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Tennessee tornado frequency, vulnerability, and relation to a large-scale climate variability

Vincent Marshall Brown
University of Tennessee - Knoxville, vbrown23@vols.utk.edu

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To the Graduate Council:

I am submitting herewith a thesis written by Vincent Marshall Brown entitled "Tennessee tornado frequency, vulnerability, and relation to a large-scale climate variability." I have examined the final electronic copy of this thesis for form and content and recommend that it be accepted in partial fulfillment of the requirements for the degree of Master of Science, with a major in Geography.

Kelsey N. Ellis, Major Professor

We have read this thesis and recommend its acceptance:

Sally P. Horn, Nicholas N. Nagle

Accepted for the Council:
Carolyn R. Hodges

Vice Provost and Dean of the Graduate School

(Original signatures are on file with official student records.)

Tennessee tornado frequency, vulnerability, and relation to large-scale climate variability

A Thesis Presented for the
Master of Science
Degree
The University of Tennessee, Knoxville

Vincent Marshall Brown
May 2016

DEDICATION

I would like to dedicate this research to my parents, Gerard and Kathy, who continually encouraged me through my educational journey.

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ABSTRACT

This work explores the climatologies of isolated tornadoes and tornado outbreaks across the state of Tennessee, a state that in some years experiences more tornadoes than states in the heart of Tornado Alley. Part one assesses tornado frequency characteristics and fatality statistics within 100 km of three major Tennessee cities (Nashville, Memphis, and Knoxville) between 1950 and 2013. Nashville reported the most tornadoes, (426) but Memphis reported the most fatalities. Knoxville and Nashville tornadoes occurred on fewer days, while Memphis tornadoes were spread across more tornado days. Spring was the most active season for tornadoes, but Memphis still experienced approximately 25% of its total tornadoes in the winter, a season prone to nocturnal tornadoes. There was no statistically significant difference between the seasonality of tornadoes for each of the cities, which is surprising given the longitudinal expanse of the state. Regional-scale analyses of this type provide insight on how tornado risk and vulnerability may vary considerably across a single state.

Part two analyzes tornado outbreak characteristics (1980–2014) from a climatological perspective and assesses how a large-scale climate oscillation may affect tornado and tornado-outbreak frequencies across Tennessee. Results indicate that 72.5% of all tornadoes in Tennessee occur in outbreaks, when an outbreak is subjectively defined as any 24-hour period with four or more tornadoes within the state. Winter, defined as Dec/Jan/Feb, had the second-highest tornado-outbreak frequency. This provides a possible explanation for the high frequency of tornado-related fatalities in Tennessee, as the winter is a time of reduced daylight and is when nocturnal tornadoes, which are twice as likely to kill, are most prevalent. The Multivariate ENSO Index (MEI) was investigated using generalized linear models with a Quasi-Poisson distribution to determine if a relationship existed between tornado activity and a large-scale climate oscillation. Results indicate that above (below) average values of MEI, or El Niño (La Niña) events, are related to times of decreased (increased) tornado activity across Tennessee, and are supported by meteorological considerations. Offering future estimations of tornado activity on a seasonal or monthly scale can aid in reducing susceptibility to these dangerous events.

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INTRODUCTION

A tornado is a “narrow, violently rotating column of air that extends from the base of a thunderstorm to the ground, and is the most violent of all atmospheric storms” (NOAA 2015). Although tornadoes occur in many different parts of the world, for example, Australia, Africa, and New Zealand, the United States has the highest frequency of tornadoes. In the United States there are two main zones of tornado activity, “Tornado Alley” and “Dixie Alley”, which are arguably one large zone that experiences tornadoes at differing times of the year (Dixon et al. 2011). Annually, 1253 tornadoes are reported in the United States on average; however, the reports range from roughly 700–1500 in any given year (NDCD 2015)

Most tornadoes spawn from supercell thunderstorms, but as few as 20% of all supercell thunderstorms produce tornadoes (NOAA 2015). The mechanism that differentiates tornadic supercell thunderstorms and non-tornadic supercell thunderstorms is still unknown. Tornadoes can also be produced by non-supercell thunderstorms, but these tornadoes occur less frequently and tend to be weaker (NOAA 2015).

Although few tornadoes result in fatalities, they habitually produce more destruction and fatalities than hurricanes and floods in the United States. In terms of economic damages, human injuries, and fatalities, tornadoes are one of the most dangerous atmospheric phenomena on the planet (Shen and Hwang 2015). The small spatial scale of tornadoes adds to the danger, as they are harder to predict and prepare for compared to larger-scale phenomena like hurricanes and floods.

The ability to forecast tornadoes and tornado outbreaks has improved in the past few decades, and the number of tornado-related fatalities during the past 50 years has decreased; however, it is evident tornado fatalities cannot entirely be prevented (Ashley 2007). One way to inform citizens of their risk and to aid decision making for preparation for natural hazards, especially tornadoes, is to assess the patterns of occurrences over time for specific locations. To achieve this goal, a researcher will create a climatology, which defines typical features, for example time, space, frequency, and magnitude, of a particular variable, such as tornadoes. Establishing a tornado climatology, especially in states that have a highly variable year-to-year tornado frequency, can be essential to protecting life and property.

Why study Tennessee tornadoes?

Tennessee is not located in the “Tornado Alley” of the Southern Plains, but its geographical location still allows for a relatively high level of tornado occurrences (Rose 2004). Tennessee has averaged 36 tornadoes and 11 tornado-related fatalities annually for the past ten years, and is ranked third (when considering all states) in ten-year total fatalities per state, with 105 fatalities (Storm Prediction Center 2015).

Parts of the Southeast have the highest occurrence of nocturnal tornadoes, which are twice as dangerous as tornadoes that occur during daylight hours (Ashley et al. 2008). Paul et al. (2003) investigated warning-response behavior during the 4–5 May 2003 tornado outbreak, and determined that residents who experienced nocturnal tornadoes in Tennessee (compared to daytime tornadoes in Kansas and Missouri during the same event) were less likely to receive warnings because they were asleep or not tuned into media outlets. Along with access and response to warnings, housing type is another issue that requires attention. Brooks and Doswell (2001) confirmed one of the leading causes for tornado-related fatalities in the United States was mobile homes, as they do not protect residents from the violent wind field. Ashley (2007) also revealed that roughly 52% of tornado-related fatalities in the Southeast occurred in mobile homes. The high probability of nocturnal tornadoes, high density of mobile homes, and lack of residents perceiving early-season tornadoes as a risk, leads to Tennessee being one of the more vulnerable states to tornadoes.

Historical Context

The main driver of tornado research is to inform the public and to provide them with information that will aid in safer decision-making during tornadic events. It is almost impossible to eliminate all tornado-related fatalities, but it is possible to reduce them from historical figures. Some historical outbreaks that have caused a large number of fatalities in Tennessee include the 3–4 April 1974 tornado outbreak, which produced at least 24 tornadoes in Tennessee and killed 38 (plus hundreds of injuries); the 5–6 February 2008 outbreak, which killed 57 people across four states; and the 27–28 April 2011 outbreak, which produced multiple EF4 tornadoes (Storm Prediction Center, 2015). With more research and a greater understanding of the Tennessee tornado climate, we can greatly reduce fatalities during these dangerous tornadic events.

Climate-Scale Considerations

As the planet continues to warm, it is important to understand the possible affects of climate change on tornadoes and severe thunderstorms (Brooks and Doswell 2001).

Researchers are currently in disagreement about whether climate change affects regional and local tornado activity. One main point of contention is the biases in the widely used tornado dataset. As noted by Brooks et al. (2014), changes in how tornadoes are reported have made it difficult to convincingly answer the question of “has climate change impacted tornado occurrences?” Researchers have been attempting to solve this question for the past few decades and continue to reach different conclusions. Doswell and Burgess (1988), Verbout et al. (2006), and Brooks et al. (2014) have reached similar conclusions with regard to tornado reports through time, suggesting that the general upward trend in reports is due to changes in reporting practices rather than climatological variability. Meanwhile, Trapp et al. (2007), Trapp et al. (2009), Diffenbaugh et al. (2013), and Elsner et al. (2015) conclude that a warming climate may create a more favorable environment for tornado genesis, which would lead to more tornado reports through time.

Researchers also question whether large-scale climate oscillations, such as the El Niño Southern Oscillation (ENSO) and the Madden Julian Oscillation (MJO), affect tornado activity across the United States, or on a regional scale. Findings have indicated that monthly-to-seasonal climate variability affects tornado activity across the United States, and it is not a result of internal atmospheric variability (Brooks et al. 2003; Shepherd et al. 2009; Tippett et al. 2012). Cook and Schaefer (2008), Lee et al. (2013), Barrett and Gensini (2013), and Thompson and Roundy (2013), hypothesized that large-scale climate oscillations, like the ones mentioned, have a significant influence on tornado activity at different scales; however, it is understood that tornadogenesis is a local-scale phenomena that requires very specific atmospheric parameters. The main conclusion that can be drawn from previous research is that certain phases of large-scale climate oscillations can make conditions more or less favorable for certain regions at differing times of the year. This provides a framework for yearly or monthly climate estimations of tornado activity and predictions of future activity.

Objective

This thesis examines the spatial and temporal characteristics of tornadoes to discern patterns that may bring awareness to the variable nature of tornadoes in Tennessee. The objective of this work is to determine the spatiotemporal frequency of isolated tornadoes and tornado outbreaks within Tennessee and disseminate that information via publications and media outlets, which will potentially reach the public. Three main questions guide the analyses within this work: (1) How do tornado frequencies and tornado-related fatalities vary across the state of Tennessee? (2) How frequent are tornado outbreaks, and how does their seasonality compare to isolated tornadoes in the state? (3) Can a large-scale climate oscillation (i.e., El Niño Southern Oscillation) be used to estimate isolated-tornado and tornado-outbreak frequencies on a monthly basis within the state of Tennessee? These questions are answered through two separate papers that are contained in the next two chapters.

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CHAPTER I
TENNESSEE TORNADO CLIMATE: A COMPARISON OF THREE CITIES

A version of this chapter was originally published by Vincent Brown, Kelsey Ellis, and Sarah Bleakney. Vincent Brown was the lead author and was assisted by his advisor, Dr. Kelsey Ellis. Fellow graduate student Sarah Bleankney (who was an undergraduate at the time) was also involved in the project and provided GIS help.

Brown, V. M., K. N. Ellis, and S. M. Bleakney, in press: Tennessee tornado climate: A comparison of three cities. *Southeastern Geographer*.

Abstract

Tornado frequency characteristics and human vulnerability are assessed within 100 km of three major Tennessee cities (Nashville, Memphis, and Knoxville) between 1950 and 2013. Tornado activity varies considerably across the longitudinal extent of Tennessee and focusing on cities and their surrounding areas provides insight on localized tornado characteristics and diminishes bias from underreported tornadoes in rural areas. Determining the spatiotemporal trends in tornado activity, especially across a state with highly variable tornado activity, can aid in reducing loss from these hazards. Nashville reported the most tornadoes (426), followed by Memphis (390), and Knoxville (176). Knoxville and Nashville tornadoes occurred on fewer days, while Memphis tornadoes were spread across more tornado days. Spring was the most active season for tornadoes, but Memphis still experienced approximately 25% of tornadoes in the winter, a season prone to nocturnal tornadoes. Memphis also averages the most tornado-related fatalities (four per year). Future work should investigate if social factors or the higher number of tornado days, including during the winter (in Memphis), affects human preparedness and response across the state of Tennessee.

Key Words: Tennessee, hazard, tornado

Introduction

The United States experiences more tornadoes than any other country (Grazulis 1990). The spatial risk of tornadoes across the country varies from year to year; however, recent research has revealed a high-risk area for tornadoes that expands from Oklahoma to Tennessee and northwestern Georgia (Coleman and Dixon 2014), with the highest risk occurring in the southeastern United States (Coleman and Dixon 2014, Dixon et al. 2011). Although many may not associate Tennessee with high tornado frequency, in some years the state experiences more tornadoes than those states in the heart of Tornado Alley. One recent example is 2011, which was one of the most active tornado years since 1936 (National Weather Service (NWS) Storm Prediction Center (SPC)). During this year, Tennessee recorded 101 tornadoes, while Kansas recorded 68 and Oklahoma recorded 119 tornadoes. However, Tennessee's tornado frequency is highly variable across time and space. In 2010, the state of Tennessee recorded 31 tornadoes, 70 fewer than the active year of 2011.

Tennessee is also particularly vulnerable to tornadic events, as evident by tornado fatality statistics presented by the SPC. Between 1981 and 2013, Tennessee ranked second for the greatest mean-annual tornado deaths (five). In the past ten years, Tennessee has recorded the highest number of tornado-related fatalities of all states

(100). The second-highest tornado-fatality rate in the past ten years belongs to Missouri, which recorded 25 fewer fatalities (NWS). Tennessee also ranks within the top five states for the number of killer tornadic events per area (Ashley 2007). Spatial analyses of the relative frequency of killer tornadic events across the United States resulted in a bull's eye of killer tornadoes spanning northeast Arkansas through southwest Tennessee, northern Mississippi, and northwest Alabama (Ashley 2007). These statistics demonstrate that understanding tornado frequency and vulnerability in Tennessee is an obvious need for protecting life and property.

Tornado climatology continues to gain research attention (Widen et al. 2015), especially with regards to how tornado activity responds to a fluctuating global climate. As the climate continues to warm, it is important to understand whether tornado devastation might worsen (Brooks and Doswell 2001). A recent study suggests that the efficiency of tornadic days is increasing (Brooks et al. 2014), as the number of days with multiple tornadoes is on the rise (Elsner et al. 2015). This finding indicates that researchers should consider the role of outbreak days versus single tornado days in tornado climatology. If the number of tornadoes per tornado day is increasing within the U.S., is it possible the same trend is occurring in Tennessee? Knowing what hazards are threats at different times of the year and at locations around the country can help weather forecasters, emergency managers, insurance companies, and the public to be better prepared (Brooks et al. 2003).

This work analyzes the climatology of tornadoes across the state of Tennessee. We focus on tornado frequency characteristics (i.e., total frequency and tornado days) and vulnerability (i.e., susceptibility to loss of life) surrounding three major cities in Tennessee: Memphis, Nashville, and Knoxville. Understanding the climatological characteristics of tornadoes in these cities is the first step to understanding and minimizing the high mortality rates associated with Tennessee tornadoes.

Data and Methods

Tornado data were obtained from the SPC (accessed 17 August 2014), which retains the most reliable record of tornadoes in the United States (Farney and Dixon 2014). The data are assembled by the NWS *Storm Data* publications and reviewed by the U.S. National Climatic Data Center (NCDC) (Verbout et al. 2006). The data include the date and time of each tornado, latitude and longitude of the genesis and dissipation locations, and other information such as fatalities and intensity. For this analysis, we obtained data for all reported tornadoes (EF 0–EF 5) from the period 1950–2013 that were, at some point during their lifetime, within 100 km of Memphis, Nashville, or Knoxville (Figure 1.1). According to a report by the Pacific Northwest National Laboratory for the U.S. Nuclear Regulatory Commission, the SPC database, although not without flaws, is in reasonably good condition and adequate for use in this type of climatology study (Ramsdell and Rishel 2007).

An initial examination of the raw dataset shows a drastic increase in the number of tornadoes reported through time, which is likely a consequence of the data collection process rather than a physical mechanism. The increase in reports is largely attributed to better reporting practices, an increase in population in rural areas (Elsner et al. 2013), the implementation of the WSR-88D weather radar in the early 1990s (Doswell 2007), and the increase in storm spotters (McCarthy and Schaefer 2004) and chasers (Elsner et al. 2013). Recent research suggests the urban-rural bias has continually decreased over time, and has become less evident in the Great Plains since the 2000s. However, the bias and its change through time have not been analyzed specifically for our study area. It should also be noted that the discovery of microbursts (strong local air downdrafts) has impacted tornado reports, and have caused a decrease in reports since 1973 (Fujita 1981).

Even today, there are almost certainly tornadoes that go un-witnessed and unreported (Elsner et al. 2013). A primary reason a tornado may go unreported in Tennessee is obstruction of sight due to tree and hill density (Farney and Dixon 2014). Doswell (2007) argues that if 1,000 years of stable and consistent tornado data were recorded, we would likely see a smooth and accurate curve of tornado frequencies throughout the year, with no one day significantly more likely to present tornadoes than neighboring days.

There are also issues of tornado intensity estimations in the SPC tornado data. The Fujita damage scale was introduced in 1971 (Fujita and Pearson 1973) for determining the strength of a tornado based on damage produced. The Fujita (F), and later enhanced Fujita (EF) scale, introduced potential impacts on the interpretation of the U.S. tornado record (Agee and Childs 2014). Both scales attempt to use tornado damage to quantify maximum wind speeds, but limitations exist in damage assessment subjectivity and use, as well as in available targets and objects that can be damaged (Doswell et al. 2009; Edwards and Brooks 2010; Edwards et al. 2013). Tornadoes that occurred prior to the implementation of the Fujita scale were rated based on photographs and newspaper accounts, which could have led to over or under estimating a tornado’s actual strength (Coleman and Dixon 2014). When the extent of the tornado damage was unknown or unclear; the lowest damage rating was used, creating bias in the data (Doswell et al. 2009). Therefore, for the purpose of this study, we limit our analyses to tornado frequency and concentrate on areas with higher populations, limiting the impact of the biases mentioned above.

Our interest is in tornadoes affecting the three most populous Tennessee cities. Since tornadoes are underreported in rural areas, especially earlier in the record (Elsner et al. 2013), focusing on activity surrounding major cities will reduce the impact of the urban-rural tornado report bias. This bias, especially earlier in the record, calls to question the reliability of the SPC tornado data, with more tornadoes reported near population centers compared to rural areas. The selected cities are located in different areas of the state. Memphis, with a population of 646,889, is located in west Tennessee; Nashville, with a population of 601,222, is located in north central Tennessee; and Knoxville, with a population of 178,874, is located in the eastern corridor of the state (2010 U.S. Census). The longitudinal distance between each of the city locations enhances the likelihood that different climatic variables influence the frequency characteristics of their tornadoes.

We first used ArcGIS (version 10.0) to place a 100-km buffer around the midpoint of each city’s center point (as reported by each city’s local government) (Figure 1.1). Next, we added the SPC tornado data layer and selected any tornado track that intersected or was contained in one of the 100-km buffers. This selection resulted in a total of 992 tornadoes (EF0–EF5) between the three cities from 1950–2013 (Figure 1.1). We use these data through the remainder of this work to analyze tornado frequency characteristics and associated vulnerability surrounding the three major cities in Tennessee. Analyses include descriptive statistics, Poisson probabilities, and a two-way analysis of variance. From this point forward, when referring to a city (Memphis, Nashville, or Knoxville) we are referring to the 100-km buffer and the tornadoes that either intersected or were contained within them.

It is important to note that tornado outbreaks can impact statistical models, especially in regional climate studies such as this one. When restricting a study to a smaller space and/or period, a few tornado outbreaks may bias the results. This preliminary study is a raw account of tornado frequency, and does not treat outbreaks any differently. Although results may be skewed, these outbreaks are a part of the overall statistical climatology. Future research should investigate how to control and account for large tornado outbreaks in regional climate studies.

Results and Discussion

Nashville reported the most tornadoes of the three cities (426), followed by Memphis (390), then Knoxville (176). The most active year (combining all of the data) was 2011, which reported 70 tornadoes. However, the most active year for each city differed. The most active years for Memphis were 1994 and 2008, with 22 tornadoes reported. Nashville's most active year was 2013, with 33 tornadoes. Knoxville's most active year was 2011, with 39 tornadoes.

Each year had at least one tornado between the three cities, but individual cities did experience zero-tornado years. In the 64-year study period, Memphis recorded 2 years without a tornado (3% of years), while Nashville had 7 years without a tornado (11% of years), and Knoxville had 23 years without a tornado (36% of years). Interestingly, Knoxville reported the fewest tornadoes (176) and the most zero-tornado years (23), but also the most active year (39 tornadoes). This highlights the importance of considering not only mean and maximum counts, but also variability within the climatology.

The Poisson distribution is useful for modeling tornado frequencies (Wikle and Anderson 2003; Simmons and Sutter 2005; Tippett et al. 2012). The Poisson probabilities for annual tornado frequency (Table 1.1) help reveal relative tornado frequencies for each city based on their observed mean (λ). There is a 45% probability of 4 to 6 tornadoes within 100-km of Memphis (λ=6.10) in any given year, while Knoxville (λ=2.75) has a 28% probability of experiencing 4 to 6 tornadoes. Nashville (λ=6.65) has roughly a 36% probability of experiencing 7 to 9, and a 12% probability of experiencing 10 to 12 tornadoes in any given year. This demonstrates that Nashville is at a slightly higher risk when it comes to tornado frequency compared to Memphis and Knoxville. Overall, Knoxville has the lowest tornado risk when analyzing tornado frequencies and probabilities, but the highly variable pattern of occurrences is still cause for concern.

Tornado Days

Tornado frequency, as Elsner et al. (2015) pointed out, is only one component of the tornado climatology. Many tornado climatology studies demonstrate risk using total tornado counts (Schaefer et al. 1986); however, more recently, greater emphasis is being placed on tornado days, defined as a day with at least one tornado within some predefined area (Concannon et al. 2000; Elsner et al. 2015; Farney and Dixon 2014). The use of tornado days reduces the reporting bias of tornadoes to an arguably indistinguishable trend since as early as about 1970 (Brooks et al. 2003, McCarthy and Schaefer 2004). Tornado days may also be changing in a fluctuating global climate. Brooks et al. (2014) and Elsner et al. (2015) discovered a consistent decrease in the number of days with at least one tornado, but at the same time, an increase in the number of days with many tornadoes.

Within our study area, Memphis had the most tornado days (220; 3.4 per year) compared to Nashville (183; 2.9 per year) and Knoxville (75; 1.2 per year). However, on those active tornado days, Memphis experienced 1.8 tornadoes per day, compared to 2.3 tornadoes per tornado day in both Nashville and Knoxville. Thus, while Memphis experiences, on average, more tornado days per year, the city experiences fewer tornadoes per tornado day.

Another interesting statistic is the single-day highest tornado count per year, which is the one single-day each year with the highest number of recorded tornadoes. For each city, the single-day highest tornado count increases over time (Figure 1.2). This increasing trend could be attributed to more tornadoes being reported (a limitation in the data) or an increasing efficiency of the atmosphere to produce tornadoes (clustering), as pointed out by Elsner et al. (2015). Future research should examine the occurrence of single tornado days compared to tornado outbreaks for each city, as evidence of large tornado clusters have been found over the Tennessee Valley (Elsner et al. 2015). This also emphasizes the differences when analyzing total tornado counts, versus tornado days, versus tornadoes per active day when considering the tornado climate for a particular location.

Tornado days can also be modeled using the Poisson distribution. For each city, for any given year, we estimate the probability of experiencing multiple tornado days (Table 1.2). The probability Memphis (λ=3.44) experiences 2 to 4 tornado days in a given year is roughly 59% and the probability of 5 to 7 tornado days per year is estimated to be 24%. The probability Nashville (λ=2.86) experiences 2 to 4 tornado days in a given year is 94%, and the estimation for 5 to 7 tornado days in a given year is 15%. Knoxville (λ=1.17) has an estimated probability of between 2 to 4 tornado days per year of 32%, and a probability of less than 1% of experiencing 5 to 7 tornado days in a given year. These descriptive statistics further demonstrate that Memphis experiences more tornado days per year compared to Nashville and Knoxville, and that the risk for multiple tornado days is higher in Memphis.

Seasonality

Next we analyzed the seasonality and timing of tornadoes in their respective season. All three cities reported the largest number of tornadoes during the spring months (March-April-May) (Figure 1.3). However, Knoxville experienced a larger proportion of activity in the spring (70%) than Nashville (62%) and Memphis (46%). The winter season (December-January-February) played a different role for each city’s climatology. Winter accounted for 25% of the Memphis tornado activity, 18% for Nashville, and only

8% for Knoxville.

A graph of the seasonality of tornadoes exhibits three patterns (Figure 1.3). First is a spring peak, which is expected considering this is the peak time for U.S. tornado activity (Verbout et al. 2006). Second, there is a lack of tornadoes during the summer months. Third, there is a spike in tornado activity during late fall (November) and late winter (January and February), which was also noticed by Brooks et al. (2003), suggesting that the South experiences a high number of tornadoes during the winter and transition seasons. It is also possible that tornadoes occurring during the late fall to mid-winter are more concentrated in outbreak type events rather than spring tornadoes (Verbout et al. 2006).

A two-way analysis of variance (ANOVA) was used to test if city, season, or the interaction between the two explained the variance in seasonal tornado frequency (Table 1.3). The results show that city and season, as categorical variables, are significant ($p < 0.05$) contributors to seasonal tornado frequency. However, the interaction between city and season is not statistically significant. The ANOVA results suggest that, while the season and city impact the number of tornadoes, the degree of seasonality is similar between cities

A cumulative monthly distribution of tornado frequency for the three cities (Figure 1.4) shows that each city on average, experiences roughly 80% of their annual tornadoes prior to 1 June, meaning most tornadoes occur during the first five months of the year. Due to the shorter days during the cool season, tornadoes that occur during the first few months of the year have a higher likelihood of occurring during a time of reduced daylight. A tornado that occurs before sunrise or after sunset is called a nocturnal tornado. Tennessee leads the country with the highest percentage of nocturnal tornadoes (45.8%) (Ashley et al. 2008).

Time of Day

Simmons and Sutter (2007) showed in their study of Florida tornadoes that most watches and warnings for nocturnal tornadic events are issued well after prime-time television and late local news, when many residents are asleep and unaware of the potential threat. It is possible that the same of lack of awareness is occurring in Tennessee. Many residents in Tennessee may be asleep and not following media broadcasts during these nocturnal events. Residents may also be unprepared for these events due to the fact that is it not officially “tornado season” yet. The strong seasonality of tornado seasons in the Great Plains (Brooks et al. 2003) facilitates awareness and preparedness, which reduces a person’s vulnerability to tornado hazards (Ashley 2007). The South has a low, yet fairly consistent risk of tornadoes through a large portion of the year, which as Biddle (1994) pointed out, can lead to a “It can’t happen here!” mentality, that in turn reduces preparedness for these hazards (Ashley 2007). Nocturnal tornadoes are almost twice as likely to kill when compared to tornadoes that occur during the daytime (Ashley et al. 2008). This suggests that Tennessee is more vulnerable to tornadoes when compared to other states due to the greater relative frequency of nocturnal tornadoes.

A more detailed look at Tennessee tornado timing shows a definite peak in the late afternoon and early evening hours, but also a slight peak in the early morning hours after midnight (Figure 1.5). The peak during the early morning hours is more noticeable for Knoxville and Nashville than Memphis. Figure 1.6 shows the timing of tornadoes separated by season. In the winter there is a late afternoon to early evening peak for Memphis and Knoxville, while Nashville has a peak in activity during the early morning hours. In the spring we see the normal pattern of late afternoon to early evening activity for each city but also a relatively high number of tornadoes occurring close to sunset (8 to 9 pm). The summer and fall follow the expected pattern with most tornadoes occurring during the late afternoon to evening hours. It is important to note that these graphs can be deceiving, because a few outbreaks may bias the results. Separating by both season and city also reduces sample size. Further research will provide insight on the synoptic and mesoscale environments surrounding tornado frequency for each city and will help explain the seasonal and temporal variability seen here.

Fatalities

Fatality information provides insight on tornado vulnerability. Between 1950 and 2013, the three cities in Tennessee reported 398 fatalities directly related to tornadic activity. Memphis recorded 256 of those fatalities, followed by Knoxville with 72 fatalities, and Nashville with 70 fatalities. On average, Memphis recorded 4 deaths each year from tornadoes, while Nashville and Knoxville averaged about one fatality. Per tornado, Memphis averaged 1.5 fatalities, but it is clear that the fatalities are associated with a few intense tornadoes rather than evenly distributed among tornadoes. Thus, the higher fatality rate in Memphis compared to the other two cities could be related to higher-intensity tornadoes seen here. The relatively high vulnerability in Memphis is evident well outside of this study area, as Ashley (2007) showed that a small area encompassing Memphis experienced more killer tornadoes per unit area than any other location in the United States. However, it is important to note that the SPC tornado database does not report fatalities along the track of the tornado. Long-track tornadoes that impact a large area and population could end in one of the city's buffers and artificially inflate the total number of fatalities. Nevertheless, Ashley (2007) also found a relatively high number of fatalities in the same region as this study.

Ashley (2007) proposed that one of the major reasons the American South has a greater fatality rate than other high-risk regions is because tornadoes here tend to occur during cool and transition seasons when day length is at a minimum. Our results suggest a similar pattern for Tennessee tornadoes. Figure 1.7 shows the total number of monthly fatalities for each city (1950–2013). Memphis had the greatest number of deaths between February and March, during a time of reduced daylight. There is a smaller peak for Memphis in May, which coincides with the peak of tornado activity. Nashville has a bimodal distribution, with two similar peaks in fatalities during February (when there is reduced daylight) and April (when tornado activity is close to its maximum). Knoxville has a single peak in fatalities during April when tornado activity is again close to its maximum for that city (see Figure 1.3). A cumulative frequency distribution of monthly fatalities (Figure 1.8) shows that each city experiences roughly 80% of fatalities in a given year prior to 1 May, suggesting that the lack of a defined tornado season in Tennessee may lead to these higher fatality rates early in the year.

The Poisson probabilities of annual tornado fatalities are shown in Table 1.4.

The probability of having between 1 to 3 tornado related deaths within 100-km of Memphis (λ=4.0) in any given year is 42%, while the probability in Nashville (λ=1.1) or Knoxville (λ=1.1) is 64%. Meanwhile, Memphis has a much greater probability (55%) of having between 4 and 6 deaths in a year compared to Nashville and Knoxville (3%). We have shown that tornado frequency is not the only explanation for the higher estimated fatalities in Memphis. Future research should investigate social factors (e.g., housing type, percent below poverty) that may be responsible for the disproportionate number of fatalities experienced in Memphis and also determine the role of tornado intensity.

Summary and Conclusions

Tennessee's tornado frequency is variable across time and space, and many tornadoes result in the loss of life. Between 1950 and 2013, 992 tornadoes were recorded within 100 km of the three most populous cities in Tennessee. Nashville recorded 426 tornadoes, followed by 390 in Memphis, and 176 in Knoxville. Of these cities, Memphis had the most tornado days (220) compared to Nashville (183) and Knoxville (75) during the 64-year study period.

Tornadoes in Memphis were spread out across more tornado days than in Nashville and Knoxville. Memphis also recorded the greatest number of fatalities among the three cities. These two statistics are related, and perhaps there is a lower public response to tornado warnings on single-tornado days than on multiple-tornado days. If a tornado occurs within the vicinity of a city, are its inhabitants more likely to pay attention to a second tornado warning, therefore reducing vulnerability during the second event? Future research should also investigate social factors that may be contributing to the relatively high number of tornado fatalities experienced in Memphis, while accounting for the role of tornado intensity and track length. This work did not account for tornado outbreaks, but future research will investigate how to control for these outbreaks and consider their role in differential vulnerability. The high number of nocturnal tornadoes across the entire state provides a great degree of vulnerability here, but Memphis clearly is the most vulnerable of the major Tennessee cities.

All three Tennessee cities experienced an annual peak in tornadoes during the spring months. The proportion of winter activity varied between cities, with Memphis having the most winter activity. However, a two-way analysis of variance demonstrated that tornado frequency variability was significantly related to season and city; but city combined with season was not statistically significant. This suggests that while the season and city impact the number of tornadoes, the degree of seasonality is similar between cities. This was somewhat unexpected, as we originally thought that the longitudinal differences between the cities would cause some differences in seasonality, and there seemed to be some evidence pointing to seasonal differences. Perhaps this expected relationship would become apparent if different data or statistical techniques were applied. For example, if analyses were performed using only significant tornadoes or only tornadoes that have occurred in the past twenty years, this may decrease the chance of bias from unobserved events and highlight the expected relationship. This will be the topic of future work, as well as the connection between Tennessee tornado variability and large-scale climate oscillations.

This preliminary analysis of the Tennessee tornado climate shows that relative tornado risk depends on which tornado characteristic is subject to analysis (i.e., total frequency or tornado days). A current initiative in tornado research aims to understand how tornadoes are changing in a changing climate (Widen et al. 2015), and results should also be applied to local (e.g., state- or regional-level) risk and vulnerability analyses. Specific to the state of Tennessee, if more tornadoes are occurring on fewer days (Brooks et al. 2014; Elsner et al. 2015), will this have the same impact across the entire state? Or will this enhance the differences in the number of tornadoes per tornado day experienced across the state? Answering questions like these will provide insight on how tornado frequency characteristics and associated vulnerability are changing on regional or local scales, and will help residents better understand their risk during tornadic events, potentially reducing their vulnerability.

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Appendix.

Table 1.1

Poisson probabilities for annual tornado occurrences per city. The number indicates the likelihood of the associated range of tornadoes within 100 km of the city center.

Tornadoes	Memphis	Nashville	Knoxville
1–3	0.14	0.10	0.64
4–6	0.45	0.40	0.28
7–9	0.32	0.36	0.02
10–12	0.08	0.12	<0.01

Table 1.2

Poisson probabilities for annual tornado days per city. The number indicates the likelihood of the associated range of tornadoes days within 100 km of the city center.

Tornado Days	Memphis	Nashville	Knoxville
2–4	0.59	0.62	0.32
5–7	0.24	0.15	<0.01
8–10	0.02	<0.01	<0.01
11–13	<0.01	<0.01	<0.01

Table 1.3

Results of a two-way ANOVA for seasonal tornado frequency based on season and city, including degrees of freedom (DF), sum of squares, mean square, F value, and significance.

Variable	DF	Sum Sq	Mean Sq	F value	p-value
City	2	143	71.35	8.14	<0.01
Season	3	742	247.39	28.22	<0.01
City:Season	6	102	16.99	1.94	0.07

Table 1.4

Poisson probabilities for annual fatality occurrences per city. The number indicates the likelihood of the associated range of tornado related fatalities within 100 km of the city center.

Fatalities	Memphis	Nashville	Knoxville
1–3	0.42	0.64	0.64
4–6	0.55	0.03	0.03
7–9	0.10	<0.01	<0.01
10–12	<0.01	<0.01	<0.01

Figures

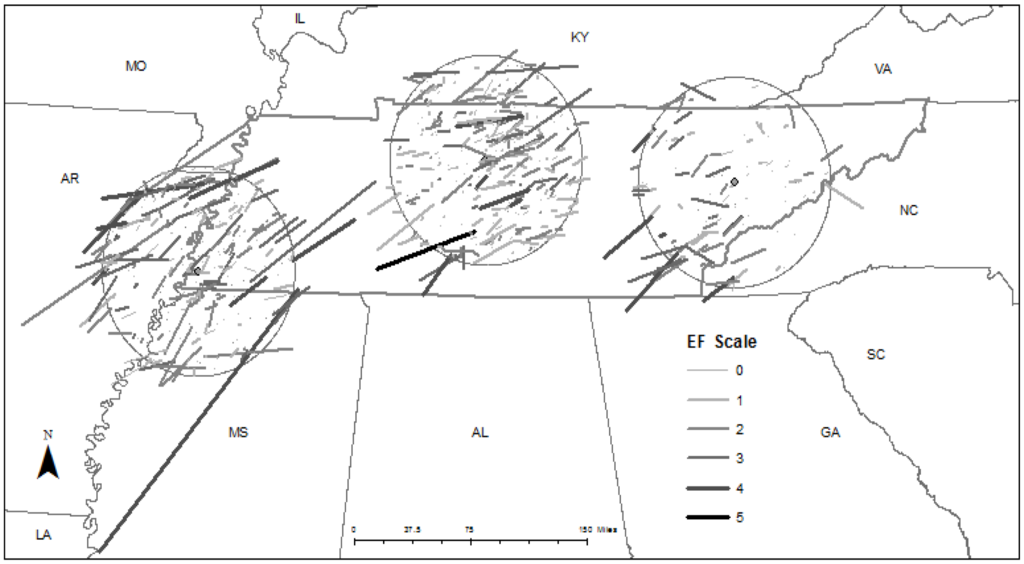

Figure 1.1

Tracks of tornadoes reported within a 100 km buffer of Memphis (left), Nashville (middle), and Knoxville (right) (1950–2013). Width and shade of track increase with tornado intensity (EF0–EF5).

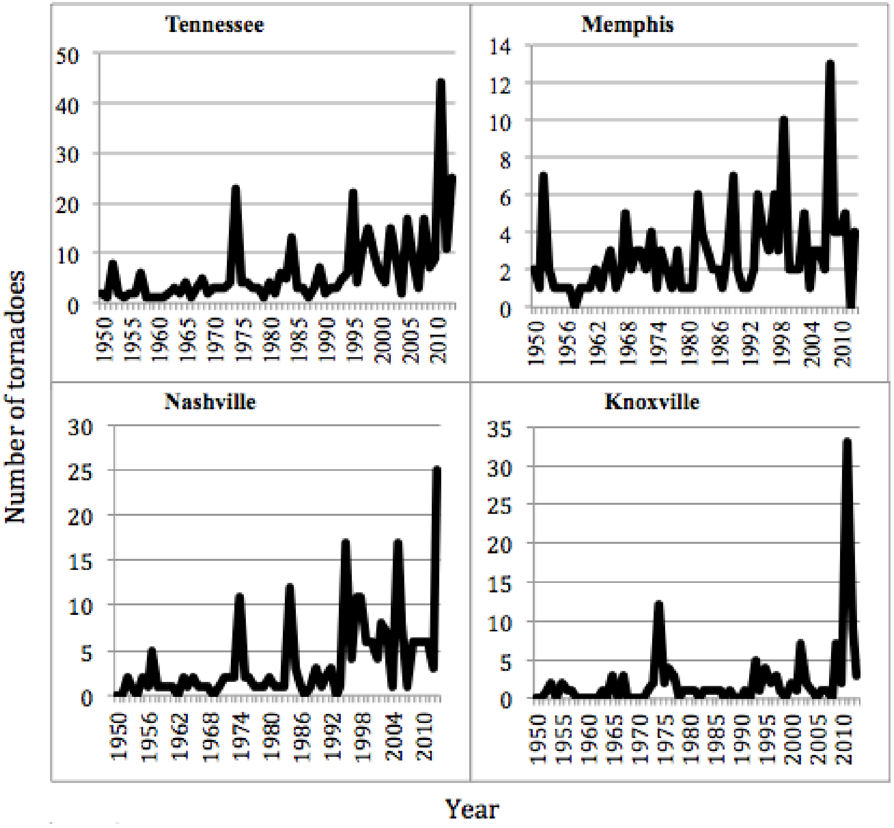

Figure 1.2

Highest single-day tornado count annually for Memphis, Nashville, and Knoxville (1950–2013).

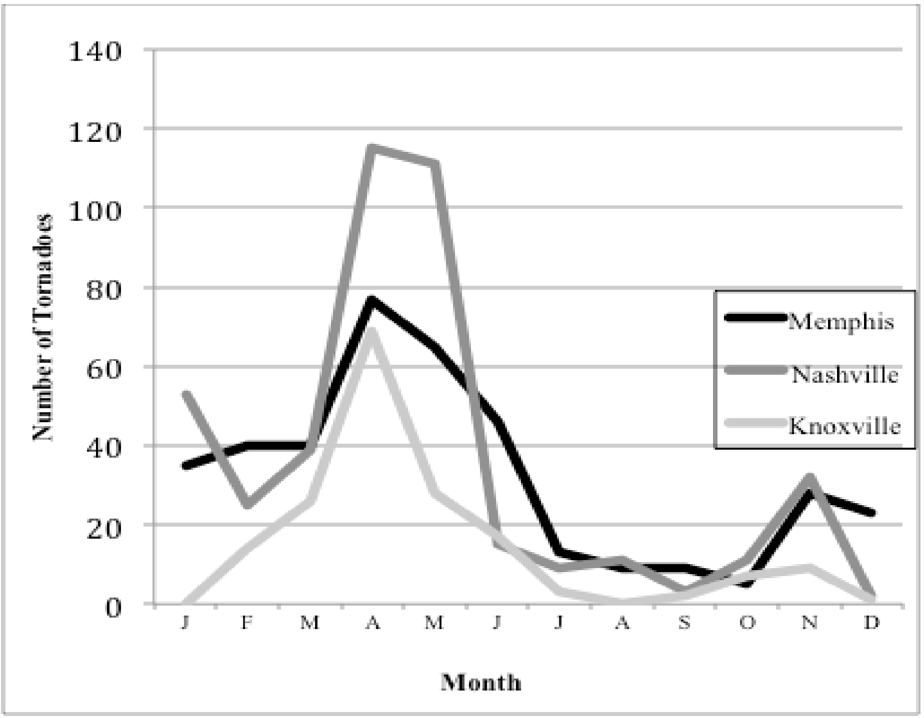

Figure 1.3
Monthly tornado distribution for Memphis, Nashville, and Knoxville (1950–2013).

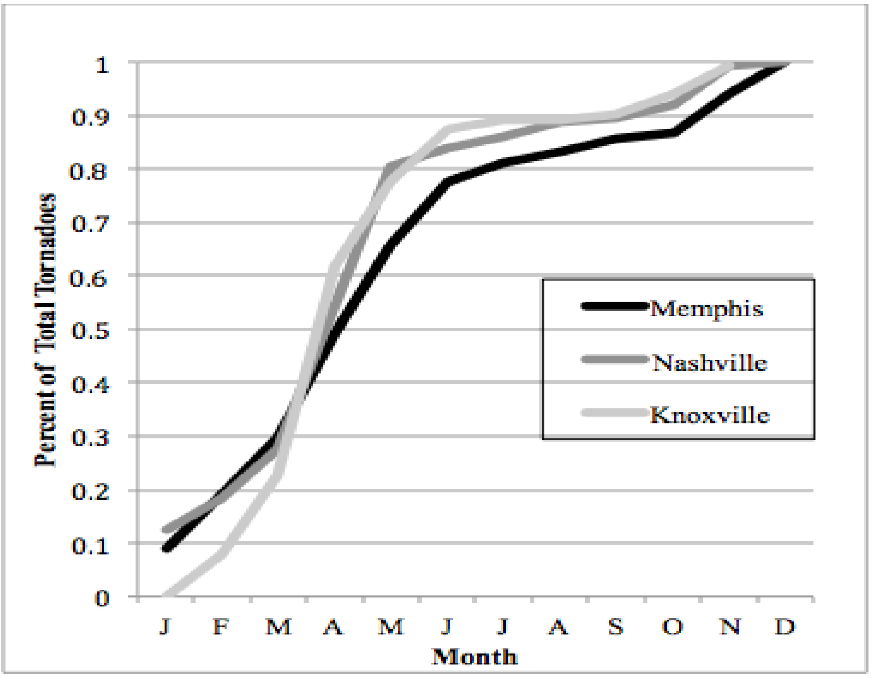

Figure 1.4

Cumulative monthly distribution of annual tornadoes for Memphis, Nashville, and Knoxville (1950–2013).

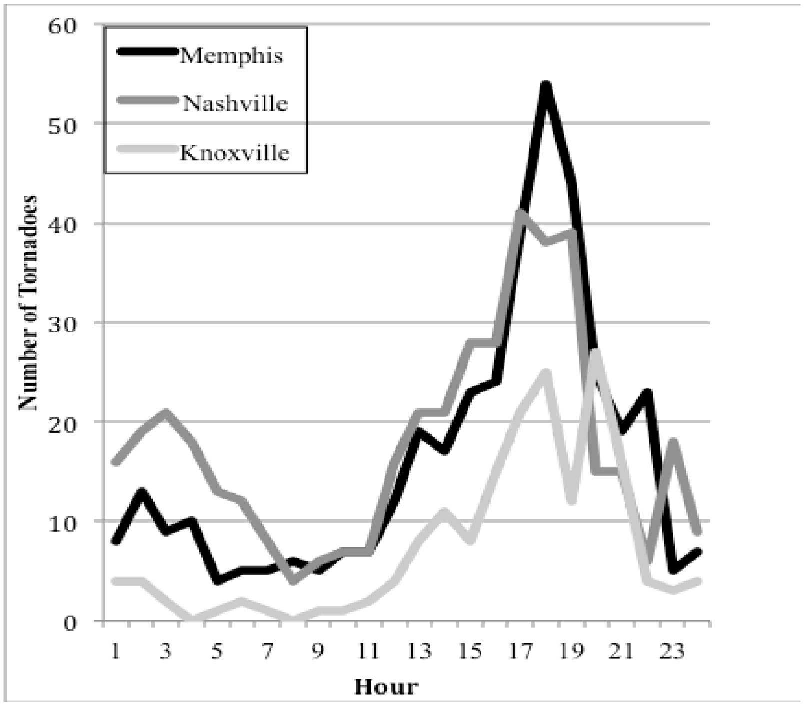

Figure 1.5
Tornado distribution by hour for Memphis, Nashville, and Knoxville (1950–2013).

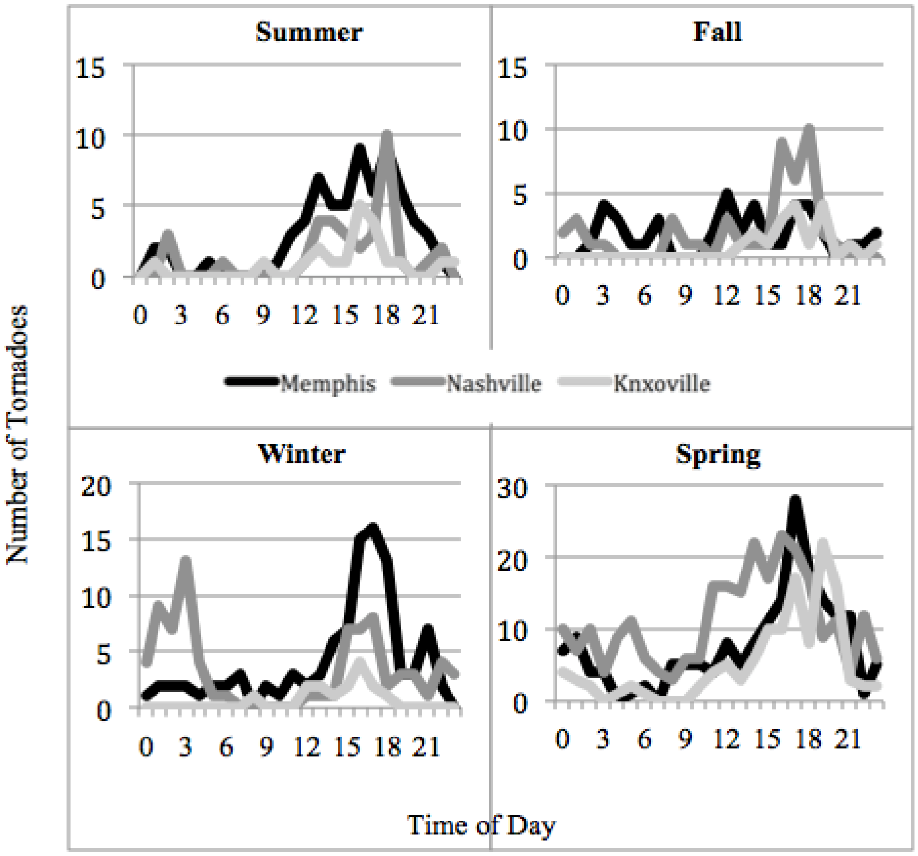

Figure 1.6

Hourly tornado distribution by season and city (1950–2013). Seasons are defined as summer (June, July, August), fall (September, October, November), winter (December, January, February) and spring (March, April, May).

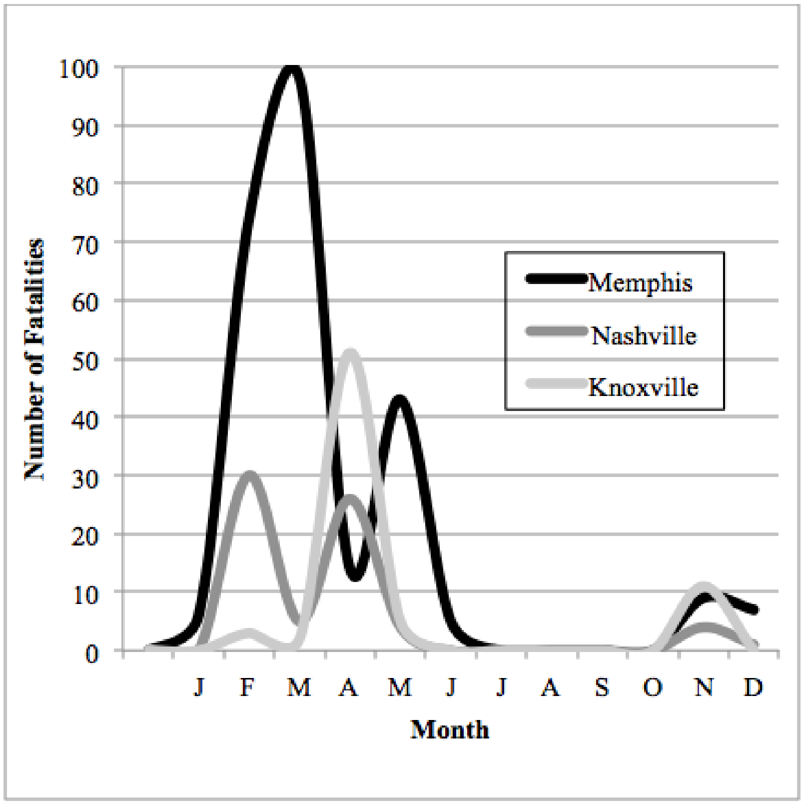

Figure 1.7
Monthly fatality distribution for Memphis, Nashville, and Knoxville (1950–2013).

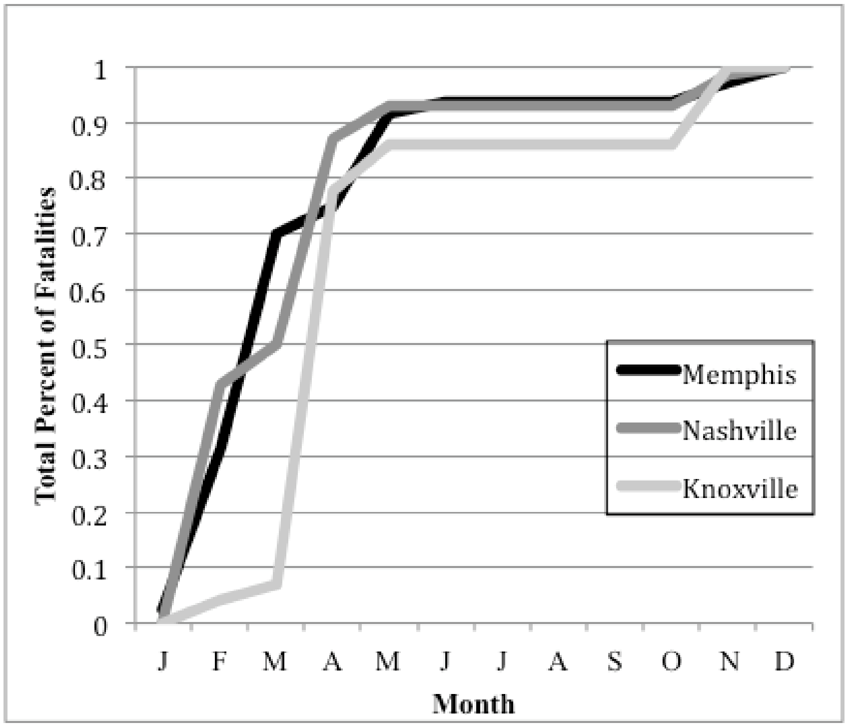

Figure 1.8

Cumulative monthly distribution of tornado fatalities by month for Memphis, Nashville, and Knoxville (1950–2013).

CHAPTER II

TENNESSEE TORNADO OUTBREAKS: A CLIMATOLOGICAL PERSPECTIVE

This article has not yet been published anywhere, but will be submitted to a journal in the near future.

Abstract

Tornado outbreaks, defined as multiple consecutive tornadoes in a relatively short period, are more likely to cause economic loss and fatalities (Galway 1975) compared to single, isolated tornadoes. In the past thirty years Tennessee has averaged six tornado-related fatalities per year (Storm Prediction Center 2015). This work analyzes tornado outbreak characteristics (1980–2014) from a climatological perspective and assesses how a large-scale climate oscillation may affect tornado and tornado-outbreak frequencies across the state of Tennessee. Results indicate that 72.5% of Tennessee tornadoes occur within outbreaks, when an outbreak is subjectively defined as any 24-hour period with four or more tornadoes within the state boundary. The winter season is a time of reduced daylight and is when nocturnal tornadoes, which are twice as likely to kill, are most prevalent. During our study period the winter season had the second-highest tornado-outbreak frequency and could possibly explain the high frequency of tornado-related fatalities in Tennessee.

The Multivariate ENSO Index (MEI) was also investigated using generalized linear models with a Quasi-Poisson distribution to determine if a relationship existed between ENSO phase and tornado and tornado-outbreak frequency. Results indicate that above (below) average values of MEI, or El Niño (La Niña) events, are related to times of decreased (increased) tornado activity across Tennessee. These results are supported by meteorological considerations related to the position of the Pacific Jet Stream. Relating large-scale climate variability to state level tornado activity can help citizens prepare for these hazards by informing seasonal forecast models.

Key Words: Outbreaks, ENSO, Tennessee

Introduction

Multiple consecutive tornadoes in a relatively short period, known as a tornado outbreak, are far more likely to produce a high number of fatalities (Galway 1975) and economic loss compared to single, isolated tornadoes. Tornado outbreaks involve numerous tornado touchdowns and tend to cover large swaths of land, increasing the number of people they will affect and the likelihood of fatalities (Brooks 2004). Approximately three-quarters of all tornado-related fatalities from 1952 to 1973 occurred in outbreaks with at least ten tornadoes (Galway 1977). Tornado outbreak days, defined as a day in which an outbreak occurs, accounted for four-fifths of all tornado-related fatalities from 1875 to 2003 (Schneider et al. 2004). As population and urban sprawl increase it is likely more people will be at risk to future tornado outbreaks (Fuhrmann et al. 2014).

This work focuses on the climatology of isolated tornadoes and tornado outbreaks in Tennessee. The tornado climatology of Tennessee is unique in that a majority of the tornadoes here occur within outbreaks, and there is no clearly defined season of tornado activity (Brown et al. 2016). Tennessee averaged 36 tornadoes and 11 tornado-related fatalities annually for the past ten years, and is ranked third in ten-year total fatalities per state (105 fatalities) (Storm Prediction Center 2015). Tennessee ranks within the top five states for the number of killer tornadic events per area (Ashley 2007), further confirming that more research is needed on tornado activity within the state. Historical tornado outbreaks that affected Tennessee include the 5–6 February 2008 outbreak (57 fatalities across four states), 29–30 January 2013 outbreak (largest winter tornado outbreak in middle Tennessee history), and the 27–28 April 2011 outbreak (300 fatalities across the Eastern U.S.).

Tornado outbreaks may play a different role in the tornado climatology across the state. Previous research shows that the western portion of the state (Memphis region) experiences more tornado days per year but fewer tornadoes per tornado day compared to other areas (Brown et al. 2016). Meanwhile, in middle Tennessee there are typically more tornadoes on a given tornado day. Areas that are prone to more tornadoes per tornado day may experience a larger proportion of their tornadoes within outbreaks.

The climatology of tornado outbreaks is different from isolated tornadoes, and shows regional variability. In general, the Southeast (including Tennessee) experiences its peak outbreak frequency in early April, while the Midwest experiences its peak outbreak activity in late May into early June (Fuhrmann et al. 2014). Non-outbreak tornadoes, or isolated tornadoes, are more dispersed throughout a year and are more frequent during the spring months for the Southeast (Fuhrmann et al. 2014). Brooks et al. (2003) discovered that the Southeast, as well as the Great Plains, has the most consistent seasonal frequency (less variation) of peak tornado activity. The Southeast experiences outbreaks earlier in the year when compared to most other U.S. regions. Isolated tornadoes are follow a different trend and are prevalent through the entire year, hence it is important to identify the role of isolated tornadoes and outbreaks within the tornado climatology.

Recently, an emphasis has been placed on determining drivers of tornado activity on a national and regional scale (Fujita 1981; Monfredo 1999; Schaefer and Tatom 1999;

Cook and Schaefer 2008; Lee et al. 2013; and others). Most studies have focused on the El Niño-Southern Oscillation (ENSO). ENSO is one of the most significant drivers of seasonal and inter-annual global climate variability on earth (Wolter and Timlin 2011). Two of the most commonly used indices for quantifying ENSO are the Southern Oscillation Index (SOI) and Oceanic Niño Index (ONI). Each index has its strengths and weaknesses. Perhaps the biggest flaw of both indices is using only one variable to quantify ENSO, the SOI using only sea level pressure (SLP) and the ONI using only sea surface temperature (SST). Often studies use categorical classifications of ENSO (weak El Niño, moderate El Niño, etc) through these indices to investigate tornado activity.

While the one-variable quantification of ENSO through SOI and ONI is useful, a more intuitive metric is the Multivariate Enso Index (MEI). The MEI quantifies the intensity of the ENSO, using not only SLP or SST, but also zonal and meridonial components of the surface winds, surface air temperature, and fractional cloud cover (NOAA 2015). This multi-variable approach better reflects the nature of the complex coupled relationship between the ocean and atmosphere, and is less vulnerable to sporadic data glitches (NOAA 2015). An individual MEI value is computed for each of the twelve sliding bi-monthly seasons (Dec/Jan, Jan/Feb, and so on) (Wolter 1987). Each MEI bi-monthly value is analogous, as they are standardized by season and to the 1950–1993 reference period (Wolter and Timlin 1993, NOAA 2015). In general, negative (positive) MEI values represent La Niña events (El Niño events), which is the cold (warm) phase of ENSO, and a value of 0 depicts a neutral phase of ENSO. It is likely that the relationship between ENSO and tornado activity varies across space and time

(Schaefer and Tatom 1999). In Schaefer and Tatom (1999), eight states were analyzed separately to determine if ENSO affected tornado occurrences; however, because of restrictions in data and the rare nature of tornadoes, the study failed to differentiate tornado activity as a function of ENSO phase.

The purpose of this study is to analyze tornado outbreaks in Tennessee through three main questions:

1. What proportion of Tennessee tornadoes occurs within outbreaks?
2. What is the seasonality of tornado outbreaks within Tennessee?
3. Is there a connection between a large-scale climate oscillation (specifically the ENSO, as quantified by MEI) and monthly tornado and tornado-outbreak frequency?

The following section explains the data used in this study, followed by the methods, our definition of tornado outbreaks, a discussion of the results, meteorological considerations, and finally a summary and conclusion.

Data

Tornado data were obtained from the SPC (accessed 11 November 2015), which retains the most reliable record of tornadoes in the United States (Farney and Dixon 2015). The data are continually compiled by the NWS *Storm Data* publications and revised by the U.S. National Climatic Data Center (NCDC) (Verbout et al. 2006). The data include the latitude and longitude of the genesis and dissipation locations, date and time of each tornado, and other information such as fatalities and intensity.

A preliminary examination of the tornado database shows an escalation in the number of tornadoes reported through time (Doswell 2007), including within the state of Tennessee (Brown et al. 2016). The increase in tornado reports is often attributed to the implementation of the WSR-88D weather radar in the early 1990s (Doswell 2007) and the increased presence of storm chasers and storms-spotter networks (McCarthy and Schaefer 2004, Elsner et al. 2013). Another concern regarding the tornado database is the affect of population density, as more tornadoes are reported within the vicinity of urban areas because more people are present to report them. Elsner et al. (2013) analyzed the urban-versus-rural reporting bias in the Great Plains and noted that it had decreased significantly since the early 2000s; however, the bias still exists and has not been analyzed specifically for this study area.

Tornado intensity is quantified using the Fujita damage scale, which was introduced in 1971 (Fujita and Pearson 1973) and attempts to estimate the strength of a tornado based on the damage produced. The creation of the Fujita (F) and enhanced Fujita (EF) scales has introduced potential intensity biases in the tornado record (Agee and Childs 2014). Both scales use tornado damage to quantify maximum wind speeds, with limitations due to damage assessment subjectivity and objects available to be damaged and later assessed (Doswell et al. 2009, Edwards and Brooks 2010, Edwards et al. 2013). The intensities of tornadoes that occurred prior to the implementation of the Fujita scale were retroactively evaluated based on pictures and newspaper accounts (Coleman and Dixon 2014), potentially leading to the over or under estimation of intensity. The discovery of microbursts (strong localized air downdrafts) has also affected tornado reports by creating a reduction in reports since 1973 (Fujita 1981). Therefore, the reliability of the tornado data prior to the 1970s is often questioned. For this analysis, we obtained data for all reported tornadoes (EF0–EF5) from the period 1980–2014. Although this reduces our sample size, it decreases the inherent biases and increases our confidence in the selected data. Data were selected using ArcGIS (version 10.0). Adding the SPC tornado data layer allowed us to select any tornado (EF0–EF5) track that intersected or was contained within the bounds of Tennessee from 1980–2014.

MEI data were gathered from NOAA's Earth System Research Laboratory. Meteorological variables are spatially filtered into clusters then MEI values are calculated by NOAA using Principle Component Analysis (Wolter 1987). For more information on how MEI values are computed access NOAA's Earth System Research Laboratory ((http://www.esrl.noaa.gov/psd/enso/mei/). We selected bimonthly values beginning in Dec/Jan of 1980 until Nov/Dec 2014 for this study.

Methods

The definition of a "tornado outbreak" is subjective and dependent on location. Shafer and Doswell (2010) defined a tornado outbreak as a cluster of tornadoes that touch down within a singular synoptic-scale system. Studies have also used the total frequency of tornado touchdowns (Galway 1977), total tornado outbreak days (Schneider et al. 2004), and overall physical magnitude (Johns and Sammler 1989) as metrics for quantifying tornado outbreaks. For this study we classified a tornado outbreak as any 24-hour period in which four or more tornadoes (EF0–EF5) occur within or intersect the state of Tennessee. An outbreak was initiated when four or more tornadoes occurred within 24-hrs; however, larger outbreaks may extend past a 24-hour limit. Therefore, we defined the end of an outbreak when four tornadoes were no longer within 24 hours of each other. We organized tornado outbreaks into four different categories based on the number of tornadoes touchdowns within the outbreak itself, similar to Elsner et al. (2015) but on a smaller scale. The four categories are: four or more ($x \geq 4$), six or more ($x \geq 6$), eight or more ($x \geq 8$), and twelve or more ($x \geq 12$) tornadoes touchdowns within the entire outbreak event.

We used both descriptive and inferential statistics to assess tornado and tornado-outbreak frequency characteristics across the state of Tennessee. Descriptive statistics included seasonality, average frequency, and the total proportion of tornadoes that occur in Tennessee tornado outbreaks. Generalized linear models were then used to determine if any relationship exists between the MEI and tornado and/or tornado-outbreak frequency on a monthly basis across Tennessee. All statistics were completed using R Project for Statistical Computing.

Tornadoes are considered rare events, and frequency counts can never be negative. For these reasons we selected a Poisson distribution to fit our data. However, MEI is only one of the many factors that could possibly predict or explain tornado activity across the state, thus we implemented a Quasi-Poisson distribution. This distribution includes other factors, (e.g., other climate oscillations and meteorological factors) as an unexplained random variable, or bit and builds that into the distribution. It is also important to note that the default Quasi-Poisson distribution in R is a log-linked function, meaning the relationship between tornado activity and MEI values is log-linked.

Thus, we used generalized linear regression with a Quasi-Poisson distribution to determine if the MEI explains the frequency of tornadoes or tornado outbreaks. The equation we derived is as follows.

$$\log(expected\ tornadoes) = b_0 + b_1(MEI) + b_2(Time) + random\ error$$

It is also important to note that tornado reports have increased through time, and that the MEI has cycles that could create false significance in our model. By including both time and month in our model, we essentially de-trended and de-seasonalized tornadoes and MEI values.

Results and Discussion

During the 35-year study period there were 831 tornadoes reported. The frequencies of each outbreak category (e.g., greater than four tornadoes), as well as the percentage of total tornadoes by each category, are shown in Table 2.1. Outbreaks of four or more tornadoes accounted for approximately 72.5% of the total tornadoes produced by outbreaks in Tennessee during a given year (Figure 2.1), revealing that a majority of the tornadoes that occur within the state occur in outbreaks. It is also important to note that during the study period fifteen outbreaks of twelve or more tornadoes occurred, accounting for 42.2% of the total tornadoes produced by outbreaks in Tennessee.

Outbreak Seasonality

Tornado activity in the United States peaks in mid May; however, as shown in Figure 2.2 and in agreement with Fuhrmann et al. (2014), Tennessee tornado outbreaks peak a month earlier in mid April. All of the outbreak categories were most frequent in the spring months (March-April-May), followed by two of the winter months (January, February), but no outbreaks were recorded during December in the study period. The season with the lowest frequency of outbreaks was summer (June-July-August), during which only one outbreak of six or more tornadoes occurred. The fall (September-October-November) also had a relatively low frequency of tornado-outbreak events, as September had no outbreaks of any kind and only eight outbreaks of four or more tornadoes occurred in October and November during the 35-year study period. These statistics reveal that outbreak-type events are prevalent in January and increase in frequency until April and May (Figure 2.3), demonstrating that the first five months of the year are when Tennessee is most susceptible to tornado outbreaks. These results confirm that the South experiences a high frequency of tornado activity during the winter and transition season, earlier in the year when compared to peak tornado activity for the United States as a whole (Brooks et al. 2003; Fuhrmann et al. 2014; Brown et al. 2016).

The annual timing of the outbreak climatology is notable because tornadoes that occur in the winter and early spring have a higher likelihood of occurring during a time of reduced daylight. Tornadoes that occur preceding sunrise and after sunset are called nocturnal tornadoes, and are twice as likely to kill when compared to tornadoes that occur during daylight hours (Ashley et al. 2008). Tennessee leads all other states with the highest proportion of nocturnal tornadoes (45.8%) (Ashley et al. 2008). By investigating the relative frequency of killer tornado events, Ashley (2007) discovered a bull’s eye of tornado-related fatalities in the American South, potentially attributing this to the high frequency of winter and transition season tornadoes. It is clear that tornado outbreaks are far more likely to kill compared to isolated tornadoes (Galway 1975) and in the study period Tennessee experienced 72.5% of its tornadoes in outbreak form. The high rate of outbreak occurrence, combined with the nocturnal nature of Tennessee's tornado activity, suggests that Tennessee may be one of the more vulnerable states to tornado outbreaks. However, it is important to note that Tennessee does experience fewer outbreaks compared to other states annually (Fuhrmann et al. 2014).

Outbreak Trends

Next we investigate potential changes in the frequency of tornado outbreaks over time within the state of Tennessee. Recent studies have noted that tornado days, defined as a day with at least one tornado within a predefined area (Concannon et al. 2000, Farney and Dixon 2015), have decreased through time, while the number of tornadoes per tornado day has increased (Brooks et al. 2014, Elsner et al. 2015). Elsner et al. (2015) described this trend (more tornadoes on less days) as an increase in the efficiency of the atmosphere to produce tornadoes, a possible response to a fluctuating global climate. Brooks et al. (2014) attributed this trend to increased variability in tornado reports because of biases in reporting practices and greater clustering of tornado activity. Both studies concluded that, while more tornadoes are occurring on fewer days, there has been no increase in annual tornado frequency (Brooks et al. 2014, Elsner et al. 2015).

We briefly investigated the frequency of outbreak events through time as an initial effort to assess changes in annual frequency. There appears to be an increase in the number of outbreaks of four and six or more tornadoes through the study period. Outbreaks of eight and twelve or more tornadoes are too rare to draw conclusions. The increase in the other outbreak categories could be explained by an increase in tornado reports through time, greater clustering of tornado activity (Brooks et al 2014), or an increasing efficiency of the atmosphere to produce tornadoes (Elsner et al. 2015).

MEI and Tornadoes

A generalized linear model with a Quasi-Poisson distribution was used to assess the relationship between monthly MEI values and both monthly tornado and tornado-outbreak frequency. By comparing individual months and accounting for time we removed some of the seasonal and yearly cycle in MEI and the increase in tornado reports through time. The results show that MEI is a significant variable when estimating expected monthly tornado frequencies (Table 2.2) and outbreaks of four or more tornadoes (Table 2.3). Tornado outbreaks of six, eight, and twelve or more tornadoes were not significantly related to MEI values, most likely because of the reduced sample size due to their rarity in Tennessee. It is also important to consider the longitudinal extent of Tennessee, as the state has different geographical zones that influence meteorological factors that can contribute to tornado activity and outbreaks.

Next we assessed whether MEI values significantly influenced tornado activity in a given month (Table 2.2). January was selected as a baseline and all months in Table 2.2 and 3.2 are in relation to this month. For example, the monthly estimate for February (Table 2.2) is -0.184, meaning this monthly estimate is roughly 18% less (expected tornadoes) than January. Considering all total reported tornadoes (831 in the study period), we expect April and May (maximum tornado activity) and September and December (minimum tornado activity) to be significantly different from January, and in our model this holds true. However, monthly significance in this context is not as important, as it is well known that more tornadoes occur in April and May (higher estimates) and fewer tornados occur in September and December (lower estimates). The more important information is that MEI is a significant contributor to monthly tornado and outbreak frequencies, and to a lesser extent so is time, as even when trying to control for temporal biases, an increase in reported tornadoes through time is still evident.

To determine the expected tornadoes per month we consider the following equation. It is also important to note that the MEI has a mean of zero and a standard deviation of 1.

Log (Expected Tornadoes) = (-0.06 + monthly estimate) -0.404 (MEI value) + 0.0029 (year)

Or

Expected tornadoes = $e^{b_0+b_2+time}e^{b_1(MEI)}$

Thus, changing MEI by +1 will multiply the expected number of tornadoes by e^{b_1}, where b_1 is the MEI estimate (-0.404 in Table 2.2), revealing that as MEI values increase (El Niño events) the number of expected tornadoes in a given month decreases (Table 2.2). This provides evidence that lower-than-average (negative) MEI values relate to times of increased monthly tornado activity across the state of Tennessee. Negative MEI values (La Niña events) correspond to a higher number of expected tornadoes according to our statistical model, as a negative MEI value multiplied by the negative MEI estimate results in positive number raised to *e*. The same type of interpretation applies to Table 2.3 (outbreaks of four or more tornadoes) but note the MEI estimate (b_1) is different (-0.036) and time is slightly more influential (0.003). It is important to take into consideration the overall climatology of tornado and tornado-outbreak frequency, as extremely negative values of MEI will not produce extreme outbreaks in the summer months because of the climatological lack of tornado activity during the season in Tennessee.

These results do not indicate that tornado activity across the state of Tennessee is solely caused by fluctuating MEI values, but suggests that MEI does affect tornado activity and should be accounted for in future models that attempt to assess the relationship between large-scale climate oscillations and tornado activity.

Meteorological considerations

The MEI is almost synonymous with the Southern Oscillation Index (SOI) and the Oceanic Niño Index (ONI), in that they both resolve warm (El Niño), cool (La Niña), and neutral phases of ENSO in the Tropical Pacific. MEI accounts for more of the factors that make up El Niño (e.g. SLP, SST, surface wind components, cloud cover, and surface air temperature), La Niña, and neutral events, resulting in is a finer resolution version of the SOI and ONI index. Typically, equatorial trade winds migrate from east to west across the Pacific Ocean. During the warm El Niño phase (cool La Niña phase) pressure increases (decreases) near Australia and decreases (increases) over Tahiti and the eastern Tropical Pacific, resulting in a weakening or reversal (strengthening) of the trade winds. Consequently, this seesaw of pressure results in El Niño (La Niña) bringing atypically dry (wet) conditions to Australia and surrounding locations and wetter (drier) conditions over the west coasts of Tropical North and South America. These changes set in motion shifts in convection and latent heat exchanges that alter the position and strength of some atmospheric circulation features, such as the Pacific Jet Stream (Cook and Schaefer 2008).

Regional Responses

Research suggests that changes in ENSO phases lead to shifts in average jet stream patterns over the contiguous United States (Hagemayer 1998; Smith et al. 1998; Nun and DeGaetano 2004), and that phases of ENSO relate to shifts in thermodynamics and upper-air profiles (Sankovich et al. 2004). During El Niño phases, the Pacific Jet Stream is typically located over the southern portion of the continental United States, bringing above-average precipitation and below-average temperatures to the area. During La Niña phases, the Pacific Jet Stream is located farther north compared to El Niño phases, and is also somewhat weaker (NOAA, 2015). This pattern is most pronounced in the winter. A general guideline in forecasting is that severe weather occurs slightly to the south of the jet stream (Miller 1972; Doswell and Schaefer 1976; Cook and Shaefer 2008); therefore, when the Pacific Jet Stream is located farther north the severe weather risk also shifts north. As concluded by NOAA's Climate Prediction Center (CPC, 2012), the position and strength of the jet stream helps determine what regions of the U.S. are more or less likely to experience severe weather, including tornadoes.

The relationship between ENSO phase and tornado activity is beyond a simple generalization of jet stream location (Cook and Shaefer 2008). Smith et al. (1998) found that during the cool phase of ENSO the Bermuda anticyclone shifts farther east, resulting in the convergence of low-level winds onshore around 850 hPa, causing moisture to pool in the Mississippi Valley. This movement of moisture, as well as the noted northward displacement of the maximum 250 hPa mean jet stream (important ingredients for tornadogenesis), reinforces findings from Cook and Shaefer (2008), that La Niña events concentrate tornado activity within a moderately sized zone that encapsulates parts of Tennessee. Cook and Shaefer (2008) were unable to fully resolve ENSO effects on tornado activity across Tennessee, most likely because of the longitudinal extent of the state and resulting gradient of tornado frequency seen from west to east (Brown et al. 2016).

The strength and position of the jet stream is not the sole factor that controls tornado activity, but our results suggest that certain phases of the MEI, which detects ENSO phases, can contribute to more or less favorable conditions for tornadogenesis. Our conclusions are similar to Lee et al. (2013), in that tornadogenesis is a mesoscale concern that demands localized and specific atmospheric conditions, and that large-scale and generalized atmospheric processes cannot predict localized tornado and/or tornado outbreak frequencies. While local conditions are the most important consideration for tornadogenesis, we argue that conditions favorable for tornadogenesis tend to occur more frequently when MEI values are negative. Our results suggest that above-average MEI values (El Niño conditions) relate to a lower number of expected tornadoes and outbreaks of four or more tornadoes, and that below-average MEI values (La Niña conditions) generate a higher number of expected tornadoes and outbreaks of four or more tornadoes across the state of Tennessee. These results are in agreement with Allen et al. (2015) and Sparrow and Mercer (2016), providing some basis for long-range seasonal forecasts of tornado activity that are crucial for protecting life and property.

Summary and Conclusion

This study focused on tornado outbreaks in Tennessee, with an outbreak being defined as four or more tornadoes within a 24-hour period, then ending when four tornadoes no longer occurred within 24 hours of each other. This allowed for large synoptic scale systems (that can persist for days) to be considered one large outbreak. During the 35-year study period 831 tornadoes were recorded, 72.5% of which occurred in outbreaks of four or more tornadoes. The seasonal pattern of tornado outbreaks was noteworthy, as the winter season had the second-highest frequency of outbreaks while the summer and fall were times of reduced outbreaks. The relatively high winter-season tornado activity is especially dangerous, primarily because people may not perceive tornadoes as a threat outside of the spring months (when tornado activity reaches its maximum), creating a mentality of “it can’t happen here!” (Biddle 1994), and leading to a failure to embrace warning information. Additionally, winter tornadoes may be more hazardous because daylight hours are reduced, increasing the probability of dangerous nocturnal tornadoes (Ashley et al. 2008).

Results indicate that the frequency of four and six or more outbreaks in Tennessee may be increasing through time. Possible explanations are better reporting practices, greater clustering of tornado activity within the United States (Brooks et al. 2014), or a physical mechanism (Elsner et al 2015). Future research should investigate the source of the variability (human reporting practices or a response to a changing climate), as it has implications for risk and vulnerability analyses of this type.

The relationship between the MEI and tornado and tornado-outbreak frequencies was also investigated. The MEI is composed of six meteorological characteristics that fluctuate and affect global circulation patterns that can influence tornado activity on a regional scale. A Quasi-Poisson regression model suggested that MEI is a significant component for understanding Tennessee's tornado and tornado-outbreak (of four or more tornado) frequency on a monthly basis. Using theoretical reasoning we suggest that ENSO patterns, as quantified through MEI values, influence the frequency of both total tornadoes and tornado outbreaks of four or more tornadoes. Outbreaks of six, eight, and twelve or more tornadoes were not significant in the model, likely because of the low frequency of these events in Tennessee.

Cyclical changes in the meteorological characteristics that are incorporated into the MEI help to explain seasonal and monthly tornado frequencies. Our model indicates that as MEI values increase (decrease), the expected number of tornadoes in a given month decreases (increases). Tornadogenesis relies on many other small-scale factors and cannot possibly be described by one large-scale climate oscillation; however, we argue that changes in meteorological characteristics over the Tropical Pacific, that are accounted for in the MEI, are a possible driver of tornado frequency across Tennessee and should be included in any potential seasonal forecast models.

All tornado-related research has flaws, mostly due to the biases in the widely used tornado dataset. The weaknesses in this paper revolve around the same issues, as some tornadoes may have spawned outside of the boundary of Tennessee and tracked into the state. The definition of an outbreak was also generalized across the entire state. It is evident that outbreaks are more frequent for the western and middle portion of the state compared to the eastern portion, where the definition of an outbreak could have been different. Another area of concern relates to the use of tornadoes without tracks and EF 0 tornadoes. A decent portion of out data consisted of weak tornadoes that could have biased the results.

Future research should investigate only significant tornadoes or a larger region to increase the sample size. Additionally, it would be valuable to assess the relationship between the MEI and tornado activity in other states and regions, as well as how the decay and transition of El Niño and La Niña conditions might influence tornado activity in the United States. This type of research could lead to seasonal forecast models that would greatly improve the ability to forecast and prepare for these events.

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Appendix.

Table 2.1

Frequency counts of each outbreak category as well as the proportion of total tornadoes by outbreak type.

Outbreak type	Number of outbreaks (total tornadoes)	Percent of total tornadoes
$X \geq 4$	61 (603)	72.5
$X \geq 6$	34 (485)	58.3
$X \geq 8$	22 (412)	49.5
$X \geq 12$	15 (351)	42.2

Table 2.2

Generalized linear model output for all tornadoes and MEI. January is the baseline month and each month in the table is in relation to January. The monthly estimate for February is -0.184, meaning this monthly estimate is roughly 18% less (expected tornadoes) than January.

All tornadoes

Coefficients	**Estimate**	**t-value**	**p-value**
Intercept	-0.0634	-0.159	0.8736
MEI	-0.4043	-3.279	0.0011*
Time	0.0029	3.463	0.0005*
February	-0.1842	-0.374	0.7087
March	0.0521	0.112	0.9109
April	1.2246	3.195	0.0015*
May	1.2058	3.027	0.0026*
June	0.1869	0.388	0.6979
July	-1.1286	-1.569	0.1174
August	-1.3802	-1.797	0.0731
September	-2.4174	-2.053	0.0407*
October	-0.6550	-1.141	0.2547
November	0.1798	0.398	0.6909
December	-2.8640	-2.013	0.0447*

Null deviance: 2797 on 419 degrees of freedom
Residual deviance: 1875 on 406 degrees of freedom
Dispersion parameter for quasipoisson = 7.65

Table 2.3

Generalized model output for outbreaks of four or more tornadoes and MEI.

Outbreaks of $x \geq 4$

Coefficients	**Estimate**	**t-value**	**p-value**
Intercept	-2.7380	-5.334	1.6e-07*
MEI	-.0364	-2.372	0.0181*
Time	0.0032	2.901	0.0039*
February	0.1728	.299	0.7654
March	0.4774	.876	0.3815
April	1.2880	2.641	0.0085*
May	0.9833	-1.873	0.0617
June	-0.0326	-0.049	0.9606
July	-1.4680	-1.398	0.1628
August	-1.5390	-1.469	0.1426
September	-17.250	-0.012	0.9905
October	-0.4940	-0.707	0.4798
November	0.0024	0.004	0.9969
December	-17.290	-0.012	0.9905

Null deviance: 261.38 on 419 degrees of freedom
Residual deviance: 187.5 on 406 degrees of freedom
Dispersion parameter for quasipoisson = .913

Figures.

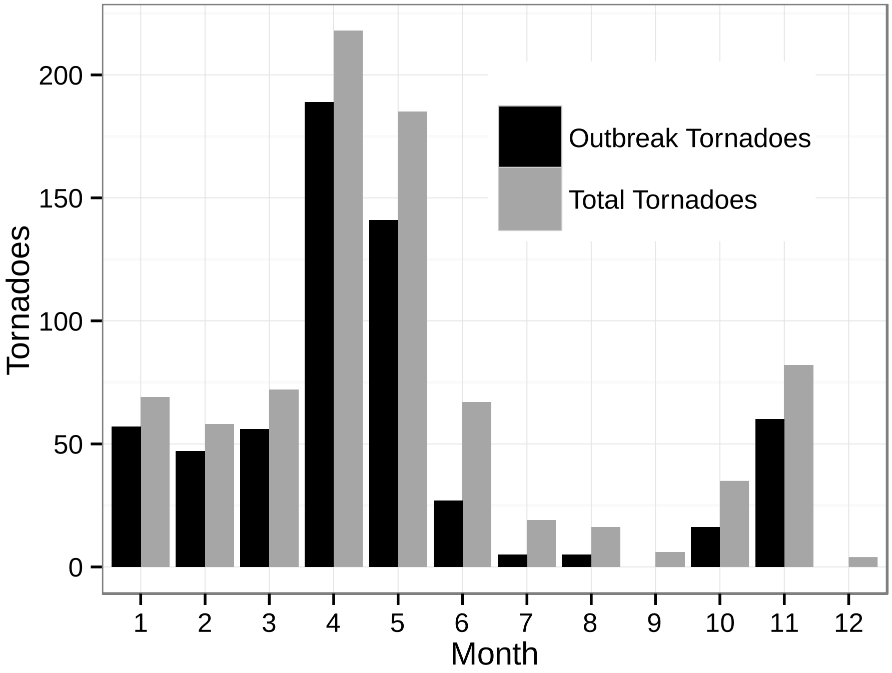

Figure 2.1

Monthly distribution of total tornadoes versus outbreak tornadoes (x≥4) in Tennessee (1980–2014).

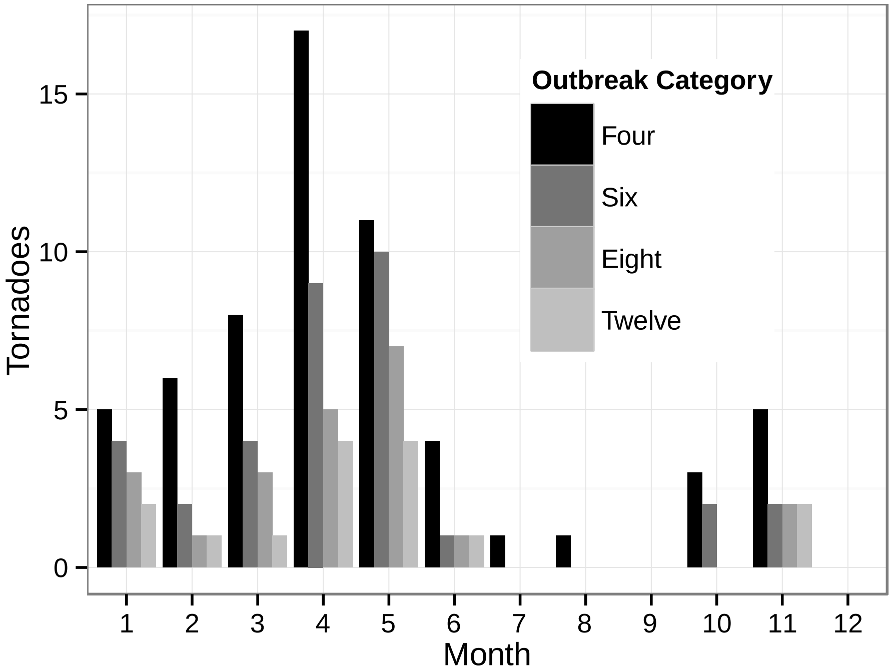

Figure 2.2
Monthly tornado outbreak distribution by outbreak type (x≥4, x≥6, ≥8, and x≥12) for Tennessee (1980–2014).

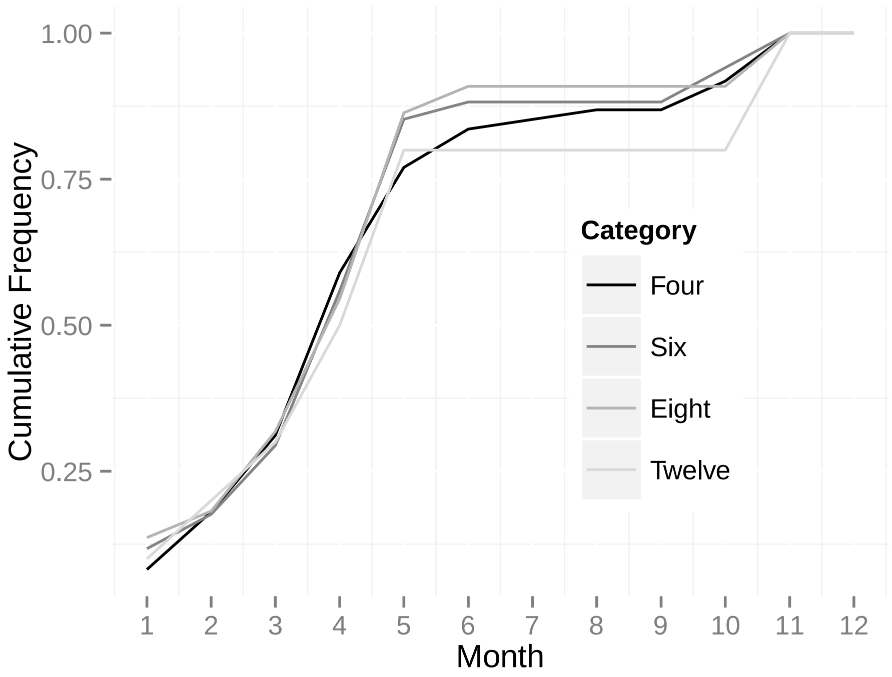

Figure 2.3

Cumulative monthly distribution of annual outbreak frequency by category for Tennessee (1980–2014).

CONCLUSION

The objective of this thesis was to determine the spatiotemporal frequency of isolated tornadoes and tornado outbreaks within Tennessee, including the influence of large-scale climate variability. This work addressed three main questions:

1) How do tornado frequencies and tornado-related fatalities vary across the state of Tennessee?

2) How frequent are tornado outbreaks, and how does their seasonality compare to isolated tornadoes in the state?

3) Can a large-scale climate oscillation (i.e., El Niño Southern Oscillation) be used to estimate isolated-tornado and tornado-outbreak frequencies on a monthly basis within the state of Tennessee?

Frequency and fatalities across the state

Tennessee's tornado frequency is variable across space and time, and many tornadic events within the state result in the loss of life. Without basic knowledge of tornado characteristics, economic loss and fatalities from tornadic events will undoubtedly continue. Tornado-related fatalities will always occur, but they have decreased significantly in the past few decades (Ashley 2007), perhaps in part due to the proliferation and dissemination of tornado-related research.

Tornado frequency was analyzed across Tennessee by investigating a 100-km radius surrounding the three most populated cities. During the study period (1950–2013) 992 tornadoes occurred within the three city buffers. Nashville recorded the most tornadoes (426), followed by Memphis (390), then Knoxville (176). Memphis's tornadoes were spread out across more tornadoes days (220) compared to Nashville (183) and Knoxville (75). Results revealed the western and middle portions of the state have a high frequency of tornadoes, while the seasonality of the tornadoes followed similar patterns. Poisson probability estimation also revealed the western and middle portions of the state were more susceptible to tornadoes, demonstrating that tornado frequency differs considerably longitudinally across the Tennessee, but without a statistical difference in the timing.

Factors that contribute to tornado-related losses and fatalities depend heavily on local dynamics. Investigating a specific region's tornado characteristics can aid in preventing future fatalities and losses. Tornado-related fatalities were also assessed within 100 km of the three most populated cities in Tennessee to determine how they varied across the state. During the study period 398 fatalities were directly related to tornadic activity. Memphis recorded 256 of those fatalities, followed by Knoxville with 72 fatalities, and Nashville with 70 fatalities. On average, Memphis records 4 deaths each year from tornadoes, while Nashville and Knoxville average about one fatality. One possible explanation for these differences could be related to lessened public awareness and response to tornado warnings on single-tornado days compared to multiple-tornado days, as Memphis is more likely to have an isolated tornado than the other two cities. Future research should investigate how societal factors (mobile home density, poverty) and tornado timing (nocturnal tornadoes) contribute to the high number of fatalities recorded there. Regardless of the reasoning, Memphis, and the surrounding 100-km area, is the area most susceptible to tornado activity and losses in Tennessee.

Frequency of tornado outbreaks versus isolated tornadoes

The difference between isolated tornadoes and outbreak tornadoes across the state was also investigated. During the 35-year study period (1980–2014) 831 tornadoes were recorded, 72.5% of which occurred in outbreaks of four or more tornadoes. It was also determined that 15 independent outbreaks of 12 or more tornadoes over the course of 35 years accounted for 42.2% of the total tornadoes, revealing a majority of Tennessee tornadoes tend to occur in outbreaks. The seasonal pattern of tornado outbreaks was notable, as the winter season had the second-highest frequency of outbreaks while the summer and fall were times of reduced outbreaks. Isolated tornadoes tended to have a higher relative frequency during the summer months when compared to outbreak tornadoes; however, the rest of the seasons showed similar frequencies.

Total tornadoes and outbreak tornadoes were also investigated temporally to determine if either was changing through time. Results indicate the frequency of total tornado reports, as well as outbreaks of four and six or more, in Tennessee may be increasing through time. It is possible the increase is due to better reporting practices, an increase in tornado clustering, or a physical mechanism related to a fluctuating climate. Future research should investigate the source of this increase (whether it is human reporting practices or a response to a changing climate), as it has implications for risk and vulnerability analyses.

Consideration of a large-scale climate oscillation

Researchers have tried to identify the main drivers of tornado occurrences for decades, but data limitations and the highly variable nature of tornadoes have been difficult challenges to overcome. In this study the relationship between ENSO and monthly tornado and tornado outbreak frequency was investigated using the Multivariate ENSO Index (MEI). The MEI is believed to be a better metric to quantify the strength of ENSO, as it takes into account more meteorological components when compared to the Southern Oscillation Index (SOI) and the Oceanic Niño Index (ONI) (NOAA and Wolter 2015). Results indicated that certain phases of ENSO relate to times of higher tornado and outbreak occurrences on a monthly basis. Our model led us to conclude that tornadoes are more frequent when ENSO is in its cool phase (La Niña), and that the warm phase (El Niño) leads to fewer expected tornadoes on a monthly basis.

This research demonstrated the need for considering tornado outbreak as a separate entity from total tornadoes, as well as the connection between large-scale climate oscillations and localized tornado activity. Seasonal and monthly predictions of future tornado outbreak activity can help citizens prepare for and reduce their susceptibility to tornadic events.

Final remarks

Tornado characteristics vary considerably across the state of Tennessee, which leads to different levels of risk and exposure for certain locations. Tornadoes are one of the most dangerous hazards in Tennessee and cause a immeasurable amount of loss within the state. Ashley (2007) revealed that tornado-related research, as well as public awareness, has significantly decreased the number of tornado related fatalities in the past 50 years. More research on the climatological patterns of tornado activity in Tennessee is needed, but research of this type will assist decision-makers in preparing residents for future tornadic events in Tennessee.

Increasingly more research is focusing on tornado risk and vulnerability with an emphasis on modeling and prediction. Technological advances will continue to have significant implications for the field of tornado research, with the goal of providing quicker and more accurate warnings to the public, and perhaps even seasonal forecast models. Without a doubt research will continue to improve upon tornado prediction, but until the danger of tornadoes and appropriate behavior during tornadic events is communicated to and understood by the public there will continue to be tornado-related injuries and fatalities.

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VITA

Vincent Marshall Brown was born in Maryland on August 17, 1992. He graduated from Urbana High School in 2010. He attended Salisbury University, in Salisbury, Maryland, where he graduated in 2014 *magna cum laude* with a Bachelor of Sciences in Geography, with a focus in Atmospheric Science. He became interested in climatology, severe and hazardous weather, and meteorology while working with Dr. Brent Skeeter and Dr. Darren Parnell.

Vincent entered the graduate program in geography at the University of Tennessee in 2014 to study tornado activity across the state of Tennessee. While at the University of Tennessee, Vincent was both a teaching assistant and research assistant for the Department of Geography. As a teaching assistant, he instructed physical geography laboratory classes for GEOG 131: Weather, Climate, and Climate Change and assisted instruction of GEOG 334: Meteorology. As a research assistant, Vincent was funded by the Institute for a Secure and Sustainable Environment (ISSE) to work on Knoxville microenvironment studies. He also received support through the Science Alliance Fellowship. After completing his M.S. degree, Vincent will continue his research on climatology as he works to earn his Ph.D.