Economic Losses and Extreme Tornado Events

Rachel Reeves
University of South Carolina

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Economic Losses and Extreme Tornado Events

by

Rachel Reeves

Bachelor of Science
University of Oklahoma, 2013

______________________________________________
Submitted in Partial Fulfillment of the Requirements
For the Degree of Master of Science in
Geography
College of Arts and Sciences
University of South Carolina
2015

Accepted by:

Susan L. Cutter, Director of Thesis

Christopher T. Emrich, Reader

Cary J. Mock, Reader

Lacy Ford, Senior Vice Provost and Dean of Graduate Studies
Abstract

Research on tornado impacts has previously focused mainly on analyzing the deaths and injuries associated with tornadoes. While economic loss from multiple hazards is a well-researched field, little has been done to assess the economic losses sustained during tornado events. Additionally, the literature regarding the Enhanced Fujita scale’s comparability to the Fujita scale is limited. This research aims to add to the literature by statistically analyzing the two tornado scales, determining the movement of tornadoes over time using a cluster analysis, comparing the location of extreme tornadoes to those which produce extreme loss, and looking at the statistical relationship between extreme tornadoes and extreme loss.

This study uses tornado data collected from the National Climatic Data Center to analyze tornadoes in the continental United States from 1990-2012. Tornadoes studied were limited to those that included a GPS location and any estimated property or crop damage, no matter how small. Loss estimates were adjusted for inflation using the Consumer Price Index and again using a county Gross Domestic Product method developed by Ash, Cutter, and Emrich (2013).
The results of this thesis conclude that the Enhanced Fujita and Fujita scales are statistically different from one another for lower-rated (0-2) tornadoes, but not for higher-rated ones (3-5). Geographically, clusters of tornadoes have moved northward and eastward over time. This research also demonstrates that the location of extreme tornadoes is not always the same as the location of tornadoes producing extreme loss. Finally, this research shows that economic losses from F/EF5 tornadoes have a greater mean, range, and standard deviation than those from F/EF4 tornadoes.

From a research perspective, this thesis demonstrates the importance of distinguishing between tornadoes rated on the Fujita and Enhanced Fujita scales, since they cannot be considered equivalent to one other. From a policy perspective, local mitigation plans would be improved by taking into account the historical movement of tornado clusters northward and eastward as identified here. Finally, this research has identified that it is not just the extreme tornadoes that deserve mitigation efforts, but also lower-rated tornadoes that are capable of producing millions of dollars in damage.
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Chapter 1: Introduction

Although tornadoes occur in every state in the U.S., historically the Great Plains region has been a hotspot for tornado development. This area, from Texas northward into South Dakota, is known as Tornado Alley. An average of 1,253 tornadoes occur each year across the U.S., with a third of them occurring in Tornado Alley (NOAA NCDC 2014). A second area of high tornado occurrence is located in the South across the states of Arkansas, Louisiana, Mississippi, and Alabama, an area increasingly becoming known as Dixie Alley (see Figure 1.1). While there is debate over whether Dixie Alley is deserving of its own distinctive region, several research studies have shown this area to have counts of damaging tornadoes much like Tornado Alley (Boruff et al. 2003; Changnon 2009; Standohar-Alfano and van de Lindt 2015), whereas other researchers are less certain. In an analysis of tornado days (the number of days in which a tornado occurred) across Tornado and Dixie Alley, Dixon et al. (2011) suggests that Dixie Alley might better be referred to as an extension of Tornado Alley rather than an alley in and of itself. However, research just three years later by Dixon and another researcher, Coleman (2014), support the conclusions of the other researchers mentioned above when limiting their analysis to tornadoes rated F2 and higher.
Before the invention of Doppler radar, the detection of tornadoes was difficult, particularly for those tornadoes located outside urban areas. Until then, the National Weather Service (NWS) would typically be informed of a tornado by the visual confirmation of a tornado by the public. This meant that the location of detected tornadoes was skewed toward populated areas. With the implementation of Doppler radar in 1989, as well as the increase in the number of storm spotters in the 1990s (McCarthy 2003), tornadoes outside cities were less likely to be missed. However, most of the increase in reported tornadoes since the implementation of Doppler radar has
come from the detection of EF-0 tornadoes (Doswell III, Brooks, and Dotzek 2009). This is because most of the more damaging tornadoes were already being detected through other means.

Before Doppler radar, the only thing that could be detected by radar was the intensity with which the rain was falling. Doppler radar has the added benefit of being able to detect the velocity of the rain (Bluestein 2006). This additional information on a storm’s movement helps to detect the spinning vortices of tornadoes without visual confirmation of a tornado on the ground. This allows for the issuance of tornado warnings before visual confirmation of a tornado, given that the atmospheric conditions are right (Friday 1994). With Doppler radar, meteorologists can identify velocity couplets, which indicate the likely presence of a tornado, even when the signature hook echo is not clearly visible on radar reflectivity. An example from Yazoo City, MS is shown below (Figure 1.2). The image on the left is the reflectivity radar and the image on the right shows the storm’s velocity (U.S. Department of Commerce 2010). In both cases the overlaid circle shows the approximate location of the tornado at the time of the radar scan. Although the hook is not clearly visible when looking at reflectivity, the rotating wind speeds (velocity couplet) are quite evident when looking at the velocity radar, indicating to meteorologists that a tornado warning should be issued for Yazoo City and its surrounding area. This particular tornado caused damage consistent with an EF-4 across northeast Louisiana and central Mississippi.
1.1 Research Questions

While tornadoes are probably better known for the number of deaths and injuries associated with them, it is also important to consider the impacts a tornado has on the local economy due to the property and crop damage that occurs. By analyzing the economic losses associated with tornadoes in the continental United States from the years 1990 to 2012, this research addresses the following:
1. Is the newly implemented Enhanced Fujita scale comparable to the original Fujita scale in the number of tornadoes reported each year for each category?

2. What is the spatial distribution of tornadoes in the United States from 1990-2012, and how has that distribution changed geographically over time?

3. How does the spatial distribution of extreme (EF-4 or EF-5) tornadoes compare to the spatial distribution of tornadoes producing extreme (> $1 million) property and crop damage?

4. Is there a statistical relationship between extreme tornadoes (in terms of damage potential) and extreme property and crop damages?

1.2 Organization of the Thesis

This thesis is organized into six chapters, a list of references, and one appendix. The second chapter provides background information and a literature review of current knowledge of tornado classification, casualties from tornado events, and economic losses from disasters. Chapter three explains the data sources and methods. Chapter four describes the results of the analysis comparing the Fujita and Enhanced Fujita scales and analyzing the geographic location of tornadoes. Chapter five includes the results of identifying areas of high economic loss from tornadoes and finding a statistical relationship between extreme economic loss and extreme tornadoes. Chapter six concludes with a summary and some thoughts on potential future research.
Chapter 2: Background

Tornado climatology is a well-researched field, but there is less information about the spatial distribution of societal impacts associated with these events. With potential increases in severe weather under changing climate conditions, an historic assessment of economic losses and their geographical patterning is long overdue.

2.1 Tornado Classification

Tornadoes in the United States are currently classified into six categories based on the amount of damage they cause. This level of damage is then translated to an estimated wind speed using the Enhanced Fujita (EF) scale. The original Fujita-Pearson scale (more commonly referred to as just the Fujita scale) was created in 1971 with the goal of categorizing different tornadoes by their area and intensity (Fujita 1971). However, this scale led to inconsistent tornado ratings due to the “lack of damage indicators, no account of construction quality and variability and no definitive correlation between damage and wind speed” (Wind Science and Engineering Center 2006, 6). To eliminate some of these problems, the National Weather Service in 2007 upgraded to the Enhanced Fujita scale, a modified version of the original scale, developed by researchers at the Wind Science and Engineering Center at Texas Tech University (Wind Science and Engineering Center 2006). A comparison of the wind speeds associated with the Fujita and Enhanced Fujita scales is in Table 2.1.
Table 2.1: Comparison of Wind Speeds and Rating, Fujita & Enhanced Fujita Scales (adapted from Standohar-Alfano and van de Lindt 2015)

<table>
<thead>
<tr>
<th>Fujita Scale</th>
<th>Enhanced Fujita Scale</th>
</tr>
</thead>
<tbody>
<tr>
<td>F Number</td>
<td>3 Second Gust (mph)</td>
</tr>
<tr>
<td>0</td>
<td>45-78</td>
</tr>
<tr>
<td>1</td>
<td>79-117</td>
</tr>
<tr>
<td>2</td>
<td>118-161</td>
</tr>
<tr>
<td>3</td>
<td>162-209</td>
</tr>
<tr>
<td>4</td>
<td>210-261</td>
</tr>
<tr>
<td>5</td>
<td>262-317</td>
</tr>
</tbody>
</table>

The EF scale includes 28 damage indicators (Table 2.2) to help classify a tornado’s intensity (Standohar-Alfano and van de Lindt 2015), while the original Fujita scale had only been based on one damage indicator – a well-constructed home (Doswell III, Brooks, and Dotzek 2009). Each indicator has between three and twelve degrees of damage, each with an estimated, lower-bound, and upper-bound wind speed assigned to it. In the field, estimated wind speeds are used unless the surveyor determines a different wind speed to be more accurate for reasons such as local building code or the damaged building’s quality of construction. To determine the overall rating of the tornado, meteorologists use the highest wind speed estimate that was determined using the damage indicators. For example, if a tornado collapsed the walls of the cafeteria at a local high school, the expected wind speed would be 114 mph, according to this particular degree of damage (level seven of eleven). After completion of the assessment, if no other damage indicator showed winds higher than 114 mph, then the tornado would be rated EF-2.
Table 2.2: EF Scale Damage Indicators (Source: Wind Science and Engineering Center 2006)

<table>
<thead>
<tr>
<th>Damage Indicator</th>
</tr>
</thead>
<tbody>
<tr>
<td>1 Small Barns of Farm Outbuildings</td>
</tr>
<tr>
<td>2 One-of Two-Family Residences</td>
</tr>
<tr>
<td>3 Manufactured Home – Single Wide</td>
</tr>
<tr>
<td>4 Manufactured Home – Double Wide</td>
</tr>
<tr>
<td>5 Apartments, Condos, Townhouses [3 Stories or Less]</td>
</tr>
<tr>
<td>6 Motel</td>
</tr>
<tr>
<td>7 Masonry Apartment or Hotel Building</td>
</tr>
<tr>
<td>8 Small Retail Building [Fast Food Restaurants]</td>
</tr>
<tr>
<td>9 Small Professional Building [Doctor’s Office, Branch Banks]</td>
</tr>
<tr>
<td>10 Strip Mall</td>
</tr>
<tr>
<td>11 Large Shopping Mall</td>
</tr>
<tr>
<td>12 Large, Isolated Retail Building</td>
</tr>
<tr>
<td>13 Automobile Showroom</td>
</tr>
<tr>
<td>14 Automobile Service Building</td>
</tr>
<tr>
<td>15 Elementary School [Single Story; Interior or Exterior Hallways]</td>
</tr>
<tr>
<td>16 Junior or Senior High School</td>
</tr>
<tr>
<td>17 Low-Rise Building [1-4 Stories]</td>
</tr>
<tr>
<td>18 Mid-Rise Building [5-20 Stories]</td>
</tr>
<tr>
<td>19 High-Rise Building [More than 20 Stories]</td>
</tr>
<tr>
<td>20 Institutional Building [Hospital, Government or University Building]</td>
</tr>
<tr>
<td>21 Metal Building System</td>
</tr>
<tr>
<td>22 Service Station Canopy</td>
</tr>
<tr>
<td>23 Warehouse Building [Tilt-up Walls or Heavy-Timber Construction]</td>
</tr>
<tr>
<td>24 Electrical Transmission Lines</td>
</tr>
<tr>
<td>25 Free-Standing Towers</td>
</tr>
<tr>
<td>26 Free-Standing Light Poles, Luminary Poles, Flag Poles</td>
</tr>
<tr>
<td>27 Trees: Hardwood</td>
</tr>
<tr>
<td>28 Trees: Softwood</td>
</tr>
</tbody>
</table>

One limitation of the EF scale is that the majority of the damage indicators only look at damage caused to structures, such as homes and other buildings. The two indicators for non-structures look at the damage caused to hardwood and softwood trees (Wind Science and Engineering Center 2006). The lack of damage indicators for
non-structures makes the location of a tornado extremely important. Two identical tornadoes in terms of size and intensity could receive two very different ratings if one is located in a densely populated area and the other develops in a rural field, simply due to the large difference in the density of structures. Consequently, a low-rated tornado in a field can cause a high amount of crop damage but still be rated low because few structures were in its path. As McCarthy (2003, 3) noted, rural tornadoes “do not have the potential” of being rated higher than EF-2 because of the wind damage estimates currently used in the Enhanced Fujita scale.

Since the actual wind speeds inside a tornado can rarely be calculated, the estimations given by the EF scale provide a proxy measure of what the winds might have looked like at the time the tornado was at its strongest. However, it is important to remember that tornadoes are rated based on damage, not wind speed. For example, on May 31, 2013, a tornado in El Reno, OK was close enough to mobile research radars that its winds could be measured in real-time. Winds associated with this storm were upwards of 250 mph (U.S. Department of Commerce 2014), causing the NWS to give the tornado a preliminary rating of EF-5. After NWS employees completed the damage assessment, the tornado was downgraded to an EF-3, because of the lack of EF-5 type damage in the tornado’s path. Because tornadoes are rated solely based on damage, the estimated wind speeds associated with the rating could under or over-represent the actual wind speeds inside the tornado.

Because of the relatively recent implementation of the Enhanced Fujita scale, not much research has been done to compare the two scales. While the EF scale was
designed to resemble the F scale, the question of how comparable the scales are has yet to be sufficiently answered. The one study that has been done (Edwards and Brooks 2010) was published only three years after the implementation of the Enhanced Fujita scale, and had limited tornado data with which to work. Nonetheless, results showed that the Enhanced Fujita scale caused an increase in the number of tornadoes rated 1 and 2, and a decrease in those rated 0, when compared to the original Fujita scale.

2.2 Tornado Casualties

Past research has compared tornado deaths to extreme tornadoes, and for good reason: from 1975 to 1994, tornadoes caused the most injuries and the second most number of deaths of any natural hazard in the United States (Mileti 1999). Fortunately, as warnings and detection technologies have improved over time, tornado deaths and injuries have decreased, with the decline apparent even when controlling for population increases (Simmons and Sutter 2011). Ashley (2007), for example, found that from 1950-2004, F4 and F5 tornadoes caused 67.5% of tornado deaths, while they only represented 2.1% of all tornadoes during the 55-yr period. His research showed that most tornado deaths occurred in the southeastern United States, whereas Tornado Alley saw a small number of deaths compared to other parts of the country. Ashley’s study looked at tornadoes from before and after the Fujita scale, and although he does not explain the re-analysis to determine Fujita scale ratings for tornadoes before 1971, it is likely that these tornadoes were rated by Fujita himself, as he and his team went back after the development of the Fujita scale and assigned F-scale ratings to historical tornadoes based on written records of damage (Wind Science and Engineering Center 2006).
2.3 Economic Losses from Disasters

Death tolls from tornadoes and other natural hazards can be decreased by the implementation of better forecasts, warnings, and family or personal emergency plans (White 1994; Brooks and Doswell 2001). However, the same cannot be said of economic losses, which have increased over time even while the number of deaths caused by disasters has decreased. Boruff et al. (2003) studied tornado hazards (defined as tornado events involving some aspect of human loss, from death, injury, or property or crop damage) from 1950 to 2000, looking specifically at the spatial distribution of tornado hazards by decade. They found that tornado deaths and injuries decreased over time, but economic losses did not show a similar pattern when adjusted for inflation.

Global economic losses have increased over the last thirty years, with 57% of the increase due to North American storms (Mohleji and Pielke 2014). In fact, since the 1990s average annual total dollar loss from disasters in the United States is $15 billion (Gall et al. 2011). This number continues to increase each year, and Gall and colleagues showed that the pattern of increase was present even when changes in wealth and population are taken into account. However, this is not a universally agreed-upon conclusion, as other research attributes the increase in loss over time to increases in population and economic assets. In particular, research by Visser, Petersen, and Ligtvoet (2014) concluded that there has been no significant change in economic loss from disasters since 1980 when accounting for these changes. Either way, this upward trend is likely to cause the increase in disaster losses to exceed economic growth in the future.
A question that arises is whether or not this type of pattern holds when examining one type of hazard – tornadoes.

An analysis of economic losses from tornadoes and other natural hazards such as hurricanes is complicated by the need to adjust the dollar amounts for changes in time. Past research (Brooks and Doswell 2001; Pielke and Landsea 1998; Simmons, Sutter, and Pielke 2013) identified three reasons for the increase in unadjusted economic losses over time: 1) increases in population increase the amount of property at risk; 2) inflation over time increases the dollar value of property; and 3) growth of personal wealth increases the amount of property people own. The third reason is based on the assumption that each generation will be wealthier than the previous generation, a premise that is no longer true.

Past research has shown Tornado Alley to be a hotspot for tornado “catastrophes,” defined by Changnon (2009) as tornadoes producing more than $1 million in insured damages. This threshold was chosen because 98% of all US loss can be represented by storms (hurricanes, tornadoes/thunderstorms, and winter storms) which produce more than $1 million in damage. While Tornado Alley is an area of lower deaths (Ashley 2007), it is also an area of higher economic losses from tornadoes. Final results of the Brooks and Doswell (2001) study of economic losses from major tornadoes across the United States from 1890 to 1999 show that increasing damages throughout time are due to increased wealth and material value, rather than changing atmospheric conditions. More recent research agrees with these results, finding that the distribution of tornado catastrophes adjusted over time for the United States does not show any
notable temporal changes in frequency or amount of damage (Changnon 2011). In contrast, Simmons, Sutter, and Pielke (2013) used a number of different normalization methods and found that each approach showed a reduction in tornado losses over time, but it was difficult to determine the exact cause of the decline, partially because of the changing reporting methods over time. Different research has produced mixed results, but there is some agreement in the literature that tornado losses increase over time. However, there is still debate whether economic losses from tornadoes have decreased or remained the same over time.

2.4 Chapter Summary

The method for rating tornadoes by NWS employees changed in 2007 with the switch from the Fujita to the Enhanced Fujita scale. Because this change occurred so recently, not much research has been done to see the differences in ratings between the two scales. Most of the research surrounding tornadoes has focused on deaths and injuries, and there is much less literature available regarding the economic losses associated with tornado events. Of the studies that have been done, results are mixed, and it is not yet clear how economic loss from tornadoes has changed over time.
Chapter 3: Methodology

3.1 Data Sources and Limitations

For this study, data were collected from the National Climatic Data Center (NCDC)'s Storm Events Database (available online at https://www.ncdc.noaa.gov/stormevents/). Information obtained from the database includes date, time, and location of the tornado (including latitudes and longitudes for the starting and ending points), as well as property and crop losses. Other information such as the number of injuries and deaths, and the length and width of the tornado appears in the database but was not used for this study.

This dataset was chosen because of the inclusion of GPS coordinates in the data as well as the way in which economic loss data is recorded. Including geographic data specific to a single point makes the Storm Events database stand out from other databases designed to measure loss, such as the Spatial Hazards Events and Losses Database of the United States (SHELDUS). In both NCDC’s Storm Events database and in SHELDUS, the data is based purely on the value of the damaged property and crops, as determined by NWS surveyors. A different option would be to use insurance data to provide the economic loss estimates. However, this greatly increases the average economic loss associated with a tornado because the insurance data also includes the contents of the structure and the cost of rebuilding (Changnon 2009). In 2006 dollars,
tornado losses amount to an estimated $982 million per year using insurance data versus $462 million per year using data from NCDC (Changnon 2009). Since the cost of rebuilding is not necessarily reflective of the amount of damage caused by the tornado event, insurance data is not included in this research.

As with any data set, there are some limitations with using the data from NCDC’s Storm Events database:

1. While information is provided on the starting and ending points of the tornado, there is no data on the location of the tornado between those two points. Very few tornadoes are accurately represented by a straight line, but by looking at the larger scale of tornado events across the continental United States, this limitation is minimized.

2. NCDC records their data in tornado segments instead of tornado tracks, meaning that a tornado that crosses a county boundary is included in the database twice, as it has two tornado segments associated with it. Unfortunately, this can lead to an overestimation in the counts of tornadoes in a given state, county, or year.

3. Due to the fact that the National Weather Service changed from the Fujita-Pearson scale to the Enhanced Fujita scale in 2007, this Storm Events database includes ratings from both systems. Because it is extremely rare to know the exact wind speed of a tornado, old ratings are unable to be adjusted to the new scale.

4. The guidelines for reporting economic losses have changed over time. Within the Storm Events database, this is visible in the change from a logarithmic scale
reporting method to a dollar amount reporting method in 1995 (Gall, Borden, and Cutter 2009). With the logarithmic scale of reporting, tornado losses are categorized as a range of values, rather than a specific amount. NCDC accounts for this in their online database by recording the losses during those years using each category’s midpoint (Boruff et al. 2003) instead of the minimum (like SHELDUS) or maximum. This means that some losses will inevitably be under-reported, while other losses will be over-reported.

5. Finally, there is the limitation of missing data. Past research has shown that there has been a decline since 1950 in the number of tornadoes, which have reported damages associated with them. Specifically, Simmons and Sutter (2011) showed that 85% of tornadoes had estimated damages included with them in 1950, but that this number has decreased to 45% of tornadoes more recently. While this seems counterintuitive, some possible explanations are the increase in tornadoes reported after the implementation of Doppler radar, or perhaps there has been a decrease over time in the amount of good loss estimates available.

3.2 Data Transformation and Normalization

Tornadoes that had no estimated damage amount or had no GPS coordinate information were excluded from this study. With the tornadoes collected from NCDC that had adequate information associated with them, the economic loss from property and crop damage was adjusted for inflation, using the Consumer Price Index (CPI) standard of 2012 dollars (U.S. Bureau of Labor Statistics 2014). Following Simmons,
Sutter, and Pielke (2013)’s example, the Gross Domestic Product (GDP) from each year was also used to adjust the data for changes in wealth. As using a national adjustment on a local scale does not provide a perfect representation of the local economy, the county GDP calculated by Ash, Cutter, and Emrich (2013) was utilized to adjust for wealth. Each of these adjustments (inflation by CPI, county GDP) was made separately and not combined, in order to see differences in the data using inflation-adjusted dollars versus wealth-adjusted dollars. A diagram showing the transformations made to the data and the general flow of the research is shown in Figure 3.1.

In this research, extreme tornadoes are defined as those rated EF-4 or EF-5, as they are the tornadoes that cause the most damage to life and property. Following the precedent set by Changnon (2011), tornadoes with extreme losses are defined as any tornado which causes more than $1 million in property and/or crop damage when adjusted for inflation or wealth. Using this threshold means that about 10% of tornadoes in this analysis are classified as causing extreme loss (9.35% using CPI inflation and 10.66% when using county GDP inflation).

3.3 Analysis

Comparison of the Fujita and Enhanced Fujita scales was done using the statistical software, SPSS. SPSS v. 22 was used to run a series of Mann-Whitney U tests to determine if the percentages for each rating of the Fujita scale are statistically significantly different from the percentages for each rating of the Enhanced Fujita scale. This test was chosen because the rating percentages consisted of independent samples.
of nonparametric data. The test was run six times to analyze each set of ratings (e.g. F0 and EF-0). Boxplots were also used as a visual comparison of the two scales. The combination of the results from the Mann-Whitney U tests and boxplots helped to answer Research Question 1.

Figure 3.1: Research Diagram for this Thesis, including Data, Methods, and Research Questions
The first part of Research Question 2 asked about the geographic location of tornadoes. Maps were produced to show tornado location by county for all tornadoes, and then again for each tornado rating. To create these maps, the tornado data had to first be summarized by county. That county data was then normalized by county size to determine the number of tornadoes per square mile in each county, to eliminate bias in the analysis due to differing county sizes.

To analyze changes in tornado locations over time, the spatial distribution of tornado clusters was tracked from 1990 to 2012. 1990 was chosen as the starting date to eliminate the bias associated with tornado locations prior to Doppler radar’s implementation in 1989. First, ArcGIS 10.2.2 was used to identify clusters of tornado occurrence by year. For each year studied, an optimized hot spot analysis was run to determine clusters where tornadoes were more active for that year. The optimized hot spot analysis looks for hot and cold spots using the Getis-Ord Gi* statistic. This statistic finds spatial clusters by calculating a z-score based on the assigned value of a geographic location and the values of its surrounding neighbors (Getis and Ord 1992). Areas with higher than expected z-scores are labeled as hot spots, and areas with lower than expected z-scores are labeled as cold spots (ESRI 2012). The optimized hot spot analysis works by overlaying a fishnet polygon (grid) on the tornado data and then counting the number of tornadoes within each polygon of the grid. Once the clusters were outputted by ArcGIS, a polygon was considered part of a cluster if 1) the analysis revealed it was a hot spot with 95% or greater statistical confidence, or 2) if the polygon was a hot spot with 90% or greater statistical confidence and connected by either a border or vertex to
a polygon identified as a hot spot with 95% or greater statistical confidence. Polygons in each cluster were labeled numerically, and the geographic center of the cluster was calculated for each group of polygons. The yearly mean geographic location was plotted in ArcGIS to produce a map of tornado cluster movement over time.

To see statistically how tornado cluster location has changed from 1990 to 2012, an analysis of variance (ANOVA) and a difference of means test comparing clusters from 1990 and 2011 were run using SPSS. Additionally, the mean latitude and longitude of the clusters identified above were plotted over time to see annual trends. The identification of areas where the occurrence of tornadoes changed over time helped to answer Research Question 2.

Bivariate maps were created using ArcMap 10.2 to answer Research Question 3. First, tornado data was summarized by county, as a bivariate analysis cannot utilize GPS data. For each county, the total number of tornadoes with losses exceeding $1 million using both inflation methods (inflation by county GDP and inflation by CPI) was determined, as well as the total number of F/EF 4 and F/EF 5 tornadoes that occurred in the county. The number of extreme tornadoes in each county was compared to the number of tornadoes producing extreme loss in each county to create the bivariate map. Two maps of bivariate analyses were created to show where extreme loss and extreme tornadoes occur in the same place.

The spatial autocorrelation statistic, Moran’s I, was also used to help answer this question. Because there were two variables in this part of the analysis (tornadoes rated
F/EF 4 and F/EF 5 and tornadoes with more than $1 million in economic loss), the software program GeoDa was used. GeoDa is unique in that unlike the traditional Moran’s I statistic, the statistic employed by GeoDa is capable of bivariate spatial autocorrelation (Anselin, Syabri, and Kho 2006). GeoDa v. 1.6.6 helped to identify clusters of counties which had high numbers of tornadoes with extreme economic loss and which were surrounded by counties with large numbers of extreme tornadoes.

The bivariate Moran’s I analyses were run using two different contiguity weights. The rook contiguity weight identifies neighbors as counties with which a county shares a border, while the queen contiguity weight defines neighbors as those that share vertices, as well as borders. This difference shows up mostly when counties are in a gridded pattern, as is the case with counties in the central United States. When counties are not in that gridded shape, the difference between the rook and queen contiguity weights is quite small (GeoDa Center for Geospatial Analysis and Computation n.d.). Local measures of spatial autocorrelation (LISA) maps were created to analyze extreme economic loss and extreme tornado count using 999 permutations and a significance filter of .05. Additionally, the number of non-extreme (F/EF 0-3) tornadoes was counted for each county, and another LISA map was created for a comparison of extreme loss and non-extreme tornadoes.

To answer Research Question 4, SPSS v. 22 was used to run descriptive statistics to determine the statistical relationship between extreme tornadoes and extreme losses. All tornadoes which were rated as F/EF 4 or F/EF5 and which had an economic loss of greater than $1 million were analyzed using both methods of inflation. The list of
tornadoes produced by each inflation method was compared using t-tests to determine their similarity with one another. Finally, a boxplot was created in SPSS to help visualize the differences between F/EF4 tornadoes producing extreme loss and F/EF5 tornadoes producing extreme economic loss.

3.4 Chapter Summary

The tornado data used in this thesis was collected from NCDC’s Storm Events database. This database was chosen over other loss-estimating databases because of NCDC’s inclusion of GPS coordinate data with each tornado event. Loss estimates for each tornado were adjusted for inflation using two methods, the standard CPI method and a county GDP method. This chapter also identified the several ways data would be analyzed in order to answer the four research questions.
Chapter 4 : All Tornadoes, Results and Discussion

4.1 Comparison of Fujita & Enhanced Fujita Scales

Research Question 1 asked if the Enhanced Fujita scale is comparable to the original Fujita scale in the number of tornadoes reported each year for each category. The number of tornadoes of each rating for each year was counted, and then divided by the total number of tornadoes that year for standardization purposes, giving each rating a percentage of tornadoes for each year. Those percentages were then analyzed in the form of a boxplot (Figure 4.1). Outliers and extreme outliers (as identified by SPSS) are shown with circles and stars, respectively. A preliminary look at the boxplots indicates that the majority of tornadoes which occur in a given year are rated as 0 on both scales, and that as the rating increases, the number of tornadoes which occur in a year decreases. Appendix A shows boxplots of each tornado rating separately to help highlight the finer details, particularly for the more highly rated tornadoes.

A Mann-Whitney U Test was run in SPSS for each pair of ratings (e.g. F0 and EF-0). Table 4.1 shows the results of each test and the n for each rating. The observed U-statistics identified as statistically significant at the alpha=.10 level are denoted with a star, and those identified as significant at alpha=.05 are denoted with two stars.
Figure 4.1: Comparison of Fujita and Enhanced Fujita Scales’ Annual Rating Percentages. Outliers are represented as circles and extreme outliers are represented as stars.

Table 4.1: Mann-Whitney U Test Comparing the Fujita and Enhanced Fujita Scales

<table>
<thead>
<tr>
<th>F/EF Rating</th>
<th>n</th>
<th>Fujita Scale Mean Rank</th>
<th>Enhanced Fujita Scale Mean Rank</th>
<th>U-statistic</th>
</tr>
</thead>
<tbody>
<tr>
<td>0</td>
<td>12,081</td>
<td>14.00</td>
<td>6.33</td>
<td>17.000**</td>
</tr>
<tr>
<td>1</td>
<td>7,166</td>
<td>10.35</td>
<td>16.67</td>
<td>23.000**</td>
</tr>
<tr>
<td>2</td>
<td>2,514</td>
<td>10.53</td>
<td>16.17</td>
<td>26.000*</td>
</tr>
<tr>
<td>3</td>
<td>875</td>
<td>11.41</td>
<td>13.67</td>
<td>41.000</td>
</tr>
<tr>
<td>4</td>
<td>229</td>
<td>12.12</td>
<td>11.67</td>
<td>49.000</td>
</tr>
<tr>
<td>5</td>
<td>31</td>
<td>11.88</td>
<td>12.33</td>
<td>49.000</td>
</tr>
</tbody>
</table>

** significant at p≤.05; * significant at p≤.10
Results of this test indicate that the Fujita and Enhanced Fujita scale are not comparable for tornadoes rated as 0, 1, and 2. The Fujita Scale mean rank is higher than the Enhanced Fujita scale mean rank for F0 and EF0 tornadoes, showing a statistically significant higher percentage of tornadoes rated as F0 than EF0. For tornadoes rated 1 and 2, the opposite is true, with a greater percentage of EF1 and EF2 tornadoes as compared to F1 and F2 tornadoes. This confirms what Edwards and Brooks (2010) discovered in their analysis of the early years (2007-2009) of the Enhanced Fujita scale. From this, it appears that there has been an increase in EF-1 and EF-2 tornadoes at the expense of EF-0 tornadoes. However, more intense, damaging tornadoes (those rated F/EF3, F/EF4, and F/EF5) do not show a statistically significant difference between the two scales.

When thinking about the switch from the Fujita to the Enhanced Fujita scale in 2007, these results make sense. While the Fujita scale only provided one damage indicator, the Enhanced Fujita scale provides 28, including indicators such as trees and outbuildings (Wind Science and Engineering Center 2006), which allows for a better analysis of the damage. This could, in turn, cause tornadoes that would have been rated F0 on the Fujita scale to be rated EF-1 or EF-2 on the new scale due to the increase in available damage indicators. Since the Enhanced Fujita scale was created to provide a better, more accurate assessment of tornado strength, it follows that some tornadoes rating as F0 on the Fujita scale were actually reporting an underestimation of intensity and damage.
4.2 Geographic Locations of Tornadoes

The location of tornadoes from 1990 to 2012 was summarized by county and plotted in ArcGIS to show the geographic clustering of tornadoes over the entire period studied. Figure 4.2 shows counts of all tornadoes by county for the 23-year period. Areas highlighted in this analysis include Florida, Dixie Alley (specifically Mississippi and Alabama) and Tornado Alley. Traditionally Colorado is not included in Tornado Alley; however, this map shows that the eastern half of Colorado also has a high number of tornadoes, and it presents itself as a westward continuation of Tornado Alley. Some counties in the southwestern United States where one would not typically expect to see tornadoes are also highlighted in this analysis, due to their larger county sizes. Larger counties can result in a larger number of tornadoes within a county because there is more space for a tornado to occur in the county. This problem is solved when the data is normalized by county area (Figure 4.3).

The results of Research Question 1 found that the Enhanced Fujita and Fujita scales are not directly comparable for tornadoes rated 0, 1, and 2. Therefore, when looking at maps of tornado counts by rating, each tornado rating must be analyzed separately (Figure 4.4). The same did not have to be done for tornadoes rated 3, 4, and 5, because the two scales did not show a statistically significant difference between them. These maps show that while much of the United States is impacted by tornadoes on the lower end of the scales, the places with more damaging tornadoes are typically confined to Tornado and Dixie Alleys (see Figures 4.5, 4.6, and 4.7).
Figure 4.2: Geographic Location of Tornadoes by County, 1990-2012.
Figure 4.3: Tornadoes per Square Mile, 1990-2012.
Figure 4.4: Geographic Locations of F/EF0-2 Tornadoes by County. a) FO, b) EF0, c) F1, d) EF1, and f) EF2.
Figure 4.5: Geographic Location of F/EF3 Tornadoes by County
Figure 4.6: Geographic Location of F/EF4 Tornadoes by County
To analyze change in tornado location over time, an optimized hot spot analysis was run in ArcMap for each year. Clusters identified by this analysis were counted and the geographic center of each cluster was calculated. The mean latitude and longitude and number of clusters identified for each year is included in Table 4.2. Utilizing the mean rather than the median allows for the inclusion of clusters which were located away from other clusters. No clusters were identified for five years of the study period: 2000, 2001, 2002, 2006, and 2012.
Table 4.2: Yearly Hot Spot Cluster Summaries

<table>
<thead>
<tr>
<th>Year</th>
<th>Number of Clusters</th>
<th>Mean Latitude</th>
<th>Mean Longitude</th>
</tr>
</thead>
<tbody>
<tr>
<td>1990</td>
<td>5</td>
<td>36.729</td>
<td>-96.250</td>
</tr>
<tr>
<td>1991</td>
<td>8</td>
<td>36.031</td>
<td>-102.844</td>
</tr>
<tr>
<td>1992</td>
<td>1</td>
<td>37.321</td>
<td>-98.681</td>
</tr>
<tr>
<td>1993</td>
<td>5</td>
<td>32.316</td>
<td>-99.782</td>
</tr>
<tr>
<td>1994</td>
<td>2</td>
<td>36.328</td>
<td>-97.698</td>
</tr>
<tr>
<td>1995</td>
<td>1</td>
<td>34.352</td>
<td>-99.187</td>
</tr>
<tr>
<td>1996</td>
<td>1</td>
<td>37.955</td>
<td>-76.479</td>
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<tr>
<td>1997</td>
<td>1</td>
<td>28.203</td>
<td>-81.737</td>
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<tr>
<td>1998</td>
<td>1</td>
<td>40.057</td>
<td>-89.290</td>
</tr>
<tr>
<td>1999</td>
<td>10</td>
<td>35.696</td>
<td>-94.587</td>
</tr>
<tr>
<td>2003</td>
<td>8</td>
<td>39.020</td>
<td>-92.925</td>
</tr>
<tr>
<td>2004</td>
<td>6</td>
<td>38.287</td>
<td>-86.706</td>
</tr>
<tr>
<td>2005</td>
<td>3</td>
<td>33.540</td>
<td>-90.332</td>
</tr>
<tr>
<td>2007</td>
<td>7</td>
<td>37.753</td>
<td>-100.560</td>
</tr>
<tr>
<td>2008</td>
<td>7</td>
<td>35.371</td>
<td>-94.146</td>
</tr>
<tr>
<td>2009</td>
<td>11</td>
<td>33.735</td>
<td>-92.927</td>
</tr>
<tr>
<td>2010</td>
<td>11</td>
<td>40.386</td>
<td>-97.501</td>
</tr>
<tr>
<td>2011</td>
<td>3</td>
<td>35.282</td>
<td>-88.284</td>
</tr>
</tbody>
</table>

An example of the optimized hot spot analysis and resulting clusters is shown in Figure 4.8 and Figure 4.9, respectively. In this year, five clusters were identified. Cluster 1 is centered in northern Kansas. Cluster 2 is a lone polygon in the panhandle of Oklahoma. Cluster 3 is centered in the Texas panhandle while Cluster 5 is centered in far east Texas. Cluster 4 is unique in that it occurs outside of Tornado and Dixie Alleys, and can be explained by a tornado outbreak occurring in June of that year that produced sixty-five tornadoes across Indiana and the Ohio Valley (National Weather Service 2015).
Figure 4.8: Raw Results of the Optimized Hot Spot Analysis for Tornadoes in 1990.
Figure 4.9: Clusters of Tornadoes in 1990, as Identified by the Optimized Hot Spot Analysis. The color shading represents the cluster number.

The mean geographic location for each year was plotted in ArcGIS to show how the tornado clusters moved spatially with time (Figure 4.10). Two years (1996 and 1997) stand out as an anomaly as they are much further east than the other years. This can be explained by the fact that each of those years produced only one significant cluster in the analysis.
Figure 4.10: Mean Geographic Location of Tornado Clusters over Time. No significant clusters were identified for 2000, 2001, 2002, 2006, or 2012.

A one-way analysis of variance (ANOVA) was run on both latitudes and longitudes (Table 4.3) using year as a factor. Both F-statistics associated with the ANOVAs were statistically significant. A two-tailed t-test was also run to compare the mean location of tornadoes in 1990 versus 2011 (the last year which had identifiable clusters). The results of the t-test are in Table 4.4. Neither t-statistic was significant at the alpha≤.05 level.
Table 4.3: One-Way ANOVA on Yearly Mean Cluster of Latitude and Longitude

<table>
<thead>
<tr>
<th></th>
<th>df (between groups)</th>
<th>df (within groups)</th>
<th>F-statistic</th>
</tr>
</thead>
<tbody>
<tr>
<td>Latitude</td>
<td>17</td>
<td>73</td>
<td>3.750*</td>
</tr>
<tr>
<td>Longitude</td>
<td>17</td>
<td>73</td>
<td>6.310*</td>
</tr>
</tbody>
</table>

* significant at p=.05

Table 4.4: Two-Tailed T-Test on Mean Latitude and Longitude from 1990 and 2011 Clusters

<table>
<thead>
<tr>
<th></th>
<th>df</th>
<th>t-statistic</th>
</tr>
</thead>
<tbody>
<tr>
<td>Latitude</td>
<td>6</td>
<td>.787</td>
</tr>
<tr>
<td>Longitude</td>
<td>6</td>
<td>-1.929</td>
</tr>
</tbody>
</table>

The ANOVA shows that there was a statistically significant change in latitude and longitude over time (using alpha=.05). However, this analysis does not say where the change occurred, and the two-tailed t-test showed that there isn’t a significant difference in mean latitude and longitude in 1990 compared to 2011. This means that any change in latitude and longitude over time took place annually between the start and end of the study period. To determine the general direction of where tornadoes may have moved between 1990 and 2011, the mean latitude and longitude for each year was plotted (Figure 4.11 and Figure 4.12, respectively).

The change in latitude over time does not show consistent movement north or south over time. However, after adding a linear trend line to the data, the change in mean latitude over time appears to move north. When looking at the change in
longitude, it appears that tornadoes have gradually been moving further east over time. However, the argument could be made that a binomial trend line is a better fit of the data (Figure 4.13). In this case, the trend line shows movement eastward from 1990 up until the early 2000s, when tornadoes began moving back westward.

Figure 4.11: Change in Mean Cluster Latitude over Time
Figure 4.12: Change in Mean Cluster Longitude over Time, Linear Trend Line

p-value: .542
This analysis has shown that tornadoes are most likely to occur in Tornado Alley, Dixie Alley, and Florida, and less likely to occur west of the Rocky Mountains and in the far northeastern United States (Figure 4.3). However, the location of tornadoes has changed over time. From 1990 to 2012, cluster analyses shows that the location of tornadoes has moved eastward and northward over time. The determination that tornadoes have moved eastward over time aligns with earlier work by Boruff et al. (2003), who used a different method to achieve similar results. However, it is possible that this eastward movement of tornadoes was halted in the early 2000s, right around
the time they published their findings. It was then, according to the binomial trend line, that tornado movement shifted back westward, although perhaps not as far west as the clusters initially were in 1990. Additionally, Boruff et al. (2003) determined the latitudinal movement of tornadoes to be southward, whereas this analysis showed that tornadoes have moved northward. This difference is likely due to the fact that Boruff and colleagues used the locations of all tornadoes in their analysis, while this analysis studied the geographic locations of spatially identified clusters. Thus, it is possible that while the location of all tornadoes has moved southward over time, spatially-identified clusters of tornadoes have moved in the opposite direction.

4.3 Chapter Summary

Research in this chapter has shown that lower-end tornadoes rated on the Fujita scale cannot be compared to lower-end tornadoes rated on the Enhanced Fujita scale, as there is a statistically significant difference between the average yearly percentages for 0-2 tornadoes. This analysis has also shown that tornadoes have moved northward and eastward over time. It is hard to determine where tornadoes will move on from here. If tornadoes continue to occur further north as time goes on, cities in northern Tornado Alley and to the north of Dixie Alley will see an increase in tornado threat. New communities which have not seen many tornadoes in the last twenty years will have to adapt to a changing tornado climate in which more tornadoes are likely to occur in their area. Additionally, it is unclear where tornadoes will move longitudinally over time. Will they continue to move back westward as the binomial trend line has suggested, or will the cycle repeat itself in the near future, with more tornadoes occurring in the east?
Future research is necessary to explore more closely the movement of tornadoes in the coming decades.
Chapter 5 : Extreme Tornadoes, Results and Discussion

5.1 Extreme Economic Loss and Extreme Tornadoes

To compare the spatial distribution of extreme tornadoes to tornadoes producing extreme economic loss, the number of F/EF 4 and F/EF 5 tornadoes in each county and the number of tornadoes producing more than $1 million in property or crop damage in each county was counted, using both inflation methods. A bivariate map was then created to visually display where these extremes occurred. Figure 5.1 compares extreme tornadoes to tornadoes with extreme losses using the CPI inflation method, while Figure 5.2 shows similar results using county GDP inflation instead.

Figures 5.1 and 5.2 both show similar areas where the highest number of extreme tornadoes and tornadoes producing extreme loss occur simultaneously. Namely, this is seen in Tornado Alley, specifically in central Kansas and Oklahoma, and in Dixie Alley, in central Mississippi and northern Alabama. The biggest difference between the two maps is that when loss is adjusted for inflation using the county’s GDP, a greater number of tornadoes produce more than $1 million in damage (2012 dollars). This occurs uniformly across the nation and is not centered in one particular area.
Figure 5.1: Geographic Locations of Extreme Economic Loss & Extreme Tornadoes, CPI Inflation Method.
Another way of comparing two variables is to use local measures of spatial autocorrelation (LISA) maps. LISA maps comparing extreme tornadoes to tornadoes producing extreme loss were created from the bivariate Moran’s I statistic available in GeoDa. To create a LISA map, GeoDa considers the characteristics of neighboring counties as well as the individual counties themselves. Therefore, four counties were excluded from the analysis because they have no neighbors – San Juan County in Washington, Richmond County in New York, and Dukes and Nantucket Counties in
Massachusetts. In order to thoroughly answer Research Question 3, the GeoDa analysis was run four times. First, the analysis compared extreme tornadoes to tornadoes with extreme losses using the traditional version of inflation (utilizing the CPI) and the rook contiguity weighting scheme. Then the analysis was run using the queen contiguity scheme and CPI inflation, and finally the analysis was repeated twice more using the GDP inflation method and the rook and queen methods of contiguity.

These four methods produced very similar results. Out of the 3,109 counties studied, only 141 counties were not placed into the same LISA cluster for all four methods. As this small number of counties accounts for merely 4.5% of all counties studied, the differences between the methods are not statistically significant at the p≤.05 level. Therefore, results using the queen contiguity weight and CPI inflation method are shown in the remaining discussion. Six different clusters were identified by GeoDa (Table 5.1), although no counties were placed in LISA Cluster 2 in the analysis.

Table 5.1: Generic LISA Cluster Descriptions

<table>
<thead>
<tr>
<th>LISA Cluster Number</th>
<th>Description</th>
<th>Map Color</th>
</tr>
</thead>
<tbody>
<tr>
<td>0</td>
<td>Not significant</td>
<td>Light Gray</td>
</tr>
<tr>
<td>1</td>
<td>High-High</td>
<td>Red</td>
</tr>
<tr>
<td>2</td>
<td>Low-Low</td>
<td>Dark Blue</td>
</tr>
<tr>
<td>3</td>
<td>Low-High</td>
<td>Light Blue</td>
</tr>
<tr>
<td>4</td>
<td>High-Low</td>
<td>Pink</td>
</tr>
<tr>
<td>5</td>
<td>Neighborless</td>
<td>Dark Gray</td>
</tr>
</tbody>
</table>
The LISA map using the queen contiguity weight and the CPI inflation method is shown in Figure 5.3. Interpretation of the LISA map takes this form: counties with high/low numbers of tornadoes with more than $1 million in economic loss are surrounded by neighboring counties with high/low numbers of tornadoes rated F/EF 4 and 5. Counties with high numbers of tornadoes with extreme losses and surrounding counties with high numbers of extreme tornadoes are shown in red, and are clustered in four general areas. First, there is a cluster of counties in central Oklahoma, extending north into central Kansas and southern Nebraska. There is also a cluster along the northern Kentucky border, where the state borders Indiana and Illinois. An additional cluster occurs in northern Alabama and extends into Tennessee, while a final cluster is present in central Mississippi. In these places, there is a large number of tornadoes with greater than $1 million in economic loss, as well as a high number of F/EF 4 and 5 tornadoes in general. Three of the four clusters also appear to occur in either Tornado or Dixie Alley.

In addition to the counties categorized as High-High (LISA Cluster 1), many counties are categorized as having a high number of tornadoes with large economic loss while being surrounded by counties in which there is a low number of F/EF 4 and F/EF 5 tornadoes (LISA Cluster 4, identified in pink in Figure 5.3). While these counties don’t form easily identifiable clusters, they tell a very interesting story. This shows that there are places that have high economic loss from tornadoes while not having many extreme tornadoes, indicating that there are some lower-rated tornadoes which cause large amounts of economic loss. For examples, Howard County, Maryland is pictured in Figure
5.3 as being part of LISA Cluster 4. When looking at the raw data for Howard County, they had seven tornadoes from 1990 to 2012 – two rated F0, two rated F1, one rated F2, one rated EF0, and one rated EF1. However, two of those tornadoes caused more than $1 million in damages. This finding suggests that extreme loss is not limited to extreme tornadoes.

![LISA Map Comparing Extreme Loss and Extreme Tornadoes](image)

Figure 5.3: LISA Map Comparing Extreme Loss and Extreme Tornadoes.

There are also a few counties defined by low numbers of tornadoes with high economic loss that are surrounded by counties with high numbers of F/EF4 and 5
tornadoes (LISA Cluster 3). These counties tend to appear near clusters of counties
categorized as High-High, but do not form their own clusters individually. This implies
there are places, particularly near Tornado and Dixie Alleys, where large numbers of
extreme tornadoes occur while not producing extreme economic damage.

Since it isn’t always the extreme tornadoes causing extreme damage, another
LISA map was created in GeoDa comparing extreme economic loss to lower-rated
tornadoes (Figure 5.4). New to this map is the addition of many counties in LISA Cluster
2 (low economic loss and low counts of lower-rated tornadoes). These clusters occur in
parts of the country that have few tornadoes of any rating (west of the Rockies, the
northeast US, and along the Appalachian Mountains). In this map, counties in red (LISA
Cluster 1) signify areas of high economic loss and high numbers of F/EF 0-3 tornadoes.
Dixie Alley, Tornado Alley, and Florida show up in this category. However, these are
places that typically have a large number of tornadoes in general. It is more interesting
to look at those places which aren’t as known for the number of tornadoes they have.
Central Iowa (north of and including Des Moines), central Illinois (northeast of
Springfield), southwestern Missouri, eastern North Carolina, and central South Carolina
also show up as areas with high economic loss and higher numbers of lower-rated
tornadoes. Howard County, Maryland is also identified in this LISA cluster. In general
these places were not identified as having high numbers of extreme tornadoes in Figure
5.3; however, they are identified as having high numbers of non-extreme tornadoes in
Figure 5.4. This confirms what was found earlier – that extreme economic loss is not
limited to extreme tornadoes.
The spatial distribution of extreme tornadoes and the spatial distribution of tornadoes producing extreme economic loss coincide in four primary locations: a central strip of Tornado Alley, northern Alabama, central Mississippi, and along the Kentucky/Illinois/Indiana border. However, a large number of counties are identified in Figure 5.3 as having high economic loss and low numbers of extreme tornadoes, which begs the question of whether there are some areas where high numbers of non-extreme tornadoes produce extreme loss. The second LISA map shows that there are
areas, particularly in Iowa, Illinois, Missouri, North Carolina, and South Carolina, which have high numbers of tornadoes that produce extreme economic loss and high numbers of lower-rated tornadoes. When looking at the continental United States as a whole, it is clear that economic loss is not limited to extreme tornadoes, and that there are tornadoes that can produce millions of dollars in loss while still being rated as non-extreme.

5.2 Statistical Relationship between Extreme Economic Loss and Extreme Tornadoes

Before determining the statistical relationship between extreme economic loss and extreme tornadoes, it was important to analyze which tornadoes were extreme and how the lists of extreme tornadoes related to one another. Paired sample t-tests were run to see if extreme tornadoes differed from tornadoes that produced extreme loss. A paired sample t-test was also run to determine if the CPI inflation and GDP inflation methods would produce the same list of tornadoes that produced extreme loss. The results of the t-tests are in Table 5.2. This test determined that all three lists of extreme tornadoes were statistically different from one another (p≤.05), a result that is not surprising in light of the fact that results from this chapter have already shown that tornadoes which produce extreme economic loss are not always the same as tornadoes which are rated as extreme on the Fujita and Enhanced Fujita scales. This test also determined that the two methods of inflation produce different lists of tornadoes with extreme economic loss.
Table 5.2: Paired Sample T-Test Comparing Different Tornado Extremes

<table>
<thead>
<tr>
<th>Pair</th>
<th>t-statistic</th>
<th>Significance</th>
</tr>
</thead>
<tbody>
<tr>
<td>Extreme Tornadoes &amp; CPI-inflated Extreme Loss Tornadoes</td>
<td>-44.133</td>
<td>.000</td>
</tr>
<tr>
<td>Extreme Tornadoes &amp; GDP-inflated Extreme Loss Tornadoes</td>
<td>-48.108</td>
<td>.000</td>
</tr>
<tr>
<td>CPI-inflated Extreme Loss Tornadoes &amp; GDP-inflated Extreme Loss Tornadoes</td>
<td>-15.988</td>
<td>.000</td>
</tr>
</tbody>
</table>

Because not all extreme tornadoes produce extreme loss and not all extreme losses come from extreme tornadoes, the remainder of this analysis looked to compare tornadoes which were rated as extreme on the Fujita or Enhanced Fujita scale and that produced extreme property or crop damage. Tornadoes rated F/EF4 and F/EF 5 that produced more than $1 million in damages after inflation were collected to analyze the statistical relationship between them. When using CPI inflation to determine which tornadoes produced extreme damages, sixty-five tornadoes rated F/EF 4 and six tornadoes rated F/EF 5 were counted. With county GDP inflation, there were again sixty-five F/EF 4 tornadoes, and seven F/EF 5 tornadoes. The fact that sixty-five F/EF 4 tornadoes were identified with both inflation methods does not mean that the tornadoes identified were the same ones, as the statistics performed earlier show that tornadoes identified using the different inflation methods were statistically different. However, it is interesting that the methods produced the same number of F/EF 4 tornadoes, despite their limited comparability. Because of the difference in tornadoes selected, descriptive statistics were analyzed for both sets of data using SPSS (Table 5.3).
Table 5.3: Descriptive Statistics of Extreme Tornadoes Producing Extreme Loss

<table>
<thead>
<tr>
<th>Inflation Method</th>
<th>Range</th>
<th>Mean</th>
<th>Standard Deviation</th>
<th>Kurtosis</th>
</tr>
</thead>
<tbody>
<tr>
<td>CPI</td>
<td>$439,000,000.00</td>
<td>$36,161,192.25</td>
<td>$72,922,914.06</td>
<td>22.509</td>
</tr>
<tr>
<td>GDP</td>
<td>$1,255,253,798.19</td>
<td>$64,346,343.92</td>
<td>$173,360,905.21</td>
<td>35.744</td>
</tr>
</tbody>
</table>

These statistics highlight the difference between the two inflation methods. When using county GDP inflation to determine tornadoes with greater than $1 million in loss, the range, mean, and standard deviation of the tornadoes’ economic losses increases as compared to tornadoes selected using the CPI inflation method. The increase in kurtosis shows that tornado loss using county GDP is more skewed than with tornado loss using CPI inflation. The difference between the two inflation scales also shows up when analyzing F/EF4 and F/EF5 tornadoes separately (Table 5.4 and Table 5.5, respectively).

Table 5.4: Descriptive Statistics of F/EF4 Tornadoes Producing Extreme Loss

<table>
<thead>
<tr>
<th>Inflation Method</th>
<th>n</th>
<th>Range</th>
<th>Mean</th>
<th>Standard Deviation</th>
<th>Kurtosis</th>
</tr>
</thead>
<tbody>
<tr>
<td>CPI</td>
<td>65</td>
<td>$409,000,000.00</td>
<td>$29,180,179.23</td>
<td>$55,298,183.12</td>
<td>36.305</td>
</tr>
<tr>
<td>GDP</td>
<td>65</td>
<td>$785,321,724.84</td>
<td>$45,253,312.19</td>
<td>$100,857,837.09</td>
<td>46.975</td>
</tr>
</tbody>
</table>
Table 5.5: Descriptive Statistics of F/EF5 Tornadoes Producing Extreme Loss

<table>
<thead>
<tr>
<th>Inflation Method</th>
<th>n</th>
<th>Range</th>
<th>Mean</th>
<th>Standard Deviation</th>
<th>Kurtosis</th>
</tr>
</thead>
<tbody>
<tr>
<td>CPI</td>
<td>6</td>
<td>$437,450,000.00</td>
<td>$111,788,833.33</td>
<td>$166,764,931.68</td>
<td>4.527</td>
</tr>
<tr>
<td>GDP</td>
<td>7</td>
<td>$1,254,259,039.47</td>
<td>$241,638,781.46</td>
<td>$454,437,972.32</td>
<td>6.314</td>
</tr>
</tbody>
</table>

Data from Table 5.4 and Table 5.5 show an increase in mean, range, and standard deviation as the tornado’s rating increases from F/EF4 to F/EF5. The kurtosis shows that F/EF5 tornadoes are not as skewed as tornadoes rated F/EF4; however, it is possible that this could be due to the small sample size more than anything else. Finally, to visualize the difference between the two ratings, boxplots were created comparing extreme economic loss to extreme tornado rating. The boxplot using CPI inflation is shown in Figure 5.5.
Figure 5.5: Boxplot Comparing Extreme Tornadoes and Extreme Economic Loss

This boxplot confirms the earlier statement that there is an increase in economic loss with the increase in tornado rating. Ideally, this should be the case for every tornado. As a tornado increases in intensity, there is more structural damage to buildings in the tornado’s path, and so it makes sense that economic loss would also increase.
5.3 Chapter Summary

This analysis has shown that the locations of extreme tornadoes and tornadoes producing extreme loss are not always the same, but that both occur together in central Tornado Alley, eastern Dixie Alley, and along the Ohio River Valley. Statistically, tornadoes can be expected to increase in property and crop damage with an increase in rating from EF-4 to EF-5. Tornadoes with F/EF5 ratings also have a higher range of economic loss than F/EF4 tornadoes, and have a distribution that is more bell-shaped (normal) than that of F/EF4 tornadoes. Additionally, the statistics provide more evidence that extreme tornadoes and tornadoes producing extreme damages are not the same. They also indicate that county GDP and CPI inflation identify different tornadoes as having caused extreme damages. This suggests that the two inflation methods are not always interchangeable, although it is impossible to tell which method provides a more accurate assessment of inflation.
Chapter 6: Conclusion

While deaths and injuries associated with tornadoes is a well-researched field, much less has been done to evaluate the relationship between economic losses and tornado events. This thesis presents an analysis of tornadoes from 1990-2012, specifically focusing on the property and crop losses sustained during these tornado events. Since the National Weather Service switched from the Fujita scale rating system to the Enhanced Fujita scale in 2007, the first part of this research analyzed the comparability between the two scales. The second part looked at the geographic location of tornadoes over time, specifically looking at the movement of tornado clusters as determined by the Getis-Ord Gi* statistic. The final part of this thesis analyzed extreme tornadoes and extreme losses, mapping them geographically and determining the statistical relationship between the two variables.

The implementation of the Enhanced Fujita scale in 2007 brought with it the question of its comparability with the previously used Fujita scale. This research has shown that the two scales are comparable when the tornadoes are rated 3, 4, or 5; however, the scales are not equal when looking at tornadoes rated 0, 1, or 2. Specifically, there has been an increase in the number of tornadoes rated 1 and 2 on the Enhanced Fujita scale, and a decrease in the number of tornadoes rated 0. This verifies previous research done comparing the early years of the two scales. The change in
rating between the two scales can be explained (at least in part) by the way tornadoes are rated on the new scale, which includes twenty-seven more indicators of tornado damage than did the original Fujita scale. Since fewer tornadoes are rated as EF0 on the new scale, it brings into question whether some tornadoes rated F0 on the Fujita scale may in fact be underrepresenting the tornado’s true intensity. As this research has shown that the Fujita and Enhanced Fujita scales are not the same for lower-rated tornadoes, they should not be treated as such in future research.

Tornadoes are most commonly known for their presence in the areas known as Tornado and Dixie Alleys. The answer to the second research question has shown that high numbers of tornadoes do in fact occur in Tornado Alley and Dixie Alley. Additionally, there is an area of high tornado occurrence in the southern portion of the Florida peninsula. An analysis of yearly mean tornado cluster location showed that tornadoes have moved northward and eastward over time. However, this analysis also introduced the possibility that while tornadoes moved eastward from 1990 to the early 2000s, tornadoes have since moved back westward. If this trend continues in the future, areas in northern Tornado Alley and northern Dixie Alley may see more tornadoes than they have in the past. On a more localized scale, communities which reside to the north of where tornadoes occur now may need to make adjustments to their emergency plans to include an increased tornado threat in the future. This research has not been able to clearly determine the movement of tornadoes longitudinally over time, and it is unclear whether tornado clusters will move eastward or westward in the future. Additional
research over a longer study period is needed to determine the future east-west movement of tornadoes.

Research Question 3 showed that areas in the United States characterized by tornadoes with extreme damages and extreme tornadoes include central Tornado Alley, eastern Dixie Alley, and along the Kentucky/Illinois/Indiana border. However, this research has also demonstrated that extreme tornadoes are not always the same tornadoes as those incurring extreme losses. There are parts of the country, particularly in Iowa, Illinois, Missouri, North Carolina, and South Carolina, where tornadoes create a large amount of economic loss but are not defined as extreme tornadoes based on their Enhanced Fujita scale rating. In these areas, non-extreme tornadoes can produce extreme damages. With the increase in the amount of things people own as population and wealth increases in the future, the number of non-extreme tornadoes causing extreme damage could potentially increase.

The fourth research question evaluated the relationship between extreme tornadoes and extreme losses and found that F/EF5 tornadoes have a greater mean, range, and standard deviation than F/EF4 tornadoes, but that the distribution was less skewed. Since an increase in tornado rating from 4 to 5 indicates structures having had greater damage, the increase in average economic loss is not surprising. This research question also looked at the different methods of declaring a tornado as extreme. As shown previously, extreme tornadoes are not the only tornadoes that produce extreme damage. This research has shown that the list of tornadoes rated F/EF4 and F/EF5 is not the same as the list of tornadoes producing more than $1 million in damages using the
CPI method of inflation, and that neither of these lists is the same as the list of
tornadoes producing more than $1 million in damages using inflation by county GDP.
This confirms the earlier statement that producing extreme economic loss is not the
same as a tornado being rated extreme on the Enhanced Fujita scale.

Studying economic losses incurred during tornado events is important to
developing a comprehensive assessment of tornado hazards. The first step,
understanding how economic loss and extreme tornadoes are related, has been started
here. A few questions arise from the results of this research: 1) Why has the location of
tornadoes over time changed, and is that trend likely to continue in the future? 2) How
will the movement of tornadoes over time affect the locations of extreme tornadoes
and tornadoes with extreme losses? 3) How could the Enhanced Fujita scale be
improved to take into account the non-extreme tornadoes that produce extreme
economic loss? Future research aiming to address these questions would help increase
scientists’ understanding of tornado events, and could provide communities with better
ways to mitigate tornado events of the future. With the uncertainty of how climate
change will affect tornado intensity and location, the answers to these questions will
become more important as communities prepare for a changing tornado climate.


Appendix A: Tornado Rating and Counts Boxplots

Figure A.1: Boxplots for F/EF0 Tornadoes
Figure A.2: Boxplots for F/EF1 Tornadoes
Figure A.3: Boxplots for F/EF2 Tornadoes
Figure A.4: Boxplots for F/EF3 Tornadoes
Figure A.5: Boxplots for F/EF4 Tornadoes
Figure A.6: Boxplots for F/EF5 Tornadoes