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Tornado Density and Return Periods in the Southeastern United States: Communicating Risk and Vulnerability at the Regional and State Levels

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Tornado Density and Return Periods in the Southeastern United States: Communicating Risk and Vulnerability at the Regional and State Levels

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by
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ABSTRACT

Tornado Density and Return Periods in the Southeastern United States: Communicating Risk and Vulnerability at the Regional and State Levels

by

Michelle Bradburn

Tornado intensity and impacts vary drastically across space, thus spatial and statistical analyses were used to identify patterns of tornado severity in the Southeastern United States and to assess the vulnerability and estimated recurrence of tornadic activity. Records from the Storm Prediction Center's tornado database (1950-2014) were used to estimate kernel density to identify areas of high and low tornado frequency at both the regional- and state-scales. Return periods (2-year, 5-year, 10-year, 25-year, 50-year, and 100-year) were calculated at both scales as well using a composite score that included EF-scale magnitude, injury counts, and fatality counts. Results showed that the highest density of tornadoes occur in Alabama, Mississippi, and Arkansas, while the highest return period intensities occur in Alabama and Mississippi. Scale-dependent analysis revealed finer details of density and intensity for each state. Better communication of high hazard areas and integration into existing mitigation plans is suggested.

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CHAPTER 1

INTRODUCTION

A tornado is “a violently rotating column of air, usually pendant to a cumulonimbus, with circulation reaching the ground,” (NWS 2016). Although tornadoes are primarily associated with the Great Plains region of the United States, tornadoes have been reported in every state (Storm Prediction Center 2016). An average of 800-1400 tornadoes occur per year in the United States, making tornadoes a threat to communities across the nation (Ashley 2007).

Tornadoes typically form as a result of a supercell thunderstorm, a thunderstorm whose defining characteristic is a “deep, persistent, rotating updraft” (Markowski and Richardson 2009). Tornadoes most often occur when cool, dry air from the northwest converges with warm, moist air from the Gulf of Mexico, most frequently over the Great Plains, creating a frontal boundary (Mogil 2007). Tornadoes can also form as a result of hurricanes and tropical storms (Gentry 1983), and through non-supercell thunderstorms. Tornadoes in the southeastern United States mostly occur between late fall and early spring, as the frontal boundary zone shifts seasonally to the south (Mogil 2007).

Developed by Theodore Fujita in 1971, the Fujita (F) Scale was used to classify tornadoes based on wind speed, and gave tornadoes rankings of F0-F5. (Doswell et al. 2009). In 2007, adjustments were made to the scale and the Enhanced Fujita (EF) Scale was released, which re-designated wind speeds to each category and took damage into account, and gave tornadoes rankings of EF0-EF5 (Doswell et al. 2009). Tornadoes are now assigned an EF ranking after a Disaster Assessment Team from the National Weather Service (NWS) surveys the damage path and determines wind speed from observed damage (Doswell et al. 1999). This information is then given to the Storm Prediction Center (SPC) and is compiled in the SPC

Tornado Database along with injury counts, fatality counts, and additional information regarding the specific tornado (Storm Prediction Center 2016).

While a single tornado can be devastating to a community, tornado outbreaks are often responsible for the bulk of tornado injuries and fatalities throughout the United States (Fuhrmann et al. 2014). Tornado outbreaks are defined by Grazulis (1993) as a group of six or more tornadoes spawned by the same general weather system. Though no official definition for ‘tornado outbreak’ has been specified by the SPC or NWS, outbreaks are often the focus of tornado research (Brooks et al. 2003; Verbout et al. 2006; Shafer and Doswell III 2011). One outbreak of particular note is the April 2011 Southeast Outbreak, which occurred from April 25 to April 28. This outbreak impacted Alabama, Arkansas, Georgia, Mississippi, and Tennessee, and generated 351 tornadoes which resulted in 338 fatalities.

In the United States, one area of particularly high tornado density is Tornado Alley. Though its precise location is not agreed upon amongst tornado researchers, the general location of Tornado Alley is across the Central Plains of the United States (Kelly et al. 1978; Coleman and Dixon 2014). While this region receives the highest number of tornadoes per year (Gagan et al. 2010), other alleys exist across the United States (Broyles and Crosbie 2004). One alley in particular, which experienced the second worst tornado outbreak in recorded history in April of 2011 (Fuhrmann et al. 2014), is an alley in the southeastern United States, colloquially called Dixie Alley.

Just as the precise location of Tornado Alley is debated among the tornado research community, so is the precise location of Dixie Alley (Ashley 2007; Gagan et al. 2010). Though Tornado Alley has more tornadoes than Dixie Alley, Dixie Alley has more injuries and fatalities.

For this reason, Dixie Alley warrants further research to better understand tornadoes in the Southeast to improve tornado safety and awareness throughout the region. With the identification of multiple alleys, prominent tornado researchers (Dixon 2016) have suggested that we stop using the term alley since this implies a clear spatial delineation between areas of high and low tornado frequency, and gives a false sense of security to the general public in "low" frequency areas. This study will examine areas of high and low tornado frequency in the Southeast USA, following much of the previous alley research while recognizing that this terminology may be in transition.

For other weather phenomena, such as rainfall, flooding, hurricanes, and wind storms, researchers have used return period calculations to determine the probability per year of an associated event of a specific magnitude (Faiers et al. 1997; Roy et al. 2001). Return periods, or recurrence intervals, are statistical estimates of the likelihood of the occurrence of an event over a given time frame. For example, Needham et al. (2012) calculated return periods for tropical cyclone-induced storm surge along the Gulf Coast using five return period methods (Pareto, Gumbel, and Beta-P distributions, and Huff-Angel and Southern Regional Climate Center (SRCC) regression methods) to determine the magnitude of storm surges in specific clustered locations and investigate how low frequency, but high magnitude, events (e.g., 100-year events) may impact communities. Similar approaches have been used in other areas of research. For example, Keim and Faiers (2000) compared return period methods for heavy rainfall in western Texas using seven return period methods (Gumbel, Log Pearson Type III, Beta-P, Three Parameter Log Normal, and Wakeby distributions, and Huff-Angel and SRCC regression methods).

The aforementioned studies detail return period analysis for climatological phenomena that affect much of the United States. Return period analysis enhances the understanding of these phenomena and can guide mitigation efforts in communities. While a vast amount of information on Southeast tornadoes is available and numerous studies have been conducted (e.g., Brooks, Carbin, & Marsh, 2014; Lu, Tippett, & Lall, 2015; Ray, Bieringer, Niu, & Whissel, 2003), few studies have examined the probability per year of tornadoes with specific intensity ratings. To understand precisely where in the Southeast to target educational tornado safety and awareness efforts, Southeast tornadoes must first be understood in terms of spatial and temporal recurrence, as well as their likely impact on a community.

Weather and climate patterns vary spatially across the United States and this is true of tornadoes. Due to this spatial variation, the scale at which analyses are performed can have a large impact on interpretation of tornado density surfaces and recurrence intervals. Not only is it helpful to predict the magnitudes of potential tornadoes, but it is also important to examine their spatial patterns at various scales. Scale is an important consideration in geographic research and has been examined through a variety of physical geography and climatological research (Meentemeyer 1989; Lam & Quattrochi 1992; Atkinson & Tate 2000; Burkett et al. 2001; Wu 2004; Sayre 2005; Joyner 2013). As Tobler's first law of geography states, "everything is related to everything else, but near things are more related than distant things" (Tobler 1970). Thus tornado intensity and impacts are autocorrelated because of related meteorological, physical, and social conditions (i.e., population density). Tornado impacts include property damage, crop damage, injury counts, and fatality counts, among others. When examining issues of scale related to climatological or meteorological events, finer resolution studies show a great amount of local detail, but coarser resolution studies provide a broad picture of trends and patterns—each of which can be useful.

This thesis is presented in "journal-style" format and contains two individual studies. The objective of Study One was to determine high and low densities of tornado frequency in the southeastern United States and recurrence intervals in clustered areas of the region based on a tornado impacts index, developed in this study. The objective of Study Two was to examine tornado densities and recurrence intervals at local (state-level) scales in the Southeast and to compare results to those of Study One. Specific research questions are as follows:

Study One

1. Where in the Southeast are higher and lower tornado densities and occurrences?
2. Within each cluster, what tornado impacts may be expected over time based on various return periods?

Study Two

1. What patterns in kernel density and return periods are revealed at the state-level within the Southeastern US, and how do states compare to one another?
2. What comparisons can be made between the previous macro-scale study and this meso-scale study and what are the implications of scale variability on the use of return periods for hazard mitigation and additional research purposes?

CHAPTER 2

TORNADO RETURN PERIODS IN THE SOUTHEASTERN UNITED STATES: WE'RE NOT IN KANSAS ANYMORE

Abstract

Tornado intensity and impacts vary considerably across space and this is especially true in the United States. Tornado researchers often study regions of the United States, instead of the entire country, to determine regional specific conclusions. For this study, spatial and statistical analyses were used to identify patterns in tornado severity in the Southeast United States and assess the vulnerability and estimated recurrence of tornadic activity. Return periods (2-, 5-, 10-, 25-, 50-, and 100-year) were calculated for the Southeast based on records from the Storm Prediction Center's tornado database (1950-2014). While the data are available from 1950 to present, data were pre-processed to only include post-1980 data. Criteria for data exclusion included inaccuracy of pre-radar data, availability of accurate Census data, and to account for the Fujita Scale (created in 1971, updated in 2007). Only EF1 and greater intensities were utilized to ensure that microburst and other non-tornadic activity were not included. The Southeast was divided into tornado risk zones using cluster analysis, then SRCC and Huff-Angel return period calculation methods were used to calculate zone-specific return periods. Return periods were calculated using a composite score that included EF-scale magnitude, injury counts, and fatality counts. The composite scores were used to create the Tornado Impact Index (TI^2) scale. The highest Kernel Densities were found in Hulls One, Four, and Five. The highest impact tornadoes on the TI^2 Scale were found in Hulls Four and Five. Results provided more accurate information about the likelihood of tornadoes (and varying intensity, injury, and fatality projections) in locations across the Southeast.

Introduction & Background

Tornadoes occur in every state in the United States, although tornado intensities and impacts vary greatly between each state (Storm Prediction Center 2016). Meteorologists forecast tornadoes by recognizing conditions under which they are likely to form. These forecasts are immensely beneficial to the public and local emergency management agencies and have become more effective and accurate as radar and other technologies have improved (Verbout et al. 2006). Additionally, long-term tornado climatological studies have revealed specific areas of high intensity and/or high frequency tornado events (Brooks et al. 2003; Fuhrmann et al. 2014; Coleman and Dixon 2014). However, few climatological studies have examined tornado recurrence intervals at regional and local scales (Meyer et al. 2002; Widen et al. 2013)

Kernel Density Estimation (KDE) is a method used for determining the density of features in a region around those features, and can be utilized to identify areas of high tornado occurrence (Rosenblatt 1956; Burt et al. 2009). It is commonly used for spatial analysis of tornado risk (Brooks et al. 2003; Fuhrmann et al. 2014; Coleman and Dixon 2014). Coleman and Dixon (2014) used KDE to explore average annual path length of significant tornadoes during the period 1973-2011. Brooks et al. (2003) studied the mean number of tornado days per year for the period 1980-1999 using KDE. Fuhrmann et al. (2014) utilized KDE to determine the average annual path length of tornadoes associated with tornado outbreaks during the period 1973-2010.

While spatial and temporal analysis of tornadoes has proven to be highly informative, the study of climatological phenomena often requires spatial partitioning, or sorting according to where phenomena are located in space. Jain (2009) reports that an essential method for understanding and learning is consolidating data into practical groups, and identifies a particular method useful for cluster analysis: K-means clustering. K-means clustering groups data into clusters as defined by the user, where all items are placed in one group only. Utilized by Needham et al. (2012), K-means clustering was used to assign storm surge into clusters for return period analysis of storm surge heights along the Gulf Coast.

Return periods, or recurrence intervals, are a statistical estimate of the likelihood of occurrence of an event over a given time frame (Keim et al. 2006; Needham et al. 2012). Return period calculations are useful for many aspects of climatology, including temporal analysis of flood events, hurricanes, and stream-flow rates (Faiers et al. 1997; Kiely 1999; Roy et al. 2001; Keim et al. 2006; Modarres 2007; Needham et al. 2012). Most often applied to precipitation data, return period calculations aid a variety of federal, state, and local agencies when determining the return rate and identifying high risk areas (Faiers et al. 1997). Previously, return period calculations were not applied to tornado data, as tornado magnitude (EF0-EF5) is not a unique value and is thus not ideal for return period calculations, which require events to be ranked by severity.

Several return period calculation regression and distribution methods have been used to determine recurrence of weather phenomena. These include the Southern Regional Climate Center (SRCC) return period method, Huff-Angel return period method, Beta-P distribution method, Pareto distribution method, and Gumbel distribution method. All five methods were utilized by Needham et al. (2012) to calculate storm surge return periods for the Gulf Coast. In response to Technical Paper 40 (TP40), produced by David Hershfield (1961) of the United States Department of Agriculture, Faiers et al. (1997) completed return period analysis of heavy rainfall in states in the SRCC region, using the SRCC and Huff-Angel return period methods. NOAA Technical Memorandum HYDRO-35, written by Frederick et al. (1977), used the Gumbel method to explore periods as short as five minutes for precipitation frequency.

These methods have not been previously applied to tornadoes, although there is a need for a deeper understanding of tornado recurrence throughout the United States, as many factors determine the number of fatalities and injuries in a tornado, including risk perception, complacency, or time of day, amongst others (Table 2.1). During 2011 alone, there were 1,700 confirmed tornadoes throughout the United States, making it the second highest ranking tornado year since 1950 (Fuhrmann et al. 2014). There were an estimated 553 tornado-related fatalities, making it the deadliest tornado year since 1936 (Hayes 2012; Fuhrmann et al. 2014). Due to an increase in population density and urban sprawl, it is likely that more people will be exposed to tornado outbreaks in future tornado seasons (Ashley et al. 2008; Fuhrmann et al. 2014).

Table 2.1. Risk factors relating to tornado fatalities and injuries

Factor	Source(s)
Risk Perception	Sims and Baumann 1972; Donner 2007
Misunderstanding of Watch vs. Warning	Donner et al. 2012
Complacency (“It can’t happen here!”)	Biddle 1994; Donner et al. 2012
Cultural Myths	Ashley 2007; Donner et al. 2012
Technology (detection and warning systems; misinterpretation of sirens)	Hammer and Schmidlin 2002; Paul and Stimers 2014
Tornado characteristics (magnitude, intensity, duration, geography)	Hammer and Schmidlin 2002
Time of Day (daytime vs. nocturnal tornadoes)	Ashley 2007; Ashley et al. 2008; Gagan et al. 2010
Believing a warning is a false alarm/ Lack of confidence in warning agency	Breznitz 1984; Peters et al. 1997; Atwood and Major 1998; Dow and Cutter 1998; Donner et al. 2012
Social networks and language barriers	Drabek and Stephenson III 1971; Kirschenbaum 1992; Hammer and Schmidlin 2002; Donner et al. 2012
Personal attributes (perception and preparedness)	Hammer and Schmidlin 2002
Shelter (type or lack of shelter; living in mobile home)	Hammer and Schmidlin 2002; Ashley 2007; Schmidlin et al. 2009
Receiving warnings	Paul and Stimers 2012

Areas of high tornado frequency are colloquially called tornado alleys. Grazulis (1993) indicated that areas that experience higher than average tornado frequency are ultimately branded tornado alleys, and that dozens of these areas are identifiable in the US. Broyles and Crosbie (2004) reported four tornado alley regions in a study that examined long track F3 to F5 tornadoes from 1880-2003.

Traditionally, Tornado Alley roughly overlies parts of the Central Plains of the United States, but there are disputes in the literature about the exact extent of the region. Coleman and Dixon (2014) defined Tornado Alley as an area that extends from Northern Texas to Iowa. Kelly et al. (1978) identified two “axis” areas: one running between 97-98° W, roughly Dallas to eastern Nebraska, and the other from southwest to northeast, extending from Texas, through Missouri, and ending in Indiana.

A second tornado alley exists in the Southeastern United States: Dixie Alley. Though the term has been used in various studies, the origin of the term Dixie Alley is traced back to Allen Pearson, a former National Severe Storms Forecast Center Director, who coined the phrase after the Mississippi Delta tornado outbreak in 1971 (Gagan et al. 2010). Similar to Tornado Alley, there is debate concerning the exact extent of Dixie Alley. Gagan et al. (2010) defined Dixie Alley as an area that includes the entirety of Arkansas, Mississippi, and Alabama, western and central Tennessee, and northern and central Georgia. Ashley (2007) reported that, within the United States, the highest concentration of tornado fatalities and killer tornado events occurs in the Southeastern United States, an area that encompasses northeast Arkansas through southwest Tennessee, northern Mississippi, and northwest Alabama.

Many differences exist between the traditional Tornado Alley and Dixie Alley, including tornado frequency and intensity, temporal variability, and human impact (Gagan et al. 2010) (Table 2.2).

Table 2.2. Alley Comparisons from 1950-2007, Gagan et al., 2010

Factor	**Traditional Tornado Alley**	**Dixie Alley**
Tornado Season	Mid-March-Mid-June	October-February, Mid-March-Mid-June
Number of Tornadoes	13,500	7,500
Number of Strong/Violent tornadoes (EF2+)	2,850	2,450
Afternoon and evening Strong/Violent tornadoes (12 pm-9 pm, CST)	76%	59%
Overnight Strong/Violent tornadoes (9 pm-7 am, CST)	19%	29%
Killer tornadoes	205	371
Fatalities	991	1,705
Injuries	14,709	26,026
Fatality and Injury timing	Mid-March-Mid-June (88% fatalities, 84% injuries)	October-February (64% fatalities, 61% injuries)

Tornadoes in Dixie Alley result in more fatalities and injuries than those in Tornado Alley. Consequently, tornadoes and tornado impacts in the Southeastern United States must be examined on a region-specific scale to identify high risk areas and quantify impact-based recurrence intervals.

To assist with bridging the gap between traditional Tornado Alley and Dixie Alley research, Southeastern tornadoes will be examined to answer the following questions:

1) Where in the Southeast are higher and lower tornado densities and occurrences? and
2) Within each cluster, what tornado impacts may be expected given various return periods?

Data & Methods

Data & Data Partitioning

Tornado data were downloaded from the NOAA/NWS Storm Prediction Center (SPC) SVRGIS database (http://www.spc.noaa.gov/gis/svrgis/), which contains data for United States severe weather, including hail (1955-2014), wind (1955-2014), and tornadoes (1950-2014).

Although the most cited source of tornado data for research (e.g., Brooks 2004; Coleman & Dixon 2014; Dixon, Mercer, Choi, & Allen 2011; Fuhrmann et al. 2014; Sutter & Simmons 2010), the SPC database comes with a plethora of data limitations. Issues include inconsistency in tornado reporting (due to storm spotters, technology enhancements, and increased population density) (Coleman & Dixon 2014), and variability in magnitude (and possible overestimation) as a result of the Fujita to Enhanced Fujita scale transition in 2007 (Fuhrmann et al. 2014; Coleman & Dixon 2014).

The full SPC tornado dataset contains 58,882 individual tornado records for the United States from 1950-2014, broken down by EF-scale (Table 2.3).

Table 2.3. Magnitude breakdown of SPC tornado dataset

EF-Scale	**EF0**	**EF1**	**EF2**	**EF3**	**EF4**	**EF5**	**Unknown**
	27,157	19,802	8,854	2,392	561	59	57
						Total	**58,882**

Records for the states of Alabama, Arkansas, Florida, Georgia, Louisiana, Mississippi, North Carolina, South Carolina, and Tennessee were extracted from the United States dataset for this study. Developed in 1971 by T. Theodore Fujita, the Fujita Scale (or F-scale) was created to assess damage following a tornado event. In 2006, the Enhanced Fujita Scale (or EF-Scale) was developed to account for limitations of the original F-scale (Edwards et al. 2013) and it began operational use in the United States in 2007. Tornadoes pre-1973 were rated using newspaper reports and photographs, making older data less accurate than more recent data. In the late 1970's local NWS offices began to assume assignment of F-scale ratings in their areas (Edwards et al. 2013). In addition, adequate population density data became available via the United States Census Bureau in 1980, allowing for better population density estimation around tornado tracks (Fuhrmann et al. 2014; personal communication with Dr. Charles Konrad). As a result, only post-1980 data were utilized for this study. Additionally, only tornadoes with magnitudes of EF1 and greater were extracted for use. By 1980, tornado reporting of F-1 tornadoes had improved, which resulted in better records for weaker tornadoes within the database (Fuhrmann et al. 2014; personal communication with Dr. Charles Konrad). Tornadoes with an unknown EF-rating were discarded, and tornadoes rated as EF0 were excluded since some high wind or downburst/microburst events may have been misidentified as EF0 tornadoes (Forbes and Wakimoto 1983). The final Southeast US tornado database contained 5,610 tornadoes, and the breakdown by EF-scale is shown in Table 2.4.

Table 2.4. Tornado breakdown by state according to the SPC tornado database

State	Number of Tornadoes	Percentage of Tornadoes
Alabama	838	14.94%
Arkansas	725	12.92%
Florida	583	10.39%
Georgia	554	9.88%
Louisiana	772	13.76%
Mississippi	854	15.22%
North Carolina	425	7.58%
South Carolina	340	6.06%
Tennessee	519	9.25%
Totals	**5,610**	**100%**

Kernel Density Estimation

Kernel Density Estimation (KDE) is an interpolation method that creates a density surface derived by calculating the distance between each point and a reference point (Rosenblatt 1956; Burt et al. 2009). Since point data are required to develop a KDE surface, centroids were calculated for each tornado track using ArcGIS. A normal kernel with fixed interval bandwidth was selected within CrimeStat, a spatial statistics program (Levine 2015). Using the appropriate kernel bandwidth is essential to creating a statistically accurate KDE surface. Bandwidth is defined as the width of the kernel, or the interval size (Levine 2015). Bandwidth calculation is necessary because it helps determine the width of the kernel that results in the smoothest density surface (Fotheringham, Brunsdon, & Charlton 2000). Bandwidth interval was calculated following the method of Fotheringham, Brunsdon, and Charlton (2000):

$$h_{opt} = (2/(3n))^{1/4}\sigma$$

where h_{opt} is optimal bandwidth, n is the sample size (n=5684 southeastern tornado centroids), and σ is the standard distance deviation for each category (calculated via the Mean Center and Standard Distance function in CrimeStat). The interval and area were calculated as miles and outputs were reported in absolute densities.

K-means Clustering

Data extracted for the study were imported into ArcMap and a shapefile was created. To perform return period analysis, regional clusters were identified to delineate areas of statistically significant tornado frequency variance. CrimeStat was utilized to calculate K-means clusters of the data (Jain 2009). Two different K-means clustering outputs were developed resulting in surfaces with five clusters and ten clusters, respectively. Cluster surfaces were compared to previously-developed KDE surfaces to determine the appropriate number of clusters, since a user cannot arbitrarily define a number of clusters and acheive meaningful results (Levine 2015). Consequently, a user will not necessarily find the correct clusters using K-means alone. When comparing the five-cluster output to the ten-cluster output, the ten-cluster output best fit the KDE surface, and was ultimately chosen as the cluster group for analyses. For this study, clusters were conveyed as convex hulls and used for the analysis.

The convex hulls were mapped and numbered. Tornadoes were assigned to a hull by their location within a hull. In most cases, it is impossible to identify the location along a tornado track where the highest magnitude, number of injuries, and number of fatalities occurred, thus tornadoes were included in more than one hull if they intersected two or more hulls.

Time Series Analysis and the Tornado Impacts Index (TI^2)

Time series were created for each hull. Given the 34-year study period, the top 34 highest impact tornadoes were chosen from each hull to calculate return periods. Return period analysis could not be calculated on magnitude alone because tornado magnitude is numbered 0-5 (and not on actual wind speed). Instead, composite values were calculated for each tornado using three variables: magnitude, number of injuries, and number of fatalities reported by the SPC. A composite score was calculated for each tornado by normalizing the value of each variable by the highest value of that variable across the Southeast, and then summing the three variables to create a composite score for each tornado. These composite scores became the Tornado Impact Index (TI^2), and were used to rank the top 34 tornadoes for each hull. If a single tornado ranked highest among each of the three variables (magnitude, injury count, and fatality count), that tornado would have had a calculated TI^2 of 3.000. No single tornado in this dataset ranked highest for each variable, and the highest TI^2 was 2.689. Tornadoes in each hull were sorted by TI^2 score.

The Weibull plotting position formula was applied to derive the annual exceedance probability for each storm in each hull (Needham et al. 2012). An exceedance probability was then calculated for each hull using the following formula:

Exceedance Probability = [Rank/(N+1)]

Where Rank is rank within 34 years (1-34), and N=34. The non-exceedance probability was then calculated using the following formula:

Non-Exceedance Probability = [1-Exceedance Probability]

Return periods were calculated using the following formula:

Return Period = [1/Exceedance Probability]

Following Faiers et al. (1997) and Huff and Angel (1992), quantile estimates were calculated using two regression models: SRCC (log-linear) and Huff-Angel (log-log).

Kolmogorov-Smirnov Statistic

The Kolmogorov-Smirnov (KS) statistic is used to determine whether two samples have the same distribution (Massey 1951). The KS statistic was used to compare expected events to actual events produced by each quantile estimate (2-, 5-, 10-, 25-, 50-, and 100-year return periods). This method was chosen following methodologies outlined by Needham et al. (2012) and Keim and Faiers (2000). KS statistics were calculated using Statistix statistical software (Statistix 2015).

Results

The highest tornado densities were found in Hulls One, Four and Five, and the lowest densities were seen in Hulls Seven, Eight, Nine, and Ten. Figure 2.1 shows the resulting KDE surface for tornadoes in the Southeast along with convex hull locations.

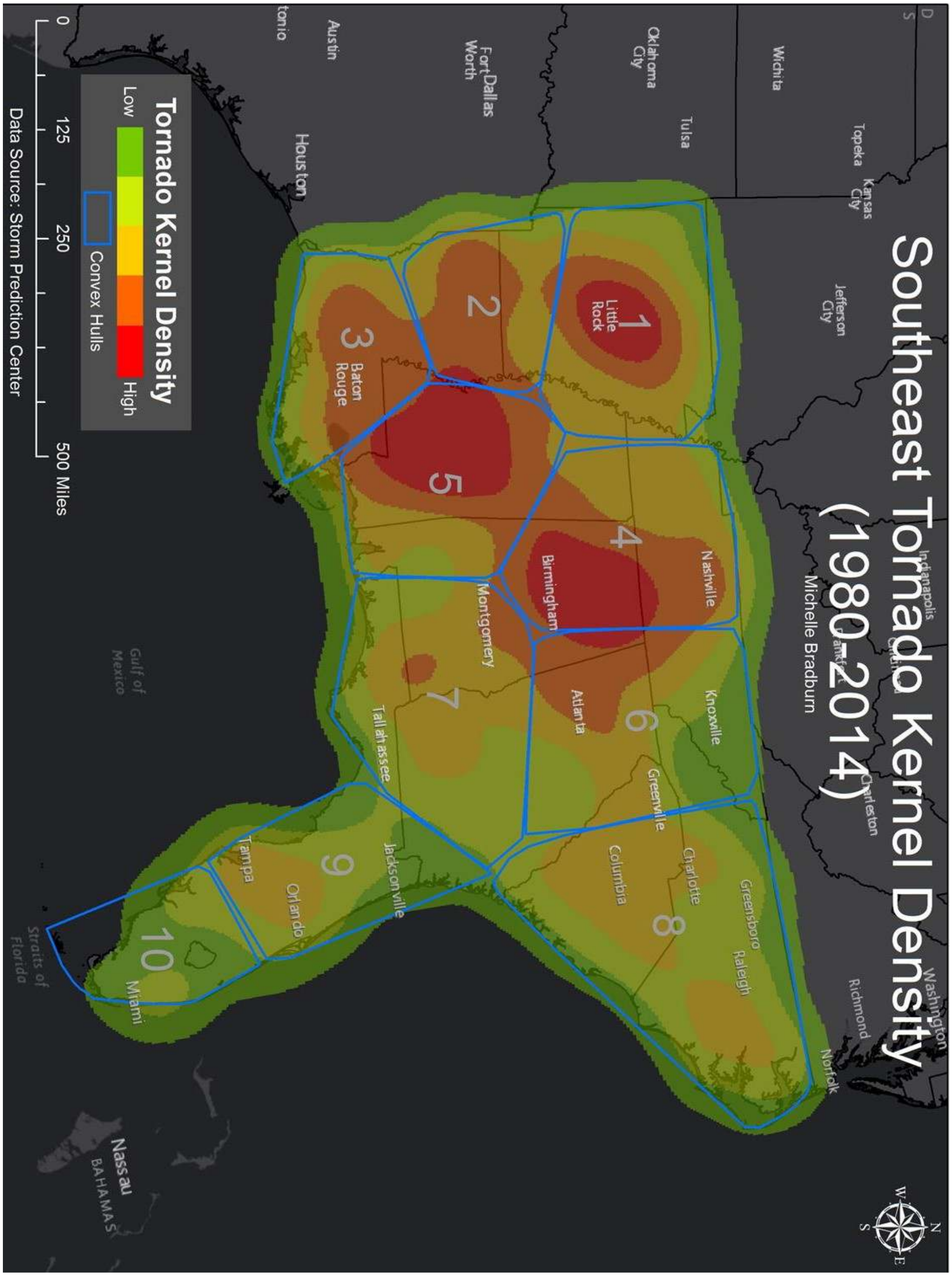

Figure 2.1. Tornado KDE in the Southeast, 1980-2014

Over the 34 years of the study, a total of 5,684 tornadoes occurred at all magnitudes and with injury and fatality counts ranging from 0-1500 injuries and 0-72 fatalities respectively in all Southeastern states (Table 2.5). Hull Four had the most injuries (n=5,797), fatalities (n=535), EF2s (n=218), EF3s (n=93), EF4s (n=22), EF5s (n=5), and total tornadoes (n=875). Hull Five had the most EF1s (n=561), and the EF1 magnitude was the most common magnitude (n=3,886). The majority of Southeast tornadoes during this time period were magnitude EF1.

Hull Ten had the fewest injuries (n=326), fatalities (n=8), EF1s (n=130), EF2s (n=23), EF3s (n=2), EF4s (n=0), and total tornadoes (n=155). Only Hulls Four, Five, and Six had EF5s, and the EF5 magnitude was the least common magnitude (n=7).

Table 2.5. Injury counts, fatality counts, magnitude, and total tornadoes by hull

Hull	**Injuries**	**Fatalities**	**EF1**	**EF2**	**EF3**	**EF4**	**EF5**	**Total Tornadoes**
1	2,385 (11.0%)	153 (10.3%)	433 (11.14%)	187 (14.5%)	61 (14.8%)	16 (17.9%)	0 (0.0%)	697 (12.3%)
2	834 (3.8%)	47 (3.15%)	294 (7.6%)	95 (7.4%)	42 (10.2%)	8 (9.0%)	0 (0.0%)	439 (7.7%)
3	605 (2.8%)	23 (1.5%)	363 (9.3%)	81 (6.3%)	15 (3.7%)	1 (1.1%)	0 (0.0%)	460 (8.1%)
4	5,797 (26.7%)	535 (35.8%)	537 (13.8%)	218 (16.9%)	93 (22.6%)	22 (24.7%)	5 (71.4%)	875 (15.4%)
5	3,664 (16.9%)	183 (12.3%)	561 (14.4%)	184 (14.3%)	69 (16.8%)	13 (14.6%)	1 (14.3%)	828 (14.6%)
6	2,525 (11.6%)	212 (14.2%)	371 (9.6%)	139 (10.8%)	56 (13.6%)	12 (13.5%)	1 (14.3%)	579 (10.2%)
7	1,512 (7.0%)	110 (7.4%)	458 (11.8%)	117 (9.1%)	22 (5.4%)	3 (3.4%)	0 (0.0%)	600 (10.6%)
8	3,211 (14.8%)	139 (9.3%)	498 (12.8%)	191 (14.8%)	41 (10.0%)	13 (14.6%)	0 (0.0%)	743 (13.1%)
9	836 (3.9%)	83 (5.6%)	241 (6.2%)	56 (4.3%)	10 (2.4%)	1 (1.1%)	0 (0.0%)	308 (5.4%)
10	326 (1.5%)	8 (0.5%)	130 (3.4%)	23 (1.8%)	2 (0.5%)	0 (0.0%)	0 (0.0%)	155 (2.7%)
Total	**21,695***	**1,493***	**3,886***	**1,291***	**411***	**89***	**7***	**5,684***

*Hull totals exceeded overall totals because some tornadoes intersected multiple hulls and were thus counted more than once

The highest TI^2 values were found in Hulls Four and Five. The maximum possible TI^2 value of 3.000 was not observed since a single tornado did not have the highest value in all three rating categories. Both of the highest TI^2 values in Hulls Four and Five were 2.689 and were a result of an EF4 tornado on April 27, 2011. It occurred during a major tornado outbreak in the Southeast that spanned April 25 to April 28, and caused 1500 injuries and 64 fatalities.

The lowest TI^2 values were found in Hull Ten. The highest TI^2 of a single tornado in Hull Ten was 0.658 and was a result of an EF3 tornado on March 17,1985. It caused 45 injuries and 2 fatalities.

The Huff-Angel method predicted that more intense storms would occur at the 50- and 100-year return periods when compared to the results of the SRCC method for all hulls. TI^2 values for each of the ten hulls are presented in Table 2.6.

Table 2.6. TI^2 values for each hull and return period

	100-year storm		50-year storm		25-year storm		10-year storm		5-year storm		2-year storm	
Hull	***SRCC***	***Huff-Angel***	***SRCC***	***Huff-Angel***	***SRCC***	***Huff-Angel***	***SRCC***	***Huff-Angel***	***SRCC***	***Huff-Angel***	***SRCC***	***Huff-Angel***
1	1.367	1.570	1.254	1.368	1.141	1.192	0.991	0.993	0.878	0.865	0.728	0.721
2	1.061	1.227	0.979	1.077	0.897	0.946	0.789	0.796	0.707	0.699	0.599	0.588
3	0.963	1.219	0.876	1.024	0.789	0.861	0.674	0.684	0.587	0.575	0.472	0.457
4	2.652	2.965	2.391	2.514	2.130	2.132	1.785	1.714	1.524	1.453	1.179	1.169
5	2.161	2.535	1.907	2.027	1.653	1.620	1.318	1.205	1.064	0.963	0.729	0.717
6	1.638	2.000	1.476	1.667	1.315	1.389	1.101	1.091	0.939	0.910	0.726	0.715
7	1.177	1.422	1.071	1.209	0.965	1.028	0.825	0.830	0.719	0.706	0.579	0.569
8	1.370	1.585	1.254	1.374	1.138	1.191	0.985	0.986	0.869	0.855	0.716	0.708
9	1.205	1.563	1.075	1.257	0.944	1.011	0.772	0.759	0.642	0.610	0.469	0.458
10	0.763	1.035	0.688	0.843	0.613	0.686	0.514	0.522	0.439	0.425	0.340	0.324

Discussion

These results confirm previous research (Ashley 2007; Gagan et al. 2010), which identified high densities and occurrences of tornadoes throughout regions of the Southeast. The highest densities were found in Hulls One, Two, Three, Four, Five, and Six (covering all of Arkansas, Louisiana, Mississippi, most of Tennessee, and large regions of Georgia and Alabama). Based on the SPC tornado database, it was expected that Hulls One, Four, and Five would have the highest tornado densities and the KDE surface confirmed th.

The lowest tornado densities were found in Hulls Nine and Ten (308 tornadoes and 155 tornadoes; covering the majority of Florida and a small portion of Georgia). Both hulls were primarily located in Florida, where weaker tornadoes associated with convective thunderstorms and, occasionally, hurricanes and tropical storms, are more common than stronger tornadoes found in other regions (Mogil, 2007).

This study provided a regional-level analysis of tornadoes in the Southeast USA. Throughout the Southeast there are vast differences from hull to hull, due to the varying meteorological conditions that spawn tornadoes throughout the Southeast.

Tornado Impact Index (TI^2)

It is important to note that no weighting was applied to the factors which comprised the TI^2 values. Each factor was considered equally important for tornado impact. Each tornado occurred in a different location with disparate population densities, at different times of day, and in areas of varied levels of tornado preparedness and education, all of which potentially led to vastly different outcomes. For example, the time of day during which a tornado occurs can be a determining factor for injury and fatality counts, as nocturnal tornadoes are 2.5 times more likely to cause fatalities than daytime tornadoes (Ashley et al. 2008). Tornado preparedness is also important for surviving a tornado, as those who are ill prepared or are unaware of their tornado risk are less likely to respond to a tornado warning (Donner et al. 2012).

Two tornadoes with identical TI^2 values may be comprised of different variable values. For example, in TI^2 Hull Five two tornadoes had a TI^2 value of 0.617. One was an EF3 (value of 0.600) that occurred in April of 1980, and resulted in 25 injuries (value of 0.017), and no fatalities (value of 0.000). Another tornado in the same hull was also an EF3 (value of 0.600) that occurred in April of 2011, and resulted in 4 injuries (value of 0.003), and 1 fatality (value of 0.014). TI^2 values will change over time, as more tornadoes occur and data become available, but current values provide a snapshot of tornado impact within the 1980-2014 time period.

The TI^2 system provides a first-of-its-kind ranking metric for tornado impact. The Kolmogorov-Smirnov (KS) statistic revealed that the SRCC and Huff-Angel methods are a best fit for the data in different hulls. With a lower KS statistic in hulls One, Four, Nine, and Ten, the SRCC method provided a best fit for the data in those areas. With a lower KS statistic in hulls Three, Five, Six, and Seven, the Huff-Angel method provided the best fit for data in those areas. Hulls Two and Eight had the same KS statistics for both methods. Results for the best return period for the Southeast dataset were inconclusive, due to the even split of KS statistics between each method.

Return Periods

For the return period calculations, tornado track data were used in lieu of tornado centroids. Though centroids were used to calculate the convex hulls, tracks were chosen for return period calculations for several reasons. Tornadoes are not point events, but track or line events. They cause damage, injuries, and fatalities along a line, and not in one isolated location, thus they may impact multiple hull-defined areas instead of only the hull where the centroid was located. Considering some of the SPC database limitations, determining which convex hull had more injuries and fatalities and the location of greatest magnitude along a tornado track would not have been possible for many events. Tornado magnitude varies along the path of a tornado, but a tornado is assigned the magnitude of the worst damaged area of the path by the NWS. For the purposes of this study, magnitude was treated as a constant, as it is the official designated intensity rating of the NWS and is most easily attained.

Tornado return period calculations are useful for the Southeast USA, as the region faces many risk factors for tornado fatalities and injuries. The cultural myth that tornadoes do not occur in the Southeast is one that many emergency managers and personnel face when advising the public to comply with tornado warnings (Donner et al. 2012). The Southeast has more nocturnal tornadoes, which yield more fatalities than daytime tornadoes (Ashley et al. 2008), and a higher mobile home density, structures which are unable to withstand even weak tornadoes (Sutter and Simmons 2010). With these risk factors in mind, and tornado return periods to help reinforce understanding of tornado occurrence throughout the Southeast, state and federal emergency managers can use this research as a driving force for public education and tornado awareness. Return periods can also be used for climatological studies, such as the VORTEX (Verification of the Origins of Rotation in Tornadoes Experiment) Southeast research program. It began in 2015 with the goal of understanding tornadoes in the Southeast (National Severe Storms Lab 2016), and could benefit from return period analysis for the Southeast, because return period analysis has identified high impact risk zones.

Future Research

Though this research provided information about the Southeast region, it may have smoothed out important, state-specific details. Study Two will include a state-level analysis to determine return periods for the nine Southeast states.

Summary

Regional clusters and KDE surfaces were created and mapped, resulting in ten statistically unique regions for the Southeast. Southeast-specific tornado information was also extracted, enumerating magnitudes, injuries, fatalities, and total tornadoes per hull. For each hull within the Southeast, return periods were calculated using the SRCC and Huff-Angel return period methods. The resulting quantile estimates were examined using a KS statistic to determine which method was the best fit for the data in each hull. Neither method proved to be the best fit for every hull in each of the regions, but the Huff-Angel yielded higher TI^2 scores at the 50- and 100-year return period. The highest TI^2 scores were found in Hulls Four and Five, along with high tornado density in Hulls One, Four, and Five. Previous KDE research resulted in similar KDE surfaces for the Southeast. This research provides a comprehensive picture of tornado densities and return periods for the Southeast USA. It can help determine high risk areas for high impact tornado-producing storms throughout the region and provide the necessary information to emergency mangers to drive their public education efforts. These return periods will be shared with the NWS, SPC, and SRCC.

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CHAPTER 3

TORNADO DENSITIES AND RETURN PERIODS AT THE STATE-LEVEL: EXPLORING ISSUES OF SCALE-DEPENDENCY

Abstract

Scale plays a critical role in the analysis and interpretation of the impacts of various climatological events and it is important to examine issues of scale when calculating tornado densities and return periods. Spatial and statistical analyses were used to identify tornado patterns within nine Southeastern states (Alabama, Arkansas, Florida, Georgia, Louisiana, Mississippi, North Carolina, South Carolina, and Tennessee) to evaluate vulnerability and estimated recurrence of tornadic activity. Return periods (2-, 5-, 10-, 25-, 50-, and 100-year) were calculated for each state using records from the Storm Prediction Center's tornado database (1950-2014). Risk zones were identified for each state using cluster analysis, and two return period calculation methods (SRCC, Huff-Angel) were examined using a Tornado Impact Index, calculated from magnitude, injury counts, and fatality counts. Results were compared to regional-level analyses and provided finer resolution information about tornado likelihood in each state (including varying intensities, injury, and fatality projections).

Introduction & Background

Climate and weather patterns vary considerably both spatially and temporally, and this is especially true across the United States (Ashley 2007; Gagan et al. 2010; Dixon et al. 2011; Needham et al. 2012). When considering the impact of tornadoes, one often thinks of the traditional Tornado Alley in the Central Plains of the United States. Sometimes overlooked, an additional “alley” exists in the Southeastern United States, colloquially termed “Dixie Alley” (Gagan et al. 2010). The exact location and even the existence of Dixie Alley is debated (Ashley 2007; Gagan et al. 2010). Nevertheless, Ashley (2007) reported that within the United States, the highest concentration of tornado fatalities and killer tornado events occurs in the Southeastern United States, in an area that encompasses northeast Arkansas through southwest Tennessee, northern Mississippi, and northwest Alabama. Although this area is reported as having a high concentration of fatalities and killer tornado events, the impacts of these events vary from state to state.

The Southeastern United States has been impacted by many tornado outbreaks, specifically the Super Outbreak of April 3-4, 1974; the Carolinas Outbreak of March 28, 1984; the Palm Sunday Outbreak of March 27, 1994; the Enterprise, Alabama, Tornado of March 1, 2007; and most recently, the April 25-28, 2011 Outbreak (Fuhrmann et al. 2014). Furhmann et al. (2014) reported that the mean frequency of strong tornado outbreak events is from early March to mid-May. Brooks et al. (2003) reported that local daily tornado probability differed by region, with much of the Southeast experiencing the highest probabilities in early and late April and early May, with small regions experiencing highest probabilities during November and June. Most historically significant tornado outbreaks in the Southeast have occurred in March and April (Table 3.1).

Table 3.1. Historically significant outbreaks in the Southeast (Fuhrmann et al. 2014)

Event Name	Dates Occurred	Number of Tornadoes	Number of Fatalities	Number of Injuries	Areas Impacted
Super Outbreak	April 3-4, 1974	148	330	5,484	13 states from AL to MI
Carolinas Outbreak	March 28, 1984	22	57	1,250	NC and SC
Palm Sunday Outbreak	March 27, 1994	27	42	491	AL, GA, NC, SC
Enterprise, AL Tornado	March 1, 2007	8	50	1	Enterprise, AL
Dixie Outbreak	April 25-28, 2011	351	338	unknown	AL, AR, GA, MS, TN

In April 2011, the Southeastern United States was devastated by a tornado outbreak second only to the Super Outbreak of 1974 (Fuhrmann et al. 2014). During a four-day span from April 25 to April 28, 351 tornadoes occurred, killing 338 people in Alabama, Arkansas, Georgia, Mississippi, and Tennessee (Casey-Lockyer et al. 2012).

An estimated 5,610 tornadoes occurred in the Southeastern United States during the period 1980-2014. As a result of these tornadoes, more than 21,000 injuries and 1,500 fatalities occurred (Storm Prediction Center 2016). Gagan et al. (2010) concluded that, though the traditional Central Plains Tornado Alley had more tornadoes (over 13,500) than Dixie Alley (7,500), a higher number of fatalities were reported in Dixie Alley (1,705 fatalities and 26,026 injuries) than in Tornado Alley (991 fatalities and 14,709 injuries) during the period 1950-2007.

A higher incidence of injuries and fatalities is due to a variety of risk factors faced by populations in the Southeast, including a higher frequency of killer tornadoes, nocturnal tornadoes, higher population density, misunderstanding of differences between tornado watches and warnings, higher rate of individuals living in mobile homes, and cultural myths surrounding presence of tornadoes in particular regions (Hammer and Schmidlin 2002; Ashley 2007; Ashley et al. 2008; Schmidlin et al. 2009; Gagan et al. 2010; Donner et al. 2012).

Dixie Alley warrants additional research to combat the high incidence of injuries and fatalities in the region. In Study One, tornado return periods were calculated for 10 regions (identified via statistical cluster detection) throughout the Southeast. Return periods were calculated for each regional cluster to determine areas of high and low return periods. This resulted in development of the Tornado Impact Index, or TI^2, an index that enumerates the impact of a tornado, taking magnitude, injury counts, and fatality counts into consideration. The results allowed recommendations to be suggested, such as inclusion of tornado return periods in state and local hazard mitigation plans, targeted public education in high risk zones, and increased tornado awareness efforts. Under the Stafford Act, disaster declarations are approved by the President following a request by the Governor of the affected state (Federal Emergency Management Agency 2013). Following a disaster declaration, states with hazard mitigation plans in place can apply for federal assistance (Stafford 2013). Information such as tornado return periods, at the state level, would be useful in a hazard mitigation plan—especially a local hazard mitigation plan (e.g. county-level). For this reason, an additional state-based study is needed.

The calculation of return periods at the state level will aid in understanding how differences in scale, between the Southeast region and individual states, manifest themselves spatially. Scale is an important factor in the study of various climatic phenomena (Murata 1992; Atkinson and Tate 2000; Burkett et al. 2001; Wu 2004; Sayre 2005; Joyner and Rohli 2010). Tobler's first law of geography states that "everything is related to everything else, but near things are more related than distant things" (Tobler 1970). Using Tobler's First Law as a guiding principle, this study was conducted on nine individual states loosely defined as the Southeastern United States and compared to results from the regional analysis developed in Study One. Study Two examines small cluster-detected regions within each state, state-specific tornadoes, and existing spatial patterns based on empirical data. Scale is defined as the ratio between the size of mapped objects and their actual size. Small scale analysis is performed on a larger geographic area (e.g. Study One Hulls were regionally based), while large scale analysis is performed on a smaller geographic area (e.g. Study Two Hulls are state based). Atkinson and Tate (2000) state that several scale-dependent issues are difficult to identify, including spatial variation, error, and patterns of spatial dependence. The small-scale analysis performed in Study One identified general trends throughout the Southeastern region, but may have smoothed out local trends.

The research questions for this study are as follows:

1. What patterns in kernel density and TI^2 return period scores are revealed at the state-level scale within the Southeastern United States compared to the regional-level analysis in Study One?
2. How do state-level patterns differ from the previous macro-scale studies and what are the implications of scale variability on the use of return periods for hazard mitigation?

Data & Methods

Data & Data Partitioning

Following methods developed in Study One, data were downloaded from the Storm Prediction Center (SPC) SVRGIS (http://www.spc.noaa.gov/gis/svrgis/). The full database contains records of 58,882 tornadoes (1950-2014), but for this study, data were extracted for the states of Alabama, Arkansas, Florida, Georgia, Louisiana, Mississippi, North Carolina, South Carolina, and Tennessee. Data were partitioned to include only data from 1980-2014 of magnitude EF1 or greater. Once the correct time period and magnitude range were extracted, data were partitioned by state. Separate shapefiles were created for each state for analysis.

Kernel Density Estimation and K-means Cluster

KDE is an interpolation method that creates a density surface derived by calculating the distance between each point and a reference point (Rosenblatt 1956; Burt et al. 2009). Point data were utilized from each state to develop state-specific KDE surfaces following the bandwidth and calculation methodologies of Study One.

To perform return period analysis on the data by state, the states were subdivided into regional clusters following the K-means clustering methodology of Study One. These clusters were used to delineate areas of statistically significant tornado frequency variance. Maps were created for each state which contained five convex hulls with tornado tracks, and each hull was assigned a number. In most cases, identifying the location along a tornado track where the highest magnitude, number of injuries, and number of fatalities occurred was impossible, thus tornadoes were included in multiple hulls if they transected two or more hulls (Konrad et al. 2014).

Time Series Analysis and the Tornado Impact Index

Time series were created for each hull in each state. With 34 years of data, the top 34 highest impact tornadoes were chosen from each hull to calculate return periods. Applying the methodology from Study One, at the state level, magnitudes, injuries, and fatalities were scaled and summed to form a composite score. These composite values became the Tornado Impact Index, or TI^2, and the resulting TI^2 scores were used to rank the top 34 tornadoes for each hull by state.

Each factor in the TI^2 score had an individual score from 0-1, thus the highest possible TI^2 score was 3.000. For a tornado to receive a TI^2 score of 3.000, it would need to have the highest magnitude, injury count, and fatality count for its state.

The Weibull plotting position formula was applied to derive the annual exceedance probability for each storm in each hull (Faiers et al. 1997). Return periods were calculated using the formula [1/Exceedance Probability]. Following Needham et al. (2012) quantile estimates were calculated using two regression models: SRCC (log-linear) and Huff-Angel (log-log). The Kolmogorov-Smirnov Statistic (KS statistic) was used to compare expected events to actual events produced by each quantile estimate (2-, 5-, 10-, 25-, 50-, and 100-year return periods). KS statistics were calculated for each hull in each state using Statistix software (Statistix 2015).

Data Analysis & Comparison

KDE and return period calculations from TI^2 scores were derived using the highest factor values from the Southeast. Data were partitioned by state, but using the highest Southeast factor values, state-specific return period values were able to be compared to the Southeast return period values. However, KDE analysis was not comparable between Study One and Study Two, because regional data were utilized for Study One and state-level data were utilized for each state in Study Two.

Results

KDE and return period analysis were completed for each of the nine states. KDE maps are presented in Figures 3.1-3.9 and return periods are presented in tables 3.2-3.3.

KDE revealed areas of high tornado kernel density within each state. The highest kernel density for the state of Alabama was found in Hulls One and Two. For Arkansas, the highest kernel density was within Hull Three. Florida had two areas of high kernel density, a small area in Hull One and a larger area spanning Hulls Three and Four. High kernel density was found in Georgia Hulls One and Two. The state of Louisiana had two areas of high kernel density in Hulls One and Three. Mississippi had a large area of high kernel density spanning Hulls Three, Four, and Five. North Carolina also two areas of high kernel density in Hulls One, Three, and Four. South Carolina had three areas of high kernel density in Hull One, Hull Three, and the largest area spanned Hulls Two, Three, and Four. Tennessee had one area of high kernel density spanning Hulls Two and Three.

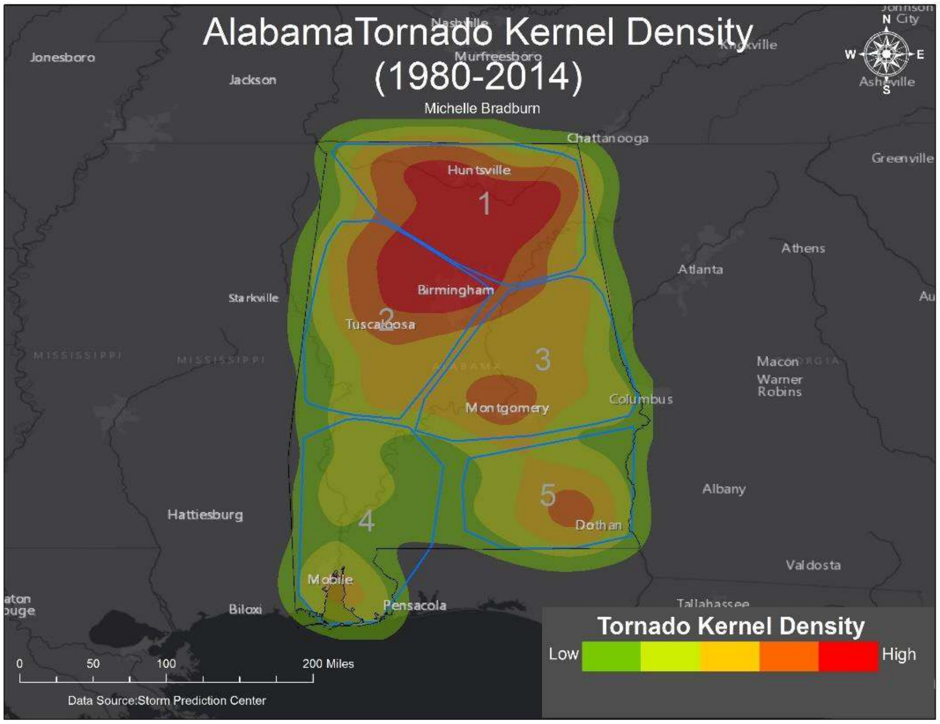

Figure 3.1. Alabama Kernel Density and Convex Hull Locations

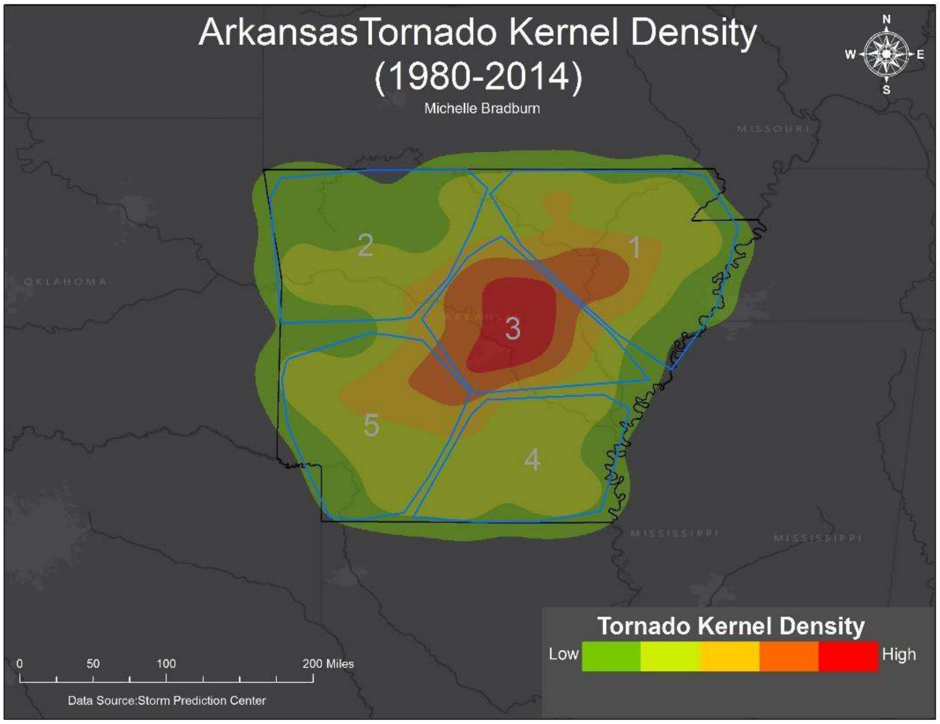

Figure 3.2. Arkansas Kernel Density and Convex Hull Locations

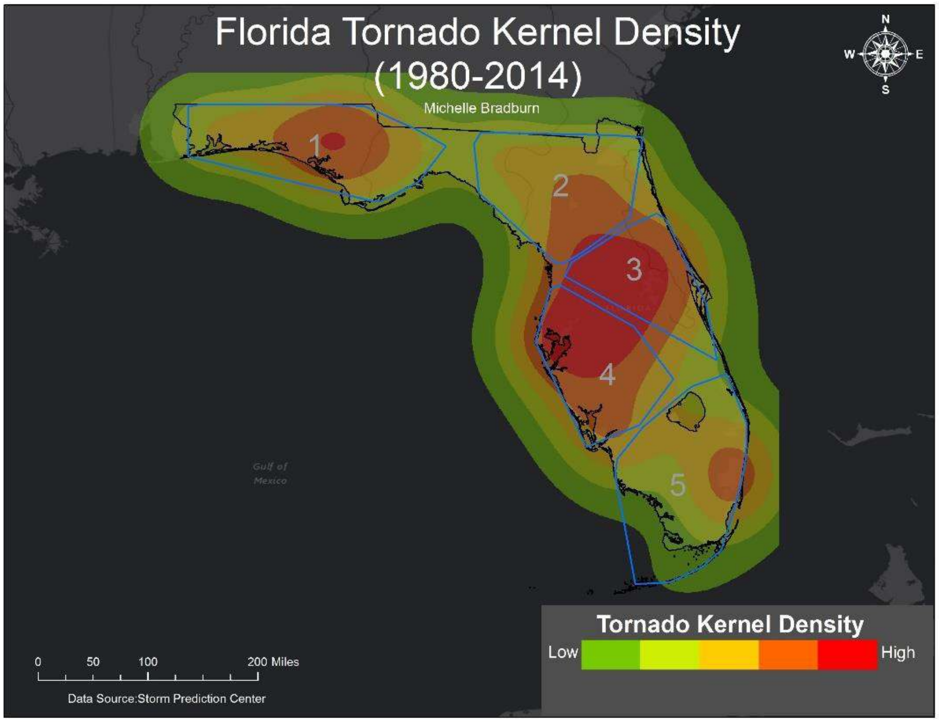

Figure 3.3. Florida Kernel Density and Convex Hull Locations

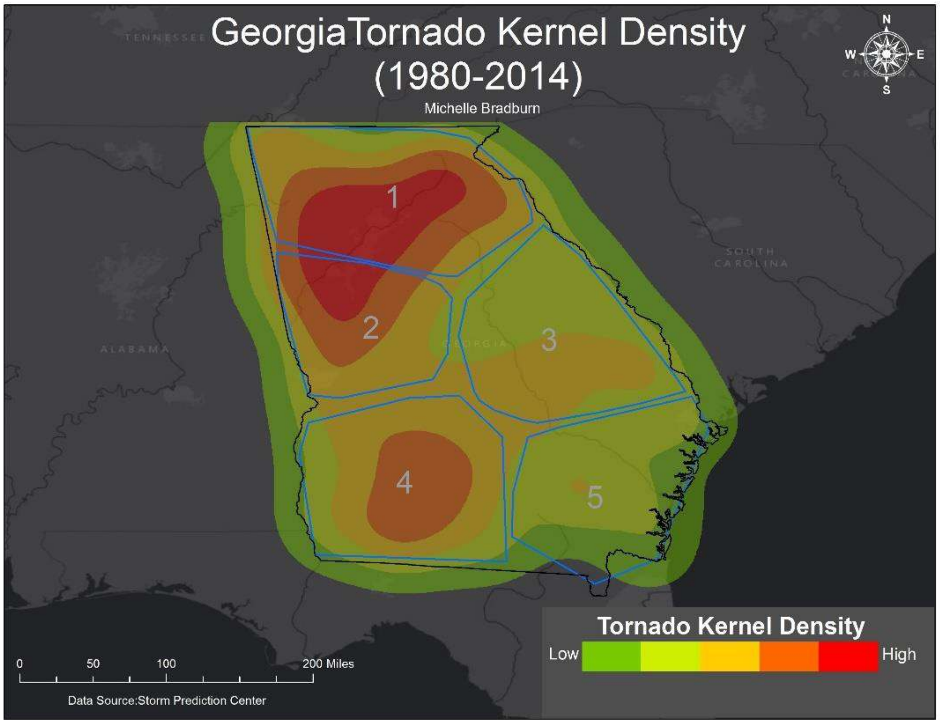

Figure 3.4. Georgia Kernel Density and Convex Hull Locations

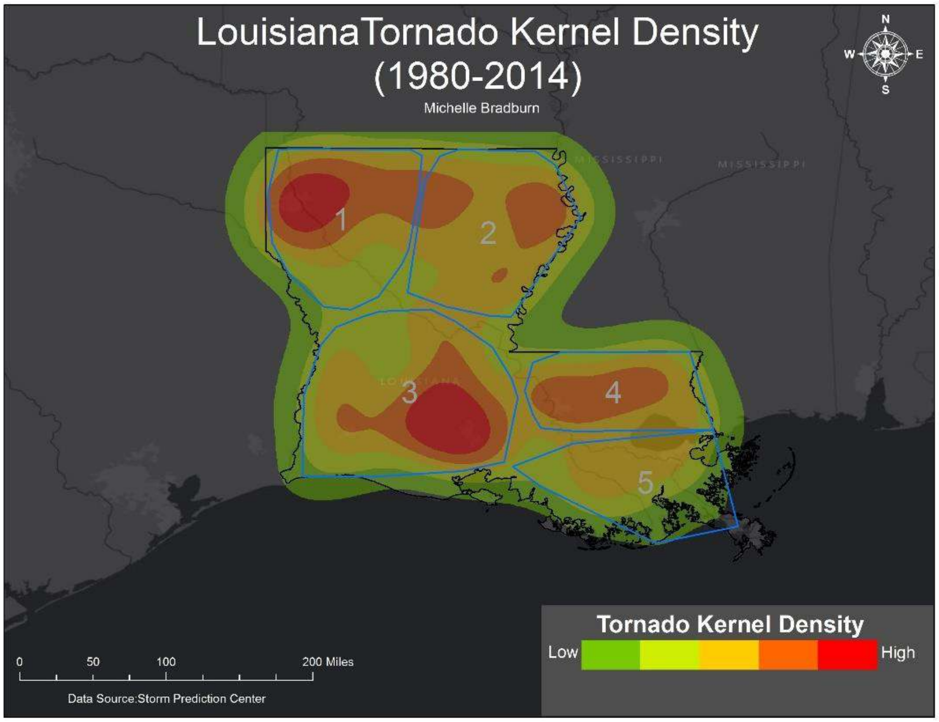

Figure 3.5. Louisiana Kernel Density and Convex Hull Locations

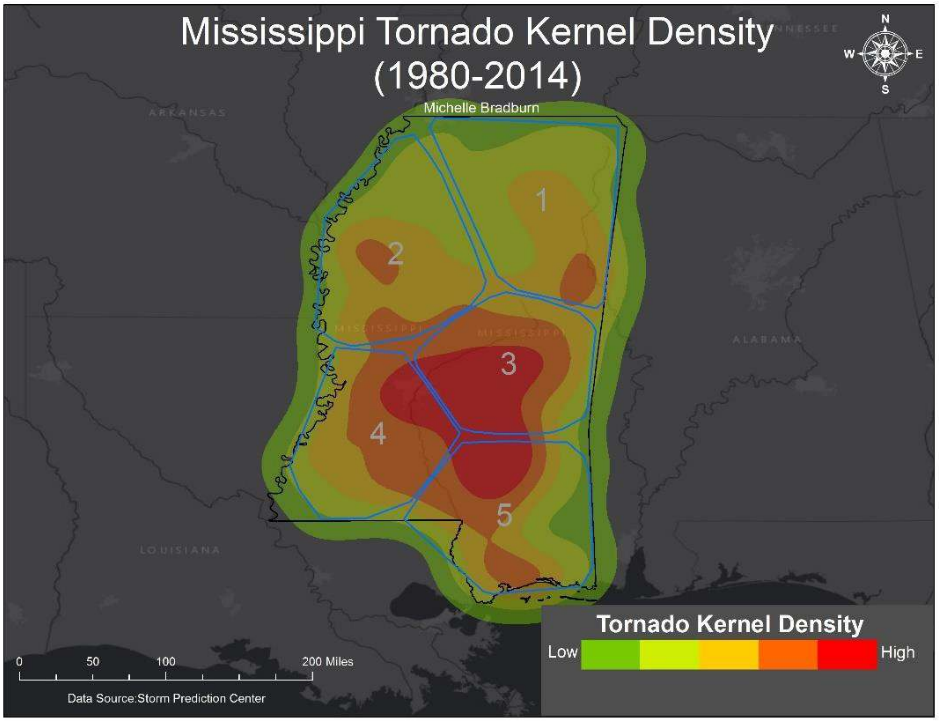

Figure 3.6. Mississippi Kernel Density and Convex Hull Locations

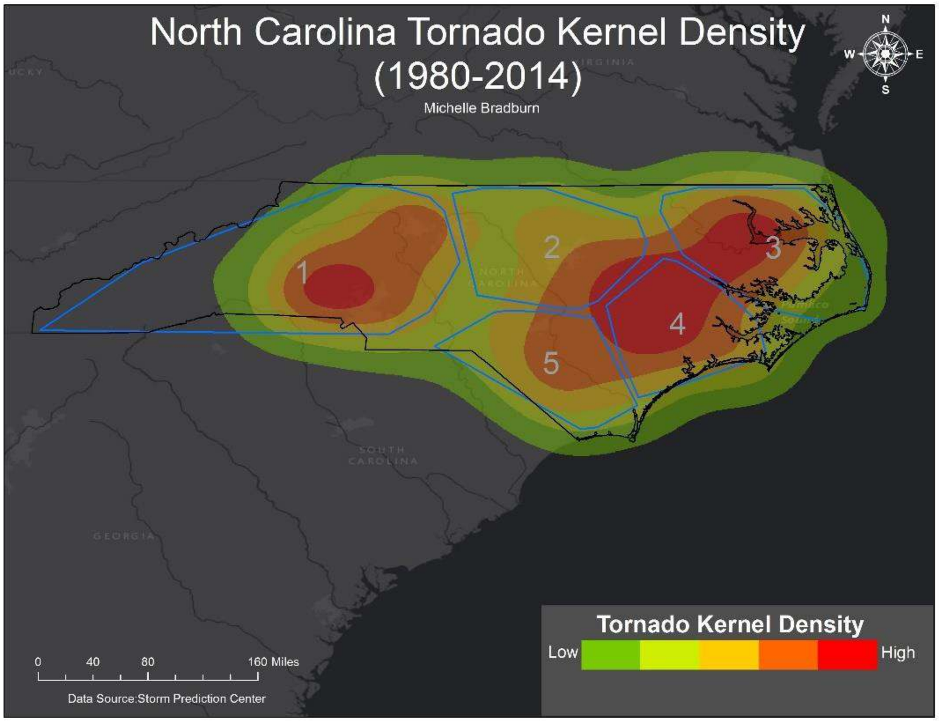

Figure 3.7. North Carolina Kernel Density and Convex Hull Locations

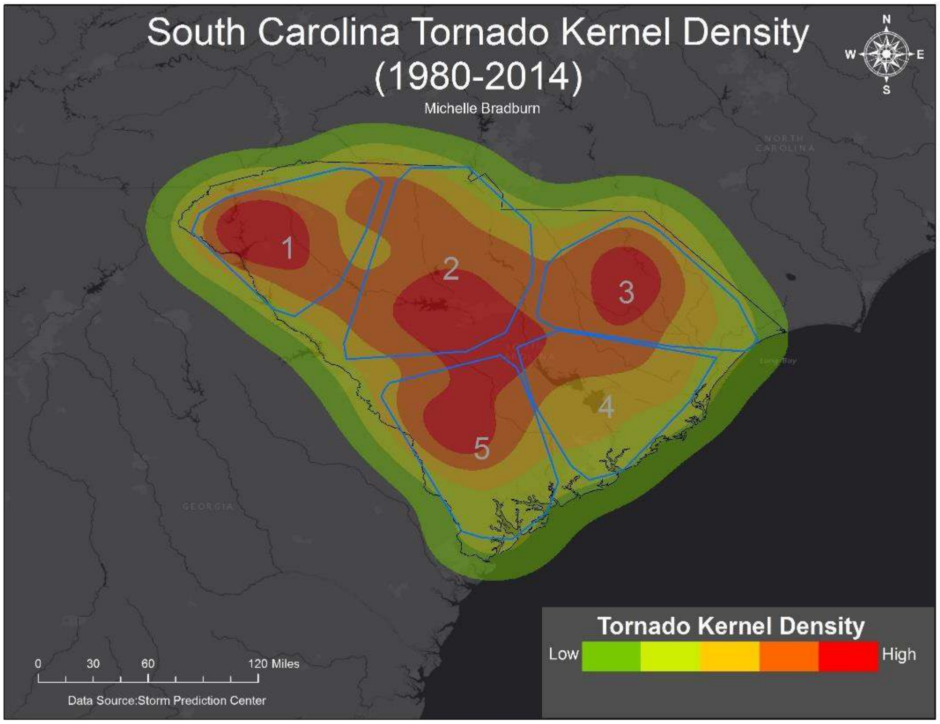

Figure 3.8. North Carolina Kernel Density and Convex Hull Locations

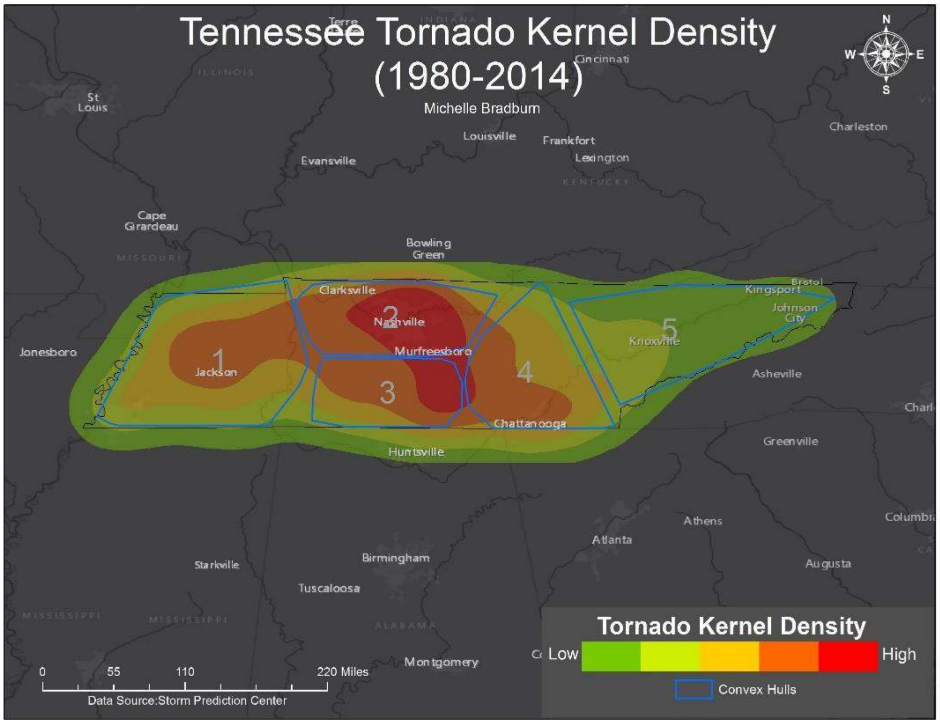

Figure 3.9. Tennessee Kernel Density and Convex Hull Locations

Table 3.2. Alabama, Arkansas, Florida, Georgia, and Louisiana Return Periods

	AL Hull 1		AL Hull 2		AL Hull 3		AL Hull 4		AL Hull 5	
Return Period	**TI^2 (SRCC)**	**TI^2 (Huff-Angel)**	**TI^2 (SRCC)**	**TI^2 (Huff-Angel)**	**TI^2 (SRCC)**	**TI^2 (Huff-Angel)**	**TI^2 (SRCC)**	**TI^2 (Huff-Angel)**	**TI^2 (SRCC)**	**TI^2 (Huff-Angel)**
100-year storm (.99 non-exceedance)	2.124	2.844	2.569	3.802	1.071	1.327	0.856	1.104	0.915	1.268
50-year storm (.98 non-exceedance)	1.876	2.222	2.221	2.720	0.962	1.095	0.773	0.912	0.814	0.997
25-year storm (.96 non-exceedance)	1.629	1.736	1.873	1.946	0.853	0.903	0.689	0.753	0.712	0.784
10-year storm (.90 non-exceedance)	1.301	1.253	1.413	1.250	0.709	0.700	0.579	0.585	0.578	0.570
5-year storm (.80 non-exceedance)	1.053	0.979	1.065	0.895	0.600	0.577	0.496	0.483	0.477	0.448
2-year storm (.50 non-exceedance)	0.726	0.707	0.605	0.575	0.456	0.447	0.385	0.375	0.342	0.326
	y=0.823x+0.478	y=0.356x+(-0.258)	y=1.156x+0.257	y=0.483x+(-0.386)	y=0.362x+0.347	y=0.278+(-0.433)	y=0.277x+0.302	y=0.267x+(-0.509)	y=0.337x+0.241	y=0.347x+(-0.591)
	AR Hull 1		**AR Hull 2**		**AR Hull 3**		**AR Hull 4**		**AR Hull 5**	
Return Period	**TI^2 (SRCC)**	**TI^2 (Huff-Angel)**	**TI^2 (SRCC)**	**TI^2 (Huff-Angel)**	**TI^2 (SRCC)**	**TI^2 (Huff-Angel)**	**TI^2 (SRCC)**	**TI^2 (Huff-Angel)**	**TI^2 (SRCC)**	**TI^2 (Huff-Angel)**
100-year storm (.99 non-exceedance)	1.315	1.406	0.913	1.866	1.317	1.563	0.942	0.879	1.121	1.422
50-year storm (.98 non-exceedance)	1.200	1.210	0.825	1.498	1.191	1.317	0.833	0.772	1.009	1.172
25-year storm (.96 non-exceedance)	1.085	1.041	0.738	1.203	1.065	1.110	0.723	0.678	0.897	0.966
10-year storm (.90 non-exceedance)	0.932	0.853	0.622	0.899	0.898	0.885	0.579	0.571	0.749	0.748
5-year storm (.80 non-exceedance)	0.817	0.734	0.534	0.722	0.772	0.746	0.470	0.502	0.637	0.617
2-year storm (.50 non-exceedance)	0.665	0.602	0.419	0.540	0.605	0.595	0.325	0.423	0.489	0.478
	y=0.383x+0.494	y=0.240x+(-0.296)	y=0.291x+0.331	y=0.317x+(-0.363)	y=0.419x+0.479	y=0.247x+(-0.300)	y=0.363x+0.216	y=0.187x+(-0.430)	y=0.372x+0.377	y=0.279x+(-0.405)
	FL Hull 1		**FL Hull 2**		**FL Hull 3**		**FL Hull 4**		**FL Hull 5**	
Return Period	**TI^2 (SRCC)**	**TI^2 (Huff-Angel)**	**TI^2 (SRCC)**	**TI^2 (Huff-Angel)**	**TI^2 (SRCC)**	**TI^2 (Huff-Angel)**	**TI^2 (SRCC)**	**TI^2 (Huff-Angel)**	**TI^2 (SRCC)**	**TI^2 (Huff-Angel)**
100-year storm (.99 non-exceedance)	0.664	0.966	0.767	1.069	1.202	1.786	0.802	1.148	0.710	1.000
50-year storm (.98 non-exceedance)	0.598	0.771	0.690	0.860	1.062	1.365	0.717	0.908	0.628	0.773
25-year storm (.96 non-exceedance)	0.532	0.616	0.612	0.692	0.922	1.043	0.633	0.719	0.545	0.597
10-year storm (.90 non-exceedance)	0.445	0.457	0.510	0.519	0.737	0.731	0.521	0.527	0.436	0.425
5-year storm (.80 non-exceedance)	0.379	0.365	0.433	0.417	0.597	0.559	0.436	0.417	0.354	0.328
2-year storm (.50 non-exceedance)	0.292	0.271	0.330	0.313	0.412	0.392	0.325	0.306	0.244	0.233
	y=0.219x+0.226	y=0.325x+(-0.665)	y=0.257x+0.253	y=0.314x+(-0.599)	y=0.465x+0.272	y=0.388x+(-0.524)	y=0.281x+0.240	y=0.338x+(-0.616)	y=0.274x+0.162	y=0.372x+(-0.744)
	GA Hull 1		**GA Hull 2**		**GA Hull 3**		**GA Hull 4**		**GA Hull 5**	
Return Period	**TI^2 (SRCC)**	**TI^2 (Huff-Angel)**	**TI^2 (SRCC)**	**TI^2 (Huff-Angel)**	**TI^2 (SRCC)**	**TI^2 (Huff-Angel)**	**TI^2 (SRCC)**	**TI^2 (Huff-Angel)**	**TI^2 (SRCC)**	**TI^2 (Huff-Angel)**
100-year storm (.99 non-exceedance)	1.668	2.415	0.746	0.798	0.926	1.050	1.051	1.413	0.886	1.396
50-year storm (.98 non-exceedance)	1.476	1.864	0.688	0.711	0.839	0.896	0.939	1.131	0.776	1.159
25-year storm (.96 non-exceedance)	1.283	1.438	0.630	0.634	0.752	0.764	0.826	0.905	0.666	0.836
10-year storm (.90 non-exceedance)	1.029	1.021	0.554	0.545	0.637	0.620	0.678	0.675	0.520	0.543
5-year storm (.80 non-exceedance)	0.837	0.788	0.496	0.485	0.550	0.529	0.566	0.540	0.410	0.392
2-year storm (.50 non-exceedance)	0.582	0.559	0.420	0.417	0.435	0.429	0.417	0.402	0.264	0.255
	y=0.639x+0.390	y=0.374x+(-0.365)	y=0.192x+0.362	y=0.166x+(-0.430)	y=0.289x+0.348	y=0.229x+(-0.436)	y=0.373x+0.305	y=0.321x+(-0.492)	y=0.366x+0.154	y=0.441x+(-0.737)
	LA Hull 1		**LA Hull 2**		**LA Hull 3**		**LA Hull 4**		**LA Hull 5**	
Return Period	**TI^2 (SRCC)**	**TI^2 (Huff-Angel)**	**TI^2 (SRCC)**	**TI^2 (Huff-Angel)**	**TI^2 (SRCC)**	**TI^2 (Huff-Angel)**	**TI^2 (SRCC)**	**TI^2 (Huff-Angel)**	**TI2 (SRCC)**	**TI2 (Huff-Angel)**
100-year storm (.99 non-exceedance)	1.013	1.194	1.007	1.202	0.783	0.859	0.717	1.033	0.910	1.466
50-year storm (.98 non-exceedance)	0.919	1.014	0.919	1.029	0.720	0.758	0.638	0.815	0.798	1.079
25-year storm (.96 non-exceedance)	0.826	0.861	0.831	0.880	0.658	0.668	0.559	0.643	0.687	0.794
10-year storm (.90 non-exceedance)	0.702	0.693	0.714	0.716	0.575	0.566	0.454	0.470	0.539	0.530
5-year storm (.80 non-exceedance)	0.608	0.589	0.626	0.613	0.512	0.499	0.375	0.371	0.427	0.390
2-year storm (.50 non-exceedance)	0.485	0.474	0.509	0.499	0.430	0.423	0.270	0.271	0.280	0.260
	y=0.311x+0.391	y=0.236x+(-0.395)	y=0.293x+0.421	y=0.225x+(-0.370)	y=0.208x+0.367	y=0.181x+(-0.428)	y=0.263x+0.191	y=0.342x+(-0.670)	y=0.371x+0.168	y=0.442x+(-0.718)

Table 3.3. Mississippi, North Carolina, South Carolina, and Tennessee Return Periods

	MS Hull 1		MS Hull 2		MS Hull 3		MS Hull 4		MS Hull 5	
Return Period	TI^2 (SRCC)	TI^2 (Huff-Angel)	TI^2 (SRCC)	TI^2 (Huff-Angel)	TI^2 (SRCC)	TI^2 (Huff-Angel)	TI^2 (SRCC)	TI^2 (Huff-Angel)	TI^2 (SRCC)	TI^2 (Huff-Angel)
100-year storm (.99 non-exceedance)	1.434	1.803	1.103	1.340	1.271	1.500	1.205	1.521	1.148	1.413
50-year storm (.98 non-exceedance)	1.281	1.463	0.989	1.103	1.156	1.280	1.073	1.225	1.036	1.177
25-year storm (.96 non-exceedance)	1.128	1.188	0.874	0.909	1.042	1.092	0.941	0.987	0.924	0.981
10-year storm (.90 non-exceedance)	0.925	0.902	0.723	0.703	0.890	0.885	0.766	0.741	0.776	0.771
5-year storm (.80 non-exceedance)	0.772	0.732	0.609	0.579	0.775	0.755	0.634	0.597	0.664	0.642
2-year storm (.50 non-exceedance)	0.569	0.555	0.457	0.448	0.624	0.612	0.459	0.449	0.516	0.505
	y=0.509x+0.416	y=0.301x+(-0.346)	y=0.380x+0.343	y=0.280x+(-0.433)	y=0.381x+0.509	y=0.229x+(-0.282)	y=0.439x+0.327	y=0.312x+(-0.442)	y=0.372x+0.404	y=0.263x+(-0.376)
	NC Hull 1		NC Hull 2		NC Hull 3		NC Hull 4		NC Hull 5	
Return Period	TI^2 (SRCC)	TI^2 (Huff-Angel)	TI^2 (SRCC)	TI^2 (Huff-Angel)	TI^2 (SRCC)	TI^2 (Huff-Angel)	TI^2 (SRCC)	TI^2 (Huff-Angel)	TI^2 (SRCC)	TI^2 (Huff-Angel)
100-year storm (.99 non-exceedance)	1.104	1.374	1.120	1.758	1.144	1.340	1.266	2.234	1.345	1.345
50-year storm (.98 non-exceedance)	0.989	1.125	0.988	1.323	1.018	1.093	1.108	1.614	1.165	1.165
25-year storm (.96 non-exceedance)	0.874	0.922	0.856	0.996	0.892	0.892	0.949	1.166	0.984	0.984
10-year storm (.90 non-exceedance)	0.722	0.708	0.682	0.684	0.726	0.682	0.740	0.759	0.746	0.746
5-year storm (.80 non-exceedance)	0.607	0.580	0.550	0.515	0.600	0.557	0.582	0.548	0.566	0.566
2-year storm (.50 non-exceedance)	0.455	0.445	0.376	0.354	0.434	0.426	0.372	0.357	0.327	0.327
	y=0.382x+0.340	y=0.288x+(-0.438)	y=0.438x+0.244	y=0.410x+(-0.575)	y=0.418x+0.308	y=0.293x+(-0.459)	y=0.536x+0.214	y=0.469x+(-0.598)	y=0.599x+0.147	y=0.563x+(-0.698)
	SC Hull 1		SC Hull 2		SC Hull 3		SC Hull 4		SC Hull 5	
Return Period	TI^2 (SRCC)	TI^2 (Huff-Angel)	TI^2 (SRCC)	TI^2 (Huff-Angel)	TI^2 (SRCC)	TI^2 (Huff-Angel)	TI^2 (SRCC)	TI^2 (Huff-Angel)	TI^2 (SRCC)	TI^2 (Huff-Angel)
100-year storm (.99 non-exceedance)	0.926	1.452	0.991	1.164	1.338	2.559	0.612	0.724	0.863	1.380
50-year storm (.98 non-exceedance)	0.817	1.094	0.898	0.986	1.161	1.761	0.542	0.583	0.765	1.045
25-year storm (.96 non-exceedance)	0.709	0.824	0.804	0.835	0.985	1.212	0.472	0.469	0.666	0.791
10-year storm (.90 non-exceedance)	0.565	0.566	0.681	0.670	0.751	0.740	0.380	0.352	0.536	0.547
5-year storm (.80 non-exceedance)	0.456	0.426	0.588	0.567	0.574	0.509	0.310	0.284	0.438	0.414
2-year storm (.50 non-exceedance)	0.313	0.293	0.464	0.455	0.341	0.311	0.218	0.213	0.307	0.286
	y=0.361x+0.204	y=0.409x+(-0.656)	y=0.310x+0.371	y=0.240x+(-0.414)	y=0.587x+0.164	y=0.539x+(-0.670)	y=0.232x+0.148	y=0.313x+(-0.766)	y=0.327x+0.209	y=0.402x+(-0.664)
	TN Hull 1		TN Hull 2		TN Hull 3		TN Hull 4		TN Hull 5	
Return Period	TI^2 (SRCC)	TI^2 (Huff-Angel)	TI^2 (SRCC)	TI^2 (Huff-Angel)	TI^2 (SRCC)	TI^2 (Huff-Angel)	TI^2 (SRCC)	TI^2 (Huff-Angel)	TI^2 (SRCC)	TI^2 (Huff-Angel)
100-year storm (.99 non-exceedance)	1.254	1.552	1.182	1.549	1.706	2.198	1.289	1.718	1.146	2.234
50-year storm (.98 non-exceedance)	1.140	1.311	1.057	1.250	1.485	1.658	1.141	1.351	1.005	1.576
25-year storm (.96 non-exceedance)	1.026	1.107	0.932	1.009	1.265	1.250	0.994	1.062	0.863	1.112
10-year storm (.90 non-exceedance)	0.876	0.885	0.766	0.760	0.973	0.861	0.799	0.773	0.676	0.701
5-year storm (.80 non-exceedance)	0.762	0.747	0.641	0.614	0.752	0.649	0.651	0.607	0.535	0.495
2-year storm (.50 non-exceedance)	0.612	0.598	0.475	0.462	0.461	0.447	0.457	0.442	0.347	0.312

Discussion & Conclusions

Tornado intensities and impacts vary with geography and this study identified spatial variations in tornado return periods for states across the Southeast USA. Concentrations of higher TI^2 scores were found in central Arkansas, southern central Mississippi, and northern Alabama in Study One, while this study sub-divided tornado cluster regions out by state, revealing finer details about tornado impacts and more specific geographic boundaries. While the regional findings are similar to that of previous researchers, the state-specific study reveals the highest intensity impact zones at the state-level.

The SRCC and Huff-Angel Methods return period utilized for this study produced varied results. KS scores revealed that the Huff-Angel method may provide the best overall fit for state-scale return periods, as this method had lower KS scores for four of the nine states, while the SRCC method had a lower KS score for three state. KS scores for two other states revealed a tie in goodness-of-fit between the Huff-Angel and SRCC methods. KS scores varied per state hull, however, and no method was the best fit for all hulls in any state (Table 3.4). Using Huff-Angel predictions, stronger storms (higher TI^2 values) are expected at both the 50- and 100-year return periods than ae predicted using the SRCC method.

Table 3.4. Results of KS Statistics in hulls across all states

State	# SRCC	# Huff-Angel	# of Ties	Best Overall
AL	2	1	2	Tie
AR	4	0	1	SRCC
FL	0	4	1	Huff-Angel
GA	1	3	1	Huff-Angel
LA	1	4	0	Huff-Angel
MS	3	1	1	SRCC
NC	4	0	1	SRCC
SC	1	4	0	Huff-Angel
TN	2	2	1	Tie

Each state and state hulls within will be discussed and compared to the Southeast (SE) Hulls from Study One below.

Alabama (AL)

The highest TI^2 score for Alabama was a 2.689 EF4 that occurred in AL Hull Two on April 27, 2011, and resulted in 1,500 injuries and 72 fatalities, although the highest TI^2 scores of each Alabama Hull varied (Table 3.5).

Table 3.5. Breakdown of Alabama highest TI^2 scores per hull

	Highest TI^2	**Magnitude**	**Injuries**	**Fatalities**
AL Hull One	2.097	5	145	72
AL Hull Two	2.689	4	1500	64
AL Hull Three	0.917	4	30	7
AL Hull Four	0.815	4	2	1
AL Hull Five	0.958	4	50	9

The state of Alabama falls within Southeast Hulls One, Three, Four, and Five. The majority of AL Hull One intersected SE Hull Four. Similarities were found between the SE Hull Four and AL Hull One SRCC TI^2 scores, as SE Hull Four had a predicted 100-year return period (100-YRP) TI^2 score of 2.801 and AL Hull One had a predicted SRCC 100-YRP score of 2.124. Similarly, on the other end of the scale, the 2-year return period (2YRP) SRCC and Huff-Angel TI^2 scores for AL Hull One were smaller than SE Hull One. AL Hulls Two, Three, Four, and Five were largely intersected by SE Hull Five, and had SRCC 100-YRP TI^2 scores with a range of 0.856-2.569 and Huff-Angel 100YRP TI^2 scores with a range of 1.104-3.802. SE Hull Five had a SRCC 100YRP TI^2 score of 2.097 and a 100YRP TI^2 score of 2.455. AL Hull Two had the highest SRCC and Huff-Angel 100YRP TI^2 scores in the state, surpassing the TI^2 scores of SE Hull Five.

AL Hull Two was the recipient of a tornado that surpassed the 100YRP SRCC TI^2 score of AL Hull Two of 2.569, making it an above 100YRP event. This was the April 27, 2011, EF4 tornado that occurred during the April 2011 outbreak, with a 100YRP SRCC TI^2 score of 2.689. AL Hull Five also received a tornado which surpassed the predicted SRCC 100YRP TI^2 score of its hull of 0.915, with a TI^2 score of 0.958. With the highest predicted TI^2 scores of any of the Southeastern states, Alabama is most likely to see high impact storms in the future.

Arkansas (AR)

The highest TI^2 score for Arkansas occurred in AR Hull Three on April 27, 2014, and was an EF4 with 193 injuries and 16 fatalities, and producing a TI^2 score of 1.151 (Table 3.6).

Table 3.6. Breakdown of Arkansas highest TI^2 scores per hull

	Highest TI^2	**Magnitude**	**Injuries**	**Fatalities**
AR Hull One	1.073	4	139	13
AR Hull Two	0.874	4	27	4
AR Hull Three	1.151	4	193	16
AR Hull Four	0.649	3	11	3
AR Hull Five	0.950	4	100	6

The state of Arkansas falls within SE Hulls One and Two. The highest predicted AR TI^2 scores were found in AR Hull Three with a 100YRP TI^2 score of 1.317 and a Huff-Angel TI^2 score of 1.563. The 100YRP SRCC TI^2 score for SE Hull One was 1.367 and the Huff-Angel 100YRP was 1.570. The AR Hull Three and SE Hull One TI^2 scores were very similar, although the SE Hull One TI^2 scores were slightly higher. AR Hulls Four and Five fell within SE Hull Two. SE Hull Two had an SRCC 100YRP of 1.061 and a Huff-Angel 100YRP of 1.227. AR Hull Four had a 0.942 SRCC 100YRP and a 0.879 100YRP, and AR Hull Five had a 1.121

SRCC 100YRP and a 1.422 Huff-Angel 100YRP. Both AR Hull Four 100YRPs were lower than SE Hull Two, but AR Hull Five 100YRPs were higher. The average of the 100YRP TI^2 scores for AR Hulls Four and Five for both SRCC (1.032) and Huff-Angel (1.151) are slightly lower than the 100YRP TI^2 scores of SE Hull Two. SE Hull Two is comprised of two other Louisiana Hulls, which had 100YRP TI^2 scores that were above 1.000, and also had an influence on the SE Hull Two TI^2 scores.

Florida (FL)

The highest TI^2 score for Florida occurred on February 2, 1998, in FL Hull Three and was an EF3, with 150 injuries and 25 fatalities, and a TI^2 score of 1.047 (Table 3.7).

Table 3.7. Breakdown of Florida highest TI^2 scores per hull

	Highest TI^2	**Magnitude**	**Injuries**	**Fatalities**
FL Hull One	0.459	2	5	4
FL Hull Two	0.668	3	18	4
FL Hull Three	1.047	3	150	25
FL Hull Four	0.692	3	75	3
FL Hull Five	0.636	3	33	1

Florida falls within SE Hulls Eight, Nine, and Ten. The highest predicted AR TI^2 scores were found in FL Hull Three with a 100YRP SRCC TI^2 score of 1.197 and a 100YRP Huff-Angel TI^2 score of 1.766. FL Hull Three fell mostly within SE Hull Nine, which had a 100YRP SRCC TI^2 score of 1.205 and a 100YRP Huff-Angel TI^2 score of 1.563. FL Hull Three predicted higher 100YRP TI^2 scores for both methods than SE Hull Nine. FL Hull One fell within SE Hull Eight, and predicted lower 100YRP TI^2 scores of 0.664 SRCC, and 0.966 Huff-Angel than SE Hull Eight with TI^2 scores of 1.370 SRCC and 1.585 Huff-Angel. SE Hull Eight also encompassed parts of Georgia and Alabama, states which both had higher predicted TI^2 scores than Florida. FL Hull Five makes up the majority of SE Hull Ten, and had very similar TI^2

scores to SE Hull Ten. FL Hull Five had a 100YRP SRCC TI^2 score of 0.710 and a Huff-Angel 100YRP TI^2 score of 1.000, while SE Hull Ten had a 100YRP SRCC TI^2 score of 0.763 and a Huff-Angel 100YRP TI^2 score of 1.035.

Georgia (GA)

The highest TI^2 score for Georgia occurred in GA Hull Three on April 27, 2011, and was an EF5 with 0 injuries and 25 fatalities, and resulted in a TI^2 score of 1.347 (Table 3.8).

Table 3.8. Breakdown of Georgia highest TI^2 scores per hull

	Highest TI^2	**Magnitude**	**Injuries**	**Fatalities**
GA Hull One	1.347	5	0	25
GA Hull Two	0.642	3	22	2
GA Hull Three	0.927	4	86	5
GA Hull Four	0.869	3	175	11
GA Hull Five	0.806	4	9	0

Georgia falls within SE Hulls Six, Seven, and Nine. The highest predicted TI^2 scores were found in GA Hull One with a 100YRP SRCC TI^2 score of 1.668 and a 100YRP Huff-Angel score of 2.415. GA Hull One falls into SE Hull Six, which had a 100YRP SRCC TI^2 score of 1.638 and a 100YRP Huff-Angel TI^2 score of 2.000. GA Hull One predicted higher 100YRP TI^2 scores for each method than SE Hull Six. SE Hull Six also encompasses portions of Alabama, North Carolina, South Carolina, and Tennessee, all of which contributed to the predicted TI^2 scores of SE Hull Six.

The highest TI^2 score for Georgia was the 100YRP SRCC TI^2 score of 0.927, which occurred on November 22, 1992 in GA Hull Three, also surpassed the 100YRP SRCC TI^2 score for GA Hull Three of 0.926. This TI^2 score was very slightly higher, but high enough to be that of a storm exceeding the predicted 100YRP for the SRCC method.

Louisiana (LA)

The highest TI^2 score Louisiana occurred in LA Hull One on April 3, 1999, and was an EF4 with 102 injuries and 7 fatalities, resulting in a TI^2 score of 0.965 (Table 3.9).

Table 3.9. Breakdown of Louisiana highest TI^2 scores per hull

	Highest TI^2	**Magnitude**	**Injuries**	**Fatalities**
LA Hull One	0.965	4	102	7
LA Hull Two	0.899	4	146	10
LA Hull Three	0.615	3	2	1
LA Hull Four	0.603	2	60	0
LA Hull Five	0.817	4	25	0

Louisiana falls within SE Hulls Two and Three. The highest predicted TI^2 scores were found in LA Hull Two with an SRCC 100YRP TI^2 score of 1.007 and a Huff-Angel 100YRP TI^2 score of 1.202. The majority of LA Hull Two falls within SE Hull Two, which had an SRCC 100YRP of 1.061 and a Huff-Angel 100YRP of 1.227. LA Hull Two had similar TI^2 scores for the 100YRP SRCC and 100YRP Huff-Angel. LA Hull Three was encompassed entirely within SE Hull Three. LA Hull Three had an SRCC 100YRP TI^2 score of 0.783 and a Huff-Angel 100YRP TI^2 score of 0.859, while SE Hull Three had an SRCC 100YRP TI^2 score of 0.963 and a Huff-Angel 100YRP TI^2 score of 1.219. SE Hull Three had higher 100YRP TI^2 scores than LA Hull Three, as SE Hull Three also encompasses other areas of Louisiana and Mississippi.

Mississippi (MS)

The highest TI^2 score for Mississippi occurred in MS Hull One on April 27, 2011, and was an EF5 with 137 injuries and 23 fatalities, resulting in a TI^2 score of 1.411 (Table 3.10).

Table 3.10. Breakdown of Mississippi highest TI^2 scores per hull

	Highest TI^2	Magnitude	Injuries	Fatalities
MS Hull One	1.411	5	137	23
MS Hull Two	1.036	4	146	10
MS Hull Three	1.048	4	122	12
MS Hull Four	1.048	4	122	12
MS Hull Five	1.117	4	350	6

Mississippi falls within SE Hulls One, Two, Three, Four, and Five. The highest predicted TI^2 scores were found in MS Hull One, with an SRCC 100YRP TI^2 score of 1.434 and a Huff-Angel 100YRP TI^2 score of 1.803. MS Hull One fell within SE Hull Four, which had an SRCC 100YRP TI^2 score of 2.801 and a Huff-Angel 100YRP TI^2 score of 4.018. SE Hull Four predicted higher SRCC and Huff-Angel TI^2 scores at the 100YRP, as it also intersects portions of Tennessee and Alabama. MS Hull Three is entirely contained within SE Hull Five, and had an SRCC 100YRP TI^2 score of 1.103 and a Huff-Angel 100YRP TI^2 score of 1.340. SE Hull Five had an SRCC 100YRP TI^2 score of 2.097 and a Huff-Angel 100YRP TI^2 score of 2.455. SE Hull Five also intersects a region of Alabama, as well as three other MS Hulls.

North Carolina (NC)

The highest TI^2 score for North Carolina occurred in NC Hulls Three and Four on March 28, 1984, and was an EF4 with 153 injuries and 16 fatalities, resulting in a TI^2 score of 1.124 (Table 3.11).

Table 3.11. Breakdown of North Carolina highest TI^2 scores per hull

	Highest TI^2	Magnitude	Injuries	Fatalities
NC Hull One	0.890	4	52	4
NC Hull Two	0.958	4	154	4
NC Hull Three	1.124	4	153	16
NC Hull Four	1.124	4	153	16
NC Hull Five	1.119	4	395	4

North Carolina is encompassed by SE Hulls Six and Eight. The highest predicted TI^2 score for North Carolina were found in NC Hull with an SRCC 100YRP TI^2 score of 1.345 and a Huff-Angel 100YRP TI^2 score of 2.679. NC Hull Five fell within SE Hull Eight, where the SRCC 100YRP TI^2 score was 1.370 and the Huff-Angel 100YRP TI^2 score was 1.585. The NC Hull Five Huff-Angel 100YRP TI^2 score was much higher than that of SE Hull Eight.

South Carolina (SC)

The highest TI^2 score for South Carolina occurred in SC Hull Three on March 28, 1984, and was an EF4 with 395 injuries and 4 fatalities, resulting in a TI^2 score of 1.119 (Table 3.12).

Table 3.12. Breakdown of South Carolina highest TI^2 scores per hull

	Highest TI^2	Magnitude	Injuries	Fatalities
SC Hull One	0.851	4	35	2
SC Hull Two	0.902	4	49	5
SC Hull Three	1.119	4	395	4
SC Hull Four	0.617	3	5	1
SC Hull Five	0.609	3	14	0

South Carolina was encompassed by SE Hulls Six and Eight. The highest predicted TI^2 scores for South Carolina were found in SC Hull Three, with an SRCC 100YRP TI^2 score of 1.338 and a Huff-Angel 100YRP TI^2 score of 2.559. SC Hull Three fell within SE Hull Eight, where the SRCC 100YRP TI^2 score was 1.370 and the Huff-Angel 100YRP TI^2 score was 1.585.

The 100YRP SRCC TI^2 scores were very similar, but the NC Hull Three 100YRP Huff-Angel TI^2 score was much higher than SE Hull Eight.

Tennessee (TN)

The highest TI^2 score Tennessee was found in TN Hull Three on April 27, 2011, and was an EF5 with 145 injuries and 72 fatalities, resulting in a TI^2 score of 2.097 (Table 3.13).

Table 3.13. Breakdown of Tennessee highest TI^2 scores per hull

	Highest TI^2	**Magnitude**	**Injuries**	**Fatalities**
TN Hull One	1.010	4	86	11
TN Hull Two	0.948	3	63	22
TN Hull Three	2.097	5	145	72
TN Hull Four	1.301	4	335	20
TN Hull Five	0.800	4	0	0

Tennessee was encompassed primarily by SE Hulls Four and Six. The highest predicted TI^2 scores for the state were in TN Hull Three, with an SRCC 100YRP TI^2 score of 1.706 and a Huff-Angel 100YRP TI^2 score of 2.198. TN Hull Three fell within SE Hull Four, which had an SRCC 100YRP TI^2 score of 2.801 and a Huff-Angel 100YRP TI^2 score of 4.108. SE Hull Four predicted higher 100YRP TI^2 scores than TN Hull Three, because it also encompassed regions of Mississippi and Alabama that had multiple strong tornadoes during the April 2011 Outbreak. TN Hull Five was mostly encompassed by SE Hull Six and had an SRCC 100YRP TI^2 score of 1.146 and a Huff-Angel 100YRP TI^2 score of 2.234. SE Hull Six had an SRCC 100YRP TI^2 score of 1.638 and a Huff-Angel 100YRP TI^2 score of 2.000. TN Hull Five predicted a stronger Huff-Angel 100YRP TI^2 score than SE Hull Six, but SE Hull Six predicted a stronger SRCC 100YRP

TI^2 score than TN Hull Five. SE Hull Six also encompassed portions of Alabama, Georgia, and South Carolina.

Tennessee also had tornadoes which exceeded the SRCC 100YRP TI^2 scores for their respective TN Hulls. TN Hull Three had a tornado with a TI^2 score of 2.097, which was the highest TI^2 score of any Tennessee tornado. This tornado had such a high TI^2 score because it had the highest magnitude (EF5) and the highest fatality (n=72) count in the Southeast. The predicted 100YRP TI^2 score was 1.706 for TN Hull Three. TN Hull Four had a tornado on April 27, 2011, with a TI^2 score of 1.301, which was an EF4 with 335 injuries and 20 fatalities. The predicted 100YRP SRCC TI^2 score for TN Hull Four was 1.289.

All States

Kernel Density Estimation (KDE) and state-level TI^2 scores may help mitigate many previously discussed risk factors regarding tornadoes in the Southeast. Many people are under the impression that tornadoes "don't happen" in their areas (Donner et al. 2012), but state-specific KDE reveals areas of relatively high tornado frequencies in every state. While there are areas within each state and region where tornadoes are less common, no area within the Southeast is immune from tornadic activity. TI^2 scores for state-specific hulls present the estimated impact of future tornadoes, providing critical information to communities that may, otherwise, not consider themselves at risk.

With a higher mobile home and population density (Ashley et al. 2008; Sutter and Simmons 2010), the Southeast experiences a higher incidence of injuries and fatalities. KDE surfaces and state-specific TI^2 scores associated with individual state hulls provided a clear image of areas of particularly high risk in the Southeast. Each state has a different high-risk area that is revealed by KDE and TI^2 scores, an area, that in comparison to the rest of the state, is particularly vulnerable for high impact tornado occurrences. These areas should be targeted for tornado preparedness education in an effort to mitigate potential fatalities and injuries during future tornadoes and tornado outbreak events.

Dixie Alley, as defined by Gagan et al. (2010) and Ashley (2007), was well-defined by KDE and return period analysis at the regional scale, but more difficult to distinguish at the state scale. Meentemeyer (1989) concluded that analysis should be conducted across multiple scales because spatial phenomena exist in different size classes. Clark (1985) reports that those debating climate-related topics must conclude that explanations, variables, and generalizations that are relevant and appropriate at one scale may not be relevant at others. This study aimed to explore tornado return periods at the regional and state levels and has confirmed that different scales are appropriate for different purposes, as it has revealed several state-specific trends that were not seen in the regional study. For example, six tornadoes exceeded the SRCC 100YRP TI^2 scores for their respective hulls, which was not previously seen in the regional study. This information lets researchers know that these events had a higher impact than any other tornadoes in their state. In addition, differences in KDE surfaces revealed higher density areas within each state, which can help emergency managers convince the public that their region is at risk for tornadoes.

Analysis of climatic phenomena at varying scales provides a multi-dimensional examination of risks and impacts (Atkinson & Tate, 2000; Burkett et al., 2001; Joyner & Rohli, 2010; Murata, 1992; Sayre, 2005; Wu, 2004). According to Lam and Quattrochi (1992), the strength of geography is enhanced when geographical phenomena are analyzed using a range of scales, and this type of study offers a distinct view and methodology that other disciplines rarely recognize. Results suggest that the state scale is useful for a variety of reasons. The state-specific study provided a detailed analysis for each state that identifies localized areas of high potential tornado risk (relative to risk elsewhere across the state) that may have been smoothed over in a regional analysis. Ultimately, state-scale results may provide local and state-wide emergency management agencies with previously unknown spatial knowledge of tornadic potential. This will help agencies better target areas of high risk for educational outreach programs. Results will also help to inform local mitigation planning efforts, as emergency managers in high risk zones can use this study to quantify their risk, and put a higher importance on tornado safety within their jurisdiction's plan.

Future Research

Many contemporary studies that use return period analysis to examine climatic phenomena (Faiers et al. 1997; Needham et al. 2012) also plot return periods using the Beta-P and Gumbel distribution curve methods and future research should examine these methods for comparison. Previous studies have found that the Huff-Angel and SRCC methods created a better probability fit, thus our selection of logarithmic-based methods, but a comparison with traditional distribution plot methods may provide additional insight. Future research should also include the development of a predictive model based on TI^2 scores. Temporal (e.g. seasonal) KDE and return period analysis is also recommended since various regions of the Southeast USA experience peak tornado frequencies at different times of the year (Brooks et al. 2003). Additionally, a comprehensive study including all 50 states would provide an all-inclusive study of tornadoes throughout the country. Effective communication of results and additional outreach is also necessary and future research is expected to include a partnership component with NWS offices, the SPC, and the SRCC that incorporates survey data and feedback on visual communication products developed from this research. The KDE maps, when shared with the public, could help people understand the risk for tornadoes within their state, and the TI^2 scores for state hulls can help them understand their state regional risk. The KDE maps, along with graphics that clearly explain TI^2 scores and projected magnitudes, injuries, and fatalities, could be shared on NWS, SPC, and SRCC social media pages for public feedback. This feedback can help the respective agencies communicate tornado risk information to the public.

Summary

State-specific clusters and KDE surfaces were created and mapped, resulting in five statistically unique regions for each of the nine Southeastern states. State-specific tornado information was also extracted, enumerating the magnitudes, injuries, fatalities, and total tornadoes for each state and sub-region within the state. For each hull within each state, return periods were calculated using the SRCC and Huff-Angel return period methods. The resulting quantile estimates were examined using a KS statistic to determine which method was the best fit for the data in each hull. Neither method proved to be the best fit for every hull in each of the nine states, but the Huff-Angel yielded higher TI^2 scores at the 50- and 100-year return periods. Six historic tornadoes had higher TI^2 scores than SRCC 100YRP storms in their state hulls, which means that they were the highest impact tornadoes in their hulls. The SRCC method predicted tornadoes with lower TI^2 scores than historically observed.

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CHAPTER 4

CONCLUSION

This thesis addresses several objectives related to temporal and spatial tornado patterns in the Southeast USA. The objectives were:

Study One

1. Identify areas throughout the Southeast USA that have high and low tornado frequencies and impacts
2. Derive return periods within each statistically identified tornado cluster and determine the expected tornado impacts over time for each return period

Study Two

1. Identify patterns in tornado density and return periods at the state-level (opposed to the regional-level analysis of Study One)
2. Examine implications of scale variability on the use of return periods for hazard mitigation and additional research purposes

Study One Conclusions

By combining magnitude, fatality, and injury data, Tornado Impact Index (TI^2) scores were calculated for each tornado. KS statistics confirmed that the Huff-Angel and SRCC methods provide the best fit for data in four of the ten convex hulls, and that two of the ten convex hulls had identical KS statistics for the Huff-Angel and SRCC methods. Additionally, a kernel density surface was created to examine spatial density patterns of tornadoes in the Southeast and identify a tornado alley (i.e. Dixie Alley), or alleys, in the region. Major impact areas were within SE Hulls Four and Five, where high KDE and high TI^2 scores for both the SRCC and Huff-Angel Methods were seen.

The major findings/developments in Study One are as follows:

1. The Tornado Impact Index (TI^2) was developed as a ranking index for historical tornadoes. This index ranked tornadoes from 1980-2014 on a scale of 0-3.
2. Predicted return period TI^2 scores ranked on a scale higher than 3 (highest at 4.081). This means that TI^2 scores are expected to exceed that of any historical tornado (i.e. higher impact tornadoes are possible when compared to the current observational record).
3. Areas of high density were found in SE Hulls 1, 2, 3, 4, 5, and 6, and areas of low density were found in SE Hulls 9 and 10.
4. The Huff-Angel method provided the best fit for data in SE Hulls 3, 5, 6, and 7, while the SRCC method provided the best fit for the data in SE hulls 1, 4, 9, and 10. The same KS statistics were observed for both SRCC and Huff-Angel in SE Hulls 2 and 8.
5. TI^2 scores and associated return periods confirm the existence of Dixie Alley, and/or a region of high tornado intensity, in the Southeast United States, while alluding to additional areas of high tornado frequency.

Study Two Conclusions

Individual density surfaces were created for each of nine Southeast states (Alabama, Arkansas, Florida, Georgia, Louisiana, Mississippi, North Carolina, South Carolina, and Tennessee) to examine local spatial density patterns of tornadoes and develop a scale comparison between state-level and regional-level density analyses. Areas of high KDE were seen in each of the nine states, and the highest TI^2 scores were found in Alabama, Georgia, North Carolina, and Tennessee (with SRCC and/or Huff-Angel 100YRP TI^2 scores of 2.000 and greater).

Major findings of Study Two are as follows:

1. Comparison of TI^2 scores between states allude to differences and similarities across geographic scale, as some state hulls had higher 100YRP TI^2 scores than SE Hulls, and some had lower or similar TI^2 scores.
2. KDE surfaces revealed local-scale areas of high tornado density, however, state-level density surfaces resulted in a less apparent “Dixie Alley” indicating that regional-level analyses may better capture larger trends in tornado frequency, while state-level analyses may better capture smaller trends in tornado frequency.
3. Areas of high KDE were seen in each state, and include AL Hulls One and Two, AR Hull Three, FL Hulls Three and Four, GA Hulls One and Two, LA Hulls One and Three, MS Hulls Three, Four, and Five, NC Hulls One, Three, and Four, South Carolina Hulls One, Two, Three, Four, and Five, and TN Hulls Two, Three, and Four.
4. Areas with high TI^2 scores (with SRCC and/or Huff-Angel 100YRP TI^2 scores of 2.000 and greater) were found in AL Hull Two, GA Hull One, NC Hull Five, and TN Hull Three.

General Conclusions & Future Research

Each study provided its own benefits to the tornado community at large. Both studies will benefit climatologists by filling a previous gap in the identification of Southeast tornado frequencies (i.e. densities) and estimation of tornado return periods. Previously, return periods were not calculated for tornadoes because wind speed data for tornadoes are not accurate and are extremely difficult to measure. Return periods have been calculated for a variety of climatological phenomena using magnitude (flood level, precipitation amount, storm surge height), but a new approach was needed for tornadoes. This thesis developed a method of return period analysis, incorporating human impact as well as relative intensity (on the EF-scale), potentially signaling a paradigm shift in how we view traditional analytical methods in this field. Numerous possibilities exist for assessing long-term vulnerability to hazards if data can be combined and scaled for climate-related phenomena where intensity is difficult to measure. Additionally, FEMA and state and local emergency managers may benefit from this new method of examining tornado impacts. Hazard mitigation plans require risk and vulnerability assessments for all potential natural hazards and until now local tornado impacts have been difficult to assess. This information will help emergency managers assess jurisdictional tornado risk and help them better prepare for future tornado events.

Future research will examine ways to better communicate new tornado return period information to the public and emergency managers through the use of interactive web mapping, social media, and inter-agency collaboration. Tornado return period calculations will be shared with the National Weather Service and Southern Regional Climate Center. The development of a predictive model, based on TI^2 scores to predict potential future intensity impact, could be extremely helpful to emergency management officials, as it quantifies risk within each state and within sub-regions (hulls). This information will help quantify tornado risk for their jurisdiction and better target areas of high risk for public education and outreach. Additional studies examining tornado densities and intensities per season, return period studies of all 50 states, and of other tornado risk zones, would provide a more comprehensive understanding of tornado return periods across the country.

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