Investigating El Nino Southern Oscillation and Tornado Activity in Texas

Joel R. Intrieri

Follow this and additional works at: https://scholarworks.wmich.edu/masters_theses

Part of the Geography Commons

Recommended Citation
https://scholarworks.wmich.edu/masters_theses/4262
INVESTIGATING EL NIÑO SOUTHERN OSCILLATION AND TORNADO ACTIVITY IN TEXAS

by

Joel R. Intrieri

A Thesis
Submitted to the
Faculty of The Graduate College
in partial fulfillment of the
requirements for the
Degree of Master of Arts
Department of Geography

Western Michigan University
Kalamazoo, Michigan
December 2002
ACKNOWLEDGMENTS

First and foremost, I would like to thank my family for their constant support and guidance. Mom, Dad, and Keith, you taught me to always believe in my abilities and for that I am eternally grateful.

Second, I would like to acknowledge my graduate committee: Dr. Elen Cutrim, Dr. Lisa DeChano, and Dr. Gregory Veeck. Amidst your own hectic teaching and research schedules, you always found time to help steer me in the right direction, away from the proverbial potholes and speed bumps associated with thesis work. I do hope that other students have the honor and privilege to work with such great scholars and friends. I would especially like to recognize my advisor, Dr. Elen Cutrim, for challenging me to explore the research topic at hand. There is no doubt that your vast knowledge and continual assistance helped bring this project to fruition.

Finally, Dr. David Dickason, thanks for providing me with the opportunity to study at such a wonderful institution. The skills I gained during my two years of graduate work will definitely last a lifetime.

Joel R. Intrieri
INVESTIGATING EL NIÑO SOUTHERN OSCILLATION AND TORNADO ACTIVITY IN TEXAS

Joel R. Intrieri, M.A.
Western Michigan University, 2002

The possible relationships between El Niño Southern Oscillation and tornado frequency and intensity (as measured by the Fujita Scale) within Texas are explored in this paper. Reported tornado occurrences from 1950 – 2000 are compared to the Japan Meteorological Agency’s Sea Surface Temperature Anomaly Index to discover significant patterns and trends throughout the state. Overall, results reveal that more intense tornadoes are likely to touchdown during the cold phase (La Niña) of the ENSO cycle. Regional differences are also observed with the La Niña extreme favoring increases in tornado frequency and intensity within distinct areas of the state. Finally, the cold swing of the ENSO pendulum is found to augment tornado frequency and intensity during the Spring (April - June) months while only enhancing tornado intensity during the Winter months (January – March). Although a causal relationship between tornadoes and ENSO is lacking, findings do indicate that both phenomena may indeed be linked.
# TABLE OF CONTENTS

ACKNOWLEDGMENTS .................................................................................................................. ii

LIST OF TABLES .......................................................................................................................... v

LIST OF FIGURES ...................................................................................................................... vi

CHAPTER

I. INTRODUCTION ...................................................................................................................... 1

II. LITERATURE REVIEW ........................................................................................................... 5

   - The Tornado ......................................................................................................................... 5
   - El Niño Southern Oscillation .............................................................................................. 11
   - Relating Tornadoes and ENSO .......................................................................................... 18

III. METHODS ............................................................................................................................ 21

   - Study Site ............................................................................................................................ 21
   - Data Sets .............................................................................................................................. 24
     - Tornado Data ................................................................................................................... 24
     - ENSO Indices .................................................................................................................... 25
   - Statistical Analysis ............................................................................................................. 27
     - Data Processing ............................................................................................................... 27
     - Statistical Testing Specifics ............................................................................................. 28

IV. RESULTS AND DISCUSSION ............................................................................................... 31
Table of Contents - continued

CHAPTER

<table>
<thead>
<tr>
<th>Section</th>
<th>Page</th>
</tr>
</thead>
<tbody>
<tr>
<td>Tornado Climatology for the State of Texas</td>
<td>31</td>
</tr>
<tr>
<td>Research Findings and Discussion</td>
<td>35</td>
</tr>
<tr>
<td>Statewide Results</td>
<td>35</td>
</tr>
<tr>
<td>Regional Results</td>
<td>39</td>
</tr>
<tr>
<td>Seasonal Results</td>
<td>48</td>
</tr>
<tr>
<td>V. CONCLUSION</td>
<td>54</td>
</tr>
<tr>
<td>BIBLIOGRAPHY</td>
<td>58</td>
</tr>
</tbody>
</table>
LIST OF TABLES

1. Fujita Scale......................................................................................... 6
2. ENSO Year According to JMA-SST Anomaly Index ......................... 26
3. Annual Mean Tornado Frequency According to ENSO Phase...... 35
4. Fujita Scale Rating According to ENSO Phase................................ 37
5. Contingency Table Categorized by Tornado Intensity and ENSO Stage.......................................................................................... 38
6. Annual Mean Tornado Frequency According to ENSO Phase and Region .......................................................................................... 43
7. Regional Fujita Scale Rating According to ENSO Phase................. 45
8. Contingency Table Categorized by Tornado Intensity and ENSO Stage by Region................................................................. 47
9. Annual Mean Tornado Frequency According to ENSO Phase and Season ....................................................................................... 49
10. Seasonal Fujita Scale Rating According to ENSO Phase............... 51
11. Contingency Table Categorized by Tornado Intensity and ENSO Stage by Season................................................................. 52
LIST OF FIGURES

1. Normal Conditions............................................................................. 14
2. El Niño Conditions............................................................................. 15
3. Texas County Population, 2000 ........................................................ 22
5. Tornado County by County, 1950 – 2000 ......................................... 33
7. Fujita Scale Rating for Texas Tornadoes 1950 – 2000.................... 34
9. Regionalization Based on Annual Mean Days with Thunder, 1961 – 1990......................................................................................... 42
CHAPTER I

INTRODUCTION

Weather plays a critical role in our lives and affects all aspects of human activity. Descriptions of particular weather events rely on attributes such as precipitation, spatial extent, intensity, distribution, temperature, wind speed, and a variety of other indicators. All of these variables may differ depending on the type of event. Although some weather features may be quite harmless, others can wreak havoc. One feature well known for its often-devastating effects is the tornado.

"Tornadoes are rapidly rotating winds that blow around a small area of intense low pressure" (Ahrens, 2000, 403). These fascinating, and many times violent, cyclones occur more than 900 times annually in the United States (Ahrens, 2000). This count is most likely low because it only includes tornadoes that are actually reported. Grazulis (2001) estimates that nearly 47 percent of all tornadoes go uncounted on a global scale. On average, tornadoes claim the lives of 90 individuals per year in the United States (Lutgens and Tarbuck, 1998). The toll taken on human life cannot be underestimated. For instance, the tornado outbreak of April 3 and 4, 1974, left 307 dead and over 5,500 injured throughout thirteen
states. This super outbreak consisted of 144 tornadoes that destroyed over half a billion dollars worth of property (Eagleman, 1990). Obviously, the environmental and societal impacts associated with these events can be truly incredible.

Tornadoes are mesoscale weather systems that are influenced by local and large-scale atmospheric patterns. In turn, these weather patterns and processes may be affected by a number of different phenomena. One such phenomenon, occurring every two to seven years, is known as El Niño. According to the National Oceanic and Atmospheric Administration (2002a), “El Niño is a disruption of the ocean-atmosphere system in the Tropical Pacific having important consequences for weather and climate around the globe” (n. pag.). Once believed to produce only localized effects in Peru, Ecuador, and Chile, scientists now recognize El Niño’s global impacts, termed “teleconnections.” A warming of the equatorial Pacific, along with an associated change in pressure systems, is believed to influence such events as hurricane, flood, and drought occurrence in numerous areas throughout the world (Glantz, 1996). Although the physical mechanisms responsible for the onslaught of El Niño are not well understood, research detailing these teleconnections has taken place throughout many parts of the world.

El Niño is only one extreme associated with the equatorial Pacific.
Directly contrasting this aforementioned disturbance is La Niña. Simply stated, La Niña is a cooling of the tropical Pacific waters believed to produce the opposite effects of its counterpart (National Oceanic and Atmospheric Administration [NOAA], 2002c). In short, El Niño and La Niña compose two extremes of a cycle termed El Niño Southern Oscillation (ENSO).

Tornadoes and ENSO have both been the subjects of numerous research projects throughout the past several decades. While these two phenomena have been studied separately in the past, research relating the two topics is rather limited. Thus far, research efforts focus on distinct regions of the country such as "tornado alley" and the Tennessee River Valley with few projects examining data at the state level. Further study of the relationship between tornadoes and ENSO is certainly warranted and may lead to a better understanding of these distinct—but possibly interrelated—phenomena.

This project, then, will examine possible relationships between El Niño Southern Oscillation and tornado frequency and intensity across the state of Texas. In all, the proposed research incorporates three main objectives: (a) creating a database of all tornadoes reported in Texas from 1950-2000; (b) analyzing Texas tornado characteristics for each stage of the ENSO cycle; and (c) determining, through the use of various statistical
tests, if significant relationships exist between tornadoes and ENSO in Texas. The research consists of one hypothesis: Although they are distinct phenomena, tornado activity and ENSO events are related. There are two key issues embedded in this hypothesis. First, does the ENSO cycle promote an increase or decrease in tornado frequency throughout Texas? Second, do the varying ENSO stages impact tornado intensity (according to the Fujita Scale) in Texas?

The following project is divided into V chapters, each serving a different purpose. Chapter II provides a scientific overview of tornadoes and El Niño Southern Oscillation. Furthermore, this chapter includes a detailed summary of research pertaining to both phenomena. In Chapter III, the study site is presented and the data sources are outlined. The chapter ends with a discussion of the statistical methods employed throughout the project. Research results are investigated in Chapter IV. Finally, Chapter V provides an overview of the project and highlights the potential for further research.
CHAPTER II

LITERATURE REVIEW

The Tornado

Also known as twisters or cyclones, tornadoes are rapidly rotating columns of air that protrude from the base of a cumulonimbus cloud. This intense rotation results from a dramatic atmospheric pressure gradient occurring over a very short distance. In the Northern Hemisphere, most tornadoes spin cyclonically (that is counterclockwise), while only a few rotate in the opposite direction. Although it is quite difficult to classify tornadoes due to their distinct characteristics, some generalizations can be formulated. First, the majority of tornadoes have a diameter of approximately 100 yards. Second, tornadoes generally move along the ground at speeds around 30 miles per hour (mph). Finally, twisters usually last for only several minutes (Aguado and Burt, 2001). However, these are merely averages and should be treated as such. Each tornado has unique characteristics.

Another important variable associated with tornadoes is wind speed. Currently, no research projects have successfully gathered
wind speed data within a cyclone. Because of this, scientists must rely on photogrammetry techniques and structural damage estimates to approximate the wind speeds associated with a tornado. One commonly used system that ranks tornadoes according to intensity is known as the Fujita Scale. Table 1 depicts the Fujita Scale rating system. Developed in the late 1960s by Dr. Theodore Fujita, this intensity scale is derived from a combination of both rotational wind speed and storm damage.

Table 1
Fujita Scale

<table>
<thead>
<tr>
<th>Rating</th>
<th>Category</th>
<th>Wind Speed (mph)</th>
<th>Probable Damage</th>
</tr>
</thead>
<tbody>
<tr>
<td>F0</td>
<td>Weak</td>
<td>40 - 71</td>
<td>Broken branches, damaged chimneys and billboards</td>
</tr>
<tr>
<td>F1</td>
<td>Weak</td>
<td>72 – 112</td>
<td>Windows broken, roof damage, mobile homes overturned</td>
</tr>
<tr>
<td>F2</td>
<td>Strong</td>
<td>113 - 157</td>
<td>Large trees uprooted, mobile homes destroyed, roofs torn from houses</td>
</tr>
<tr>
<td>F3</td>
<td>Strong</td>
<td>158 - 206</td>
<td>Cars overturned, walls torn from homes, trains upturned</td>
</tr>
<tr>
<td>F4</td>
<td>Violent</td>
<td>207 - 260</td>
<td>Frame houses demolished, cars thrown</td>
</tr>
<tr>
<td>F5</td>
<td>Violent</td>
<td>261 - 318</td>
<td>Concrete structures damaged, cars moved over 100 meters, trees debarked</td>
</tr>
<tr>
<td>F6</td>
<td>Violent</td>
<td>&gt; 319</td>
<td>Incomprehensible</td>
</tr>
</tbody>
</table>

"Statistics reveal that the majority of tornadoes are F0 and F1 (weak tornadoes) and only a few percent each year are above the F3
classification (violent) with approximately one F5 tornado reported annually” (Ahrens, 2000, 406). Regardless of intensity, the mechanisms responsible for tornado formation are not well known.

Many of the specifics related to tornado development (also referred to as tornadogenesis) remain a mystery to meteorologists. However, researchers do know that tornadoes spawn from severe thunderstorm events including squall lines, mid-latitude cyclones, and supercells. According to Aguado and Burt (2001), tornadoes resulting from supercells are usually the most intense and destructive. Tornado formation within a supercell begins with a mesocyclone.

A mesocyclone is a bi-product of vertical wind shear and strong updrafts. First, wind shear creates a large, horizontal vortex of air within the interior of a cumulonimbus cloud. In some instances, updrafts shift this vortex from a horizontal to vertical position. Under the right conditions, the mesocyclone intensifies and a small column of spinning air extends downward (Aguado and Burt, 2001). If this column exits the cloud, the cyclone is termed a funnel. Once the funnel cloud touches the ground, the cyclone becomes a tornado. Although Doppler radar can detect mesocyclones, not all mesocyclones produce tornadoes and not all tornadoes are produced from mesocyclones.

Fortunately, meteorologists around the world realize the
importance of studying tornadoes. For this reason, these weather features have been the subject of extensive research efforts for many decades. Leathers (1993) investigated the spatial and temporal characteristics associated with tornadoes occurring in the northeastern portion of the United States. Along with a detailed summary of 37 years of tornado data, Leathers also highlighted the synoptic patterns associated with tornado development within the study area. He found that most of the tornadoes occurred between the late afternoon and early evening hours. Furthermore, the majority of twisters occurred between May and August, with a peak in July. In geographical terms, Leathers identified western and southeastern Pennsylvania and northern Massachusetts as preferred areas for tornado development in the northeast U.S. Finally, by analyzing surface pressure, 500 millibar heights, and 850 millibar temperatures, Leathers discovered that synoptic patterns associated with tornadic events remain relatively constant throughout the year.

Kelly, Schaefer, McNulty, Doswell, and Abbey (1978) provided a statistical study for nearly 15,000 tornadoes happening from 1950 – 1976. Their data indicated that 62 percent of tornadoes were classified as weak (F0 – F1) while only 2 percent were categorized as violent (F4 – F5). However, the latter is deceiving considering that violent tornadoes caused 68 percent of tornado fatalities within the same time period. Finally,
weak and strong tornadoes showed diurnal trends while violent tornadoes exhibited no temporal dependence.

Doswell and Burgess (1988) detailed some of the lingering problems associated with climatological data related to tornadoes. More specifically, they focused on two distinct tornado variables, Fujita Scale rating as well as path length. First, the authors argued that the Fujita Scale actually measures damage caused by a tornado, not the intensity of the tornado itself. For instance, intense tornadoes that touchdown in open areas may not necessarily cause heavy damage to structures. However, this does not mean the tornado in question lacks strength. Also, Doswell and Burgess presented evidence that some tornadoes, classified as long-path, were actually a series of short-path tornadoes associated with one supercell.

Galway (1977) investigated tornado outbreaks (ten or more tornadoes) which occurred from 1870 – 1975. After studying these outbreaks, the researcher categorized each outbreak as being one of three types: local, progressive, and line. Basically, each outbreak was categorized according to exhibited spatial and temporal characteristics. First, local outbreaks occurred in small sections of a state or adjoining states and usually lasted no more than seven hours. Second, progressive outbreaks covered several hundred miles and moved primarily in a west
to east direction. Furthermore, these outbreaks had a life cycle averaging 9.5 hours. Finally, Galway defined a line outbreak as developing on a north-south axis with little eastward movement and lasting about eight hours.

One relatively well-known tornado project, entitled Verification of the Origins of Rotation in Tornadoes EXperiment (VORTEX), took place during the spring seasons of 1994 and 1995. Sponsored by the National Severe Storms Laboratory, the main objective of this study was to gain a better understanding of the causes of tornado development in the central and southern Plains states. The data gathered from this study is still being analyzed today.

Although knowledge surrounding tornadoes continues to increase, many questions still remain unanswered. For instance, are there techniques and technologies that meteorologists can employ to effectively predict the formation of a twister? Also, what atmospheric factors spawn the development of tornado outbreaks? Finally, are these natural disasters controllable or even preventable? Currently, these are just a few of the many questions being raised by the scientific community. Further study may benefit both the physical environment and its inhabitants as well as generating basic data that will help us understand these phenomena more completely.
Throughout the past decade, the media and general public have become fascinated with a physical process known as El Niño. Although only gaining recent notoriety, El Niño was evident as far back as the 1700s. During the 18th century, Peruvian fishermen recognized a warming of the Pacific Ocean along the western coast of South America. These fishermen named this warming El Niño (in reference to the Christ Child) due to its occurrence around the month of December (Glantz, 1996). Since then, the term El Niño has come to mean many things to many people. Unfortunately, the multitude of definitions surrounding this weather occurrence leads to many misconceptions.

In its simplest form, El Niño describes any warming taking place along the western coast of South America. However, some individuals have more accurately classified El Niño as being an unusual warming happening off the coast of Peru, Ecuador, and Northern Chile that harms the local fishing and guano industries while having global implications. Still, others use the word to describe both the warming of the water off the west coast of South America and an associated pressure change which occurs in the equatorial Pacific (NOAA, 2002b). This aforesaid pressure change is known as Southern Oscillation.
Although the term El Niño has become somewhat of a buzzword in recent years, it is important to recognize that atmospheric components do play a critical role in the equatorial Pacific cycle. One such factor often overlooked by the scientific community and general public is known as Southern Oscillation (SO). The Southern Oscillation pertains to a fluctuation of sea level atmospheric pressure across the tropical Pacific. Subsequently, these changes provide a basis for understanding some of the climatological anomalies occurring throughout the equatorial region on an annual basis. The researcher responsible for first studying these variations in pressure was Sir Gilbert Walker.

A British mathematician, and the Director General of Meteorological Observatories in India, Walker became interested in studying the monsoons that afflicted millions of Indian residents. More specifically, he wanted to devise a method to better predict these devastating weather events for future years in order to mitigate the loss of life and property associated with the unpredictable beginnings of these monsoons. Upon investigating temperature, atmospheric pressure, and rainfall data from a number of weather stations across the globe, Walker noticed a unique relationship. According to Glantz (1996), “The particular pattern he observed, which in 1924 he labeled ‘the Southern Oscillation,’ was the result of a seesaw-like oscillation of sea level pressure changes at
various locations across the Pacific Basin” (36). Furthermore, Walker recognized that when atmospheric pressure was high in the eastern tropical Pacific and low in the west, monsoon rains were generally heavy. On the other hand, when pressure differences were small, India endured drought conditions. Although Walker never discovered the physical mechanisms responsible for Southern Oscillation, he was truly one of the pioneers in the study of ENSO. Today, scientists employ many of Walker's ideas in their study of the ENSO phenomenon.

The Southern Oscillation Index (SOI) is derived from measurements reflecting air pressure fluctuations in Tahiti and Darwin, Australia. Basically, pressure centered near Tahiti is inversely proportional to pressure centered near Darwin. Thus, when pressure near Tahiti is high, the pressure near Darwin is low, and vice versa. Mathematically, the Southern Oscillation Index is expressed as

\[
SOI = T_p - D_p,
\]

where \( T_p \) is equal to the sea level pressure at Tahiti and \( D_p \) is equal to the sea level pressure at Darwin. This difference in pressure is used as an index to describe the varying stages of ENSO. Negative SOI values indicate periods of El Niño (warm phase), while positive SOI values point towards the La Niña extreme (cool phase) of ENSO. Although El Niño and Southern Oscillation were once believed to be distinct entities, research has shown that these phenomena are related.
Joseph Bjerknes (1969) described a complex ocean-atmosphere interaction present in the equatorial Pacific. Basically, this pioneering study was the first to link El Niño and Southern Oscillation. Bjerknes coined the term Walker circulation, in honor of Sir Gilbert Walker, to describe the physical mechanisms relating these two abovementioned events. During normal conditions, low pressure exists near the Indonesian archipelago while high pressure dominates the southeastern Pacific (Figure 1). This pressure system promotes strong easterly trade winds along the equator. These strong trade winds, along with equatorial currents, push warm surface waters westward which eventually leads to
higher sea level in the western Pacific compared to the eastern Pacific. A strong northward flowing Peruvian current replaces the displaced water with cool, nutrient-rich waters along the western coast of South America. Under the usual conditions, Walker Circulation facilitates rising air and heavy rains over the western Pacific and sinking air with drier weather over the eastern Pacific. A La Niña results when these normal conditions intensify.

However, the development of El Niño begins with a reversal of this “normal” equatorial Pacific pressure pattern. Atmospheric pressure over the southeastern Pacific decreases while pressure rises over the western Pacific (Figure 2). Subsequently, this transformation causes the trade

![Image of El Niño Conditions](image)

Figure 2. El Niño Conditions (Lutgens and Tarbuck, 1998).

winds to weaken or reverse direction. The result is an eastward movement of warm surface water towards the western coast of South America, leading to higher sea levels in the eastern Pacific basin as compared to the western Pacific. Under El Niño conditions, Walker Circulation aids the development of subsiding air over the western tropical Pacific with rising air throughout the central and eastern Pacific. Because of this, areas throughout the western Pacific basin become cooler and drier while areas in the central and eastern Pacific endure warmer temperatures, causing an increase in convective activity.

As Figures 1 and 2 show, El Niño and Southern Oscillation are strongly related. Today, scientists refer to their combined occurrence as ENSO (El Niño Southern Oscillation) events. Although it was once thought that ENSO events only impact Peru, Ecuador, and Northern Chile, scientists now recognize that these events have a global significance. The climatological anomalies that result from the varying phases of ENSO are known as teleconnections. Due to its global impacts, ENSO has been studied by a multitude of researchers over the past several decades.

Dixon, Butler, DeChano, and Henry (1999) studied the connection between avalanche hazards and El Niño in Glacier National Park, Montana. They found there to be a decrease in snow avalanches during El
Niño years. Furthermore, all high avalanche years corresponded with non-El Niño conditions. The researchers felt that decreases in snow avalanches may be a result of lower precipitation occurring during the El Niño extreme.

Kirono, Tapper, and McBride (1999) examined Indonesian rainfall during the El Niño event of 1997 – 1998. Forty-eight years of rainfall data were analyzed for the study. The results of the project showed that almost all of Indonesia had rainfall below the tenth percentile from March 1997 to February 1998, with nearly 40 percent of the recording weather stations reporting the lowest rainfall on record. The authors also found that rainfall amounts and the Southern Oscillation Index (SOI) were strongly related. Thus, this relationship may provide scientists with an early warning about the severity of ENSO events.

Rasmusson and Carpenter (1983) detailed the relationship between sea surface temperature in the eastern equatorial Pacific and rainfall over India and Sri Lanka. Monsoon precipitation data for a 105-year period (1875 – 1979) showed that during El Niño events, the study area endured below normal summer monsoons (June to September). However, during the years both preceding and following a warm episode as well as the remaining El Niño months, this relationship diminished. Rasmusson and Carpenter also noted that although a relationship is evident, other remote
and local factors (excluding El Niño) played a critical role in precipitation occurrence.

Currently, many research centers are dedicated to the study of ENSO. Two such centers are the Scripps Institution for Oceanography and the Center for Ocean-Atmospheric Prediction Studies (COAPS). Among many other things, the Scripps Experimental Climate Prediction Center's work revolves around the development of computer models that may aid in the production of accurate El Niño forecasts. Among other topics, current research at COAPS includes an investigation of "ENSO and Atlantic Hurricane Frequency" as well as "ENSO and Chilean Precipitations (1961 – 1994)" (Center for Ocean-Atmospheric Prediction Studies [COAPS], 2002).

Relating Tornadoes and ENSO

Attempts to relate tornadoes and ENSO are scarce in the scientific literature and start appearing in the last decade. Schaefer and Tatom (1999) analyzed the possible linkage between ENSO and tornadic activity across three distinct areas of the United States. These areas included "tornado alley," mideastern United States, and Florida. They found no statistical correlation between ENSO and tornado frequency, intensity, and annual coverage within these locations.
Bove (1997) also examined this possible correlation on both an annual and seasonal basis. Using data from 1950 – 1992, findings from his research supported the idea that El Niño events reduced tornadic activity over tornado alley while La Niña episodes increased activity over the Ohio and Tennessee River valleys. Further results showed that El Niño occurrences hindered the chances for multiple tornado outbreaks. On the other hand, La Niña events promoted the possibility of such outbreaks.

Monfredo (1999) found that tornado seasons in the southcentral United States may be impacted by varying phases of ENSO. More specifically, his results showed that El Niño events significantly correlated with a decrease in the frequency of strong and violent tornadoes (F2 or greater) while La Niña events significantly correlated with an increase in the frequency of strong and violent tornadoes. Monfredo proposed that these findings may be a result of changes in large-scale upper-level circulation patterns (i.e. Rossby waves), directly influenced by ENSO events.

Finally, Nagle (2000) explored seasonal tornado frequency over six different zones of the eastern two-thirds of the United States throughout the ENSO cycle. The researcher found that La Niña impacted tornado climatology throughout the entire area of investigation. More specifically,
La Niña increased the number of significant tornadoes and tornado days occurring in the spring season (April – June) for all six zones. On the other hand, El Niño had its greatest effect on the tornado climatology within a zone that covered most of Texas, Oklahoma, and Kansas (i.e. "tornado alley").

As the abovementioned research indicates, scientists have made valuable strides in learning more about tornado and ENSO interaction. However, literature relating these phenomena is relatively limited at the present time. Further study of these natural occurrences is essential and may help answer some of the difficult questions plaguing researchers today.
Texas, the largest state in the contiguous United States, covers an area of approximately 695,619 square kilometers. Due to its tremendous size, the state is home to nearly 21,000,000 people, making it the second most populated state in the entire U.S (United States Census Bureau, 2002). Figure 3 depicts total population counts for the 254 counties composing Texas. The size of Texas, along with its geographical location and topographical makeup (including escarpments, plateaus, prairies and plains), lead to a diverse climatological structure throughout the state. Some areas are wet while other areas are quite arid. Similarly, some locations endure warm temperatures during the entire year while other locales face somewhat cooler temperatures. According to the Köppen climatology scale, Texas exhibits two dominant climate types: dry climate steppe (BSH) and midlatitude rainy with a mild winter (Cfa). For the BSH classification, evaporation exceeds precipitation for the year with an average annual temperature above 18° Celsius (64.4° Fahrenheit). On
Number of Persons

- 67,104,312
- 104,313 - 354,452
- 354,453 - 812,280
- 812,281 - 2,218,899
- 2,218,900 - 3,400,578

Projection: USA Contiguous Albers Equal Area Conic
Data Source: United States Census Bureau, 2002
the other hand, the Cfa classification represents areas with the coolest month averaging a temperature below 18° Celsius (64.4° Fahrenheit) and above -3° Celsius (26.6° Fahrenheit). Furthermore, the warmest month is above 22° Celsius (71.6° Fahrenheit) (Hidore and Oliver, 1993).

Although tornadoes occur throughout each state in the U.S., Texas, in particular, endures a multitude of these violent cyclones. From 1950 – 2000, an average of 128 tornadoes occurred annually in Texas, making it the country's leader. Much of the state is part of a larger region known as “tornado alley.” This area has been popular with stormchasers due to the fact that tornadoes are more prevalent here than anywhere else in the country.

“Tornado alley” experiences the most twister occurrences because the atmosphere within the region regularly contains the predominant ingredients needed for tornado formation. According to Hidore and Oliver (1993), tornado development requires a mass of very warm, moist air at the surface, an unstable vertical temperature structure, and the presence of a rotation mechanism. Many times, Texas experiences warm, continental tropical air moving in from the west while maritime tropical air blows from the Gulf of Mexico. In some instances, the result is a dryline that forms near the Texas panhandle and separates these opposing air masses. The thermodynamic environment near this dryline
promotes severe thunderstorm activity at times, including tornado development.

Data Sets

Tornado Data

The Storm Prediction Center (SPC) in Norman, Oklahoma maintains tornado databases for every state in the U.S. These raw tornado data are available in an antiquated format originally used with the National Severe Storms Forecast Center's (now the SPC) Data General mainframe and are distributed to the public as zip files. The attributes associated with each tornado include, but are not limited to, date, time, mean path width, starting latitude and longitude, Fujita Scale rating, and in many instances, ending latitude and longitude. The last year for tornado data archived at SPC was 1995.

The National Climatic Data Center (NCDC) in Asheville, North Carolina documents all of the post-1995 tornado data for the United States. Surprisingly, unlike the SPC recording system, the NCDC does not provide zipped data files. For this reason, all relevant tornado information must be manually entered into a database. Attribute information for tornadoes occurring after 1995 is similar in content to those prior to 1995 with the addition of a description of each tornado
event. These descriptions range in size from one sentence to an entire paragraph and may consist of storm and tornado development specifics as well as damage reports.

**ENSO Indices**

In order to determine extremes in the ENSO cycle, scientific agencies, organizations, and researchers have created a number of El Niño indices with no one index being universally accepted. These indices include the SOI, Multivariate ENSO Index (MEI), and the Japan Meteorological Agency’s Sea Surface Temperature Anomaly Index (JMA-SST), but there are others as well. Each index is based on specific mathematical computations and takes into account distinct variables. For instance, the MEI is based on six parameters including sea level pressure, sea surface temperature, zonal and meridional components of the surface wind, surface air temperature, and total cloudiness fraction of the sky (Wolter, 2002). The JMA-SST Index is based upon sea surface temperature only. The ENSO index employed in this research project is the Japan Meteorological Agency’s Sea Surface Temperature Anomaly.

Developed by the Japan Meteorological Agency, the JMA – SST Index is a five-month running mean of spatially averaged SST anomalies covering the equatorial Pacific. In this case, the equatorial Pacific is
defined as an area lying between 4° South and 4° North latitude and 150° West and 90° West longitude. “If index values are 0.5° or greater for 6 consecutive months (including OND) [October, November, December], the ENSO year of October through the following September is categorized as El Niño” (COAPS, 2002, n. pag.). On the other hand, when index values are -0.5° or less for 6 consecutive months (including OND), the ENSO year of October through the following September is categorized as La Niña. All other ENSO years are classified as neutral. Table 2 lists the ENSO year categorization according to the JMA-SST Anomaly Index for the ENSO years 1950 – 1999. Each year in the table corresponds to the first three

Table 2

<table>
<thead>
<tr>
<th>Year</th>
<th>195X</th>
<th>196X</th>
<th>197X</th>
<th>198X</th>
<th>199X</th>
</tr>
</thead>
<tbody>
<tr>
<td>0</td>
<td>N</td>
<td>N</td>
<td>L</td>
<td>N</td>
<td>N</td>
</tr>
<tr>
<td>1</td>
<td>E</td>
<td>N</td>
<td>L</td>
<td>N</td>
<td>E</td>
</tr>
<tr>
<td>2</td>
<td>N</td>
<td>N</td>
<td>E</td>
<td>E</td>
<td>N</td>
</tr>
<tr>
<td>3</td>
<td>N</td>
<td>E</td>
<td>L</td>
<td>N</td>
<td>N</td>
</tr>
<tr>
<td>4</td>
<td>L</td>
<td>L</td>
<td>N</td>
<td>N</td>
<td>N</td>
</tr>
<tr>
<td>5</td>
<td>L</td>
<td>E</td>
<td>L</td>
<td>N</td>
<td>N</td>
</tr>
<tr>
<td>6</td>
<td>L</td>
<td>N</td>
<td>E</td>
<td>E</td>
<td>N</td>
</tr>
<tr>
<td>7</td>
<td>E</td>
<td>L</td>
<td>N</td>
<td>E</td>
<td>E</td>
</tr>
<tr>
<td>8</td>
<td>N</td>
<td>N</td>
<td>N</td>
<td>L</td>
<td>L</td>
</tr>
<tr>
<td>9</td>
<td>N</td>
<td>E</td>
<td>N</td>
<td>N</td>
<td>L</td>
</tr>
</tbody>
</table>

Source: Adapted from COAPS, 2002.
months (October, November, December) of the ENSO year. For instance, the El Niño ENSO year of 1951 begins in October 1951 and ends September 1952.

Statistical Analysis

Data Processing

The tornado database was created using Microsoft Excel 2000 (Microsoft Corporation, 1999). Each observation in the database contains a tornado event reported from 1950 – 2000 in the state of Texas. Furthermore, each tornado occurrence has associated attribute information. Some of these attributes include time, date, path length, human deaths and injuries, and Fujita Scale rating. Also, each tornado event includes the county that endured the tornado’s initial touchdown. Once pre- and post-1995 tornado data were combined, each event was categorized according to ENSO stage.

As stated earlier, an ENSO year begins in October and runs through the following September. For example, the La Niña ENSO year of 1999 begins in October 1999 and ends September 2000. This means that all those tornadoes happening from October 1, 1999 to September 30, 2000 are classified as La Niña. According to the JMA-SST Anomaly Index, 12 ENSO years are classified as El Niño, 12 as La Niña, and 26 as
neutral beginning with the ENSO year 1950 and ending in 1999. The
third and final processing step was data tabulation.

SPSS 10.0 for Windows (SPSS, Incorporated, 1999) was the
software package used for statistical analysis and testing. The methods
and techniques available via SPSS 10.0 range from simple descriptive
statistics to complex parametric and nonparametric testing.

Statistical Testing Specifics

Before any statistical tests are performed, the nature of the
population from which the samples are taken is analyzed. This analysis
determines whether parametric or nonparametric tests are appropriate
for the dataset. Parametric testing is only used when the population
distribution is normal and when the data meets a number of restrictions.
On the other hand, nonparametric tests are used when the population
distribution is unknown. In this project, both tornado frequency and
tornado intensity (according to the Fujita Scale) are assumed to be non-
normally distributed. For this reason, the appropriate statistical analysis
methods are nonparametric. Three distinct nonparametric tests are
employed to compare tornado climatology and ENSO events. These tests
include the Mann-Whitney U test, Kruskal-Wallis test, and chi-square
test ($\chi^2$).
The Mann-Whitney U test allows for the comparison of two samples. The main question asked in the Mann-Whitney test is whether or not two samples come from the same population. "By assuming only that the two population distributions have the same shape, the test is used to determine whether the two populations have the identical location or position" (Burt and Barber, 1996, 338). According to Earickson and Harlin (1994), "If the two independent samples are drawn from the same population, then the mean ranks of the two samples should be approximately equal" (232). For instance, the median number of tornadoes taking place in El Niño years can be tested against the median number of tornadoes taking place in La Niña years. In this case, the null hypothesis is that no significant difference exists between the median tornado frequencies for the two ENSO phases. While the Mann-Whitney test allows for the comparison of only two samples, the Kruskal-Wallis test takes into account three or more samples.

The Kruskal-Wallis test is the nonparametric equivalent of the Analysis of Variance (ANOVA) test. "This test again involves combining the values for the subsamples and ranking them, but keeping track of the ranks for each subsample as you proceed" (Earickson and Harlin, 1994, 235). All three ENSO phases can be compared using the Kruskal-Wallis test. In this instance, the null hypothesis states that the populations
represented by the three samples do not differ with respect to tornado frequency.

The third and final test is termed the chi-square test. The chi-square test allows for the comparison of two sets of frequencies. More specifically, the test determines the statistical independence, or lack thereof, between two sets of frequencies. Earickson and Harlin (1994) state, “If the differences between the observed and expected frequencies are small, the conclusion is that the differences could have arisen by chance” (239). In this research, the test provides a basis for detecting whether a clear difference is present when examining intense tornadoes (F2 or greater) during the El Niño phase as opposed to the La Niña phase of the ENSO cycle.
Texas leads the United States in the number of tornadoes occurring annually. From January 1, 1950 to December 31, 2000, the state endured a total of 6,511 reported tornadoes (Figure 4). This equates to an average of approximately 128 tornado occurrences per year. During this 51-year period, Texas encountered a minimum number (13) of tornado events in 1960. During this same period, Texas experienced a maximum number (220) of tornado events in 1979. This range indicates that the number of tornadoes occurring in Texas varies significantly from year to year, with some years experiencing a higher frequency of tornado activity than others.
1952 and a maximum (232) during 1967. The upward trend in tornado events reported on a yearly basis is a direct result of an improvement in tornado reporting efficiency (Schaefer and Tatom, 1999). Figure 5 shows the spatial distribution of tornado occurrences aggregated to the county level. Although the counties are shaded according to each tornado's initial touchdown point, it is important to note that a tornado may impact more than one county per occurrence. From 1950 – 2000, Harris had the highest tornado count (173) of any Texas county while the smallest amount belonged to Menard (0).

The majority of tornadoes within Texas occur during the primary convective season between April and June, with a peak frequency in May (Figure 6). About 63 percent of all tornadoes reported take place during this three-month period. As expected, the months of December through February see the lowest number of tornado touchdowns.

As stated earlier, the Fujita Scale was developed in order to categorize tornadoes according to intensity. Of the 6,511 tornadoes in Texas, 6,299 (97 percent) of those have Fujita Scale ratings (Figure 7). The remaining 3 percent of tornadoes do not have associated intensity rating information. According to the data, 78 percent of the tornadoes are classified as weak (F0, F1), 21 percent strong (F2, F3) and 0.8 percent violent (F4, F5).
Figure 5. Tornado Count by County, 1950 – 2000.

Data Source: Storm Prediction Center, 1999; National Climatic Data Center, 2002b

Projection: USA Contiguous Albers Equal Area Conic
Figure 6. Monthly Tornado Count in Texas, 1950 – 2000.

Figure 7. Fujita Scale Rating for Texas Tornadoes, 1950 – 2000.
Statewide Results

The first step in the research project deals with analyzing tornado activity and ENSO on a statewide level. The descriptive statistics shown in Table 3 pertain directly to the mean annual tornado frequency during the different phases (El Niño, La Niña, neutral) of the ENSO cycle. The table indicates that during El Niño years, the state of Texas averages nearly 108 tornado occurrences. However, this mean frequency increases to approximately 134 touchdowns throughout neutral years. And finally, the average tornado frequency during La Niña years is 137. The range for tornadoes occurring in El Niño (161) and La Niña (162) years is nearly equal. Unlike the two extremes, this number sharply increases during

Table 3
Annual Mean Tornado Frequency According to ENSO Phase

<table>
<thead>
<tr>
<th></th>
<th>El Niño</th>
<th>Neutral</th>
<th>La Niña</th>
</tr>
</thead>
<tbody>
<tr>
<td>Mean</td>
<td>107.8</td>
<td>133.7</td>
<td>137</td>
</tr>
<tr>
<td>Median</td>
<td>110</td>
<td>139.5</td>
<td>136</td>
</tr>
<tr>
<td>Minimum</td>
<td>12</td>
<td>15</td>
<td>45</td>
</tr>
<tr>
<td>Maximum</td>
<td>173</td>
<td>244</td>
<td>207</td>
</tr>
<tr>
<td>Std. Deviation</td>
<td>43.8</td>
<td>55</td>
<td>44.8</td>
</tr>
</tbody>
</table>
neutral years (229). The reason for the higher range most likely revolves around an increase in sample size.

Two statistical tests, the Kruskal-Wallis test and Mann-Whitney U test, are employed to discover significant relationships between ENSO phase and tornado frequency. First, all three ENSO phases are compared using the Kruskal-Wallis test. In this case, the null hypothesis states that the populations represented by the three samples do not differ with respect to tornado frequency. The overall question that the test answers is relatively straightforward: Does a significant difference in mean annual tornado frequency exist for La Niña, El Niño, and neutral years? A p-value of approximately 0.27 supports the null hypothesis. There is no significant relationship between tornado frequency and the three ENSO stages. After studying the entire ENSO cycle on a statewide level, the two ENSO extremes (El Niño and La Niña) are examined.

The Mann-Whitney test allows for the comparison of two samples. The main question associated with the Mann-Whitney test is whether or not two samples come from the same population. More specifically, the Mann-Whitney test is used to determine if a significant difference in mean annual tornado frequency exists for El Niño and La Niña years. A p-value of approximately 0.13 supports no significant relationship between tornado frequency and the ENSO extremes. Although a large difference
between average annual tornado frequency is evident when comparing the cold and warm phases (137 during La Niña years compared to 107.8 during El Niño years), a high-level of variance prohibits significant findings at the 5 percent and 10 percent levels. Tornado frequency is only one variable associated with the study. Another important characteristic pertaining to tornadoes is intensity.

Table 4 displays tornado intensity counts classified by Fujita Scale rating and subdivided into the varying stages of the ENSO cycle. Throughout the period of study (October 1, 1950 – September 30, 2000), a total of 6,248 reported tornadoes have associated intensity information. Of these twisters, 54 percent occur during neutral years of the ENSO cycle. This large percentage results from the fact that 26 of the 50 ENSO years under investigation are classified as neutral. Of the remaining tornadoes, 20 percent and 25 percent take place during El Niño and La Niña years respectively.

<table>
<thead>
<tr>
<th>ENSO Stage</th>
<th>Fujita Scale Rating (observed count)</th>
<th>Total</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>F0</td>
<td>F1</td>
</tr>
<tr>
<td>El Niño</td>
<td>565</td>
<td>446</td>
</tr>
<tr>
<td>La Niña</td>
<td>560</td>
<td>587</td>
</tr>
<tr>
<td>Neutral</td>
<td>1787</td>
<td>916</td>
</tr>
</tbody>
</table>
In this project, all tornadoes rated F0 or F1 are classified as weak and all tornadoes F2 or greater are categorized as intense. A chi-square test is used to compare intensity counts for those tornadoes occurring in El Niño and those in La Niña years. The chi-square test allows for the comparison of two sets of frequencies. A contingency table of tornado intensity and ENSO stage provides a useful visualization for this particular test.

Table 5 is a simple contingency table depicting tornado intensity (either weak or strong) according to the two ENSO extremes. Overall, the chi-square test determines whether the columns are contingent on the rows in the table. If the columns are not contingent on the rows, then the row and column frequencies are said to be independent.

Table 5

Contingency Table Categorized by Tornado Intensity and ENSO Stage

<table>
<thead>
<tr>
<th>ENSO Stage</th>
<th>Tornado Intensity</th>
<th>Total</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>F0 - F1 (weak)</td>
<td>F2 - F5 (intense)</td>
</tr>
<tr>
<td>El Niño</td>
<td>observed count</td>
<td>1011</td>
</tr>
<tr>
<td></td>
<td>expected count</td>
<td>957.3</td>
</tr>
<tr>
<td></td>
<td>% within stage</td>
<td>79.6%</td>
</tr>
<tr>
<td></td>
<td>% within intensity</td>
<td>46.8%</td>
</tr>
<tr>
<td>La Niña</td>
<td>observed count</td>
<td>1147</td>
</tr>
<tr>
<td></td>
<td>expected count</td>
<td>1200.7</td>
</tr>
<tr>
<td></td>
<td>% within stage</td>
<td>72%</td>
</tr>
<tr>
<td></td>
<td>% within intensity</td>
<td>53.2%</td>
</tr>
</tbody>
</table>
The chi-square test is used to determine if a significant difference in tornado intensity exists for El Niño and La Niña years. As Table 5 shows, 1,011 weak and 259 intense tornadoes are reported during all El Niño years while 1,147 weak and 446 intense tornadoes are reported during La Niña years. A Pearson chi-square value of 22 (p-value = 0.00) supports the alternate hypothesis, there is a relationship between tornado intensity and the ENSO extremes for the state of Texas. A large $\chi^2$ value makes sense when this relationship is explored in greater detail. The four highlighted cells within Table 5 list both the observed and expected counts for each ENSO extreme. First, although 312.7 intense tornadoes are expected to occur in all El Niño years, only 259 are actually observed. On the other hand, 392.3 intense tornadoes are expected during all La Niña years with 446 events actually happening. These numbers support the idea that more intense tornadoes touchdown during La Niña years as opposed to El Niño years. However, there are situations in which this trend varies. For instance, the largest number of F5 (most violent) tornadoes reported in the state actually take place during El Niño years and not La Niña years.

Regional Results

The possible relationship between ENSO and tornado activity is
analyzed at a smaller geographical scale. In order to regionalize the state of Texas, another weather variable is necessary to avoid sampling bias. For this study, Texas is subdivided into four distinct regions based upon annual mean days with thunder. The data is created using records from weather stations located throughout Texas from a period of 1961 to 1990. This information is part of a larger dataset known as the Climatic Map of the United States and is available via the National Climatic Data Center's website. Figure 8 shows annual mean days with thunder for the state from 1961 – 1990. Due to the fact that thunder data and county boundaries do not exactly match, further data manipulation is necessary. In the end, each county in Texas is categorized as belonging to one, and only one, region. Figure 9 represents the regional breakdown of the state based upon mean days of thunder occurring annually from 1961 to 1990.

Region 1 consists of 74 counties and encounters 30.5 – 40.4 thunder days annually. The largest region, Region 2, is composed of 138 counties and endures 40.5 – 50.4 thunder days on a yearly basis. Region 3 is made up of 33 counties and sees between 50.5 and 60.4 thunder days each year. Finally, the smallest subdivision, Region 4, includes 9 counties and experiences 60.5 – 70.4 thunder days on an annual basis. Due to the small areal extent of the 20.5 – 30.4 thunder days classification, no counties are categorized as belonging to this group.
Figure 8. Annual Mean Days with Thunder, 1961 – 1990.

Thunder Days

- 20.5 · 30.4
- 30.5 · 40.4
- 40.5 · 50.4
- 50.5 · 60.4
- 60.5 · 70.4

Projection: USA Contiguous Albers Equal Area Conic
Data Source: National Climatic Data Center, 2002a
Regions

One
Two
Three
Four

Projection: USA Contiguous Albers Equal Area Conic
Data Source: National Climatic Data Center, 2002a
The annual average tornado frequency according to ENSO phase and separated by region is portrayed in Table 6. For example, Region 1 endures an average of approximately 21 tornadoes annually during each El Niño extreme. This number increases only slightly (22.8) during a La Niña ENSO year. Similarly, the mean is around 20 for each neutral ENSO year.

<table>
<thead>
<tr>
<th>Region</th>
<th>El Nino</th>
<th>La Nina</th>
<th>Neutral</th>
</tr>
</thead>
<tbody>
<tr>
<td>One</td>
<td>21.2</td>
<td>22.8</td>
<td>20.2</td>
</tr>
<tr>
<td>Two</td>
<td>62.4</td>
<td>87.6</td>
<td>90.9</td>
</tr>
<tr>
<td>Three</td>
<td>19.3</td>
<td>20.2</td>
<td>20.4</td>
</tr>
<tr>
<td>Four</td>
<td>4.9</td>
<td>6.4</td>
<td>4</td>
</tr>
</tbody>
</table>

Regardless of ENSO phase, the data show that Region 2 has the highest number of tornadoes on a yearly basis. This region, composed of 138 counties, sees an average of about 62 reported twisters during each El Niño year. On the other hand, approximately 88 cyclones touchdown in this region throughout each La Niña year. Region 4 has the smallest number of average tornado reports from the 1950 ENSO year to the 1999 ENSO year. The numbers within this region are quite similar with each El Niño year seeing nearly 5 tornadoes while its counterpart endures
about 6. The miniscule numbers for Region 4 are most likely a result of its small spatial extent. This region consists of a total of 9 Texas counties, approximately 24 fewer than the next closest region.

The Mann-Whitney U test is employed to determine whether a significant difference in mean annual tornado frequency exists for the two ENSO extremes on a regional basis. When El Niño and La Niña years are compared, it is found that Region 1 has a Mann-Whitney value of 65. This equals a p-value of approximately 0.69, indicating no significant relationship between the two extremes. Unlike the previous region, Region 2 shows a significant pattern. The Mann-Whitney value for this region is 37.5 (p-value = 0.05). This leads to the conclusion that Region 2 endures more annual tornado touchdowns during La Niña years as opposed to its El Niño counterpart. As shown in Table 6, the region, on average, has about 25 more tornadoes reported during the La Niña extreme compared to an El Niño year. Region 3 has a Mann-Whitney value equal to 58.5 (p-value = 0.44) during the investigation period, indicating no significant relationship. Finally, Region 4 has a Mann-Whitney value of 66.5 when El Niño and La Niña ENSO years are compared. This large Mann-Whitney value leads to a p-value of 0.75.

In summary, the null hypothesis cannot be rejected for Regions 1, 3, and 4. More specifically, no significant relationship exists between the
two ENSO extremes and tornado events for these three regions. However, a Mann-Whitney value of 37.5 (p-value = 0.05) for Region 2 supports the idea that the occurrence of El Niño and La Niña actually impacts the number of reported tornadoes on a yearly basis. In this instance, Region 2 appears to have a higher average tornado count during La Niña years.

The total count for all rated tornadoes is found in Table 7. These counts are subdivided according to Fujita Scale rating, ENSO stage

Table 7

Regional Fujita Scale Rating According to ENSO Phase

<table>
<thead>
<tr>
<th>Region</th>
<th>ENSO Stage</th>
<th>Fujita Scale Rating (count)</th>
<th>Total</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td></td>
<td>F0</td>
<td>F1</td>
</tr>
<tr>
<td>1</td>
<td>El Niño</td>
<td>138</td>
<td>76</td>
</tr>
<tr>
<td></td>
<td>La Niña</td>
<td>119</td>
<td>91</td>
</tr>
<tr>
<td></td>
<td>Neutral</td>
<td>278</td>
<td>125</td>
</tr>
<tr>
<td>2</td>
<td>El Niño</td>
<td>318</td>
<td>264</td>
</tr>
<tr>
<td></td>
<td>La Niña</td>
<td>352</td>
<td>378</td>
</tr>
<tr>
<td></td>
<td>Neutral</td>
<td>1278</td>
<td>576</td>
</tr>
<tr>
<td>3</td>
<td>El Niño</td>
<td>84</td>
<td>86</td>
</tr>
<tr>
<td></td>
<td>La Niña</td>
<td>65</td>
<td>87</td>
</tr>
<tr>
<td></td>
<td>Neutral</td>
<td>194</td>
<td>174</td>
</tr>
<tr>
<td>4</td>
<td>El Niño</td>
<td>25</td>
<td>20</td>
</tr>
<tr>
<td></td>
<td>La Niña</td>
<td>24</td>
<td>31</td>
</tr>
<tr>
<td></td>
<td>Neutral</td>
<td>37</td>
<td>41</td>
</tr>
</tbody>
</table>

and region. For instance, Region 1 encounters a total of 23 F2 tornadoes during all the El Niño phases combined while Region 4 endures 10 F2 events during the same phase. A few interesting patterns emerge within
the table. First, regardless of region, the total number of rated tornadoes is greater during all the La Niña years when compared to El Niño years. For instance, during all 12 El Niño ENSO years, Region 4 sees 59 twisters while this number increased to 77 during the 12 La Niña years. A second trend deals with the most violent tornadoes, those being F5 in nature. Not only does Region 2 face the highest number of reported tornadoes, it also endures all six of the F5 cyclones that occur within the state.

Another contingency table is included to answer whether or not the ENSO stage affects tornado intensity on a regional basis (Table 8). The table depicts regional frequency counts for all those rated tornadoes occurring in either an El Niño or La Niña ENSO year. Once again, tornadoes in the F0 to F1 range are categorized as weak while all remaining tornadoes (≥ F2) are listed as intense. In Region 3, for example, 152 weak tornadoes are reported during all La Niña years combined. Not surprisingly, a smaller number (83) of intense tornadoes occur during the same time period. On the other hand, Region 1 endures 210 tornado touchdowns during the La Niña phase while facing 50 twisters listed as F2 or greater.

A chi-square test was initiated for all four regions. In this case, the null hypothesis states that ENSO stage and tornado intensity are independent on a regional level. The Pearson chi-square values,
Table 8
Contingency Table Categorized by Tornado Intensity and ENSO Stage by Region

<table>
<thead>
<tr>
<th>Region</th>
<th>ENSO Stage</th>
<th>Tornado Intensity</th>
<th>Total</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td></td>
<td>weak</td>
<td>intense</td>
</tr>
<tr>
<td>1</td>
<td>El Niño</td>
<td>observed count</td>
<td>214</td>
</tr>
<tr>
<td></td>
<td></td>
<td>expected count</td>
<td>206.1</td>
</tr>
<tr>
<td></td>
<td>La Niña</td>
<td>observed count</td>
<td>210</td>
</tr>
<tr>
<td></td>
<td></td>
<td>expected count</td>
<td>217.9</td>
</tr>
<tr>
<td>2</td>
<td>El Niño</td>
<td>observed count</td>
<td>582</td>
</tr>
<tr>
<td></td>
<td></td>
<td>expected count</td>
<td>550</td>
</tr>
<tr>
<td></td>
<td>La Niña</td>
<td>observed count</td>
<td>730</td>
</tr>
<tr>
<td></td>
<td></td>
<td>expected count</td>
<td>762</td>
</tr>
<tr>
<td>3</td>
<td>El Niño</td>
<td>observed count</td>
<td>170</td>
</tr>
<tr>
<td></td>
<td></td>
<td>expected count</td>
<td>158.6</td>
</tr>
<tr>
<td></td>
<td>La Niña</td>
<td>observed count</td>
<td>152</td>
</tr>
<tr>
<td></td>
<td></td>
<td>expected count</td>
<td>163.4</td>
</tr>
<tr>
<td>4</td>
<td>El Niño</td>
<td>observed count</td>
<td>45</td>
</tr>
<tr>
<td></td>
<td></td>
<td>expected count</td>
<td>43.4</td>
</tr>
<tr>
<td></td>
<td>La Niña</td>
<td>observed count</td>
<td>55</td>
</tr>
<tr>
<td></td>
<td></td>
<td>expected count</td>
<td>56.6</td>
</tr>
</tbody>
</table>

beginning with Region 1 and ending with Region 4 are 3.6, 12.6, 5.3, and 0.4 respectively. A value of 3.6 equates to a p-value of 0.06 for Region 1. Region 2 has a p-value of 0.00. Region 3 has a chi-square value of 5.3 which leads to a p-value equaling 0.02. The only region without significant findings at the 5 percent or 10 percent levels is Region 4 (p-value = 0.53). According to the findings, ENSO stage and tornado intensity appear to be related for Regions 1, 2, and 3.

The results of this test are not unexpected when the table is
analyzed thoroughly. The highlighted cells represent the observed and expected intense tornado counts revolving around Regions 1, 2, and 3. First, Region 1 endures 32 intense tornadoes during all the El Niño years even though approximately 39.9 are expected. However, the same region witnesses 50 intense tornadoes during the La Niña phase while only 42.1 intense tornadoes are expected. Similarly, Region 2 sees 155 intense tornadoes during all of the El Niño years combined with 187 expected. Also, the region encounters 291 intense tornadoes during La Niña years with an expected value totaling 259. Finally, there are 58 observed touchdowns during El Niño years in Region 3 while 69.4 are expected. While the expected number of tornado occurrences during La Niña years equals 71.6 for Region 3, the area actually endures 83 total. The observed and expected counts for Region 1, 2, and 3 support the idea that more intense tornadoes occur during La Niña years when compared to the El Niño extreme within these regions.

**Seasonal Results**

The final step in analysis revolves around investigating average annual tornado frequency and intensity throughout the different seasons. For this research, the calendar year is equally divided into 3-month increments. The four arbitrary seasons include: Winter – January
through March; Spring – April through June; Summer – July through September; and Fall – October through December. The annual mean tornado frequency according to ENSO phase and season is shown in Table 9. Generally, the data found in this table are not too surprising. The largest number of average tornadoes, regardless of ENSO phase, takes place during Texas’ primary convective months (i.e. Spring). On the other hand, the Fall season sees the fewest number of mean annual tornadoes.

Table 9

<table>
<thead>
<tr>
<th>Season</th>
<th>El Niño</th>
<th>La Niña</th>
<th>Neutral</th>
</tr>
</thead>
<tbody>
<tr>
<td>Winter (Jan. – Mar.)</td>
<td>16.2</td>
<td>19.8</td>
<td>11.4</td>
</tr>
<tr>
<td>Spring (Apr. – June)</td>
<td>60.4</td>
<td>86.7</td>
<td>90</td>
</tr>
<tr>
<td>Summer (July – Sept.)</td>
<td>20.8</td>
<td>16.8</td>
<td>21.4</td>
</tr>
<tr>
<td>Fall (Oct. – Dec.)</td>
<td>10.4</td>
<td>13.7</td>
<td>12.6</td>
</tr>
</tbody>
</table>

A Mann-Whitney test is run in order to discover significant relationships between mean annual tornado frequency and ENSO stage on a seasonal basis. Similar to the earlier tests performed on a statewide and regional level, the Mann-Whitney U test answers the question: Is there a significant relationship between El Niño, La Niña, and average tornado frequency for the Winter, Spring, Summer, and Fall seasons. First, the test statistic for the Winter season equals 52. A Mann-
Whitney value of 52 leads to a p-value of approximately 0.25, therefore not being significant. The Spring season has a Mann-Whitney value of 40.5 (p-value = 0.07), making the results significant at the 10 percent level. There appears to be a relationship between the two ENSO extremes and tornado frequency during the springtime months. More specifically, the data indicate that La Niña increases tornadic activity from April through June. The Summer and Fall seasons have Mann-Whitney values of 53.5 (p-value = 0.29) and 67.5 (p-value = 0.79) respectively. The null hypothesis cannot be rejected for both the Summer and Fall months.

A breakdown of seasonal Fujita Scale ratings according to ENSO phase is represented in Table 10. These data are further subdivided according to season. The table includes all 6,248 rated tornadoes occurring from the ENSO year of 1950 up to and including the 1999 ENSO year. For example, a total of 8 F3 twisters occur in the Winter season during all El Niño years combined while a total of 138 F1 tornadoes take place in the Summer season during those years classified as neutral. It appears as though a few generalizations can be made. First, the data show that the most intense tornadoes seem to occur in the Spring season. The Spring season sees a total of 41 cyclones ranked F4 or F5 while the remaining three seasons endure a grand total of 8. Second, Spring is the only season in which at least one F5 tornado strikes.
Table 10

Seasonal Fujita Scale Rating According to ENSO Phase

<table>
<thead>
<tr>
<th>Season</th>
<th>ENSO Stage</th>
<th>Fujita Scale Rating (count)</th>
<th>Total</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td></td>
<td>F0</td>
<td>F1</td>
</tr>
<tr>
<td>Winter</td>
<td>El Niño</td>
<td>70</td>
<td>81</td>
</tr>
<tr>
<td></td>
<td>La Niña</td>
<td>82</td>
<td>73</td>
</tr>
<tr>
<td></td>
<td>Neutral</td>
<td>129</td>
<td>89</td>
</tr>
<tr>
<td>Spring</td>
<td>El Niño</td>
<td>332</td>
<td>238</td>
</tr>
<tr>
<td></td>
<td>La Niña</td>
<td>354</td>
<td>363</td>
</tr>
<tr>
<td></td>
<td>Neutral</td>
<td>1281</td>
<td>571</td>
</tr>
<tr>
<td>Summer</td>
<td>El Niño</td>
<td>130</td>
<td>78</td>
</tr>
<tr>
<td></td>
<td>La Niña</td>
<td>79</td>
<td>82</td>
</tr>
<tr>
<td></td>
<td>Neutral</td>
<td>262</td>
<td>138</td>
</tr>
<tr>
<td>Fall</td>
<td>El Niño</td>
<td>33</td>
<td>49</td>
</tr>
<tr>
<td></td>
<td>La Niña</td>
<td>45</td>
<td>69</td>
</tr>
<tr>
<td></td>
<td>Neutral</td>
<td>115</td>
<td>118</td>
</tr>
</tbody>
</table>

In order to determine the potential relationships between the ENSO extremes and tornado intensity on a seasonal basis, Pearson chi-square values are calculated. First, the Winter season has a chi-square value equaling 7 (p-value = 0.01), significant at the 5 percent level. Second, Spring shows the highest Pearson value, 14.9 (p-value = 0.00), of all the seasons. In this case, the relationship between the ENSO extremes and tornado intensity is significant for both the Winter and Spring seasons. However, this significant relationship disappears when Summer and Fall are examined. The Summer and Fall seasons have Pearson chi-square values of 1.96 (p-value = 0.16) and 0.59 (p-value = 0.44) respectively. Once again, it is valuable to explore these numbers in
greater detail. A contingency table categorized by tornado intensity and ENSO stage allows for the comparison of expected and observed counts for intense tornadoes occurring throughout the four seasons (Table 11).

Table 11
Contingency Table Categorized by Tornado Intensity and ENSO Stage by Season

<table>
<thead>
<tr>
<th>Season</th>
<th>ENSO Stage</th>
<th>Tornado Intensity</th>
<th>Total</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td></td>
<td>weak</td>
<td>intense</td>
</tr>
<tr>
<td>Winter</td>
<td>El Niño</td>
<td>observed count</td>
<td>151</td>
</tr>
<tr>
<td></td>
<td></td>
<td>expected count</td>
<td>138.7</td>
</tr>
<tr>
<td></td>
<td>La Niña</td>
<td>observed count</td>
<td>155</td>
</tr>
<tr>
<td></td>
<td></td>
<td>expected count</td>
<td>167.3</td>
</tr>
<tr>
<td></td>
<td></td>
<td>observed count</td>
<td>570</td>
</tr>
<tr>
<td></td>
<td></td>
<td>expected count</td>
<td>535.8</td>
</tr>
<tr>
<td></td>
<td>La Niña</td>
<td>observed count</td>
<td>717</td>
</tr>
<tr>
<td></td>
<td></td>
<td>expected count</td>
<td>751.2</td>
</tr>
<tr>
<td></td>
<td></td>
<td>observed count</td>
<td>208</td>
</tr>
<tr>
<td></td>
<td></td>
<td>expected count</td>
<td>203</td>
</tr>
<tr>
<td></td>
<td>La Niña</td>
<td>observed count</td>
<td>161</td>
</tr>
<tr>
<td></td>
<td></td>
<td>expected count</td>
<td>166</td>
</tr>
<tr>
<td></td>
<td></td>
<td>observed count</td>
<td>82</td>
</tr>
<tr>
<td></td>
<td></td>
<td>expected count</td>
<td>85</td>
</tr>
<tr>
<td></td>
<td>La Niña</td>
<td>observed count</td>
<td>114</td>
</tr>
<tr>
<td></td>
<td></td>
<td>expected count</td>
<td>111</td>
</tr>
</tbody>
</table>

The significant values appear highlighted in the table above.

During all the El Niño’s occurring in Winter, approximately 55.3 intense tornadoes are expected, but only 43 are actually observed. On the other hand, throughout all the La Niña’s combined, 66.7 intense tornadoes are expected, but a larger number (79) were observed. The same pattern is
found for the Spring season as well (El Niño expected = 180.2, El Niño observed = 146, La Niña expected = 252.8, La Niña observed = 287). These numbers support the alternate hypothesis that the Winter and Spring seasons endure more intense tornadoes during La Niña years as opposed to El Niño years.

In summary, statewide results reveal that more intense twisters are likely to occur during the La Niña extreme. Also, cold ENSO events are shown to impact Region 2 by augmenting tornado frequency within the region. Furthermore, La Niña is found to enhance tornado intensity in Regions 1, 2, and 3. Finally, research findings indicate that the cold phase of ENSO promotes tornado frequency and intensity during the Spring months while only favoring an increase in tornado intensity for the Winter months.
CHAPTER V

CONCLUSION

It would be incorrect to assume that a tornado touchdown can be directly attributed to an ENSO stage. However, as some of the findings indicate, an association between both phenomena is a distinct possibility. Overall, results reveal that La Niña events favor the occurrence of more intense tornadoes (F2 or greater) in Texas. Also, the data support the idea that La Niña increases both tornado frequency and intensity in specific regions of the state. Finally, the cold phase of the ENSO cycle is shown to enhance tornado frequency and intensity in the Spring months of April through June while increasing the possibility for more intense tornadoes in the Winter months (January – March).

The physical mechanisms that may link tornado activity and the ENSO cycle are incredibly complex. Although the main goal of this work is to discover significant statistical relationships between tornadoes and ENSO, it is beneficial to highlight some of the explanations atmospheric scientists and climatologists have proposed when attempting to relate both phenomena.

First, past study shows that varying stages of the ENSO cycle may
impact large-scale upper-level circulation patterns (i.e. Rossby waves). In turn, these patterns affect the thermodynamic environment. More specifically, Monfredo (1999) believes that cap strength may be weakened during the warm phase of ENSO and strengthened during the cold phase. A strong cap or temperature inversion promotes tornado production by allowing moisture and heat to be trapped in the lower levels of the atmosphere. At times, this lid can erode or break, leading to tremendous severe storm activity, including tornadoes.

Also, researchers feel that the reverse Pacific North American (PNA) pattern and PNA pattern are influenced by the ENSO cycle (Horel and Wallace, 1981; Ropelewski and Halpert 1986; Monfredo, 1999). The reverse PNA pattern consists of ridges of high-pressure in the central and eastern United States with low-pressure troughs throughout the western U.S. According to Monfredo (1999), “The anticyclonic mid-level flow brings very dry and warm southwesterly winds off the Mexican plateau, particularly during ENSO cold phases” (419). The movement of this warm, dry air promotes the formation of a strong cap. On the other hand, troughs in the eastern portions of the United States and ridges in the western U.S characterize the PNA pattern. The PNA pattern associated with the El Niño extreme does not support the southwesterly flow of warm, continental tropical air. Thus, the formation of a strong
temperature inversion is less likely when compared to the reverse Pacific North American pattern (Monfredo, 1999). However, this is not to say that the development of a strong cap or inversion is impossible during the warm phase of the ENSO cycle.

These are only a few of the explanations detailing the possible physical mechanisms responsible for tornado and ENSO interaction. Exploring each of these mechanisms with empirical evidence is beyond the scope of this study, but would be a beneficial topic of research in the future.

Today, tornadoes remain one of the most awe-inspiring and destructive forces found in nature. The study of these mysterious features continues to increase within the scientific community. Advancements in technology and field study throughout the past several decades have helped meteorologists better understand tornado dynamics. Subsequently, this has led to improvements in forecasting tornado events. However, although great strides have been made in the past, further research is a necessity.

Tornadoes are complex mesoscale weather systems that are influenced by both local and large-scale atmospheric patterns. These patterns and processes may be impacted by a number of different phenomena. One such phenomenon related to tornado activity is El Niño
Southern Oscillation. Thesis results support the idea that ENSO, does in fact, impact tornado dynamics (including tornado frequency and tornado intensity) within the state of Texas. This paper, along with future research efforts revolving around this potential relationship are advantageous and may help improve forecasting methods, hopefully leading to a reduction in the loss of life and property caused by these dangerous events.
BIBLIOGRAPHY


