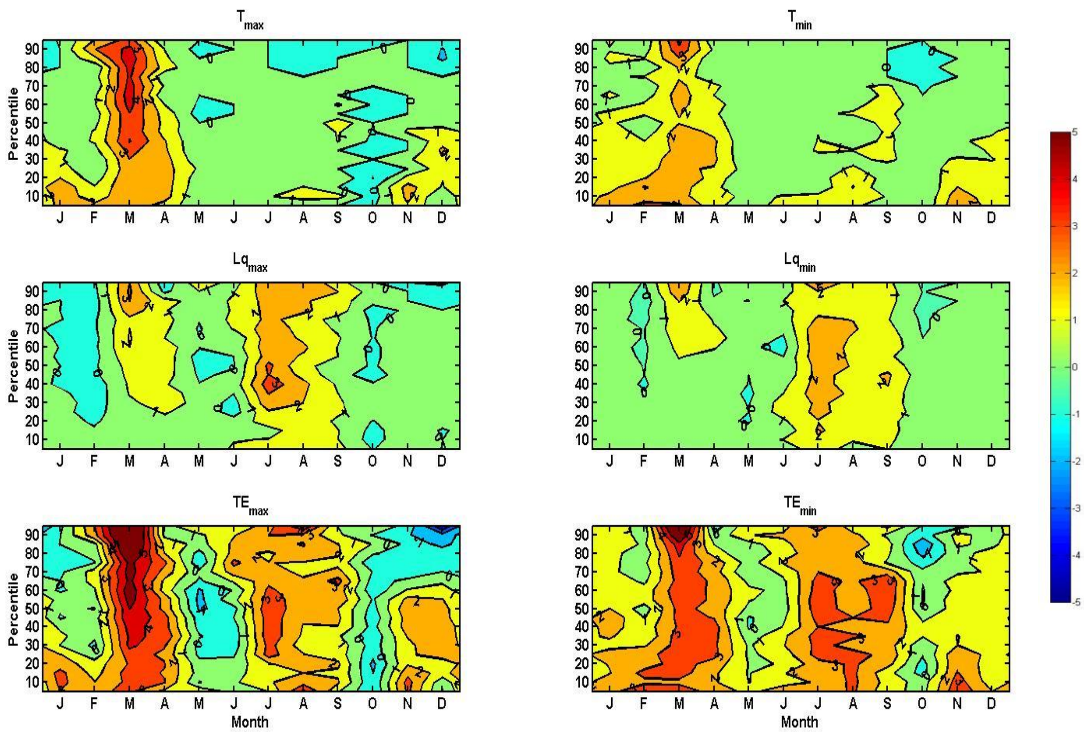
APPENDIX B

St. Louis, Missouri (1929-2011)

Period	Site Ground Elevation (m)	Barometric Height Above Ground (m)	Lat/Long (decimal degrees)	Comments
1929-37	170.91	0.00	38.75/-90.38333	Located at St. Louis Lambert Airport/ Barometric height change
1937-45	174.85	3.94	38.75/-90.38333	Change in site ground elevation
1945-53	174.85	0.00	38.75/-90.38333	No verifiable changes
1953-61	170.91	3.94	38.75/-90.38333	Site ground elevation change.
1961-69	170.91	3.94	38.75/-90.38333	No verifiable changes
1969-77	162.12	9.09	38.75/-90.36667	Barometric height, elevation, and Site location change—moved approximately 1.442 km east
1977-85	162.12	9.09	38.75/-90.36667	No verifiable changes
1985-93	172.12	0.00	38.75/-90.36667	Site ground elevation change
1993-2001	160.91	11.21	38.7525/-90.3736	Location change--moved 598.4 m west; site ground elevation change and barometric height change
2001-2009	160.91	3.94	37.7525/-90.3736	No verifiable changes
2009-11	160.91	3.94	37. 7525/-93.3736	No verifiable changes

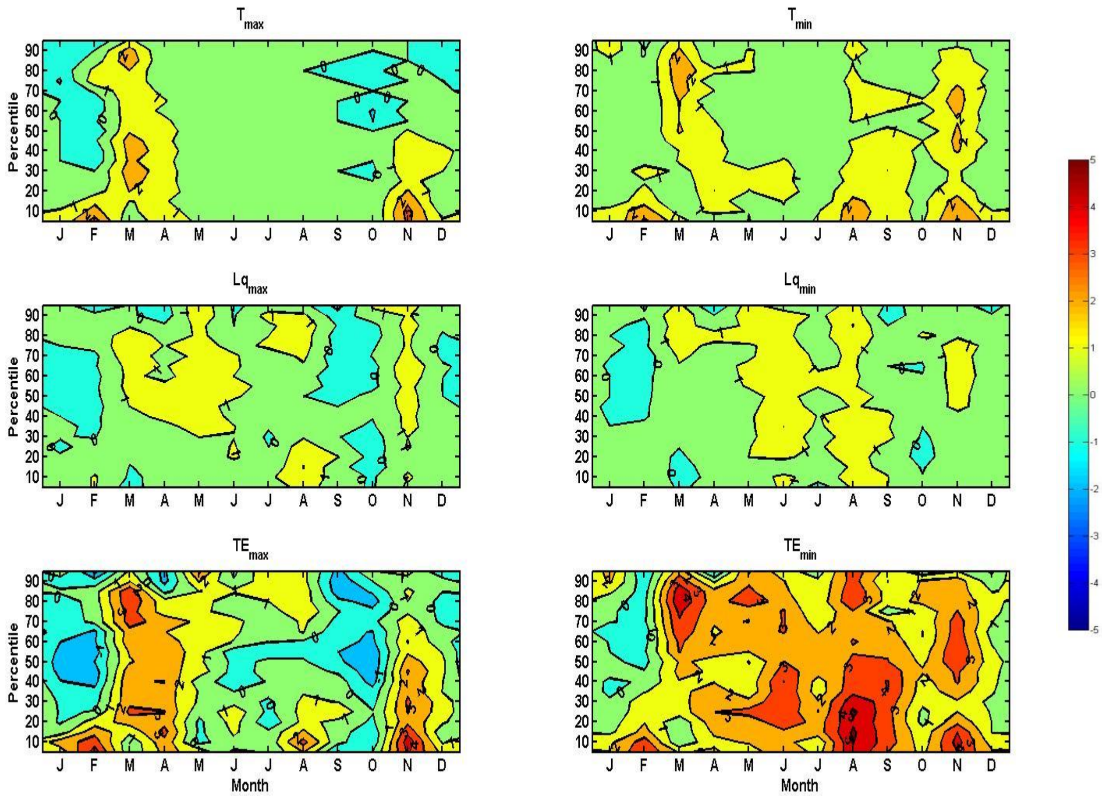
APPENDIX C

Time-varying percentile trends for T, L_q, and T_E for all of the stations are shown in this appendix. Maxima are represented by the left column of plots and minima are represented by the right column of plots. Months are plotted on horizontal axes and percentiles are plotted on vertical axes. The color bar represents the $℃/50$ year trend. Additivity is easily reflected in these plots as one can see to what extent T and L_q contributed to the overall magnitude of T_E. This is the plot for Des Moines, Iowa (1951-2011).



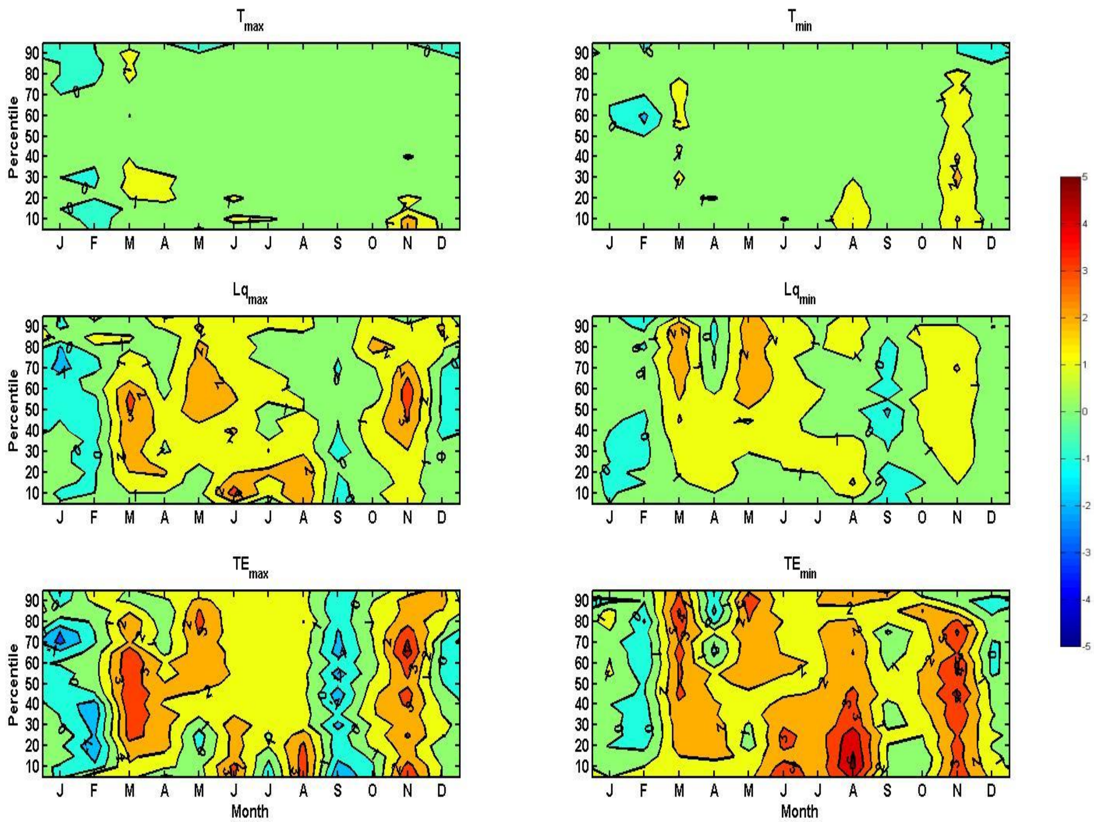
APPENDIX C

Indianapolis, Indiana (1951-2011)



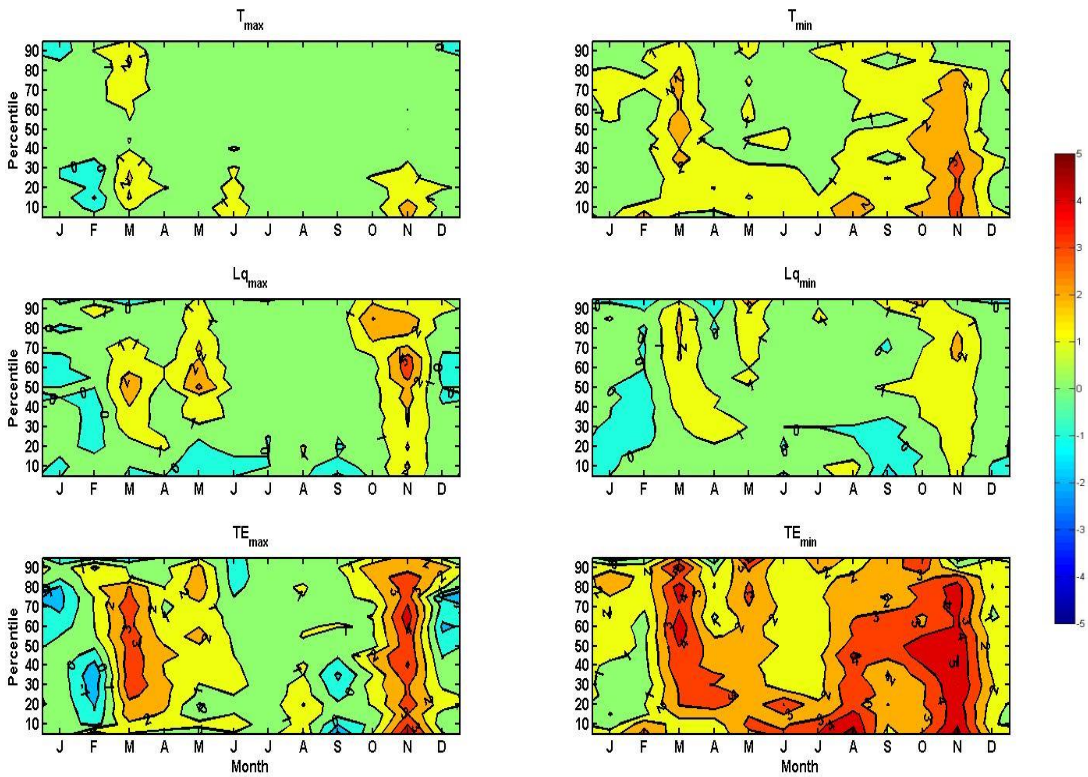
APPENDIX C

Little Rock, Arkansas (1951-2011)



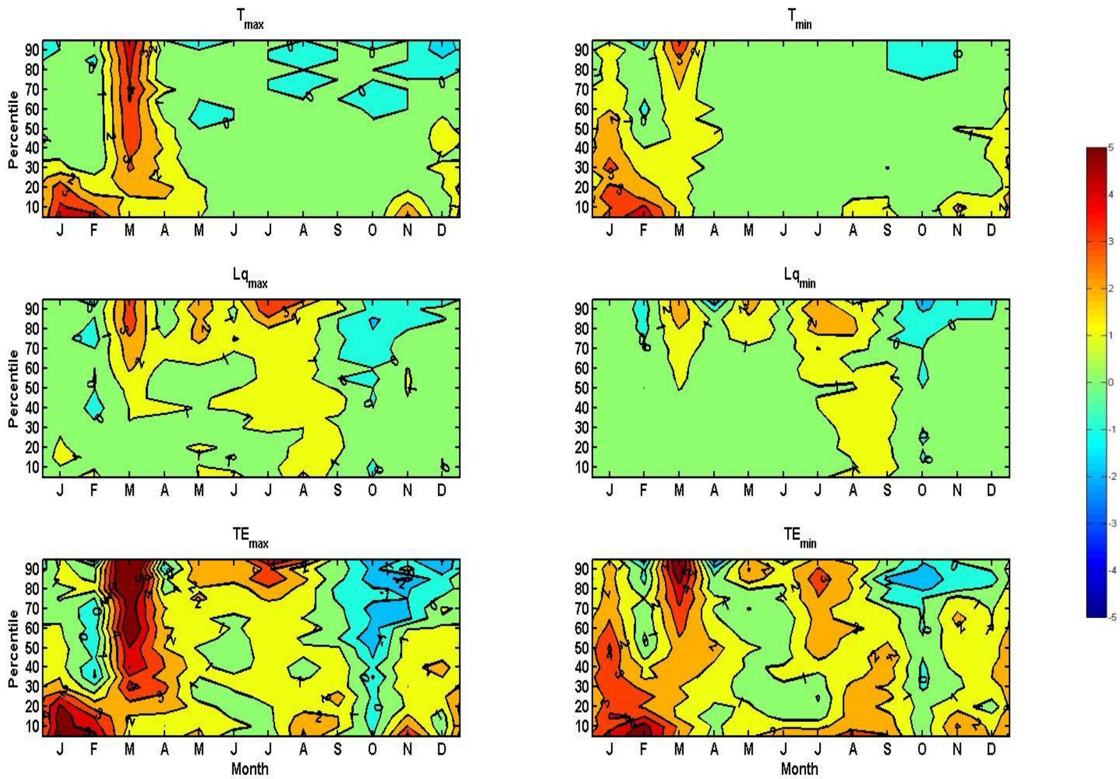
APPENDIX C

Memphis, Tennessee (1951-2011)



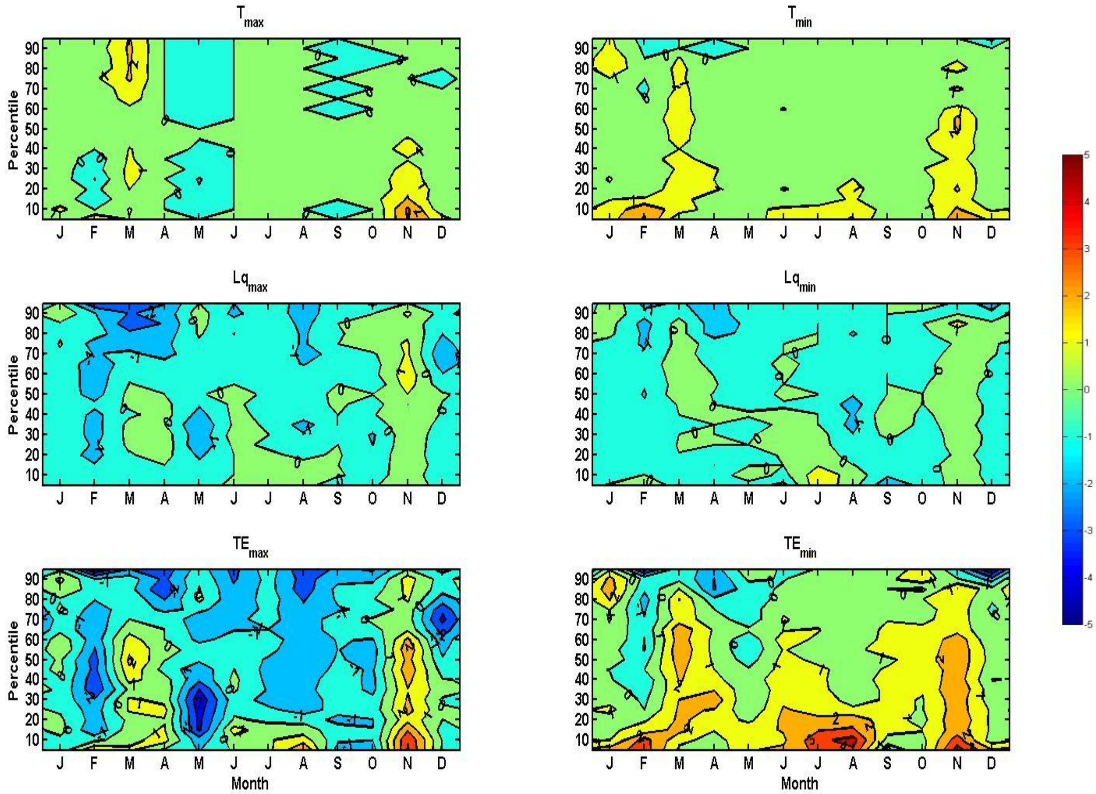
APPENDIX C

Moline, Illinois (1951-2011)



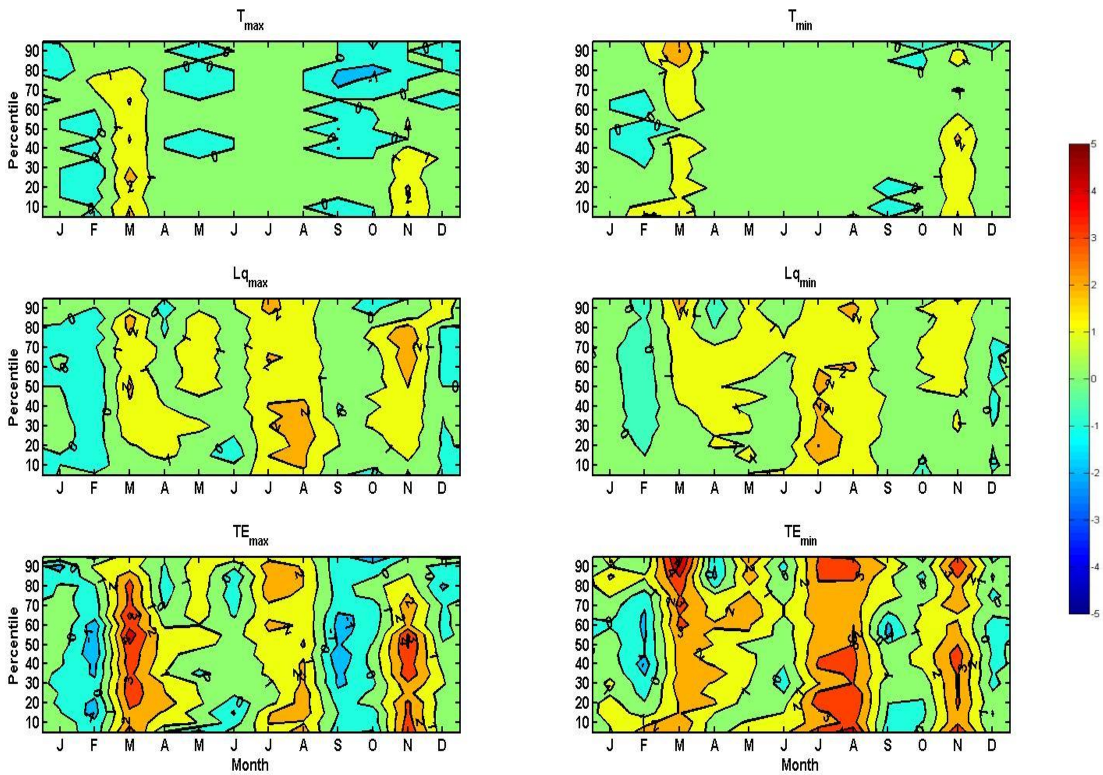
APPENDIX C

Nashville, Tennessee (1951-2011)



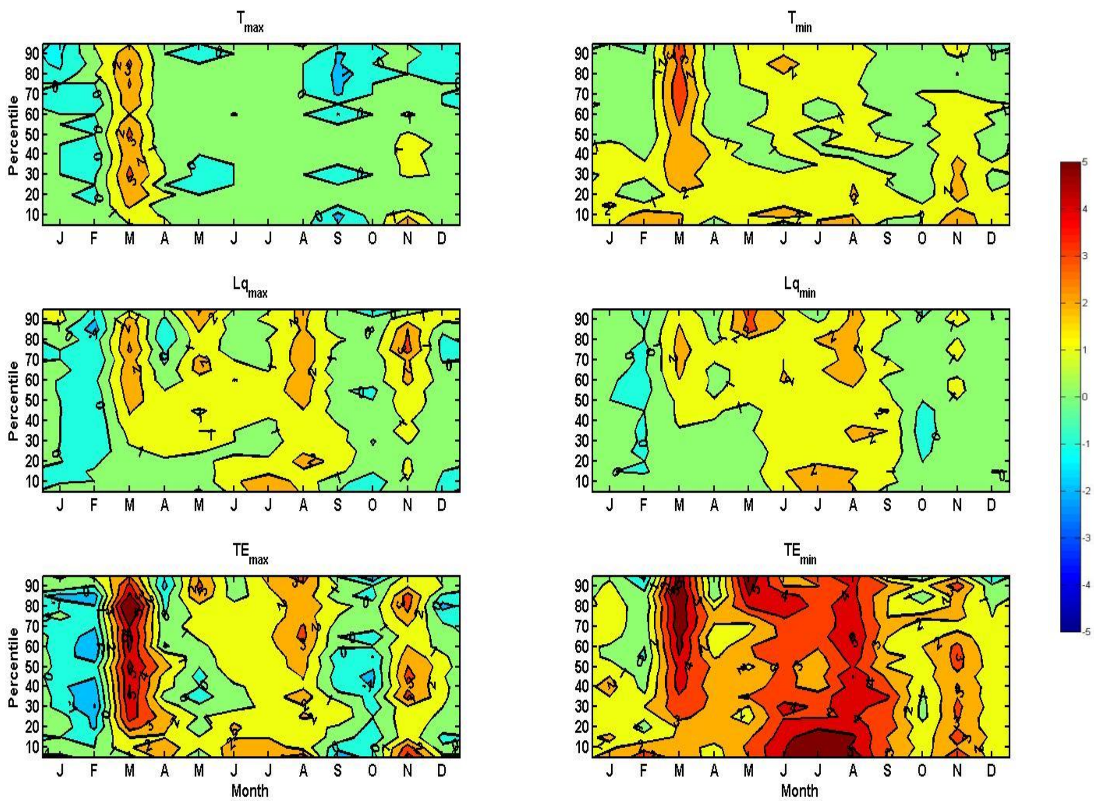
APPENDIX C

Springfield, Missouri (1951-2011)



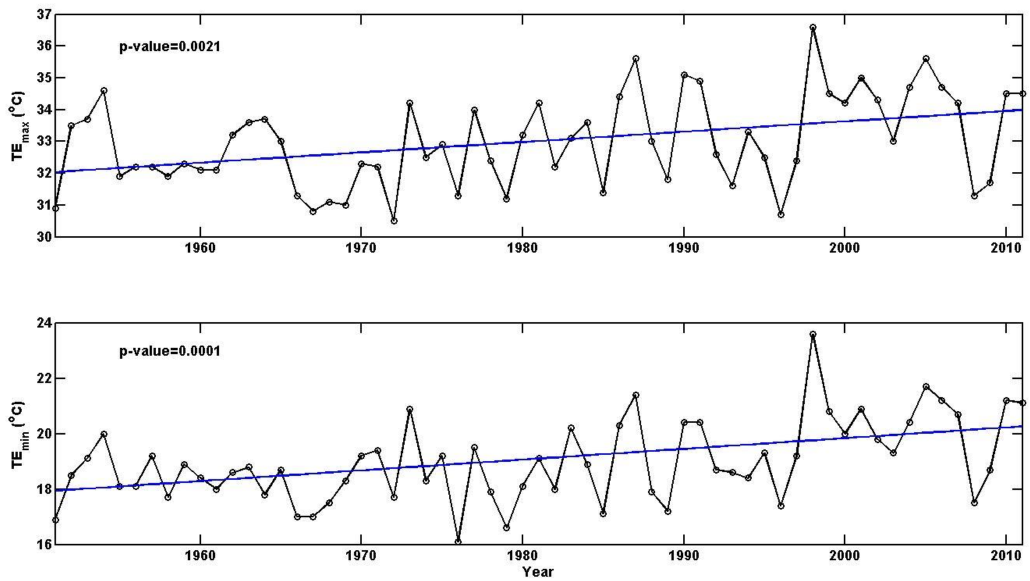
APPENDIX C

St. Louis, Missouri (1951-2011)

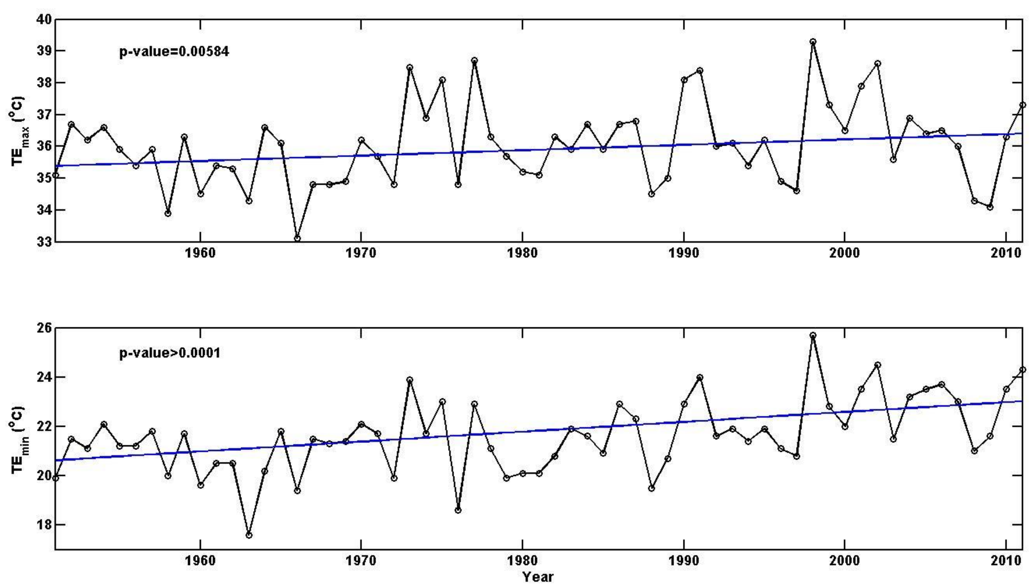


APPENDIX D

This appendix shows annual time series of T_E for all of the stations.. P-values are given and the blue line is the MPWS trend line. The slopes were both highly significant ($\alpha = 0.05$). These are the time series for Des Moines, Iowa (1951-2011).

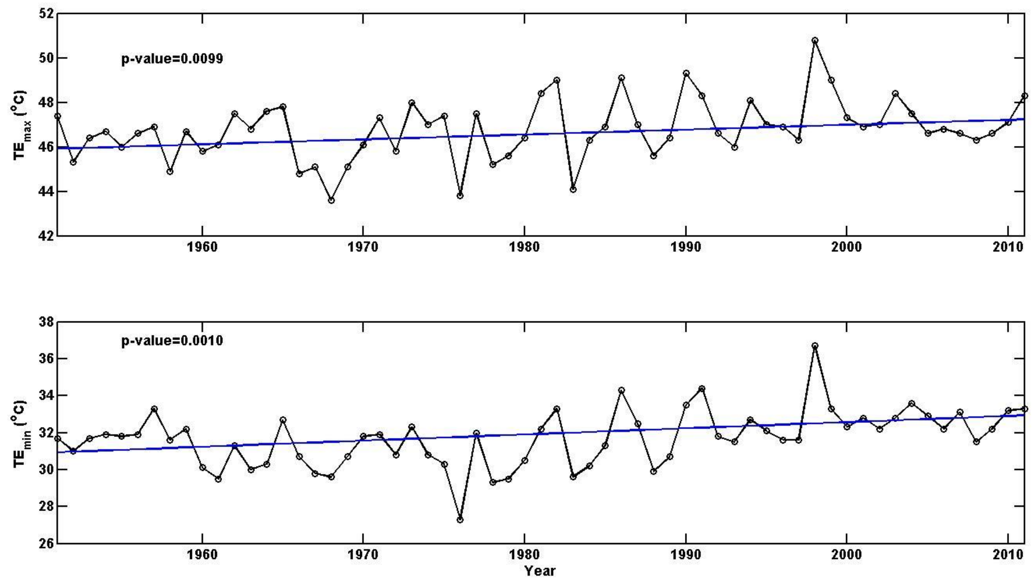


Indianapolis, Indiana (1951-2011)

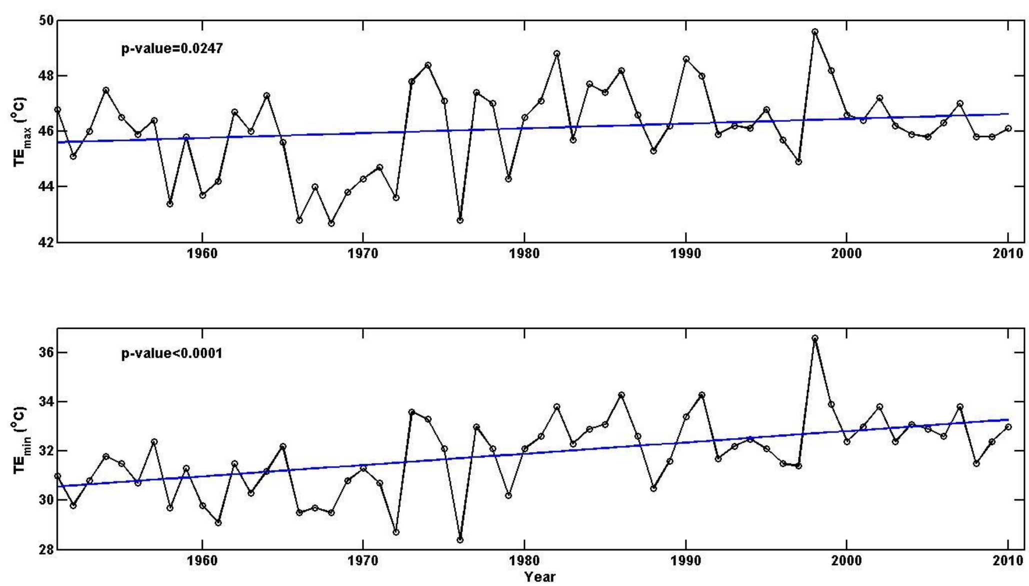


APPENDIX D

Little Rock, Arkansas (1951-2011)

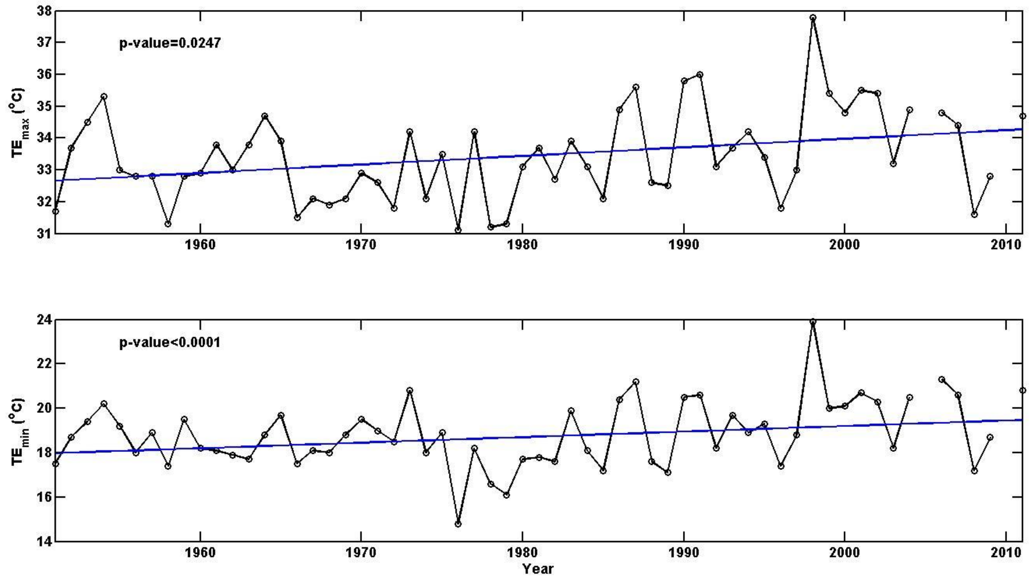


Memphis, Tennessee (1951-2011

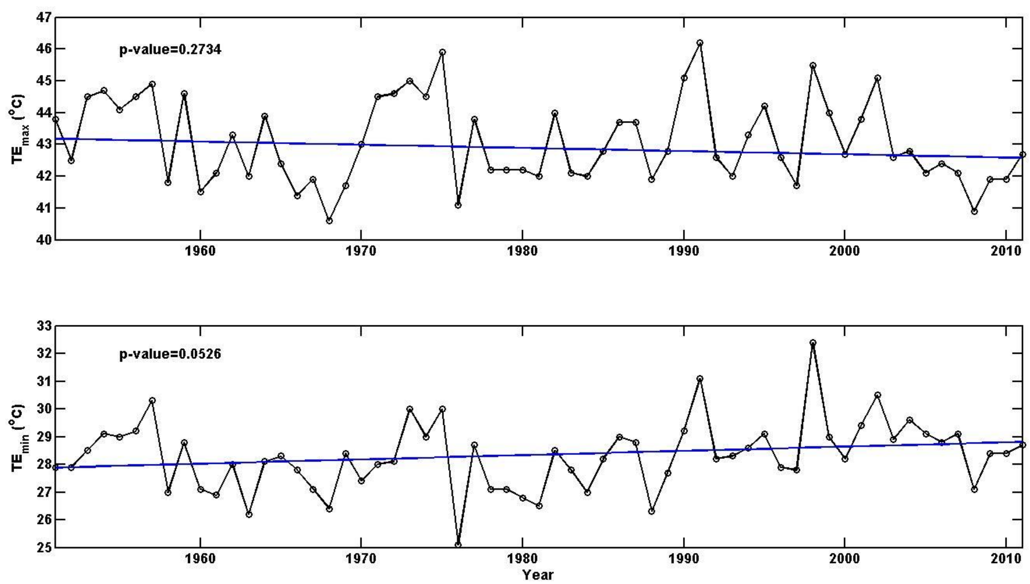


APPENDIX D

Moline, Illinois (1951-2011)

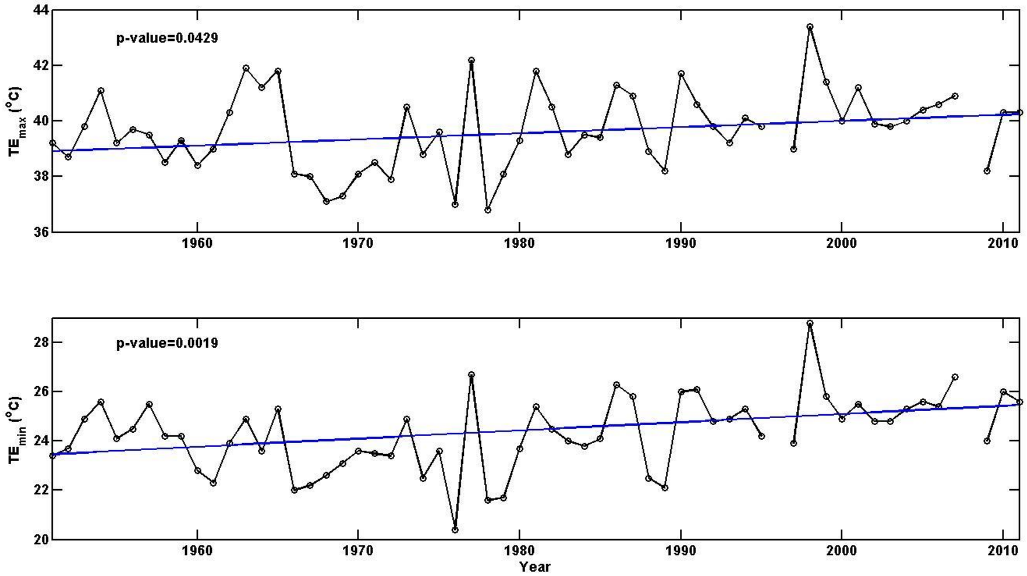


Nashville, Tennessee (1951-2011)

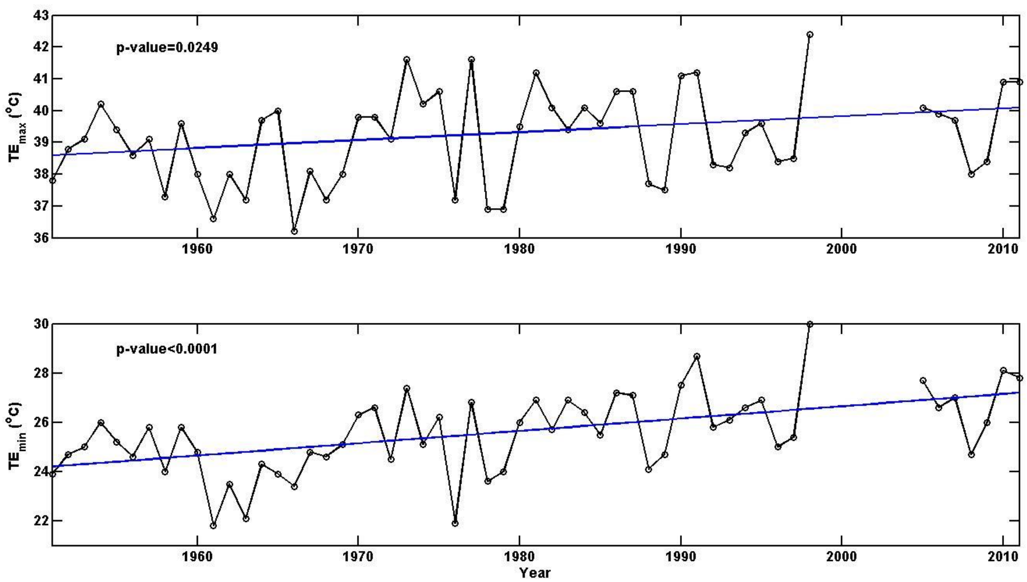


APPENDIX D

Springfield, Missouri (1951-2011)

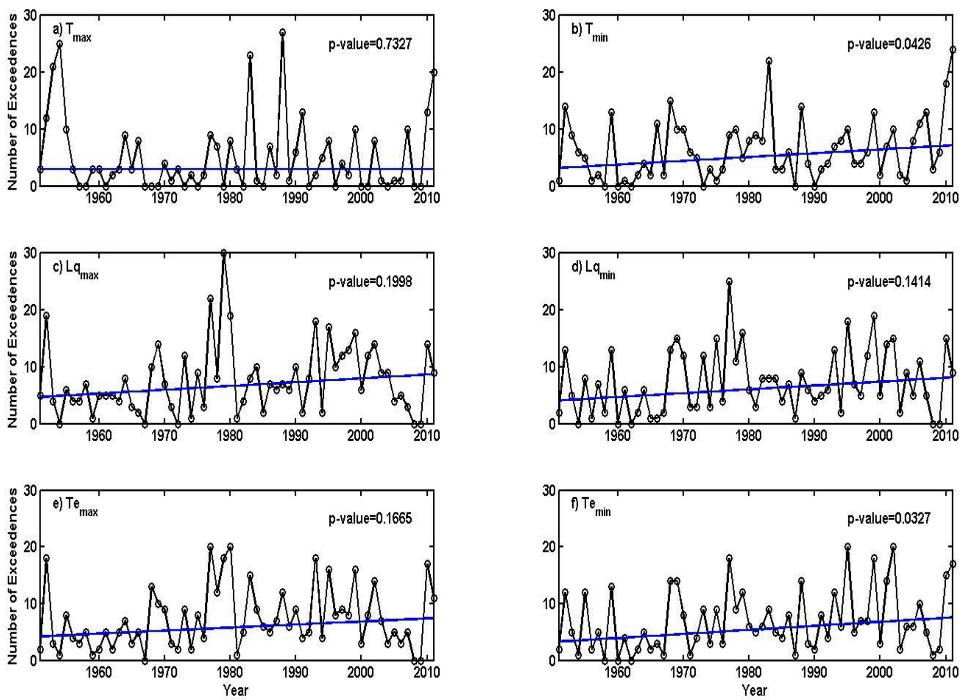


St. Louis, Missouri (1951-2011)



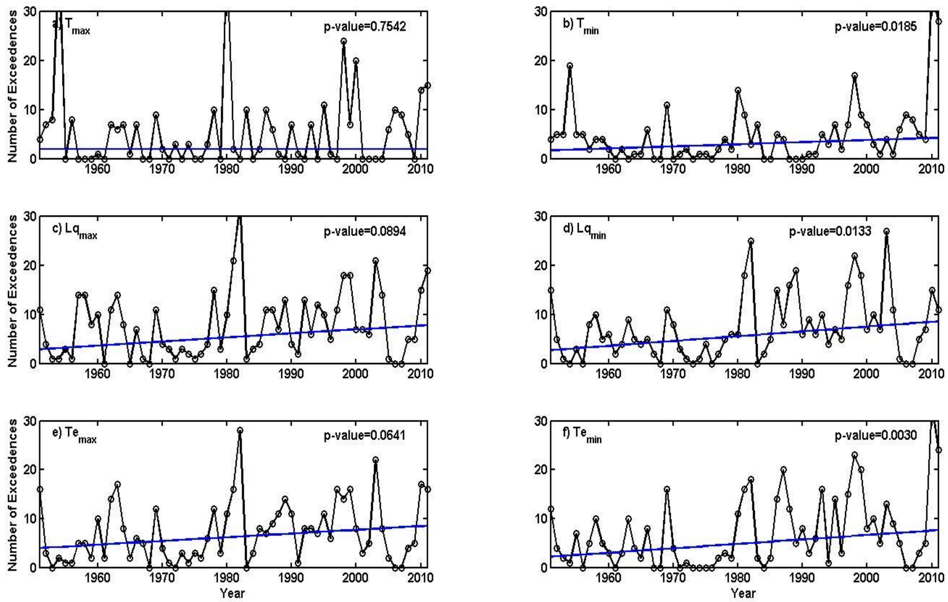
APPENDIX E

This appendix shows the frequency of days per year where T, L_q, and T_E maxima (minima) exceeded the 90th percentile for all of the stations. Indianapolis, Indiana (1951-2011). Percentiles are based on July-August values. The trend was calculated (shown by the blue line) and the significance of the slope was calculated ($\alpha = 0.05$). Plot for Indianapolis, Indiana (1951-2011).



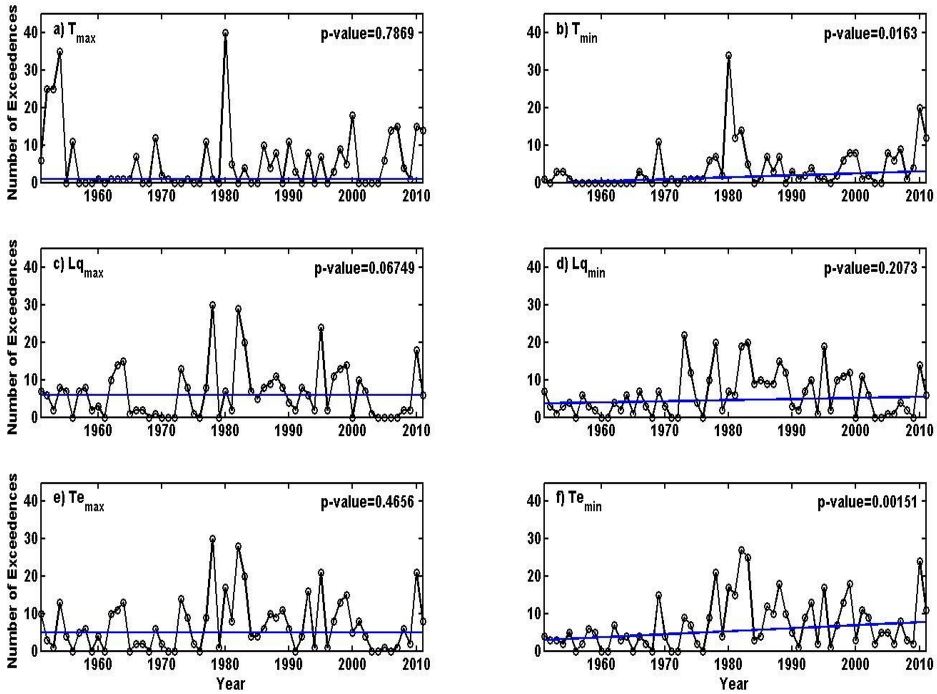
APPENDIX E

Little Rock, Arkansas (1951-2011)



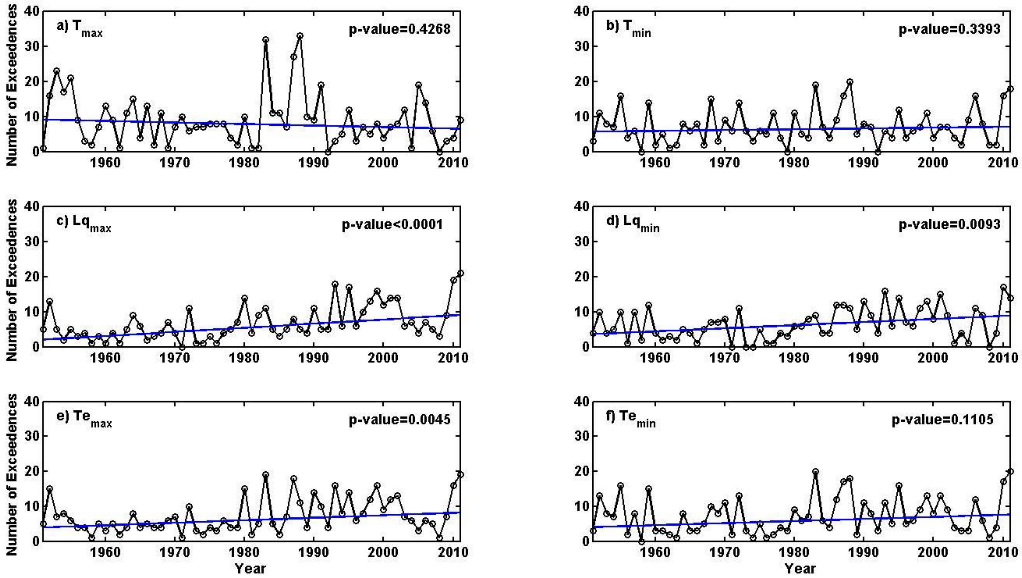
APPENDIX E

Memphis, Tennessee (1951-2011)



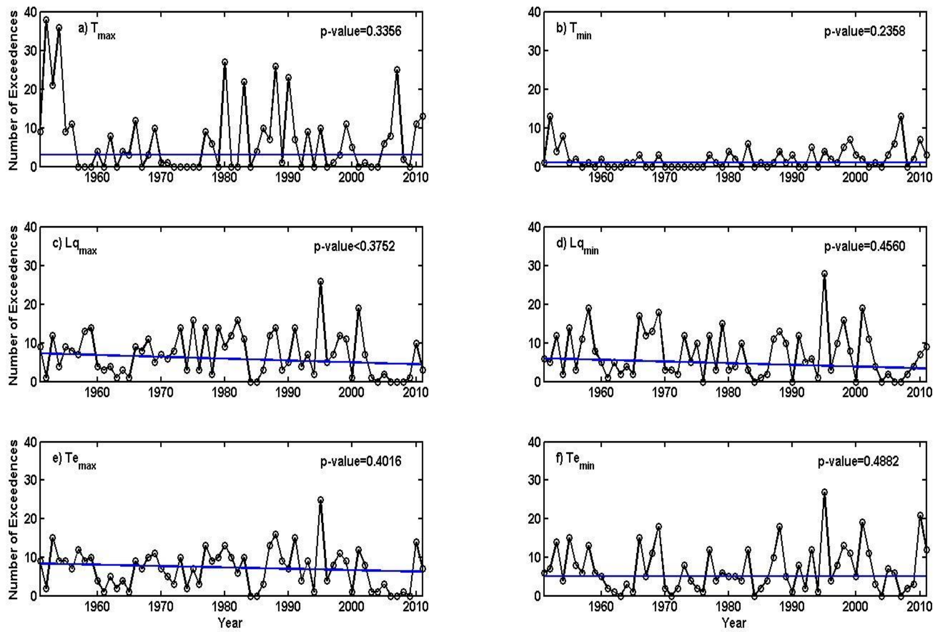
APPENDIX E

Moline, Illinois (1951-2011)



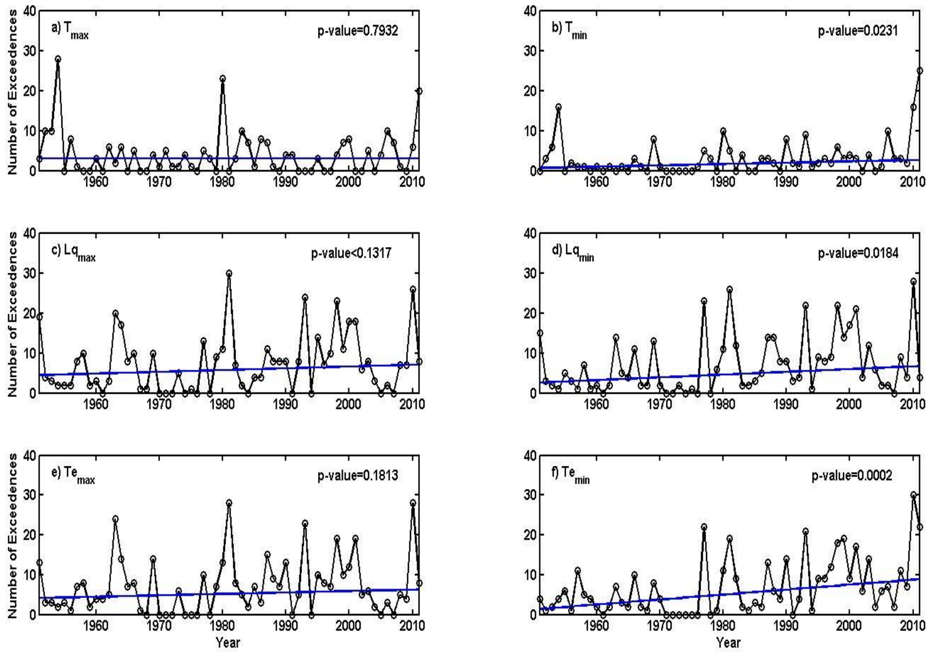
APPENDIX E

Nashville, Tennessee (1951-2011)



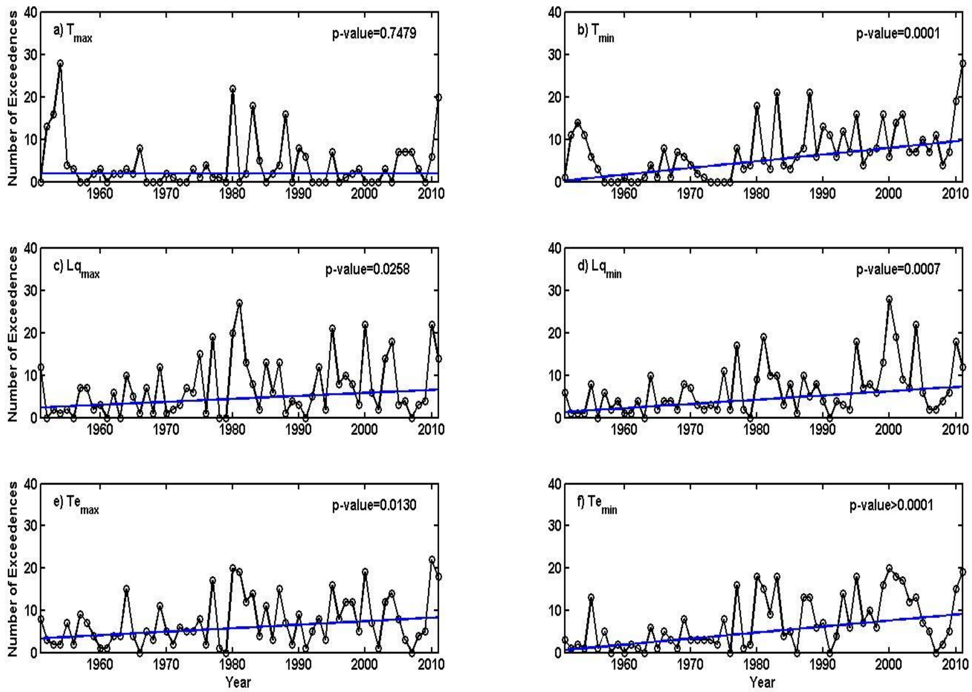
APPENDIX E

Springfield, Missouri (1951-2011)



APPENDIX E

St. Louis, Missouri (1951-2011)



APPENDIX F

Shows the p-values ($H_\theta : \beta = 0$)for the MPWS trends in the annual frequency of days meeting the HHHW threshold.

Station	P-value
Des Moines	0.6607
Indianapolis	0.8589
Little Rock	0.1166
Memphis	0.899
Moline	0.6612
Nashville	0.499
Springfield	0.0924
St. Louis	0.2373

APPENDIX F

Shows the p-values ($H_\theta : \beta = 0$) for the MPWS trends in the annual frequency of days meeting the LHHW threshold. '*' denotes significant ($\alpha = 0.05$) trend.

Station	P-value
Des Moines	0.6607
Indianapolis	0.2818
Little Rock	0.596
Memphis	0.8254
Moline	0.1184
Nashville	0.3374
Springfield	0.2231
St. Louis	***0.0342**

APPENDIX G

P-values for the MPWS trend of the time series of the proportion of high humidity heat waves ($T_{max} > P_{75}$ and $L_{qmax} > P_{50}$) (1951-2011).

Station	P-value
Des Moines	****0.0012**
Indianapolis	0.6203
Little Rock	0.1063
Memphis	0.6854
Moline	****0.0076**
Nashville	0.7973
Springfield	***0.0432**
St. Louis	****0.0032**

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Bachelor of Science, Geography and Environmental Resources, May 2012

Thesis Title:
Investigating Trends in Lower Tropospheric Heat Content and Heat Waves over the Central USA Using Equivalent Temperature (1951-2011).

Major Professor: Justin T. Schoof