THESIS

COLD-SEASON TORNADOES: CLIMATOLOGICAL, METEOROLOGICAL, AND SOCIAL PERSPECTIVES

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ABSTRACT

COLD-SEASON TORNADOES: CLIMATOLOGICAL, METEORLOGICAL, AND SOCIAL PERSPECTIVES

Tornadoes that occur during the cold season, defined here as November–February (NDJF), pose many unique societal risks. For example, people can be caught off-guard because in general one does not expect severe weather and tornadoes during winter months. The public can also be unsuspecting of significant weather due to the bustle of major holidays like Thanksgiving, Christmas, and New Year's, when most people are concerned with family activities and not thinking about the weather. Cold-season tornadoes also have a propensity to be nocturnal and occur most frequently in the South and Southeastern U.S., where variable terrain, inadequate resources, and a relatively high mobile home density add additional social vulnerabilities. Over the period 1953–2015 within a study domain of (25-42.5°N, 75-100°W), some 937 people lost their lives as a result of NDJF tornadoes.

Despite this enhanced societal risk of cold-season tornadoes in the South, very little attention has been given to their meteorological characteristics and climate patterns, and public awareness of their potential impacts is lacking. This thesis aims to greatly advance the current state of knowledge of NDJF tornadoes by providing an in-depth investigation from three different science perspectives. First, a climatology of all (E)F1-(E)F5 NDJF tornadoes is developed, spanning the period 1953–2015 within a domain of (25-42.5°N, 75-100°W), in order to assess frequency and spatial changes over time. A large increasing trend in cold-season tornado occurrence is found across much of the Southeastern U.S., with the greatest uptick in Tennessee, while a decreasing trend is found across eastern Oklahoma. Spectral analysis reveals a cyclic pattern of enhanced NDJF counts every 3-7 years, coincident with the known period for ENSO. Indeed, La Niña episodes are found to be correlated with NDJF tornado counts, although a stronger teleconnection correlation exists with the Arctic Oscillation (AO), which explains 25% of the variance in counts. A second perspective focuses on meteorological environments that characterize NDJF tornadoes through use of the NCEP/NCAR Reanalysis. Upon comparing the most tornadic and least tornadic cold seasons, it is found that active seasons are characterized by a large trough in the western U.S.; warm and moist conditions across the Southeast, likely due to an enhanced low-level jet transport from the western Gulf of Mexico; and enhanced 1000-500-hPa wind speed shear. The third perspective addressed in this thesis is that of social science. A case study of four tornado events from November 2016–February 2017, in which a post-event survey is disseminated to NWS meteorologists, broadcast meteorologists, and emergency managers, is carried out to assess strategies and barriers professionals face when communicating cold-season tornado risk and warnings to their respective communities. The survey also aims to shed light on the perceived levels of human preparedness, vulnerability, and resiliency from the professional's point of view. In addition to unique, case-specific challenges, the professionals expressed major barriers to communication due to inconsistency of messages and graphics, and an inability to give the public information on fine enough temporal and spatial scales. Each decision-making sector noted a high local vulnerability to tornadoes in general, mostly brought on by lack of education and/or resources. However, most professionals perceive their communities to be aware of cold-season tornado risk and thus adequately prepared and resilient when they occur. The survey results also confirm the desire and need for better collaboration among professionals, and with social scientists, in order to adequately educate and warn all sectors of society from tornado risk, especially those during times of year they are not typically expected. Harnessing all three perspectives presented in this study provides a much deeper understanding of NDJF tornadoes and their societal impacts, an understanding that serves to increase public awareness and ultimately save lives.

ACKNOWLEDGEMENTS

Ralph Waldo Emerson once said, “Do not go where the path may lead. Go instead where there is no path and make a trail.” In many ways, this quote has epitomized my research endeavors throughout my pursuit of a Master’s degree at Colorado State University (CSU). For a research scientist, a major goal is to investigate something new and intriguing; that is, to make a trail where there is no path. Not only has this been the case in my thesis project, with its focus on the largely unknown realm of cold-season tornadoes, but also in my path through the graduate program at CSU in general. The path did not appear to be leading me here, and other roads indeed seemed more logical or comfortable, but in the end an opportunity arose for me to come to CSU, and in faith I decided to take the newly-formed trail. After almost two years, I can look back and be confident that this was the trail meant for me, as the blessings received and knowledge gained have been immense. However, the culmination of my thesis project has not been without the help and support of numerous individuals, so it is in great appreciation that I acknowledge them.

First and foremost, I give thanks to God and my Lord and Savior Jesus Christ. I would not be writing this if God did not give me the grace and strength to get through each day. I pray He gets the glory in the outworking of my research.

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refreshing for me to witness. Next, I thank my other committee members, Steve Rutledge and Craig Trumbo. It has been wonderful to work with these men, who both bring a respected professionalism yet endearing nature to the table. The other students in the Schumacher Research Group – Erik, Greg, Stacey, and Nathan – have not only been supportive and provided crucial feedback of my research, but have given me a new crop of friends and colleagues to work alongside during my Master's years. The Atmospheric Science Department as a whole deserves a big thanks, as numerous faculty, staff, and fellow students have supported or helped me in various facets along the way. After almost two years in the department, it is very clear that this is a special place, unlike any other Atmospheric Science program in the country. In particular, I must thank Trent Davis, my fellow student, friend, and roommate of over a year. Many a night was had in our apartment living room watching Netflix and conversing about what to make of our new sphere of life in Colorado.

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My career as a student researcher to this point is greatly indebted to Ernest Agee, my undergraduate research advisor at Purdue University. Dr. Agee gave me a first opportunity for research in 2012, and we quickly developed a unique bond and friendship. Three co-authored journal publications and various conference presentations were outcomes of my work with Dr. Agee, which is a testament to the time and energy he invests in undergraduate students. To this day, he continues to help young people see their potential to make an impact in our field. I also thank Scott Weaver, who mentored me in my NOAA Hollings Scholarship Program in summer 2014 at the Climate Prediction Center. It was here that I first began to investigate cold-season tornadoes with Scott's encouragement.

I have been blessed to have my thesis work be supported by two graduate fellowships. First, I thank the American Meteorological Society for providing funding for my first year as a Master's student, and for allowing me numerous opportunities to present at their conferences over the past few years. Next, I thank the National Science Foundation

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INSPIRATION

It was Sunday morning, 17 November 2013, on the campus of Purdue University in West Lafayette, Indiana. The Storm Prediction Center had just upgraded eastern Illinois and western Indiana to a 'High' risk of severe weather, particularly for destructive winds and tornadoes. As a weather enthusiast and one pursuing an Atmospheric Science degree, this immediately caught my attention, as a 'High' risk at this time of year seemed unprecedented. The storm system bearing down on Indiana had been forecast for several days, but the degree of severity had been a question until early Sunday morning, when it became clear that the environment was primed for potentially destructive tornadoes. Indeed, the threat was realized, as the day became the largest November tornado outbreak ever recorded in the state of Indiana. Although no fatalities were reported in Indiana, the tornadoes caused great damage throughout the northern half of the state. In Illinois, multiple casualties were attributed to the state's only EF4 tornado in November history.

At the time, I was a Resident Assistant (RA) for Crosswalk Commons, my unique apartment community that served as an outreach for international students. Out of approximately 100 residents were students from 17 different counties, many of whom had very limited knowledge of U.S. weather and would be very unsuspecting of a mid-November tornado outbreak (as would many Americans, for that matter). As an RA, I felt a responsibility to ensure that my residents were protected on this day as it became clear that the university would be under the gun for severe winds and potential tornadoes. I remember rushing home from church, and, upon a 'Tornado Warning' being issued for the county west of us, going door to door imploring residents to gather in the basement of the building away from windows. Sure enough, I got strange stares from some residents, probably frustrated that a trip downstairs would disrupt their sleeping or studying. Thankfully, everyone did eventually heed my warning, and as the sirens blared minutes later, all of us were safely sheltered. While no tornadoes ended up occurring on Purdue's campus, some areas (including Crosswalk Commons) lost power for about 2 days, leading to a couple cold nights huddled around candles, as the weather turned much colder after the 17th. Tornadoes did touch down in other parts of the county, most notably one that destroyed an elementary school and became an Internet sensation due to the security cameras in the gymnasium and hallway capturing the roof collapse. One can only imagine what the outcome would have been if it were a school day with hundreds of children in those halls.

I have been interested in severe weather and tornadoes for many years, including forecasting and tracking severe weather. However, the 17 November 2013 event marked the first time I felt responsible to protect a group of people who were largely ignorant of a tornado's potential impacts. I realized that I had knowledge and expertise that could directly affect the state of people's lives on a day when dangerous tornadoes were in the area, a realization that was a bit daunting but also affirming. I had something to offer that nobody else in that context did, and I therefore felt particularly useful. This event also taught me how vulnerable certain sectors of society, in this case international students, can be. From their limited experience, these students would be expecting colder weather and the start of snow once November hits, not warmth and destructive tornadoes. Thus, the idea to study "cold-season" tornadoes, those that strike when people are least expecting them, was born. Questions began to be formed in my head as to their frequency of occurrence, changes in frequency over time as the climate warms, likelihood of causing damage and fatalities, and signals that might indicate their potential occurrence. Given my experience at Crosswalk Commons, I also began to develop a vision for helping the sectors of society most susceptible to tornado impacts by improving communication, access to technology, and education. It seemed logical to me that people would be more at-risk during these times of year when tornadoes are not expected, and thus the need would exist for a more comprehensive evaluation of the science and social impacts of cold-season tornadoes. Initial work begun during an internship at the Climate Prediction Center proved intriguing, and thus the bud of interest that emerged from the harrowing 17 November 2013 experience blossomed into the full-fledged Master's project contained in the following pages of this thesis.

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CHAPTER 1: INTRODUCTION

In a given year, around 1200 tornadoes touch down throughout the U.S. and are responsible for an average of 80 fatalities, 1500 injuries, and over $1 billion in damage each year (NSSL). While the majority of U.S. tornadoes occur during the spring, they are not limited to the warm season. In fact, numerous winter tornado events and outbreaks have wreaked havoc in recent years. One may recall the Christmas week tornadoes of 2015 in Mississippi, Tennessee, and the Dallas, Texas area that killed at least 25 people. Another powerful Christmastime tornado outbreak hit Alabama in 2012. Others may remember the 17 November 2013 outbreak across the Midwest that spawned 75 tornadoes, killed multiple people, and produced the only November EF4 tornado in Illinois state history. The so-called 'Super Tuesday Outbreak' of February 2008 across the Southeast produced a staggering 27 significant (EF2+) tornadoes with widespread damage and over 50 casualties (Livingston 2013). Even more recently, the 2016-17 winter season saw several rounds of powerful tornadoes. At least five people were killed in northern Alabama and Tennessee in late November 2016 from a series of supercell tornadoes. Then in January 2017, strong EF3 tornadoes hit both Hattiesburg, MS and East New Orleans, LA, with the East New Orleans event being the strongest tornado ever recorded in Orleans Parish. In fact, the 134 tornado reports in January 2017 make it the second-most tornadic January since 1950 (NCEI 2017). The magnitude and human casualties of these events are a sobering reminder that cold-season tornadoes can be just as destructive, and in some cases even more so, than their warm-season counterparts. Knowing more about these cold-season events and what factors contribute to their occurrence would be quite valuable, yet no modern comprehensive climatology exists. As such, this study aims to fill that research hole through an in-depth analysis of cold-season tornadoes spanning multiple angles and disciplines.

A. Background and Motivation

Tornadoes have long been a fascination of the scientific community and general public alike. Known for their mysterious and intriguing appearance, but also for their destructive potential, tornadoes continue to be the subject of much research. The understanding of tornado dynamics and mechanisms prompting their formation has proven quite elusive to atmospheric scientists, although progress is being made in recent years as technological capability improves (Markowski et al. 2008, Rotunno 2013, Davies-Jones 2015). Parameters which are useful in discriminating between thunderstorm and tornado environments, and significant versus weak tornadoes, are being discovered and implemented in modeling studies to help forecasters know what signals to look for during evaluation of tornado risk (Rasmussen and Blanchard 1998, Brooks et al. 2003b, Thompson et al. 2007, Tippett et al. 2012, 2014). From a more large-scale perspective, trends in tornado counts and tornado days through time have been investigated to search for changes in spatial and temporal variability and frequency of tornadoes (Brooks et al. 2014, Elsner et al. 2015, Agee et al. 2016), as well as their relationship to teleconnection patterns (Cook and Schaefer 2007). Recent work has even entered into the realm of providing statistical and probabilistic tornado predictions on seasonal time scales using a variety of metrics (Allen et al. 2015, Elsner and Widen 2016, Gensini and Marinaro 2016). Of course, having this developing body of research does not eliminate the potentially destructive societal impacts associated with a tornado. There is a great need for meteorologists and other professionals to effectively inform the public before, during, and after a tornado event of its forecasted location and intensity, potential for damage, and the proper procedures that should be taken to protect life and property. To this end are numerous studies that, for example, investigate the tornado warning process (Brotzge and Donner 2013), human perception of and compliance to warnings (Paul et al. 2014, Drost et al. 2016, NOAA 2016), relationships between decision-makers and the public during a tornado event (League et al. 2010, Schumacher et al. 2010), and the emerging impact of social media in tornado risk communication (Ripberger et al. 2014, Stokes and Senkbeil 2017).

Probing the depths of tornado studies reveals a relative absence of work that specifically accentuates tornadoes that occur in the months in which they are least common. Galway and Pearson (1981) were perhaps the first to analyze aspects of cold-season tornadoes, doing so from a tornado outbreak point of view. More recently, a few studies explore meteorological parameters that define common cold-season tornado environments (Hanstrum et al. 2002, Guyer and Dean 2010, Cohen et al. 2015) or attempt to relate cold-season tornado frequency to the El Niño Southern Oscillation (Nunn and DeGaetano 2004), but the work presented here represents the most comprehensive study to date specifically regarding tornadoes occurring in the U.S. between the months of November and February (NDJF). While research involving tornado outbreaks, events, and environments during spring months may appear more attractive and therefore more prevalent in the literature, there is great worth in expanding the current state of knowledge base into the winter months. Tornadoes pose many risks to society, and these dangers are even more enhanced during the cold season. For example, the public is less likely to anticipate tornadoes during the winter, often leading to complacency (Simmons and Sutter 2007). Further, many cold-season tornadoes occur at night (Kis and Straka 2010, Sherburn et al. 2016), which when coupled with their prevalence over the rural and relatively poor southeastern U.S. (Ashley et al. 2007), creates a potential recipe for disaster (Ashley et al. 2008, Emrich and Cutter 2011).

Given the research gap that exists for cold-season tornadoes, and the high vulnerability of the population these tornadoes are impacting, this study aims to greatly expand the current state of knowledge regarding cold-season tornadoes and motivate action toward mitigation of their impacts. In particular, the study seeks to answer the following key research questions:

(1) How are cold-season tornadoes changing in frequency over time, and where are the greatest spatial shifts in frequency happening across the country?

(2) Are there any climate signals that bear a relationship to cold-season tornado counts?

(3) What is the typical environmental set-up for a cold-season tornado event, and how does it differ from the more common springtime events?

(4) How does the meteorological community perceive the risk and human vulnerability associated with cold-season tornadoes?

(5) What barriers do professionals face when attempting to communicate cold-season tornado risk to the public in a real-time event?

B. Research Outline

Three unique approaches are taken in this study of cold-season tornadoes that incorporate aspects of both the physical and social sciences. First, Chapter 2 defines the study parameters such as the spatial and temporal domain, and then turns its focus to climatological aspects of cold-season tornadoes, including assessment of geographical and temporal changes in tornado counts over time and a time series spectral analysis with an eye toward potential relationships between cold-season tornado frequency and teleconnection patterns. Next, Chapter 3 investigates the meteorological side of cold-season tornadoes, namely using Reanalysis data to assess the environments and ingredients which tend to characterize a particularly tornadic cold season, as well as invoking the SPC Storm Mode database for an analysis of how convective mode varies for cold-season tornadoes. Chapter 4 applies the physical research to the societal sphere via a case study analysis of 2016-17 cold-season tornado events wherein a survey is developed and disseminated to professionals to gauge their perception of cold-season tornado communication and risk barriers. Each of Chapters 2-4 is organized in a similar fashion. First, there is a background section that reviews the applicable literature and motivates the work. Then an explanation of the specific research methods employed is given. Results of the analyses are presented next, followed by any appropriate discussion. Chapter 5 concludes the study by offering an overall summary of results, entertaining next steps and future research prospects, assessing limitations, and arguing for the great significance of the work in vastly expanding the current understanding of cold-season tornadoes.

CHAPTER 2: CLIMATOLOGICAL PERSPECTIVE

The first step in evaluating cold-season tornadoes is to establish a comprehensive climatology on which to base the subsequent analysis and motivate research into the associated meteorological and societal perspectives. This chapter begins with a literature review of both cold-season tornadoes and tornadoes as a whole. Then, the methods used to gather and parse the tornado information and climate indices are discussed, including issues related to the tornado database and strategies employed to build and analyze the climatology. Next, findings are presented which highlight the overall frequency, intensity, and spatial distribution of cold-season tornadoes, as well as trends in their counts in time and space. Spectral analysis of cold-season tornado counts is also performed, which prompts an investigation into potential relationships to teleconnection indices, specifically the El Niño Southern Oscillation (ENSO), Arctic Oscillation (AO), and North Atlantic Oscillation (NAO). The chapter concludes with a summary of major results, potential implications, and connection to physical meteorology.

A. Motivation

An ever-evolving tornado database has led to continual fresh studies which investigate tornado climatology from a multitude of angles. For example, recent work has shown an increasing variability in tornado occurrence associated with more tornadoes on fewer days (Brooks et al. 2014, Elsner et al. 2015). Spatial variability and frequency of tornadoes is also changing (Farney and Dixon 2014, Agee et al. 2016, Guo et al. 2016).

Further, statistical models for assessing and predicting tornado risk have been developed (Coleman and Dixon 2014, Elsner and Widen 2016).

However, there has been much less work done in reference to so-called "cold-season", "cool-season", or "off-season" tornadoes. For this study, the "cold season" is defined as November–February (NDJF), the four months with the fewest average tornado counts in the U.S (NCEI). In what can perhaps be considered the first major study specifically highlighting a climatology of cold-season tornadoes, Galway and Pearson (1981) found that 68% of all December–February (DJF) tornadoes from 1950–1979 occurred in the southeastern United States. By far, however, most of the limited cold-season tornado literature focuses on the environmental set-up for severe weather and tornadoes. This realm is explored in Chapter 3 using the specific metrics of this study. Of note, Hanstrum et al. (2002) investigate the synoptic and mesoscale environments for cool-season tornado events in California and Australia, which provides a source of comparison for cold-season environments investigated in this study. Cold-season tornado environments in the U.S. are also found to be similar to those of European warm seasons (Brooks 2009, Cohen et al. 2015), with generally limited buoyancy but strong large-scale forcing for ascent and convection (see also Guyer and Dean 2010). This "low-CAPE-high-shear" relationship is repeatedly found to be characteristic of cold-season severe weather and tornadoes, as are other ingredients to be discussed in Chapter 3 (Guyer et al. 2006, Guyer and Dean 2010, Sherburn and Parker 2014).

There has also been some investigation into the relationship between teleconnection patterns, in particular ENSO, with wintertime tornado events. Nunn and DeGaetano (2004) and Cook and Schaefer (2008) both approach the issue from the perspective of the number of tornadoes occurring on a tornado day. While there are hints of a relationship between tornado frequency and ENSO phase, both studies beg for more conclusive findings. Marzban and Schaefer (2001) fail to find any geographical shifts in tornado activity east of the Rocky Mountains from season to season due to ENSO phase. Analysis by Sankovich et al. (2004) shows that thermodynamic parameters such as Lifted Index and CAPE favor a more unstable environment conducive to severe weather during La Niña, but kinematic parameters such as shear and storm-relative helicity favor severe weather during El Niño and Neutral phases. Other work shows an enhancement of tornado counts during La Niña conditions, though not necessarily in wintertime (Schaefer and Tatom 1999, Knowles and Pielke Sr. 2005, Allen et al. 2015). Given the unclear influence of teleconnection patterns on tornadoes, this study aims to take a fresh look not only at the ENSO relationship, but also relationships with AO and NAO, by taking a statistical correlation approach and assessing seasonal shifts in tornado counts under various teleconnection phases.

Due to the limited emphasis on cold-season tornadoes, it is of worth to create a more complete climatology and use it to investigate changes in frequency and spatial distribution over time. This information can shed light on if and where NDJF tornadoes are becoming more prevalent and consequently promote any new understanding and potential adjustments to communication strategies between forecasters and the public.

B. Methodology

In developing the NDJF climatology, a series of decisions are made as to the intensity and geographical domain of the tornadoes used, as well as the timeframe over which to analyze the tornado data. From these stipulations, a well-defined climatology is created and used to investigate several facets of cold-season tornadoes. This section also addresses the methods used to gather teleconnection indices for statistical correlation analysis.

1. Tornado data

Any study invoking tornado statistics and climatology must first deal with the issue of data integrity and homogeneity. The Storm Prediction Center (SPC) *Storm Data* archive (available online at http://www.spc.noaa.gov/wcm/) currently contains tornado data from 1950 to present day, but several points of caution must be taken when utilizing the data. Many past studies have articulated the shortcomings associated with the tornado database at length (Doswell and Burgess 1988, Brooks et al. 2003a, Verbout et al. 2006, Agee and Childs 2014), which motivate the following aspects of the climatology developed here.

(i) TEMPORAL RANGE

A first question that must be asked is how far back in time can the tornado record be deemed reliable. While efforts have been made to document tornadoes prior to 1950 (Grazulis 1993), there is simply not enough data to include pre-1950 tornadoes in a climatology study. The earliest years in the modern tornado record (1950–1952) are also suspect due to reliance on rudimentary sources such as newspaper clippings and photographs to document tornado events (Schaefer and Edwards 1999). With the formation of the National Severe Storms Forecast Center in 1953, however, tornado documentation became more regular and systematic. While some tornado climatology studies begin analysis with the year 1950 (Farney and Dixon 2014, Guo et al. 2016), most recognize the reliability issue in the early years of record-keeping and consequently begin analysis with either 1953 or 1954 (Verbout et al. 2006, Agee and Childs 2014, Brooks et al.

2014, Elsner et al. 2015, Agee et al. 2016). As such, the current work begins analysis with the 1953-54 cold season. The data period for this study ends with February 2015, and thus comprises 62 cold seasons.

(ii) INTENSITY RANGE

Another question facing tornado climatology research is what range of Enhanced Fujita (EF) Scale intensities to use. It is well documented that there is a consistent upward trend in tornado counts when all tornado intensities are considered (Brooks et al. 2003a, Verbout et al. 2006, Brooks et al. 2014, Widen et al. 2015), but this trend is misleading due to a variety of issues regarding how tornadoes in the modern database have been documented and rated. Many factors have led to better reporting of tornadoes over time. For one, there are simply more people in the country to witness and report tornadoes as time goes on (Anderson et al. 2007). The National Weather Service (NWS) has changed and improved their procedure for documenting tornadoes over time, although discrepancies in standards still exist between offices (Doswell 2007, Edwards et al. 2013). Increased media coverage; technological advancements in modeling, radar, and social media; and sensationalism have led to a rise in storm chasers and public awareness of tornadoes in general, resulting in more complete reporting (McCarthy and Schaefer 2004, Verbout et al. 2006, Edwards et al. 2013, Elsner et al. 2013). The most monumental technological change in tornado data has been with the introduction of the Fujita (F) Scale, and eventually the Enhanced Fujita (EF) Scale. Pioneered by Dr. Ted Fujita, the F-scale intensity rating for tornadoes uses damage indicators to rate the strength of a tornado (Fujita 1971, Fujita and Pearson 1973). The F-scale began to be incorporated into the SPC tornado database in 1974 and was officially adopted by the NWS in the late 1970s (Edwards et al. 2013).

Numerous issues with the F-scale arose over the following decades (Minor et al. 1977, Doswell and Burgess 1988), sparking a desire for an updated tornado rating scale. Thus, the EF-scale was created in the mid-2000s and implemented into standard NWS intensity documentation procedure in 2007. While it is yet too early to determine any impacts the EF-scale is having on tornado trends, early indications are that the more rigorous standards adopted with the EF-scale may favor EF1-2 tornadoes at the expense of EF0 tornadoes (Edwards and Brooks 2010). Further, both the F and EF-scales suffer from the subjectivity associated with using damage indicators to rate the strength of a tornado rather than a direct wind speed measurement. Two main issues related to tornado intensity are of importance in establishing the cold-season tornado climatology presented here, namely the F1/F2 rating problem before F-scale implementation, and the inhomogeneity in the (E)F0 tornado record.

First, it has been found that tornadoes rated after the F-scale was initiated (i.e. prior to 1974) are plagued by an over (under) counting of F2 (F1) tornadoes. That is, many tornadoes that were assigned an F2 rating actually belong in the F1 category. This discrepancy has been noted by Grazulis (1993) and McCarthy and Schaefer (2004), and addressed in depth by Agee and Childs (2014). As will be shown in the next section, this over/under reporting issue shows up even in the cold-season months of NDJF. To address this issue, Agee and Childs (2014) make an adjustment in the tornado database by finding a count correction factor, which decreases the F2 count by 52 total tornadoes per year for the period 1953–1973. A similar strategy is employed here for NDJF tornadoes, which account for roughly 15% of annual total counts. Therefore, 15% of 52 (approximately 8)

F2 tornadoes for each cold season prior to 1974 should be re-categorized as F1 tornadoes. The implications of this adjustment are discussed in the Results section to come.

Second, there exists a major inhomogeneity in the (E)F0 tornado record. With the advent of the NEXRAD WSR-88D Doppler radar system in the early 1990s (Crum et al. 1998), a new way to identify tornadoes was born. Since most of the tornado signatures discerned from Doppler radar lie within the F0 wind speed threshold, a large uptick in F0 counts is seen beginning in the mid-1990s, creating a major discontinuity in the tornado record (see Figure 2 in Agee and Childs 2014). This inhomogeneity can lead to inaccurate conclusions regarding the trends in overall U.S. tornado counts. Verbout et al. (2006) show that while there is a clear and consistent upward trend in counts of tornadoes of all strengths, there is virtually no trend in the tornado record when the (E)F0 tornadoes are removed. That is, (E)F0 tornado reports have been consistently increasing over time thanks to many of the aforementioned non-meteorological factors and the advent of Doppler radar. Trends in weaker tornadoes are also more subject to population bias, especially in the 20th Century, since they are more likely to go unnoticed; conversely, strong tornadoes are more readily reported and thus have a more homogeneous data record (Anderson et al. 2007). Many recent studies take note of the consistency issues with the (E)F0 record and therefore remove these weak tornadoes from their climatological analyses (Doswell et al. 2009, Brooks et al. 2014, Widen et al. 2015, Agee et al. 2016, Guo et al. 2016). While it is true that eliminating (E)F0 tornadoes from this cold-season climatology severely limits the sample size (NDJF are the four months of least mean annual tornado reports, and (E)F0 is the most-reported tornado intensity in all months), this study restricts analysis to (E)F1-(E)F5 tornadoes in order to work with a consistent data record and thereby obtain more reliable statistics. In so doing, the tornadoes with the greatest potential to produce destruction and posing the greatest risk to society are retained.

It is also noted that many tornado climatology studies use the "tornado day" metric rather than or in addition to raw counts (Brooks et al. 2003a, Brooks et al. 2014, Farney and Dixon 2014, Elsner et al. 2015). However, the use of counts in this cold-season study is preferred, as a tornado day analysis for winter months would create even more of a sample size limitation than is already imposed by eliminating (E)F0 tornadoes (Doswell 2007).

(iii) SPATIAL DOMAIN

Tornadoes can occur anywhere in the Contiguous United States (CONUS), but are predominantly found east of the Rocky Mountains. During the cold season (NDJF), tornadoes are more confined across the South and Mississippi Valley regions, with very few occurring in the western Great Plains and far northern U.S. As such, this study uses a spatial domain of (25-42.5°N, 75-100°W). Figure 2.1 shows the extent of this domain and the location of all NDJF (E)F1-(E)F5 tornadoes from 1953–2015 within the domain, partitioned by intensity. A tornado's geographical location in Fig. 2.1 is assigned based on its starting latitude and longitude given in *Storm Data*. In a few instances, a tornado that would have otherwise met this study's stipulations was thrown out due to a missing starting location in the database. In these 62 cold seasons, there were 4293 tornadoes in the domain, which accounts for 96.4% of all U.S. NDJF tornadoes over this time frame (i.e. only about 2 tornadoes per cold season occurred outside of these spatial bounds, most of those being in California). The tornado database is also carefully combed to remove any repetitious tornado reports (i.e. tornadoes which are counted more than once because of traversal through multiple states). In summary, this study analyzes all NDJF (E)F1-(E)F5 tornadoes occurring from November 1953–February 2015 within the domain of (25-42.5°N, 75-100°W).

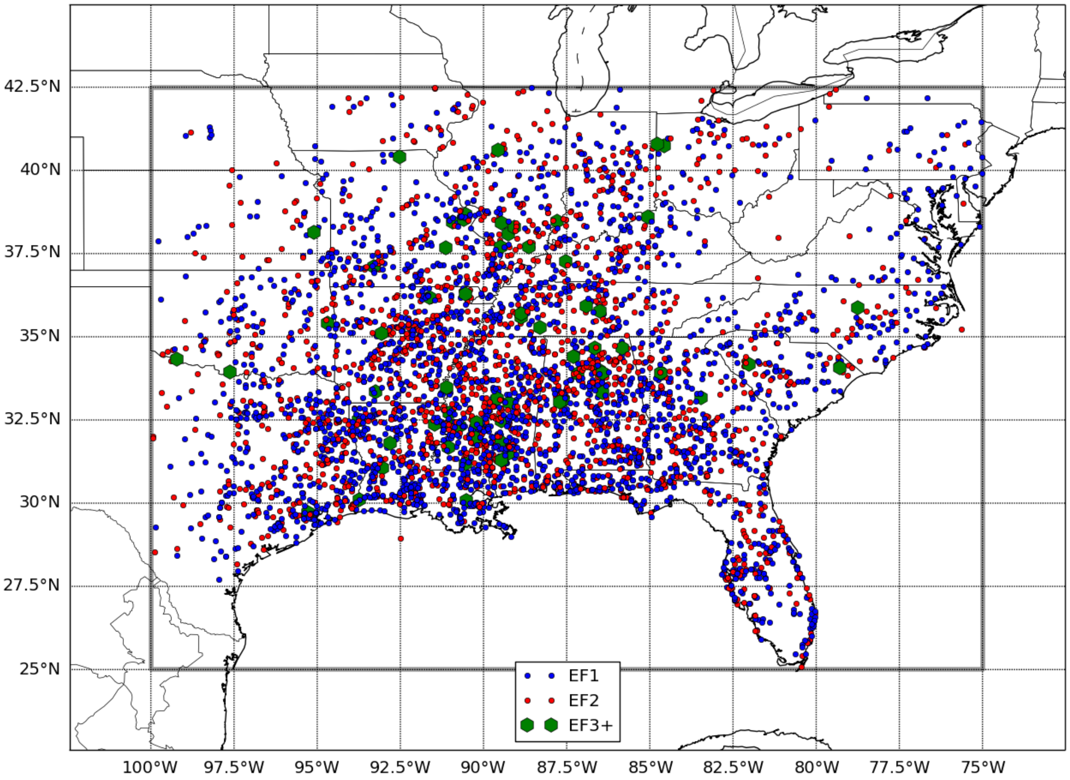


Figure 2.1: NDJF (E)F1-(E)F5 tornadoes from 1953-54 through 2014-15. Each colored dot represents the starting location of a tornado with given intensity, and the large gray box denotes the boundaries of the study domain.

2. Temporal divisions

Two ways of assessing changes in cold-season tornado frequency are employed in this study. First, two consecutive 31-year periods are defined and compared [1953/54–1983/84 (Period I) and 1984/85–2014/15 (Period II)]. These two Periods can be described based on average annual CONUS temperatures in a similar vein to Agee et al. (2016) as a relatively cool Period I and relatively warm Period II. Although a change in temperatures is not a direct cause for tornadoes, it can influence other meteorological parameters more applicable to tornadogenesis (Agee et al. 2016). Therefore, by dividing the data period in half, one can see whether NDJF tornadoes are becoming more prevalent under a warmer environment. This way of comparison is incomplete, however, and even though the division creates convenient equal-length periods, making a break point at 1984 is somewhat arbitrary. That is, results could be slightly different if the temporal division was made a few years before or after 1984. To make multiple temporal divisions, however, is not advisable in this study; for example, comparing tornado frequency changes by decade would suffer from too small a sample size.

Therefore, the second strategy for assessing temporal changes is through a trend analysis that uses linear regression to see how NDJF tornado frequency and variability are changing over the 62-year period. The spatial domain (25-42.5°N, 75-100°W) is divided into 70 grid boxes of equal size (2.5° X 2.5°) for analysis. This grid box size corresponds to the resolution of the NCEP/NCAR Reanalysis dataset to be used for assessing meteorological parameters in Chapter 3.

3. Teleconnection datasets

For the correlation analysis to be presented in the following section, three teleconnection indices are used: (a) ENSO Oceanic Niño Index (ONI), (b) Arctic Oscillation Index (AO), and (c) North Atlantic Oscillation Index (NAO). Briefly, ENSO refers to the ocean-atmosphere interaction characterized by shifts in Pacific Ocean sea surface temperatures. The warm-phase El Niño brings anomalously warm waters to the eastern equatorial Pacific, and the cold-phase La Niña is characterized by anomalously warm waters in the western Pacific. In general, a southern shift in the storm track and a stronger subtropical jet is seen in U.S. winters during the El Niño phase, which typically results in cooler and wetter conditions in the southern U.S. Conversely, the La Niña phase is marked by a weaker, meandering subtropical jet with a northward-shifted storm track, resulting in warmer and drier conditions across the southern tier of the country (Bell and Kousky 1995, Higgins et al. 2002).

The NAO and AO both relate to pressure differences between the high northern latitudes and the central/north Atlantic Ocean, with the NAO specifically focused on the North Atlantic and the AO related to the entire Arctic region. In a positive phase NAO or AO, anomalously high pressure is located in the central Atlantic and eastern United States, with anomalously low pressure in the northern latitudes. These pressure anomalies are reversed in the negative phase, with lower pressures in the central Atlantic and eastern U.S. and higher pressure further north. Changes in the NAO and AO phase can in turn alter precipitation and temperature patterns across the U.S. (Thompson and Wallace 1998). For example, as discussed below, a positive phase AO keeps Arctic air suppressed to the north due to a strong polar jet, but the jet is more prone to break down during negative phase AO, allowing for southward penetration of cold air into the eastern U.S. during winter.

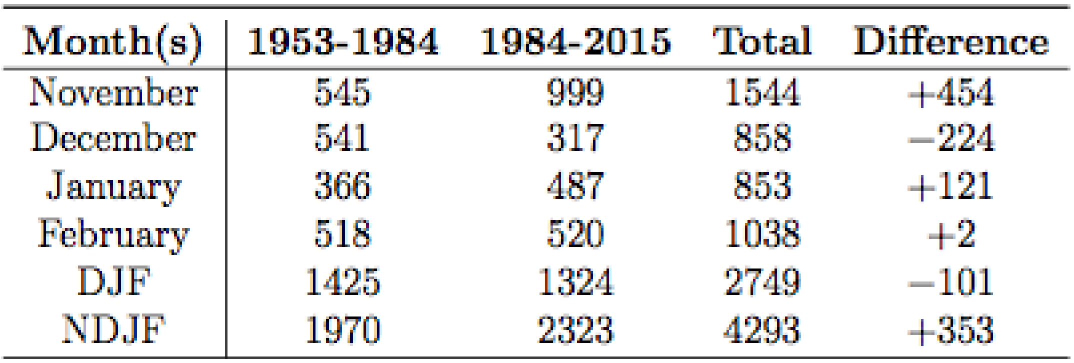
The Climate Prediction Center maintains online datasets of monthly values of these indices, which are used in this study (http://www.cpc.ncep.noaa.gov/products/precip/CWlink/MJO/enso.shtml and http://www.cpc.ncep.noaa.gov/products/precip/CWlink/daily_ao_index/teleconnections.shtml). For each index (ONI, NAO, AO), a time series is created by averaging the four monthly values of the index for November–February of each cold season. This results in a 62-year time series that is then correlated with the cold-season tornado count record.

C. Results

1. Frequency trends

Employing the stipulations discussed in the Methodology section above, this cold-season tornado climatology contains a total of 4293 (E)F1-(E)F5 tornadoes occurring during NDJF from November 1953 through February 2015. One could make an argument that the month of November has atmospheric conditions that more closely resemble spring months than those of December–February; therefore, subsets of DJF tornadoes as well as each individual cold-season month are also analyzed in this section for comparison. However, the months of NDJF are indeed the 4 months of lowest mean tornado counts over the modern tornado record (NCEI), and thus the rest of the study will retain NDJF as the seasonal time period of choice. Table 2.1 lists tornado counts for NDJF, DJF, and individual months, and reveals that the majority of NDJF tornadoes occur in November (1544) and February (1038).

Table 2.1: Monthly tornado counts for Period I, Period II, total of entire time period, and the difference (Period II – Period I).



Month(s)	1953-1984	1984-2015	Total	Difference
November	545	999	1544	+454
December	541	317	858	−224
January	366	487	853	+121
February	518	520	1038	+2
DJF	1425	1324	2749	−101
NDJF	1970	2323	4293	+353

In order to assess how tornado frequency is changing over time, two metrics are used. First, following Agee et al. (2016), the 62 cold seasons are halved into two consecutive 31-year periods for analysis. These two periods correspond to a relatively cool temperature regime across the CONUS (Period I, November 1953–February 1984), followed by a warmer temperature regime (Period II, November 1984–February 2015). Specifically, Agee et al. (2016) use annual mean surface air temperature data from National Centers for Environmental Prediction (NCEI) to show a slight temperature decrease over Period I and a strong temperature increase over Period II. As mentioned, although temperature increases do not directly cause tornadoes, it is hypothesized that increasing temperatures may affect other atmospheric variables known to be associated with tornadic environments, such as low-level moisture. Therefore, analyzing frequency changes (and spatial shifts) in cold-season tornadoes from Period I to Period II is of interest.

Table 2.1 shows that NDJF tornadoes have increased by 353 events from Period I to Period II, while DJF tornadoes have actually decreased by 101 events. This indicates that November tornado counts must be increasing substantially in recent decades; indeed they have been, namely increasing from 545 reports in Period I to 999 reports in Period II. January tornado counts have also been on the rise, with 121 more reports in Period II than in Period I. Conversely, December tornadoes are decreasing, with 224 fewer reports in the more recent period, leading to the overall decrease in DJF tornadoes in Period II. Interestingly, there is a difference of only 2 tornadoes in the month of February from Period I to Period II. The large increase of NDJF tornadoes over time is in relative contrast to the overall national annual trend in (E)F1-(E)F5 tornadoes, which is quite flat (Verbout et al. 2006).

A second metric for assessing changes in frequency (and spatial distribution) is linear regression. Figure 2.2 presents time series of both annual and NDJF tornado counts from 1953–2015 with respective trend lines. The slopes of both regression lines are positive, but the NDJF slope (0.488) is much larger than the Annual slope (0.123). This corresponds to an increase of approximately 1 tornado every 10 years in the annual record, but a much larger increase of 1 tornado per 2 cold seasons. In other words, an upcoming cold season can expect to experience roughly 30 more tornadoes than the cold season of 1953-54, while a present day annual tornado count is predicted to be higher than in the early 1950s by roughly 8 tornadoes. To summarize, cold-season tornadoes have increased over the past ~60 years, and at a much faster pace than annual tornadoes.

A hypothesis test for the significance of the linear trend of NDJF counts (with a null hypothesis that the slope is zero) yields a p-value of 0.06, which makes the trend significant at the 90% confidence level, but not at the 95% confidence level. For stronger statistical weight, a bootstrap method is employed, which creates 500 trend lines from randomly ordered NDJF tornado count time series. The mean slope of these 500 lines is essentially zero (as expected), and the 95% bounds are (-0.536, 0.476). The actual slope of the NDJF time series (0.488) falls outside of these bounds and is therefore deemed significant. With this clear uptick in NDJF tornadoes over time, there exists a need to ensure that communication of cold-season tornado risk to the general public is clear and effective, especially given the bevy of societal risks that come with wintertime tornadoes (to be discussed at length in Chapter 4).

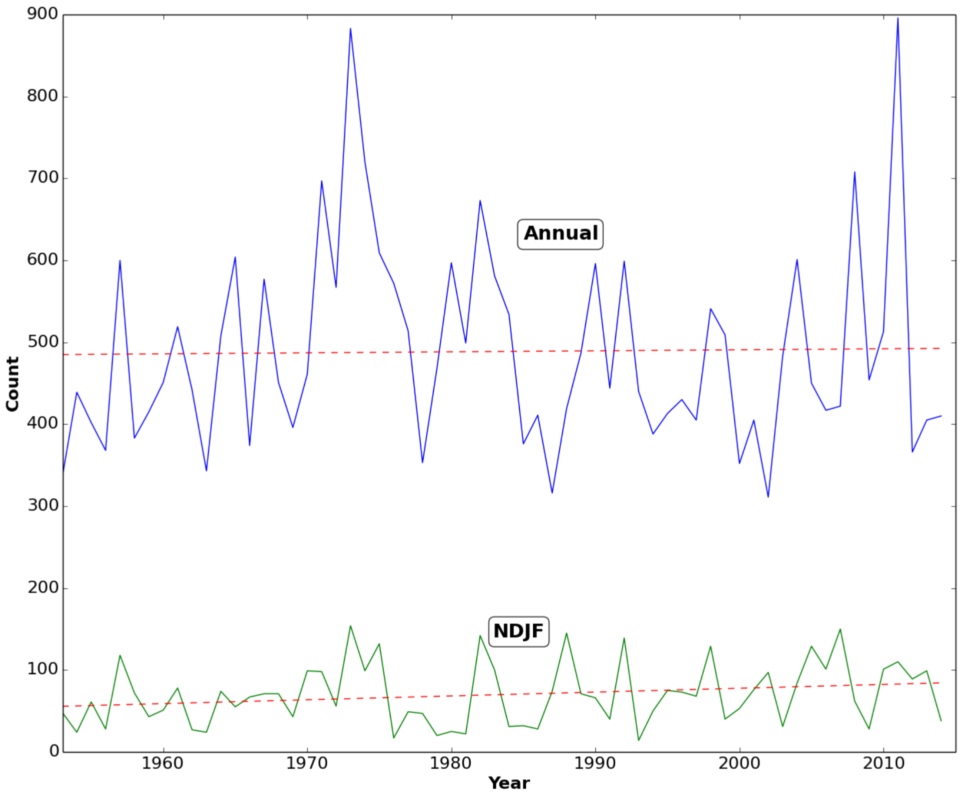


Figure 2.2: Annual and NDJF (E)F1-(E)F5 tornado counts for the period 1953–2015 with linear trend lines.

More visibly apparent in the trend plots of Annual and NDJF tornadoes is the high degree of variability that exists through the record. The well-known outbreak years of 2011 and 1974 appear as outliers in the Annual trend plot, with more than 850 tornadoes in each of these two years. The NDJF record has several elevated cold seasons, but no evident outlier. The largest cold-season tornado count occurs in 1973-74, when 154 tornadoes struck the domain. There are twelve cold seasons in the data record, however, with more than 100 recorded tornadoes. The lowest number of tornadoes in a cold season is 14, which occurred in 1993-94.

The meteorological community today seems to be obsessed with the idea of "extremes". That is, how often are extremely high (or low) years of some variable occurring, and is that frequency changing? In the case of NDJF (E)F1-(E)F5 tornado counts, diagnosing extremes can be measured by the variance of the data record. As such, Figure 2.3 plots a 10-year running variance, beginning with 1953–1962 and ending with 2006–2015 (the 1953 data point represents the 1953–1962 variance, the 1954 data point represents the 1954–1963 variance, etc.). Quite interestingly, the variance of NDJF tornado counts is quite low in the early part of the record, followed by much higher variability from the mid-1970s through the late 1990s. This accords well with the few cold seasons of counts near or above 100 in the mid-1970s followed by a prolonged period of very low counts in the late 1970s and early 1980s. The variance is lower for 10-year periods starting around 1990 and continuing through present day, although these times still show more variability than in the 1950s and 1960s. Overall, there is an upward trend in 10-year variability by about 12 units each year. This finding is consistent with Brooks et al. (2014), who show a general increase in variability of annual tornado occurrence since the 1970s. The past few decades, however, are characterized by a leveling off in NDJF tornado variability. To what degree meteorological factors are contributing to the more consistent NDJF counts remains to be seen, but it does not seem logical that non-meteorological factors would be causing less variability in tornado counts. There is sufficient technology in the recent decades to avoid the errors of counting tornadoes that do not occur in one year and then missing tornadoes that do occur the next year, which would lead to a similar count and reduced variability. It must simply be the case that NDJF tornado counts have been occurring in similar numbers. Still, year-to-year variability certainly exists in recent years; for example, 99 NDJF tornadoes occurred in 2013-14 followed by only 38 in 2014-15.

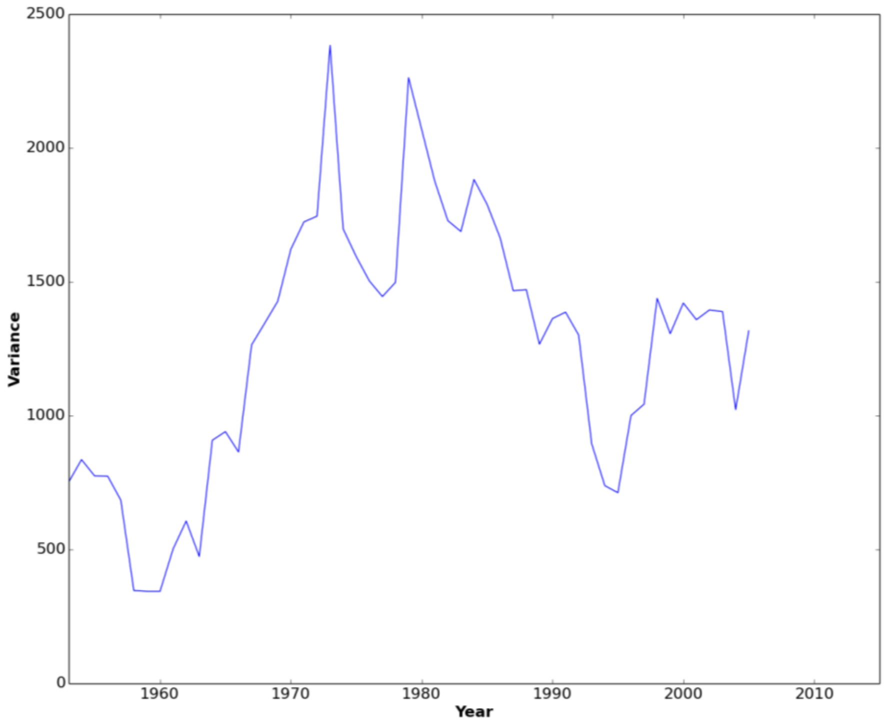


Figure 2.3: Ten-year running variance for NDJF (E)F1-(E)F5 tornado counts. The first data point represents the 1953–1962 variance, while the final data point represents the 2006–2015 variance.

2. Spatial trends

(i) PERIOD I vs. PERIOD II

While it is evident that cold-season tornado counts are increasing, it is also intriguing to investigate how the geographical distribution of these tornadoes is shifting over time in the gridded domain. First, the spatial orientation of NDJF and DJF tornadoes in Period I and Period II are compared (Fig. 2.4). Tornado counts have been normalized to account for some grid boxes having very few NDJF tornadoes each year. Both NDJF and DJF show a maximum in tornado counts along the Gulf Coast in southern Mississippi and Alabama in Period I (Fig. 2.4, top) and a westward shift in the maximum along the

Mississippi-Louisiana border in Period II (Fig. 2.4, middle). The preference in activity in the Southeast during the cold season is not a new finding (Galway and Pearson 1981, Brooks et al. 2003a, Guyer et al. 2006, Ashley 2007, Ashley and Strader 2016). Perhaps of greater value, however, is the location of greatest increase in counts between the two Periods (Period II – Period I), as shown in the bottom row of Figure 4. Although NDJF (DJF) counts have increased (decreased) from Period I to Period II, the spatial shifts in tornado occurrence shows a similar pattern. Both NDJF and DJF have seen a large increase in tornadoes in the mid-Mississippi Valley region, stretching from southern Kentucky southwestward to northern Louisiana, with a bulls-eye of maximum increase in western Tennessee. Two areas of notable decrease in NDJF tornadoes from Period I to Period II are seen in eastern Oklahoma and southern Georgia/Florida panhandle area. The decreasing trend in Oklahoma seems surprising given that it is in the heart of the traditional "Tornado Alley" and is a state that most people associated with frequent and violent tornadoes. However, this finding is consistent with Farney and Dixon (2014) who report that the greatest decline in tornado days over the past 22 years is located in Oklahoma and northern Texas. Further, Dixon et al. (2011) report that the highest tornado day density is located in the Southeast, specifically across Mississippi, Alabama, Arkansas, and Louisiana – not Oklahoma. Agee et al. (2016) also show a very similar changing spatial distribution of annual tornado counts. Thus, it appears that the geographical shifts in NDJF tornadoes are consistent with shifts in annual counts.

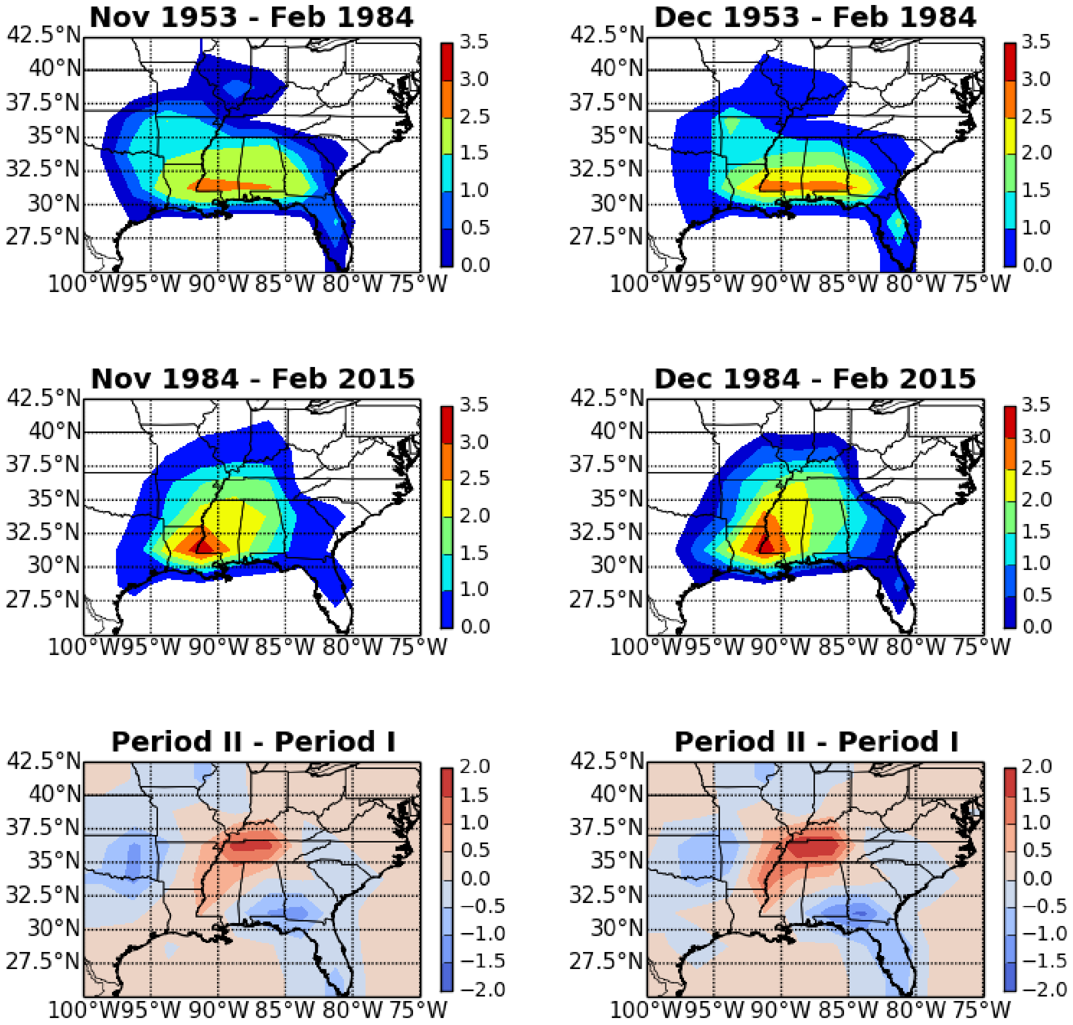


Figure 2.4: Spatial distribution of normalized NDJF (left) and DJF (right) tornado counts for Period I (top), Period II (middle), and their difference (bottom).

Figure 2.5 partitions the spatial shifts by individual month. As expected, November counts are increasing across much of the domain, although a sharp decline is noted across eastern Oklahoma. December counts also show large decreases across eastern Oklahoma stretching northeastward into Indiana, while a large increase is noted in December across Louisiana and Mississippi. Spatial changes in January counts look most like the NDJF and DJF spatial shifts, with large increases across Tennessee and decreases in the eastern Gulf

Coast areas. For February, the majority of the domain has seen a decrease in tornado counts from Period I to Period II, but a sharp increase across Tennessee and Alabama offset the decreases to result in the month see virtually no change in counts overall. Most of the NDJF increase in the Mississippi Valley region can thus be attributed to the months of November and January, which are also the two months that show large increases in tornado counts from Period I to Period II. Therefore, these months are driving not only frequency changes but also spatial shifts in the tornado climatology. The decreases seen in Oklahoma in the NDJF distribution also show up in each individual month, especially November and December. Finally, the decreases in the eastern Gulf Coast region can be attributed most to December, January, and February.

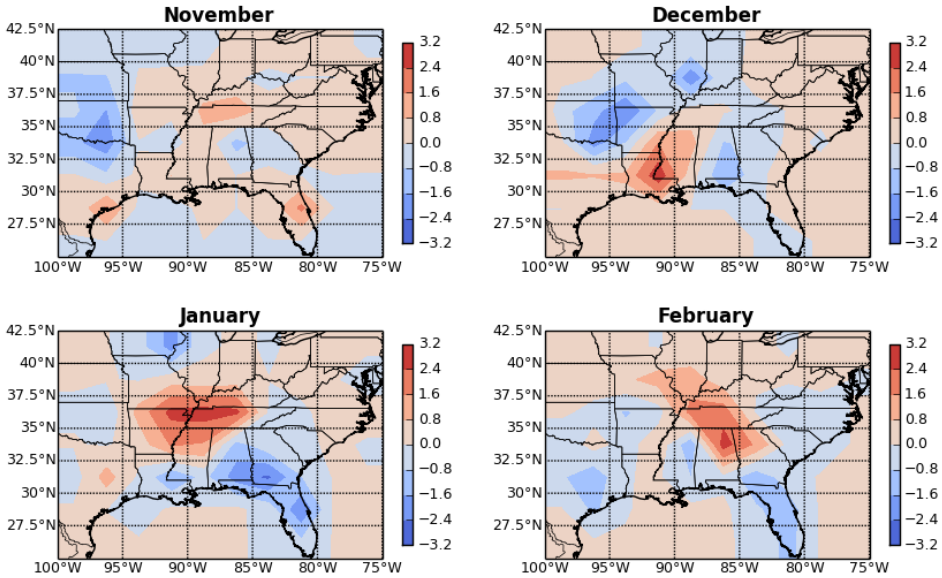


Figure 2.5: Monthly tornado count spatial changes (Period II – Period I).

It should also be noted that tornado days have been briefly investigated for NDJF. Defining a tornado day as a day with at least one (E)F1-(E)F5 tornado, the entire domain shows a decrease from 537 to 452 total tornado days from Period I to Period II, consistent with Brooks et al. (2014) and Elsner et al. (2015), who show that the number of tornado days are decreasing across the CONUS (although the number of tornadoes on tornado days show an increasing trend). Individual grid-box analysis of tornado days is not investigated due to small sample size limitations.

(ii) GRIDDED TRENDS

A second method of analyzing geographical shifts in tornado frequency is through use of linear regression. To do this, a linear regression is run for each of the 70 grid boxes from 1953/54–2014/15; that is, the number of tornadoes per cold season per grid box is tracked through time. Figure 2.6 shows the regression coefficient spatial distribution over the domain. Similar patterns are seen here as when the two Periods are compared. The majority of grid boxes show an increasing trend through time, with the largest increasing trends across the Mississippi Valley and west-central Tennessee and largest decreasing trend across eastern Oklahoma.

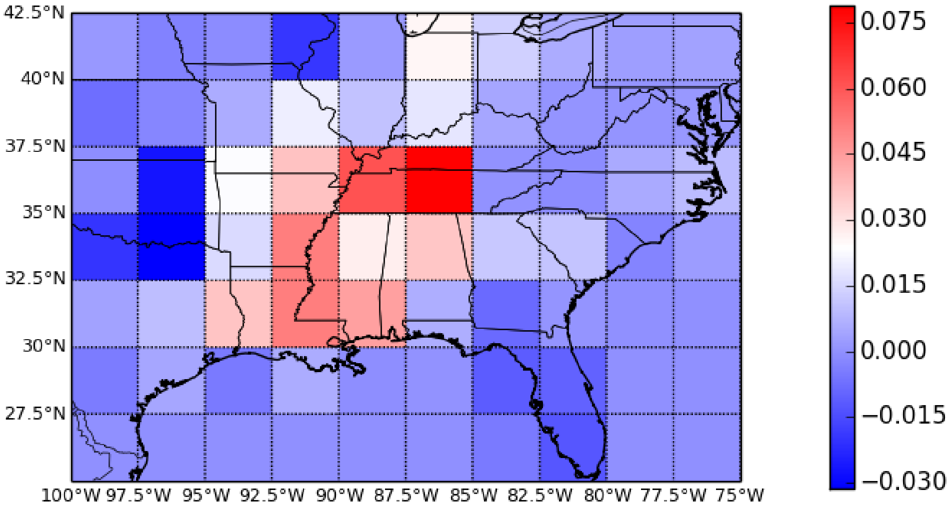


Figure 2.6: NDJF tornado count trend per grid box (i.e. regression coefficient) for the period 1953/54–2014/15.

Testing for the significance of the trends for each grid box, it is found that three grid boxes have a significant increasing or decreasing trend. These include the grid box over central Tennessee and south-central Kentucky (increasing trend, significant at 99% level), eastern Tennessee (increasing trend, significant at 95% level), and northeastern Oklahoma (decreasing trend, significant at 99% level). Time series of NDJF tornado counts are presented for these three grid boxes in Figure 2.7. These results are further bolstered by employing a bootstrap on the time series of each of the 5 grid boxes having the greatest increasing trend and each of the 5 grid boxes having the greatest decreasing trend. From the bootstrapping, it is found that the three grid boxes mentioned above have trends that fall outside the 95% bounds. Curiously, all three grid boxes are located between 35 and 37.5 North latitude. In both of the grid boxes with significantly increasing trends, a tendency for more frequent extreme seasons is seen after about 1995 (Fig. 2.7a, b). The grid box in northeastern Oklahoma does not show a tendency for more extreme seasons of high counts in the early part of the record followed by a sharp decline, as might be expected, but rather a slow and consistent decrease through time (Fig. 2.7c).

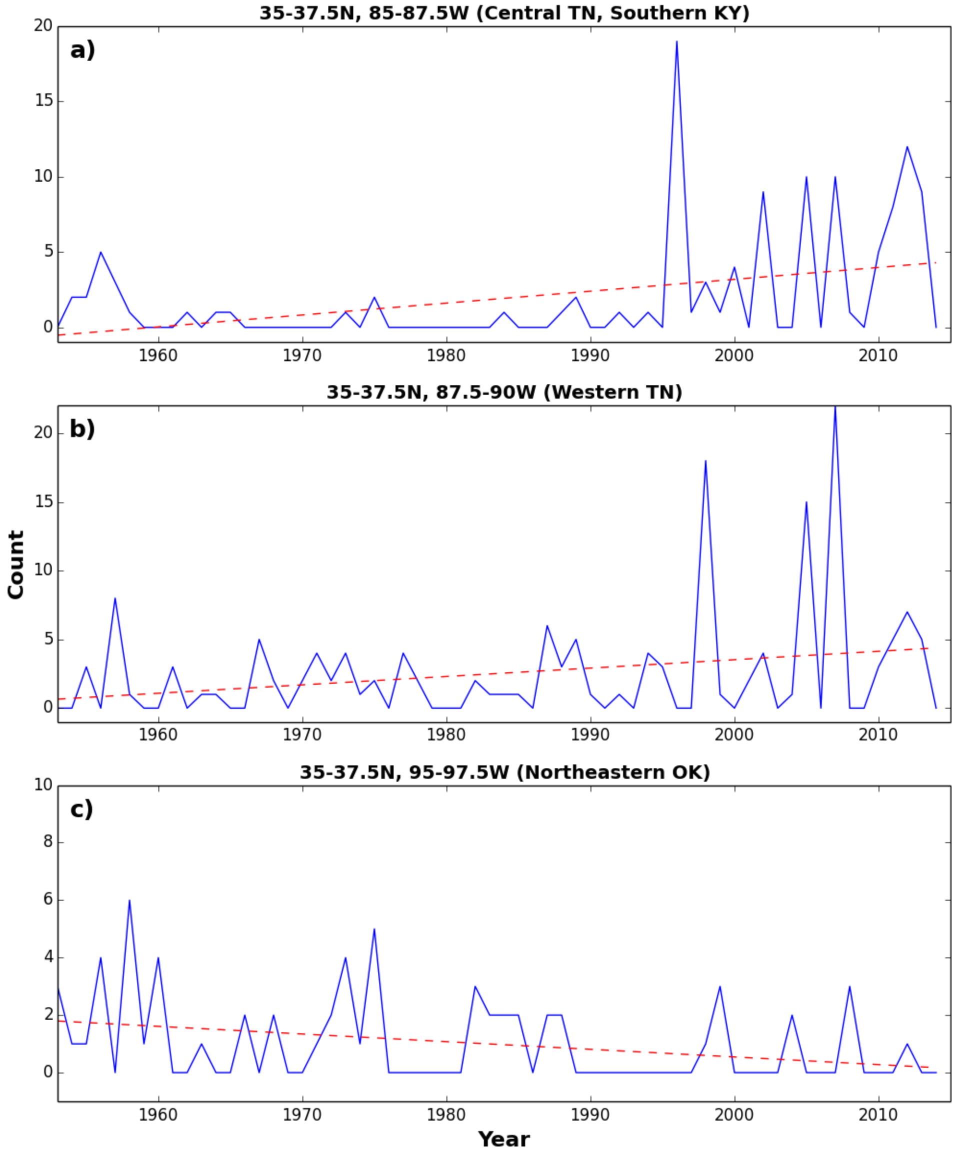


Figure 2.7: Time series for the grid boxes showing statistically-significant increasing trend (a and b) and decreasing trend (c) in NDJF tornado counts.

In terms of the variability in tornado counts across the domain, the peak in variance for the entire 62-year record at each grid box is across northeastern Arkansas (Fig. 2.8).

This maximum is west of the tornado count trend maximum located over eastern Tennessee. This does make logical sense, as one can imagine a high variability in counts near the intersection point of increasing and decreasing counts through time (i.e. where there are equal amounts of high and low count years resulting in very little or no trend).

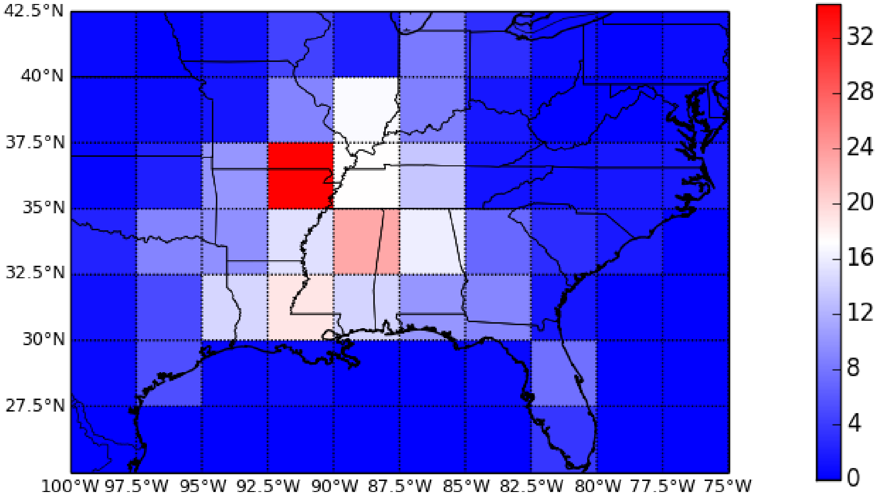


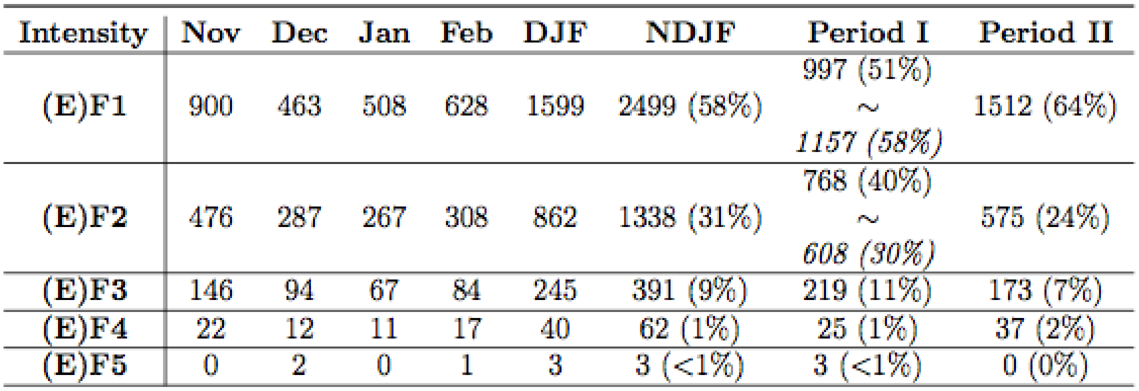
Figure 2.8: Variance in NDJF tornado counts per grid box for the period 1953–2015.

3. Tornado intensity

It is also of interest to assess how the intensity of cold-season tornadoes is distributed and changing through time. As such, Table 2.2 presents a breakdown of intensity rating by month, season, and the two Periods. For each month, (E)F1 and (E)F2 tornadoes dominate the climatology, with roughly 90% of all tornadoes falling into these two categories. As seen in later analysis, this dominance of weaker tornadoes is consistent with a low-CAPE-high-shear environment that tends to be prevalent in the winter months across the Southeast (Schneider et al. 2006, Guyer and Dean 2010, Sherburn and Parker 2014). A couple of additional interesting findings can be gleaned from Table 2.2. For one, the under (over) counting of F1 (F2) counts discussed by Agee and Childs (2014), which was addressed earlier in this chapter, is revealed. An increase of 515 (E)F1 tornadoes and a decrease of 193 (E)F2 tornadoes are noted in the more recent Period II. Further, from Period I to Period II, (E)F1 tornadoes have gone from accounting for 51% to 64% of total NDJF tornadoes, while (E)F2 tornadoes have gone from accounting for 40% to 24% of total NDJF tornadoes. Clearly, a discrepancy due to over (under) rating is an issue here. As such, an adjustment is made, following Agee and Childs (2014), to raise (lower) the Period I F1 (F2) count. Specifically, Agee and Childs (2014) find a count correction factor that decreases the F2 count by 52 total tornadoes for their Period I (1953–1973). In this study, only four months out of a year are analyzed, which combined account for roughly 15% of annual tornado counts. Therefore, 15% of 52, or approximately eight F2 tornadoes per each cold season prior to 1974 should be re-categorized as F1 tornadoes. This results in (20 years * 8 tornadoes/year) = 160 tornadoes originally in the F2 category in Period I being reassigned an F1 rating. These adjustments are represented in Table 2.2 by the italicized counts and percentages. When this adjustment is made, the NDJF F1 total for Period I is increased to 1157, which is still below but closer to the Period II count of 1512. The adjusted NDJF F2 count for Period I is now 608, which makes it only slightly greater than the 575 (E)F2 tornadoes in Period II. In other words, when the adjustment is applied, there is still a substantial increase in (E)F1 tornadoes in the more recent period, but only a modest increase in (E)F2 tornadoes. The percent contribution of F1 (F2) tornadoes in Period I is now 58% (30%), which creates a smaller difference from their respective percent contribution in Period II (64% for (E)F1 and 24% for (E)F2). Even with the adjustment, the increase in tornado count in Period II is still dominated by an increase in (E)F1 tornadoes.

Another intriguing tidbit gleaned from Table 2.2 is that although December sees the least number of tornadoes overall, a greater proportion of stronger tornadoes occur in December than in any other month. Specifically, (E)F3-(E)F5 tornadoes account for 12.6% of the total December tornado count through the data record, compared to 10.8% in November, 9.8% in February, and 9.1% in January. Further, of the three (E)F5 tornadoes in the NDJF record, two of those occurred in December (although it is noted they occurred in 1953 and 1957, when reporting practices and intensity ratings are more suspect). Even if the overcounting of F2 tornadoes prior to 1974 were considered on a monthly rather than annual basis, there is no sound logic to conclude that December tornadoes would have been overcounted more than tornadoes in other months, so this interesting finding of a greater proportion of stronger tornadoes occurring in December would still hold.

Table 2.2: Cold-season tornado (E)F-scale intensity by month and Period. The italicized (E)F1 and (E)F2 counts for Period I represent an adjustment for overcounting of F2 tornadoes prior to F-scale implementation, following Agee and Childs (2014).



Intensity	Nov	Dec	Jan	Feb	DJF	NDJF	Period I	Period II
(E)F1	900	463	508	628	1599	2499 (58%)	997 (51%) ~ *1157 (58%)*	1512 (64%)
(E)F2	476	287	267	308	862	1338 (31%)	768 (40%) ~ *608 (30%)*	575 (24%)
(E)F3	146	94	67	84	245	391 (9%)	219 (11%)	173 (7%)
(E)F4	22	12	11	17	40	62 (1%)	25 (1%)	37 (2%)
(E)F5	0	2	0	1	3	3 (<1%)	3 (<1%)	0 (0%)

4. Spectral analysis and teleconnections

(i) TIME SERIES POWER SPECTRA

Delving further into the time series of cold-season tornadoes, counts for each individual month, as well as for NDJF and DJF, over the full 62-year period, are plotted in Figure 2.9. Each month and season shows an upward trend except for December, which has a trend line slope of -0.045. It should be noted that although DJF counts have decreased in the more recent Period II (Table 2.1), there is still a slight upward trend in the DJF time series due to a much higher variability in Period II, with a few very active seasons and several seasons with a dearth in tornadoes. No individual month has a statistically significant trend according to a bootstrap test for each month's tornado time series. Also of interest is the clear difference between the November and December time series. Although these are subsequent months in the year, five of the six most tornadic Novembers have occurred since 1986, but each of the six most tornadic Decembers occurred prior to 1984.

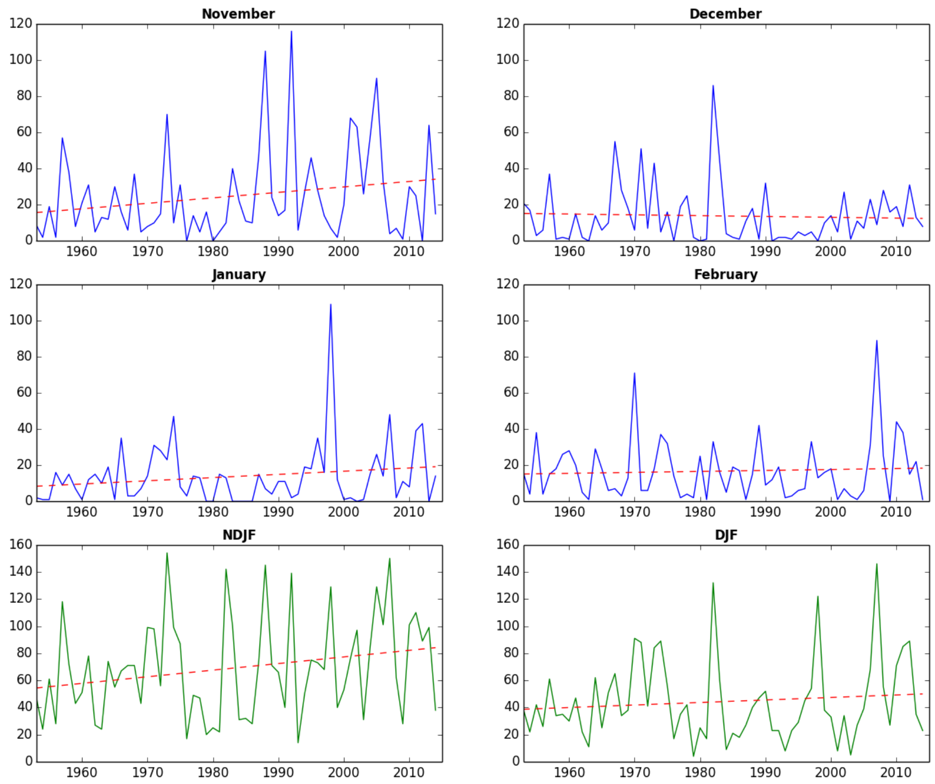


Figure 2.9: Monthly cold-season tornado count time series with linear trend lines.

Next, power spectra are calculated for each of the time series given in Figure 2.9 to investigate any periodicity present in the count data. Welch's approach is used, which chunks the data in half and employs a Hanning window with 50% overlap (Welch 1967). This gives four degrees of freedom for the data set. Figure 2.10 shows the normalized power spectra with variance plotted as a function of frequency. Each month and season has at least one clearly discernible spectral peak, with every month except January showing a peak in the 0.13-0.26 cycles-per-season range. Physically, this corresponds to a season of enhanced tornado counts every 3-7 years, which is curiously aligned with the recognized period of ENSO activity.

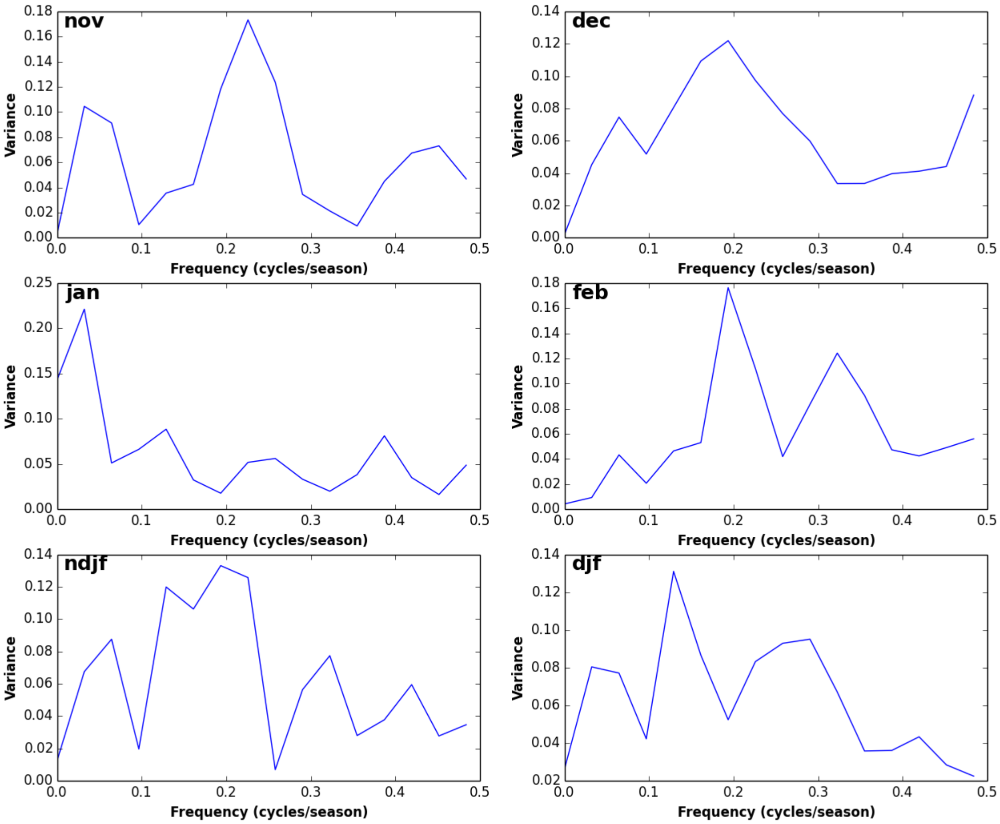
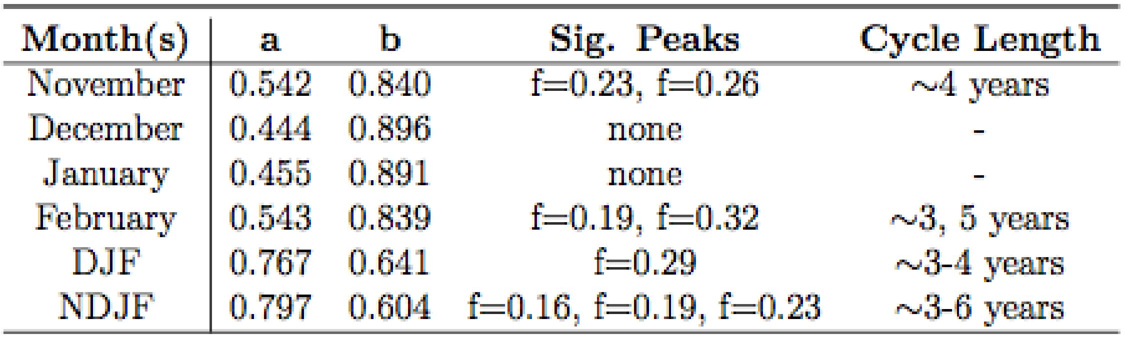


Figure 2.10: Normalized power spectra for tornado counts of individual months and seasons. Variance is shown as a function of frequency (cycles per cold season).

Each of the notable spectral peaks in Figure 2.10 is tested for statistical significance. To do this, a null hypothesis that a set of data is simply red-noise is assumed for the standardized time series. The lag-1 autocorrelation is then calculated, denoted as the coefficient ‘a’ in Table 2.3. This provides a measure of how much memory is retained from one season to the next. This coefficient is subsequently used to find the second autocorrelation coefficient ‘b’. From these two coefficients, a red-noise time series that resembles the original time series is created, drawing from a random normal distribution. A power spectrum is then generated from the red-noise time series and compared to that of the original standardized data through the F-test. Specifically, the F-statistic is given as the ratio of variance of the original time series power to the variance of the red-noise time series power. A critical F-value is computed from the degrees of freedom, in this case 120 for the red-noise case and 4 for the original time series. At the 99% confidence level, this F-critical value is 3.48. Thus, if the F-statistic at a specific frequency exceeds this value, then the spectral peak at that frequency is considered to be a significant departure from red noise. The power spectra for each month and season are tested in this way, and the resulting significant peaks are presented in Table 2.3, along with the corresponding cycle length and the coefficients of autocorrelation.

Table 2.3: Coefficients of autocorrelation used to compute red-noise null time series, and significant spectral peaks for each month(s) with physical cycle length.



Month(s)	a	b	Sig. Peaks	Cycle Length
November	0.542	0.840	f=0.23, f=0.26	~4 years
December	0.444	0.896	none	-
January	0.455	0.891	none	-
February	0.543	0.839	f=0.19, f=0.32	~3, 5 years
DJF	0.767	0.641	f=0.29	~3-4 years
NDJF	0.797	0.604	f=0.16, f=0.19, f=0.23	~3-6 years

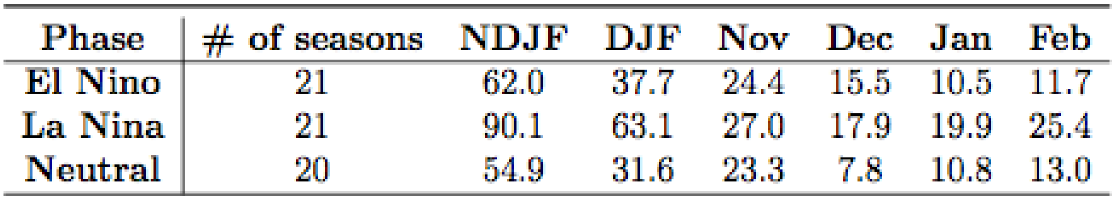
While this spectral analysis falls short of providing concrete rationale for seasons of enhanced tornado counts, it does hint at a cycle every 3-7 years and thus provides forecasters with an idea of how often a particularly tornadic winter should occur. For example, if the southern United States has gone 5 or 6 years without an elevated cold-season tornado count, an active cold season can be reasonably expected within the next 2 years. This sort of information is quite valuable, and when effectively delivered to and received by the public, can help heighten awareness about a potential tornadic winter season ahead. This 3-7-year cyclic pattern motivates the following investigation into relationships between ENSO and other teleconnections with NDJF tornado activity.

(ii) ENSO vs. NDJF TORNADOES

As mentioned in the Methodology section of this Chapter, several studies have been undertaken to search for a signal between ENSO and tornado activity but have not yielded consistent or conclusive results (Marzban and Schaefer 2001, Cook and Schaefer 2007, Allen et al. 2015). Most past studies use an abbreviated data set and/or do not strictly investigate wintertime tornadoes, so this study with its 62-year cold-season tornado climatology presents a fresh and expanded perspective on this supposed conundrum.

For the 62 seasons analyzed here, an average ONI is computed from the four November–February ONI values (obtained from the Climate Prediction Center database at http://www.cpc.ncep.noaa.gov/products/precip/CWlink/MJO/enso.shtml). A 4-month average ONI > 0.5 is denoted as El Niño (EN), while a 4-month average ONI < -0.5 is denoted as La Niña (LN). Neutral (N) conditions lie between -0.5 and 0.5. Quite fortuitously, applying this definition yields 21 EN, 21 LN, and 20 N seasons for the data period, allowing for easy comparison. Table 2.4 shows the average tornado count per season for each of the three ENSO phases. In each month, as well as the NDJF and DJF seasons, the average tornado count is largest during LN conditions. There are roughly 30 more tornadoes on average across the entire domain for a given cold-season during LN than during EN or N. Individual months vary as to whether EN or N conditions give the fewest average tornadoes for that month, with the most striking dearth of tornadoes being in December under Neutral conditions (only 7.8 tornadoes per month). The average (E)F-scale rating for all EN, LN, and N tornadoes is 1.56, 1.54, and 1.51 respectively, showing that the intensity of tornadoes does is not highly dependent on ENSO phase.

Table 2.4: Average tornado count per season and month for each ENSO phase.



Phase	# of seasons	NDJF	DJF	Nov	Dec	Jan	Feb
El Nino	21	62.0	37.7	24.4	15.5	10.5	11.7
La Nina	21	90.1	63.1	27.0	17.9	19.9	25.4
Neutral	20	54.9	31.6	23.3	7.8	10.8	13.0

The spatial distribution of tornadoes for each phase is plotted in Figure 2.11. It is seen that in general, tornadoes during EN are centered further west and south than those during LN or N conditions. Specifically, the centroid of NDJF tornadoes (found by taking the average starting latitude and longitude of all tornadoes associated with each ENSO phase) is located at (33.1°N, 89.1°W) for EN, (34.2°N, 89.1°W) for LN, and (34.0°N, 88.4°W) for N. This spatial difference is consistent with many previous studies (Nunn and DeGaetano 2004, Cook and Schaefer 2008, Allen et al. 2015), which attribute the variation to shifts in the mean jet stream position and storm track during different phases of ENSO. In short, El Niño conditions are associated with a southward-shifted storm track, cooler temperatures in the South and Gulf Coast, and shallower moisture advection, leading to a reduction in severe weather and tornado environments north of the immediate Gulf Coast areas. La Niña conditions bring a northward-shifted jet stream and stronger temperature gradients across the Plains and South (Allen et al. 2015), along with a northward surge of Gulf moisture. These conditions are favorable for enhanced severe weather in the Mississippi Valley region during winter, as confirmed by the higher NDJF tornado counts during La Niña.

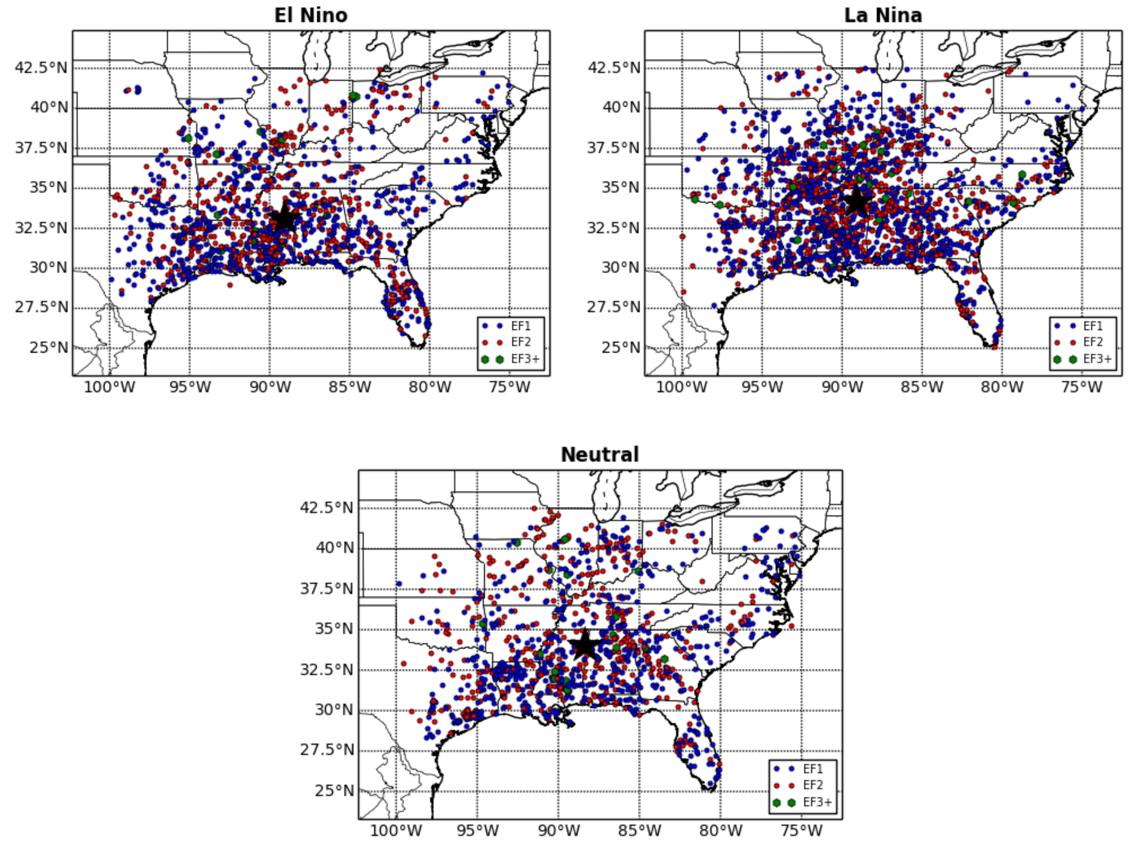


Figure 2.11: Spatial distribution of NDJF tornado counts and associated intensity for different phases of ENSO for the period 1953–2015. The black star denotes the geographical center of the distribution for each phase.

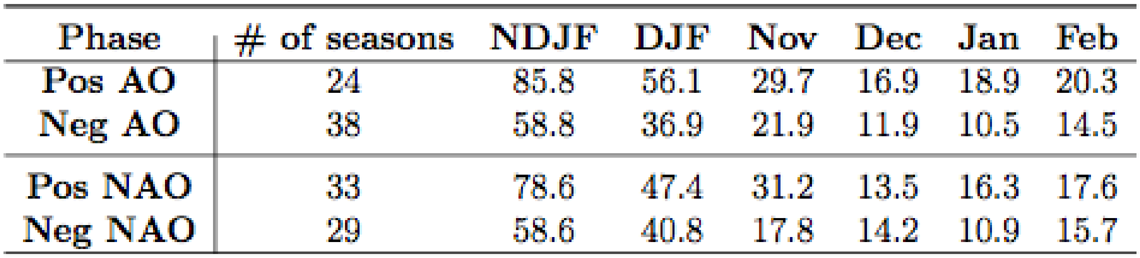
(iii) AO and NAO vs. NDJF TORNADOES

A similar analysis to the ENSO assessment above is done for the Arctic Oscillation (AO) and North Atlantic Oscillation (NAO). Both of these teleconnections relate to differences in pressure patterns over the Arctic region. The AO captures differences in pressures between the Arctic and northern mid-latitudes, and is most relevant during the winter months when the atmospheric circulation is more robust. During its positive phase, high pressure is located over the north and mid-Atlantic, Europe, and the United States, while low pressure is located over the Arctic, north of the jet stream. The jet stream and trade winds are also stronger in a positive-phase AO, which tends to confine the colder air to the Arctic region, push the storm track northward, and make the southern and eastern United States experience warmer and less snowy winters. Negative AO conditions are the opposite, with high pressure over the Arctic and low pressure in the mid-latitudes. The jet stream is weaker and wavier under negative AO conditions, which allows cold air from the Arctic to penetrate further south into the United States, often creating scenarios such as the 2013-14 "Polar Vortex" scare. The storm track is shifted further south under negative AO conditions, increasing the occurrence of extratropical cyclones in the southern and eastern United States (Thompson and Wallace 1998). With the colder temperatures, many of these cyclones are heavy snow producers for the southern and eastern United States (NSIDC, NCEI).

The NAO is a more specific outworking of the AO, measuring pressure differences between the Azores High, located in the mid-latitudes, and the Icelandic Low further north (NCEI). A positive phase NAO is characterized by a large difference in pressure, with higher latitudes seeing below-normal pressure and the subtropics seeing above-normal pressure. This results in a strong and mostly west-to-east jet stream and generally leads to higher temperatures over the eastern and southern United States. These warmer conditions do not necessarily result in drier conditions, and in fact often produce a wetter pattern with more of the precipitation falling as rain. Conversely, a negative phase NAO has a small gradient in pressure between the Arctic and subtropics. This pattern is associated with a weaker and wavier jet stream and more frequent cold-air intrusion into the eastern United States. Similar to the negative phase AO, the negative phase NAO creates colder temperatures with more snowfall, but often a drier pattern overall for the southern and eastern U.S. (NC State Climate Office).

The methodology for computing the AO and NAO indices involves projecting daily height anomalies onto the respective EOF pattern. An in-depth description of the index methods can be accessed via the Climate Prediction Center (CPC, http://www.cpc.ncep.noaa.gov/products/precip/CWlink/daily_ao_index/teleconnections.shtml). Positive and negative AO and NAO regimes are determined for the past 62 cold seasons by taking the 4-month mean of monthly AO and NAO index, again available from CPC data files (http://www.cpc.ncep.noaa.gov/products/precip/CWlink/daily_ao_index/teleconnections.shtml), for November–February for a given season. The computed index averages result in 24 (33) seasons of positive AO (NAO) and 38 (29) seasons of negative AO (NAO). Table 2.5 gives the average tornado counts for the seasons and individual months given the positive or negative AO/NAO index. Although there are many more instances of negative phase AO than positive phase AO, the average tornado counts per season (and each individual month) are substantially higher under positive AO conditions. Interestingly, in the more recent 31-year Period II, there was nearly an equal proportion of positive (16) and negative (15) AO cold seasons. This means 16 out of 24 positive AO cold seasons happened in the period of increasing tornado activity. As with La Niña conditions, positive AO conditions result in approximately 30 more tornadoes per cold season than negative AO conditions. The fewest average number of tornadoes is seen during negative AO conditions in January. The increase in tornadoes during positive-phase AO is not surprising given the warmer temperatures and stronger jet stream associated with this phase. For NAO, once again the positive phase yields more average cold-season tornadoes, in this case roughly 20 more per season than the negative phase. Bolstering this relationship is the fact that 20 out of the 33 positive-phase NAO cold seasons have occurred in the more recent Period II, when tornadoes have been increasing in number. The average intensity of a tornado during positive and negative AO conditions is 1.50 and 1.58 respectively, while the average intensity during positive and negative NAO conditions is 1.51 and 1.58 respectively. Thus, NDJF tornadoes are fewer in number during negative AO and NAO conditions, but tend to be of similar or slightly greater intensity.

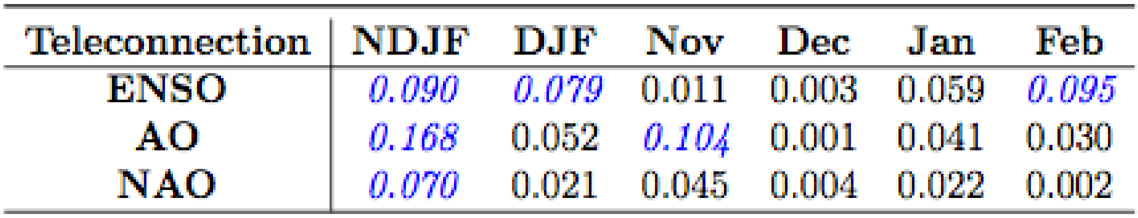
Table 2.5: Average tornado count per season and month for AO and NAO phases.



Phase	# of seasons	NDJF	DJF	Nov	Dec	Jan	Feb
Pos AO	24	85.8	56.1	29.7	16.9	18.9	20.3
Neg AO	38	58.8	36.9	21.9	11.9	10.5	14.5
Pos NAO	33	78.6	47.4	31.2	13.5	16.3	17.6
Neg NAO	29	58.6	40.8	17.8	14.2	10.9	15.7

The spatial distribution of NDJF tornadoes during both phases of AO and NAO (not shown) are very similar. Despite the propensity for tornadoes under positive AO/NAO conditions, four of the top 10 most tornadic cold seasons actually occurred under a negative AO regime. In the same vein, four of the top 10 least tornadic cold seasons occurred during a positive-phase NAO. These findings affirm the difficulty in establishing a direct teleconnection link to tornadoes. However, a correlation analysis does indicate some relationships. Table 2.6 shows correlations (r^2) between the time series of the 4-month average ONI, AO, and NAO indices with NDJF tornado counts. The ONI correlation coefficients (not shown) are all negative, implying that as ONI increases (i.e. moving toward El Niño conditions) the tornado count decreases. The largest monthly tornado count correlation with ONI is February ($r^2 = 0.095$), but only explains 10% of the variance. The overall NDJF correlation is even weaker ($r^2 = 0.09$). The small correlations align with the general consensus among the meteorological community that the relationship between ENSO and tornadoes is weak. A higher amount of variance in NDJF tornadoes is explained by the AO index (17%), with the highest monthly correlation of $r^2 = 0.108$ in November. The AO correlation coefficients are all positive, implying more tornadoes as the AO index increases. The NAO index explains the least amount of variance in cold-season counts across almost all months and seasons. The strongest correlation is positive, once again implying more tornadoes with a higher NAO index, but only explains 7% of the NDJF tornado count variance ($r^2 = 0.070$).

Table 2.6: Variance explained (r^2) for monthly tornado counts by average ONI, AO, and NAO indices. Colored italicized numbers indicate rejection of the null hypothesis of no correlation using a Pearson Correlation Test.



Teleconnection	NDJF	DJF	Nov	Dec	Jan	Feb
ENSO	*0.090*	*0.079*	0.011	0.003	0.059	*0.095*
AO	*0.168*	0.052	*0.104*	0.001	0.041	0.030
NAO	*0.070*	0.021	0.045	0.004	0.022	0.002

It is also important to test for statistical significance between the teleconnection indices and tornado counts to see if any robust relationships exist. First, a simple difference of means t-test is performed which compares the mean NDJF tornado counts with means of the different teleconnection indices. When this test is done with ENSO, it is found that mean counts under the La Niña phase are significantly different than mean counts under El Niño (p=0.014) and Neutral (p=0.003) phases at the 95% and 99% confidence levels respectively. The tornado counts under the different AO and NAO conditions are also found to be significantly different at the 99% (AO, p=0.004) and 95% (NAO, p=0.03) confidence level. However, a Mood's median test, which tests whether two samples come from populations having the same median value, does not return a statistically significant relationship. The p-values for NDJF tornado counts and ENSO, AO, and NAO indices using the Mood's median test are 0.06, 0.19, and 0.30 respectively. Therefore, La Niña and El Niño tornado counts can be said to have statistically significant medians, yet only at the 90% confidence level.

To test statistical significance of the correlations, a Pearson Correlation Test is employed, which assumes a normal distribution of the teleconnection index values. This test involves a critical t-statistic, using (N-3) degrees of freedom. In this case, N=62 years, and the corresponding $t_c = 2.0$. Therefore, if the t-statistic computed from the correlation coefficient exceeds 2.0, then a null hypothesis that there is no correlation between tornado counts and teleconnection indices can be rejected. Following this method, the NDJF, DJF, and February tornado count correlations are found to be statistically significant with ONI (Table 2.6). The NDJF tornado counts also show statistically significant correlation with AO and NAO indices, as do the November tornado counts with the AO index. To ensure that averaging over four months of teleconnection indices is indeed a justifiable approach, the mean ONI and AO indices for a composite of the ten most and ten least tornadic cold seasons are found. Consistent with the above results, during most tornadic years, the mean cold-season ONI (-0.35) and AO (0.48) favor La Niña and positive AO conditions, while during the least tornadic years the mean cold-season ONI (0.37) and AO (-0.88) favor El Niño and negative AO. Finally, a correlation analysis of the entire AO monthly record through the 62-year period (no averaging) with the full monthly tornado count time series still yields a statistically significant correlation, though slightly less than when a 4-month average is taken (r = 0.142). Taking the results of these statistical tests as a whole, one can conclude that there is indeed some relationship between these teleconnection indices and cold-season tornado occurrence, and though correlations are low there does exist statistical significance.

Previous work has attempted to find a direct link between ONI and tornadoes, but to little avail (Agee and Zurn-Birkhimer 1998, Marzban and Schaefer 2001, Cook and Schaefer 2008, Farney and Dixon 2014). However, research has shown that La Niña conditions do modulate the environment to make it more conducive to tornado events (Nunn and DeGaetano 2004, Allen et al. 2015), consistent with the results shown here that indicate a cold season under the La Niña phase tends to produce more tornadoes than a cold season under El Niño or Neutral conditions. Tornadoes occurring during a La Niña also tend to result in more violent tornadoes and more tornado outbreaks (Knowles and Pielke Sr. 2005). Other studies have investigated the ENSO-tornado count relationship from different angles, such as recent work by Sparrow and Mercer (2016) who use the Niño 3.4 index in tandem with 500-hPa geopotential heights to show a relationship with tornado frequency. Further, Lee et al. (2016) use North Atlantic SSTs and alternative springtime ENSO phases as a predictive measure for tornadoes. It should also be noted that many other teleconnection indices exist, and some have been analyzed for relationships with U.S. tornadoes. For example, Lee et al. (2013) show that the Trans-Niño Index (TNI) is strongly correlated to tornado frequency. However, given the noted complexities, it is best to conclude that teleconnections such as ENSO, AO, and NAO do show *some* relationship to tornado frequency, but their relationship is one of modulating the environment to support (or not support) severe weather and tornadoes, rather than explicitly causing tornadoes. Finally, we have not delved into the additional complexities of trying to predict ENSO phase (or any other teleconnection phase) for an upcoming cold-season. The meteorological community, while improving greatly, is not yet to the point of predicting teleconnections with a strong degree of success. However, the results of this chapter can prove very valuable with continued understanding of teleconnections and improvements in their forecasting, since it is shown that there is a greater probability of enhanced cold-season tornado counts particularly under La Niña and positive AO conditions. As our ability to predict ENSO and AO phase months in advance improves, seasonal forecasts giving tornado probabilities for an upcoming tornadic cold season could be issued, which would in turn help with awareness, preparation, and eventual mitigation of societal risks from cold-season tornadoes.

This chapter has presented a comprehensive climatology of cold-season tornadoes from 1953–2015 from a variety of angles. Results show an increasing trend in NDJF tornadoes throughout the Southeast and Mississippi Valley regions of the U.S. A cycle of enhanced counts every 3-7 years is found via spectral analysis and subsequently investigated to reveal weak yet significant relationships between teleconnection patterns and frequency of NDJF tornado occurrence, with more tornadoes during La Niña and positive AO/NAO phase. The next step in this cold-season tornado evaluation is to go to the finer meteorological scale in order to search for the typical environments and ingredients associated with active and inactive years.

CHAPTER 3: METEOROLOGICAL PERSPECTIVE

Having established a comprehensive climatology of cold-season tornadoes from 1953–2015, the next step is to assess meteorological factors contributing to their occurrence. This chapter begins with recalling relevant literature in the field related to tornado environments and parameters. The methods taken to analyze selected parameters from Reanalysis datasets are then discussed, as well as a tangent approach to assess storm mode classification of cold-season tornadoes. Results are presented to arrive at discerning a typical environment of cold-season tornadoes and how that environment differs from tornado environments during the warm season. Concluding thoughts that reaffirm the findings and relevant implications close the chapter.

A. Motivation

Understanding the atmospheric environments in which cold-season tornadoes occur is an important goal toward improving forecasts of such events and hopefully reducing societal harm. In so doing, it can be gleaned how favorable cold-season environments compare to those at other times of the year when more tornadoes occur. Tornado environments can be delineated using a plethora of meteorological variables that highlight the dynamical and kinematic states, and moisture level, of the atmosphere. Over the years, there have been numerous efforts to refine a suite of environmental parameters which most favor tornadogenesis. Though differences abound in the parameters considered to be the best discriminators between tornadic and non-tornadic environments, some form of vertical wind shear and instability need to be present. Several efforts have employed proximity soundings to propose the best tornado discriminators (Rasmussen and Blanchard 1998, Brooks et al. 2003b, Thompson et al. 2007, 2012), with some combination of a shear and thermodynamic parameter proving to be the best. Thompson et al. (2007, 2012) in particular show that low-level vertical wind shear, effective storm relative helicity (ESRH), and LCL heights show robust discrimination between significant tornado and non-tornado supercell environments. More recently, Tippett et al. (2012) mine a variety of monthly mean values of parameters related to vertical shear and updraft strength from the North American Regional Reanalysis (NARR), and arrive at an index based on convective precipitation and SRH. This index is tested and found to have a good relationship with monthly tornado climatology, yet fails to capture cool-season tornadoes (Tippett et al. 2014). Grams et al. (2012) propose that kinematic variables are of greater worth than thermodynamic variables for distinguishing between significant tornado and non-tornado environments. They also investigate convective mode frequencies and geography of tornadoes but admit that Southeast wintertime tornadoes prove to be the most difficult to forecast.

As hinted, there is difficulty in discerning favorable cold-season tornado environments, although general synoptic and mesoscale patterns have been established. Early work by Galway and Pearson (1981) looks at winter tornado outbreaks and finds a recurring low pressure that forms around southeast Colorado, ample low-level moisture, and a low-level jet (LLJ) that transports Gulf moisture north and east during such outbreaks. More recently, Guyer et al. (2006) show that significant winter tornadoes most often occur in the presence of a strong southerly or southwesterly LLJ > 30 knots, and downstream of an upper-level trough. From a mesoscale perspective, many studies have shown that cold-season tornadoes are of the low-CAPE-high-shear variety (Guyer et al. 2006, Schneider et al. 2006, Sherburn and Parker 2014), and are most prevalent across the Southeast during overnight and early morning hours (Sherburn et al. 2016). In fact, Guyer et al. (2006) show that 90% of cool-season significant tornadoes occur with 0-1 km bulk shear > 20 knots, and Guyer and Dean (2010) further reveal that 60% of all DJF tornadoes have weak MLCAPE (< 500 J kg^{-1}) with high low-level moisture. Sherburn and Parker (2014) go further in identifying skillful parameters for discriminating between cases of significant severe low-CAPE-high-shear environments and null events. They find the 0-3 km lapse rate and the 700-500-hPa lapse rate do the best job at distinguishing severe environments, while the addition of the effective shear to these parameters stands up best when specifically distinguishing low-CAPE-high-shear significant tornadoes.

Kounkou et al. (2009) and Hanstrum et al. (2002) both assess cool-season tornado environments in Australia and reveal a long list of common synoptic and mesoscale patterns associated with tornado occurrence. For example, cool-season tornadoes in Australia are found to generally occur in environments of high shear, low CAPE, and low surface lifted index (Hanstrum et al. 2002). Synoptically, these tornadoes tend to occur downstream of a low-level wind maximum and on the cyclonic side of an upper-level jet streak (Kounkou et al. 2009). In a similar vein, Brooks (2009) and Cohen et al. (2015) relate Southeastern U.S. tornado environments with those in Europe, characterized by low CAPE and high shear. In fact, Brooks (2009) finds that the same value of (CAPE * 0-1 km Shear) is more likely to produce severe weather in the Southeast during winter than during any other time of the year, likely due to the prevalence of synoptic systems and boundaries aiding convective initiation in the winter.

Identifying appreciable trends in favorable tornado environments with any confidence has been difficult (Gensini and Ashley 2011, Robinson et al. 2013), although Lu et al. (2015) show that the quantity (CAPE * SRH^4) is increasing and aligns well with the upward trend in peak tornado activity, and tornado occurrence starting earlier in the year. Trapp et al. (2007) propose that an increase in CAPE and decrease in vertical wind shear may shift tornado occurrence poleward, but it is not clear what result these changes in CAPE and shear over time may have on tornado frequency (Diffenbaugh et al. 2008). However, more recent work by Diffenbaugh et al. (2013) using the Coupled Model Intercomparison Project Phase 5 (CMIP5) model shows an increasing number of days with high CAPE and high low-level shear with increased greenhouse gas warming, thereby increasing the number of days conducive to severe thunderstorms and tornadoes.

In light of the aforementioned findings, it is of great worth to assess tornado parameters within the 1953–2015 cold-season climatology established in Chapter 2. The main goal is to see how certain parameters differ between tornadic cold seasons and non-tornadic cold seasons, in hopes of establishing a typical cold-season tornadic environment. Changes in some of these tornado parameters over time are also addressed. In addition, an analysis of the storm mode of a subset of cold-season tornadoes from the SPC Storm Mode Database (Smith et al. 2012, Thompson et al. 2012) is undertaken to look for frequency of tornado occurrence under different modes, and how parameters differ between the modes.

B. Methodology

Both broad and fine scale approaches are taken to investigate favorable cold-season tornado environments. First, from a coarser perspective, the NCEP/NCAR Reanalysis

(Kalnay 1996) is used to compare monthly mean and seasonal mean values of several derived variables with the corresponding tornado count data (Brooks et al. 2007). Specific variables investigated include surface values of temperature, relative humidity (RH), pressure, precipitable water (PWAT), and lifted index (LI), as well as 850-hPa temperatures and 500-hPa heights. These parameters are all analyzed for each individual month of November through February and the combined seasons of DJF and NDJF. In addition, the 1000-500-hPa wind speed shear is computed for these months and seasons. Finally, sea surface temperatures (SSTs) from the COBE-SST2 dataset (Hirahara et al. 2014) are gathered from ESRL/PSD (http://www.esrl.noaa.gov/psd/) for investigation, particularly in the Gulf of Mexico vicinity.

Use of the NCEP/NCAR Reanalysis is limited by its relatively low spatial resolution (2.5° X 2.5°), so only general patterns can be appropriately found. This reanalysis also has a limited tornado parameter list and coarse time resolution (i.e. monthly and/or seasonal averages). However, this dataset is desirable because data can be obtained for the entire length of the study time period (i.e. 1953–2015). To overcome the resolution barriers while still maintaining the desired long time scale of the NCEP/NCAR Reanalysis, the results are bolstered with finer scale analysis of convective parameters from code run by collaborator John Allen. This code generates 6-hourly values of a variety of CAPE, CIN, lapse rate, LCL height, wind shear, and SRH variables, as well as Significant Tornado Parameter (STP) and specific humidity in the boundary layer. All meteorological variables are analyzed for the cold season in the same spatial domain as the climatological analysis from Chapter 2 (25-42.5°N, 75-100°W). To help gain a better understanding of what makes a cold season particularly favorable for tornadoes, a composite of the suite of variables for the ten least active cold seasons is subtracted from a composite of the ten most active cold seasons.

It is also of interest to assess the convective mode nature of cold-season tornadoes to see if one particular mode dominates during this time of year. To do so, the SPC Storm Mode database is used (Smith et al. 2012, Thompson et al. 2012). This database contains convective mode data, as well as other meteorological parameters, for tornadoes from 2003–2015. At the broadest level, tornadoes are characterized into one of four convective mode bins (which will be the basis of the analysis presented here): discrete, cell in line, cell in cluster, and QLCS. The data is parsed to isolate all tornadoes occurring during NDJF of EF1 intensity or greater over the study domain. Previous results using this database show that the southern U.S. has the greatest variability of tornado storm mode throughout the year (Smith et al. 2012). This is important since tornado environments can be quite different between the different modes. For example, Thompson et al. (2012) find that 75% of all wintertime QLCS tornadoes have CAPE < 350 J kg^{-1}, but 75% of wintertime significant tornadoes from right-moving supercells have CAPE > 350 J kg^{-1}. Based on numerous other studies mentioned above which find a propensity for cold-season tornadoes to be of the low-CAPE variety, one would hypothesize that QLCS tornadoes are favored during this time of year. Analysis of the Storm Mode database for this 12-year subset of tornadoes aims to investigate this issue.

C. Results

1. NCEP/NCAR Reanalysis monthly means

Seasonal (NDJF) means of several meteorological variables are presented in Figure 3.1. The change in the variable between the same two Periods from Chapter 2 (Period II (1984–2015) – Period I (1953-1984)) is shown in the top panels, and the difference in the variable between a composite of most tornadic and least tornadic cold seasons is shown in the bottom panels.

(i) SURFACE VARIABLES

The first look within the NCEP/NCAR Reanalysis is at surface temperature, RH, PWAT, LI, and pressure for NDJF tornadoes (Fig. 3.1). While temperature does not directly cause tornadoes, it does serve to change the environment in which tornadoes occur and can affect quantitative values of other variables known to be associated with tornado activity. For example, higher temperatures in one area adjacent to much lower temperatures can create a temperature gradient sufficient for producing lift needed to generate convection. The expected south-to-north increase in temperature is seen for the 1953–2015 seasonal means, as well as each individual monthly mean (not shown). Comparing Period I to Period II (Fig. 3.1, top left), most of the domain has witnessed an increase in temperature in the more recent period. The month of January in particular has seen strong increases in excess of 2°C, while December has seen the most widespread decreases in temperature, across the Gulf Coast and Plains areas. Interestingly, there is an area of cooling along the immediate Gulf Coast for NDJF, which will be discussed below. The most tornadic NDJF seasons have a general pattern of warmer temperatures (up to

4°C) across the Southeast and East and cooler temperatures across the Plains where very few cold-season tornadoes occur to begin with.

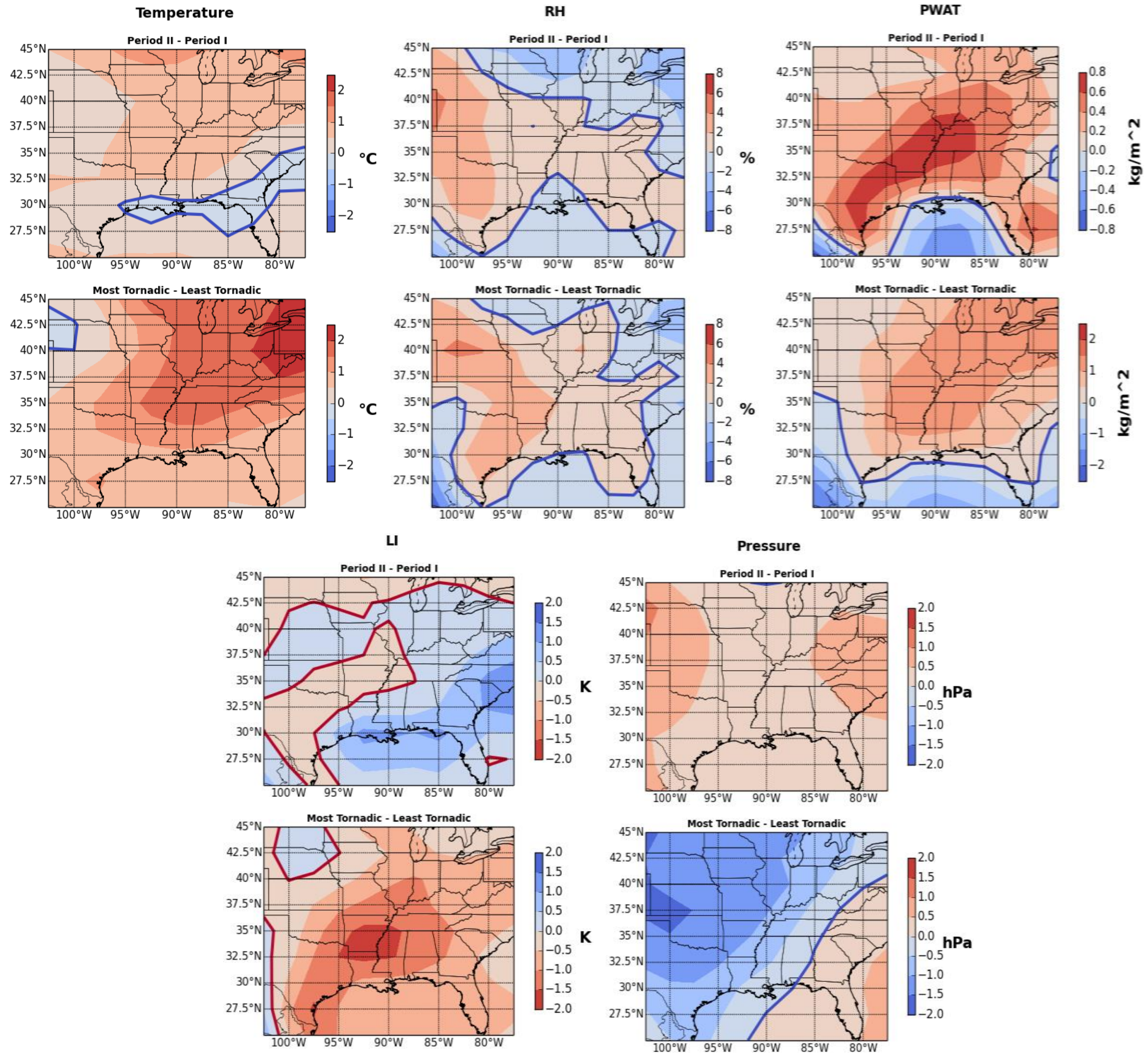


Figure 3.1: Differences in NDJF mean values for surface variables from NCEP/NCAR Reanalysis database. Top panels show (Period II – Period I); bottom panels show (Top 10 tornadic – Bottom 10 tornadic).

Turning to moisture variables, relative humidity has remained relatively constant between Period I and Period II in the Southeast for NDJF (Fig. 3.1, top middle), although the month of November shows RH increases in excess of 4% across the Mississippi Valley region (not shown). The enhanced moisture during this month may help explain the large increase in tornadoes during November (+454) in the more recent period. For the most tornadic seasons, mean RH values are generally 2-8% higher than the least tornadic seasons. Similar results are seen in the precipitable water (PWAT) field, which is simply a measure of how much water vapor is in a column of atmosphere (Fig 3.1, top right). The more recent Period II shows the most enhanced mean NDJF PWAT in an arcing band from Texas to the Ohio Valley. This would hint at a warmer Gulf that is advecting moisture northward and eastward in more recent years; however, the cooler temperatures along the immediate Gulf Coast does not seem to gel with this finding. For most tornadic seasons, PWAT is enhanced across almost the entire domain (in some cases upwards of 4 kg m^{-2}, and most notably in areas where NDJF tornadoes are increasing the most.

Lifted Index (Fig. 3.1, bottom left) is defined such that more negative values indicate favorable conditions for severe weather (note the inverted color bar to have red denote more favorable tornadic conditions). Very little change is seen in mean LI from Period I to Period II, but LI is much more negative in the Southeast during the most tornadic seasons. It is also interesting that the shape of the area of greatest increase mirrors that of the PWAT field, hinting at the importance of a moisture stream from the western Gulf of Mexico moving northward and then eastward in creating conditions ripe for cold-season tornadoes.

Analysis of the surface pressure field (Fig. 3.1, bottom right) reveals a consistent increase in mean pressure by up to 1.2 hPa in Period II compared to Period I across the domain. In comparing most active to least active seasons, the NDJF mean surface pressure is lower over the areas where tornadoes are prevalent and higher along and off the East

Coast in the most tornadic seasons. Each individual month shows the same pattern, and in fact the pressure variable as a whole shows the strongest agreement between the different months and seasons, both qualitatively and quantitatively. This adds great worth to the present study because pressure distribution can be related to the storm track and teleconnection patterns. The lower pressure across the South and Midwest during most active tornado seasons points toward a greater frequency of extra-tropical cyclones impacting this part of the country, which in turn leads to more tornado production. In addition, higher pressure over the East Coast and Atlantic aligns with positive phase AO and La Niña conditions. As discussed in Chapter 2, a positive-phase AO and negative ONI tend to be associated with more cold-season tornadoes.

Finally, as noted, it is of interest to look at SST changes between the two Periods and the most and least active tornado seasons in order to help explain the advection of Gulf moisture and warmth into the South and Southeast where NDJF tornadoes are on the rise. Surface temperatures immediately adjacent to the Gulf of Mexico have cooled in the most recent 31-year Period II (Fig. 3.1, top left), yet Period II has seen a large increase in cold-season tornadoes. Figure 3.2 shows the seasonal (NDJF) mean differences of SSTs for (Period II – Period I) and (Most Tornadic – Least Tornadic). Comparing the two 31-year Periods, it is seen that NDJF seasonal mean SSTs (as well as each individual month) are lower in Period II in the near-shore Gulf and Atlantic Ocean, with higher SSTs in the central Gulf and the rest of the Atlantic. This would not seem conducive to increased tornado activity, but a more convincing SST pattern is seen when comparing active and inactive seasons (Fig. 3.2, bottom left). For the individual months of December, January, and February (not shown), the Gulf waters adjacent to the shore are consistently warmer by at least 0.5°C during the most tornadic seasons. The NDJF pattern does not show as strong a warming in this area due to cooler waters in November from New Orleans eastward (Fig. 3.2, bottom right). Warmer waters are still the rule over the western half of the Gulf in Novembers of active seasons, however, which would accord with increased tornado activity in the South owing to the northward advection of moisture and warmth from the western Gulf. The strong and consistent warming in the Gulf of Mexico during all other cold-season months suggests that SSTs do play a role in priming the environment for tornadoes, but this hypothesis is not as strong as it could be since the month and Period with greatest increase in tornadoes (November during Period II) does not have as strong a warming signal in the Gulf waters.

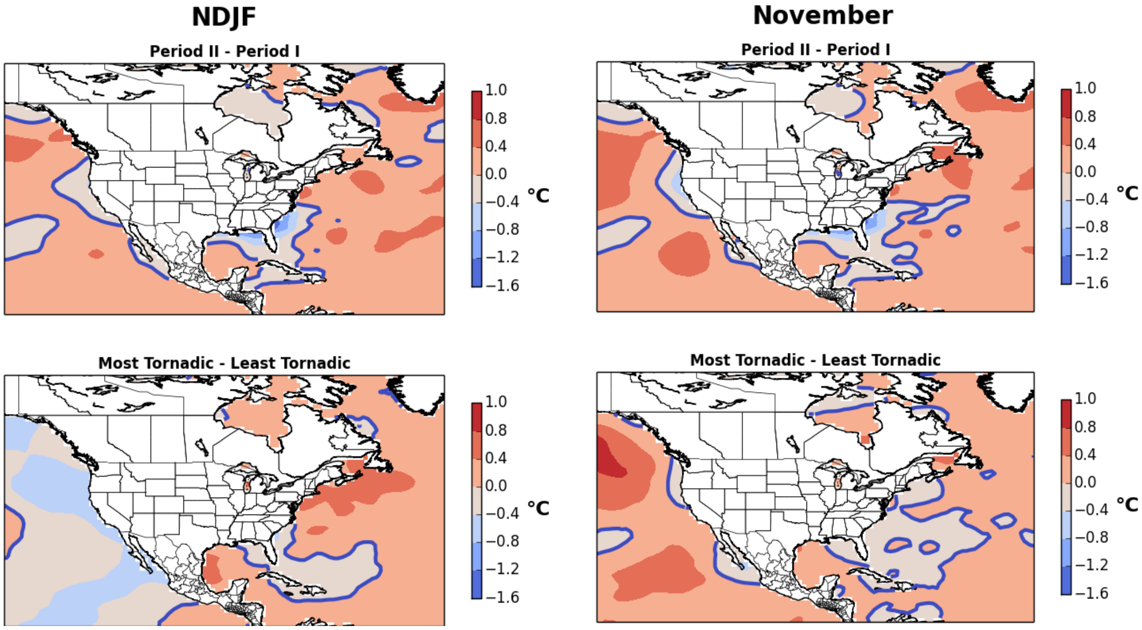


Figure 3.2: NDJF (left) and November (right) sea surface temperature differences between Period I and Period II and between most active and least active tornado seasons.

(ii) SYNOPTIC SET-UP: 500-hPa HEIGHTS

From a more large-scale perspective, it is intuitive to look at how height fields differ over time, and more notably between active and inactive tornado seasons (Fig. 3.3). For (Period II – Period I), the seasonal means show increased heights across much of North America and decreased heights in the North Atlantic during Period II (Fig. 3.3, top). Such a pattern is indicative of positive-phase AO and NAO, both of which tend to yield warmer winter temperatures and stronger westerlies across the eastern U.S., thereby providing a more conducive synoptic environment for severe weather and tornadoes (provided other ingredients are in place). Sure enough, as shown in Chapter 2, positive-phase AO and NAO do indeed favor enhanced cold-season tornado activity. Height differences between most tornadic and least tornadic cold seasons are also intriguing. The NDJF seasonal difference shows higher heights across the eastern U.S. and lower heights across the western U.S. for most tornadic seasons (Fig. 3.3, bottom). Each individual month also shows enhanced heights east of the Mississippi River and lower heights further west. This looks like an anomalous large-scale trough over the western U.S. and a ridge over the East. The bulls-eye for severe weather often sets up downstream of a trough, which in this case would put it across the Mississippi Valley region. Sure enough, this is where cold-season tornadoes most frequently occur and are increasing. In addition, each month and season shows lower heights from Greenland northward for most tornadic seasons, which again hints at a positive phase AO pattern that is associated with enhanced counts. In short, the synoptic, upper-level height pattern is consistent with what one would expect for severe weather occurring over the Mississippi Valley region.

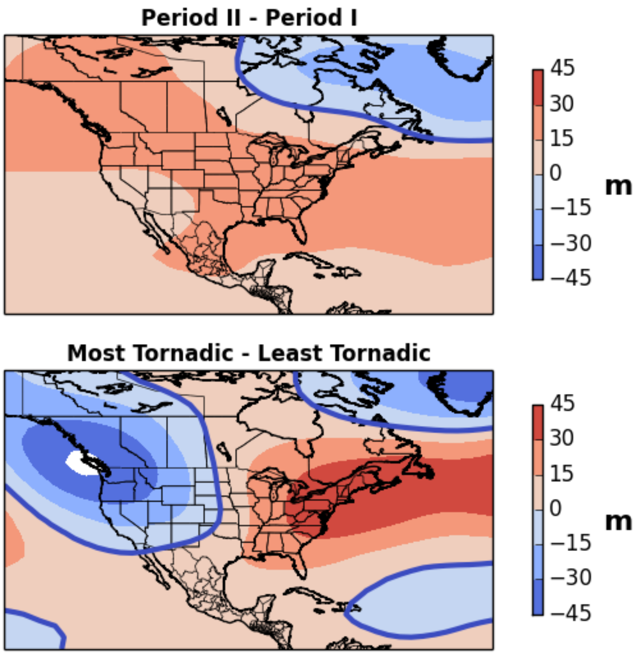


Figure 3.3: Difference in NDJF mean 500-hPa height for (Period II – Period I) and (Most Tornadic – Least Tornadic).

2. NCEP/NCAR Reanalysis 6-hourly means

For a more fine-scale approach at the meteorological perspective of cold-season tornado environments, various severe weather parameters are investigated at 6-hourly resolution. As mentioned in the Motivation section, there are numerous atmospheric parameters shown to be good distinguishers for severe weather and tornadoes, including various flavors of CAPE, shear, SRH, LCL height, and lapse rates. In addition, specific humidity and the Significant Tornado Parameter (STP; Thompson et al. 2004) are included in the 6-hourly analysis. The same approach taken with the monthly mean data is employed here, with differences between the two Periods and the most and least active tornado seasons highlighted. Particular emphasis is directed toward how the distribution of a variable is different spatially and in magnitude between active and inactive tornado seasons in order to glean the conditions that make an environment ripe for cold-season tornadoes. It is important to remember that these meteorological parameters are not predictors of cold-season tornadoes (or tornadoes in general), but rather give a glimpse of the atmospheric conditions present at the time. Larger scale variables such as lapse rates and geopotential heights are more indicative of the likelihood for severe weather.

Ask any typical atmospheric scientist which two variables he or she thinks of when discussing tornado environments, and undoubtedly CAPE and shear will be the answers. As discussed earlier, many previous studies have shown a tendency for low-CAPE-high-shear environments in cold or cool-season severe weather (Guyer et al. 2006, Schneider et al. 2006, Brooks 2009, Sherburn and Parker 2014, Cohen et al. 2015), although each of these studies use a slightly different tornado climatology. To add more weight to this assertion, 6-hourly NDJF mean CAPE and shear values are evaluated spatially for the cold-season across each 2.5° X 2.5° grid box. Figure 3.4 presents SBCAPE, MLCAPE, 0-1 km shear, and 0-6 km shear for (Most Tornadic – Least Tornadic) seasons. Of course, these plots are generated from a mean of many 6-hourly data points (and thus the difference in the means between Period I and Period II are insignificant), but the difference between active and inactive seasons should still paint a good picture of where and by how much CAPE and shear vary.

From Figure 3.4 (top), it is seen that both SBCAPE and MLCAPE are enhanced in most active seasons across almost all of the domain, but especially in areas adjacent to the western Gulf of Mexico, indicative of a more unstable moisture transport from the Gulf. Mean SBCAPE values are up to 50 J kg^{-1} higher across a wide swath of the lower Mississippi Valley region in tornadic cold-seasons. As shown later, CAPE values are indeed quite low overall during cold-season tornado environments, but it is apparent that when CAPE is present, albeit in lower quantities than warm-season environments, tornadoes are more likely.

A somewhat more puzzling result is seen in the wind shear variables. For 0-1 km vertical wind shear (Fig. 3.4, bottom left), most tornadic seasons have enhanced shear domain-wide, but the greatest increase is noted in areas where NDJF tornadoes are decreasing overall, in the lower Great Plains. Mean 0-6 km wind shear (Fig. 3.5, bottom right) shows a similar increase during tornadic seasons in the Plains, but also a modest decrease across much of the Southeast, including the areas where NDJF tornadoes are most prevalent. However, this pattern is likely just indicative of the mean jet during this time of year, with a trough in the Plains and ridge in the East, as confirmed by 300-hPa wind speed differences between most tornadic and least tornadic years (not shown). This puts the Mississippi Valley region in the exit region of the jet streak and downstream of the trough axis, in most tornadic years. This is a favorable setup for convection, even though the wind shear is technically lower here in these active years (Kounkou et al. 2009). It is also important to note that shear values are much higher in cold-season tornado environments than in other times of the year, as expected due to the prevalence of extratropical cyclones in wintertime. Thus, these spatial results show that vertical wind shear, especially the 0-6 km shear, is either not the best discriminator between seasons of enhanced and lower counts, or in the seasonal mean sense is simply not telling much of the story.

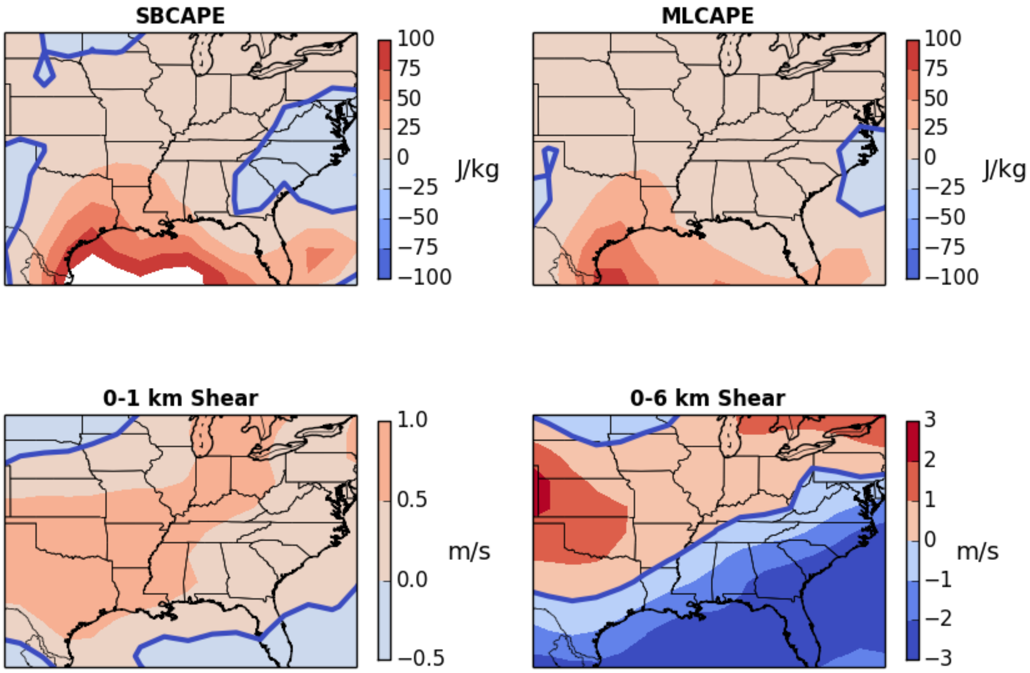


Figure 3.4: Differences in 6-hourly mean NDJF CAPE and shear between most tornadic and least tornadic seasons.

Another metric for assessing these results is a frequency of a particular variable, or combination of variables, exceeding a threshold. Several variables, and combinations of variables, have been assessed for how many times they are observed to exceed a certain value during the ten most active NDJF seasons and the ten least active NDJF seasons within the given study domain. Thresholds are assigned based on general severe weather conditions, and results are summarized in Table 3.1. In addition, a spatial depiction of four parameters which show large differences in observations between active and inactive seasons (STP, MLCAPE, 0-1km Shear, and a combination of MLCAPE and 0-6 km Shear) is given in Figure 3.5 From the "CAPE versus shear" perspective, Table 3.1 shows that there are almost twice as many MLCAPE observations greater than 1000 J kg^{-1} in active seasons than in inactive seasons, and SBCAPE observations greater than 2000 J kg^{-1} are similarly almost twice as frequent in most active seasons. Both of these differences are statistically significant via a test of independent proportions. Vertical shear between 0-1 km that exceeds 20 m s^{-1} is also much more frequent in active seasons, while 0-6 km shear is not nearly as discriminating. When CAPE and shear variables are combined with their respective thresholds, it is seen that there are very few observations of enhanced CAPE and high shear in all seasons. However, a statistically significant difference does emerge with the combination of MLCAPE > 750 J kg^{-1} and 0-6 km Shear > 30 m s^{-1}. This result is shown spatially in Figure 3.5 (bottom left) and reveals that most of the observations meeting these thresholds in tornadic seasons occur over Louisiana, Arkansas, eastern Texas and Oklahoma, and western Mississippi. A hypothesis is that the warmer western Gulf of Mexico during most tornadic seasons is creative more unstable conditions in these areas. Similar plots are shown in Figure 3.5 for MLCAPE > 750 J kg^{-1} (top left) and 0-1 km Shear > 30 m s^{-1} (top right). The MLCAPE observations that exceed the threshold are dominated spatially over the ocean, but there is a clear enhancement over the Southern states in most active seasons. The 0-1 km shear observations exceeding the threshold are aligned spatially, with the bulls-eye over the Mid-Atlantic region. This seems puzzling, but one explanation is simply that the pattern highlights a winter climatology signal. For example, a Nor'easter cyclone storm track would provide enhanced observations of northerly shear in this area but not typically lead to severe weather. In summary, the results presented affirm the propensity of low-CAPE-high-shear environments for cold-season tornadoes in the Southeast. Very few instances of CAPE > 2000 J kg^{-1} exist, even in the most tornadic seasons. Shear is enhanced during the winter to begin with due to a stronger jet stream, so when adequate CAPE also exists, the potential for damaging tornadoes goes up.

Table 3.1: Number of 6-hourly observations of various parameters exceeding threshold values within the study domain for top 10 and bottom 10 tornadic cold seasons.

	Frequency of Exceedance			
	0-1 km SHR > 20 m s^{-1}	0-6 km SHR > 60 m s^{-1}	0-1 km SRH > 250 m^{2} s^{-2}	MLLCL < 500 m
TOP 10	5409	2957	221689	546483
BOTTOM 10	3291	2587	231654	571408
	SBCAPE > 1000 J kg^{-1}	SBCAPE > 2000 J kg^{-1}	MLCAPE > 1000 J kg^{-1}	MLCAPE > 2000 J kg^{-1}
TOP 10	39158	4170	6688	87
BOTTOM 10	30926	2369	3384	17
	0-3 km Lapse > 9.5°C km^{-1}	2-4 km Lapse > 9.5°C km^{-1}	700-500 hPa Lapse > 9.5°C km^{-1}	STP > 1.0
TOP 10	377	260	214	532
BOTTOM 10	260	68	45	354
	SBCAPE > 1000 J kg^{-1} 0-6 km SHR > 40 m s^{-1}	SBCAPE > 1000 J kg^{-1} 0-1 km SHR > 20 m s^{-1}	MLCAPE > 1000 J kg^{-1} 0-1 km SHR > 20 m s^{-1}	MLCAPE > 750 J kg^{-1} 0-6 km SHR > 30 m s^{-1}
TOP 10	38	5	5	415
BOTTOM 10	6	0	1	220

Also shown in Table 3.1 and Figure 3.5 (bottom right) are frequency of exceedance for STP, a good indicator of tornado potential. Although it is enhanced in the most active seasons across much of the domain, the dearth of tornadoes during this time of year in general means that very few 6-hourly observations of STP > 1.0 exist, whether in an active or inactive season. Thus, it is more revealing to note that during the top 10 most active tornado cold seasons, there were 532 observations of STP > 1.0, compared to only 354 observations during the 10 least active cold seasons, which by a test of two independent proportions shows statistical significance. Taken with the combined MLCAPE and 0-6 km shear parameter, the bottom panels of Figure 3.5 nicely reveal that combinations of ingredients can produce very different (and more noticeable) patterns than when ingredients are considered separately.

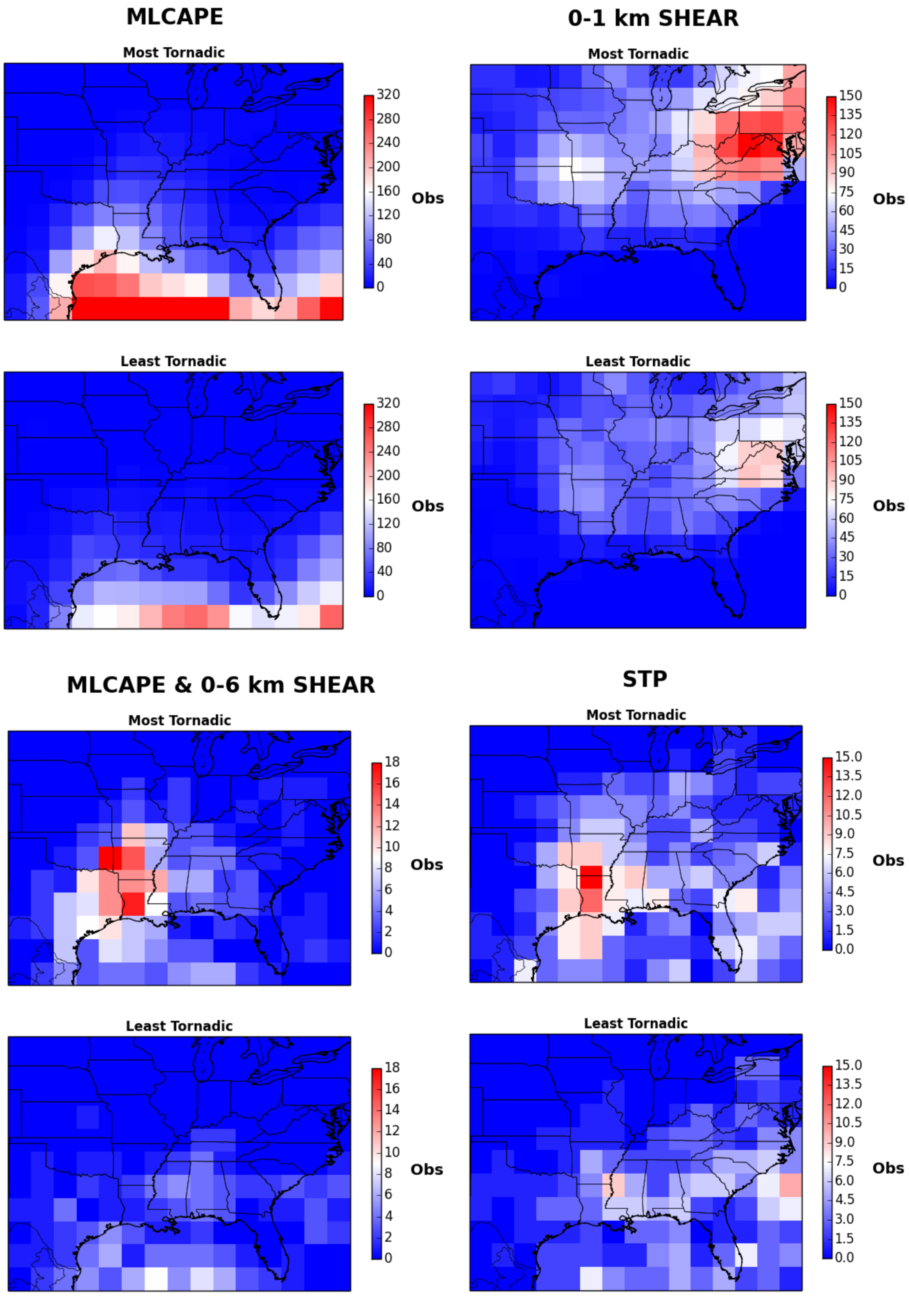


Figure 3.5: Number of 6-hourly observations exceeding thresholds for most tornadic and least tornadic seasons: MLCAPE > 750 J kg^{-1}; 0-1 km Shear > 20 m s^{-1}; MLCAPE > 750 J kg^{-1} and 0-6 km Shear > 30 m s^{-1}; and STP > 1.0.

A few other parameters from the 6-hourly reanalysis data are also worthy of attention. Figure 3.6 presents differences in 6-hourly NDJF means (in a similar fashion as in Fig. 3.4) for 0-1 km SRH, mid-level Specific Humidity, 700-500-hPa Lapse Rate, and STP. Table 3.1 also shows some of these additional variables and their frequency of exceeding observational thresholds. The 0-1 km SRH is lower across nearly the entire domain during the most active cold seasons (Fig. 3.6, upper left), and a similar result exists for 0-3 km SRH (not shown). While it may seem counterintuitive to have lower SRH during active tornado seasons (Thompson et al. 2007, Tippett et al. 2014), it is important to note that SRH is a rather noisy field, especially when taking a mean over many time steps. Helicity can be high for reasons not related to tornado potential, so this variable is neither the best discriminator nor predictor for cold-season tornado environments. This result is actually consistent with Tippett et al. (2014) who show that in their index of convective precipitation and SRH, the SRH variable explains much less of the interannual variability in tornado counts than does convective precipitation. The 700-500-hPa lapse rate, which has been used in previous work as a discriminator between tornadic and non-tornadic environments (Sherburn and Parker 2014), is steeper across most of the domain in the most active tornado seasons, with values up to 0.3°C km^{-1} higher in the Mississippi Valley region where the majority of cold-season tornadoes occur (Fig. 3.6, upper right). In fact, Table 3.1 reveals that each of three different lapse rate metrics show a much greater frequency of exceeding a dry adiabatic lapse rate of 9.5°C km^{-1} in most tornadic seasons, and each proportional difference is statistically significant. This steeper lapse rate signal gels with the understanding that steeper lapse rates indicate a more unstable environment and thus a higher potential for severe weather and tornadoes. Moreover, the steeper lapse rates in the most tornadic cold seasons seem to arise from much warmer surface temperatures compared to only slightly warmer 500-hPa temperatures (not shown). The anomalous trough seen in the western United States in most active seasons (Fig. 3.3) would help usher in bouts of colder air aloft in the Mississippi Valley region, which, combined with much warmer surface temperatures, would culminate in steeper lapse rates. The STP spatial distribution (Fig. 3.6, bottom left), as discussed above, reveals a small increase across much of the interior of the domain. Finally, mid-level (i.e. 700-500-hPa) specific humidity is greatly enhanced during most active tornado seasons (Fig. 3.6, lower right). The spatial distribution signature of specific humidity looks similar to the other moisture variables and LI patterns shown before (Fig. 3.1), and further confirms the significance of moisture and moisture advection from the western Gulf of Mexico to creation of cold-season tornado environments.

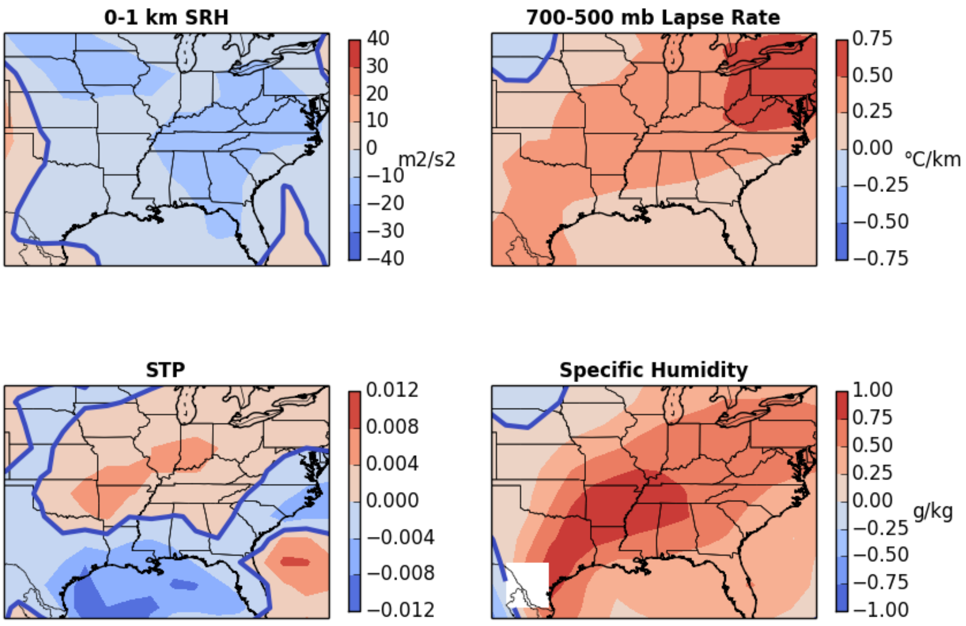


Figure 3.6: Differences in NDJF 6-hourly mean values of various severe weather parameters between most tornadic and least tornadic seasons.

3. Convective mode analysis

To supplement these results from reanalysis data, an investigation into the convective modes associated with cold-season tornadoes is performed. As mentioned in the Methodology, the SPC Storm Mode database, which contains tornado data from 2003–2015, is used to investigate convective mode distributions of cold-season tornadoes. The four main modes given in Thompson et al. (2012) – namely discrete, cell in line, cell in cluster, and QLCS – are retained here. Figure 3.7 gives an example of each of these modes on Doppler radar, using real events in the database.

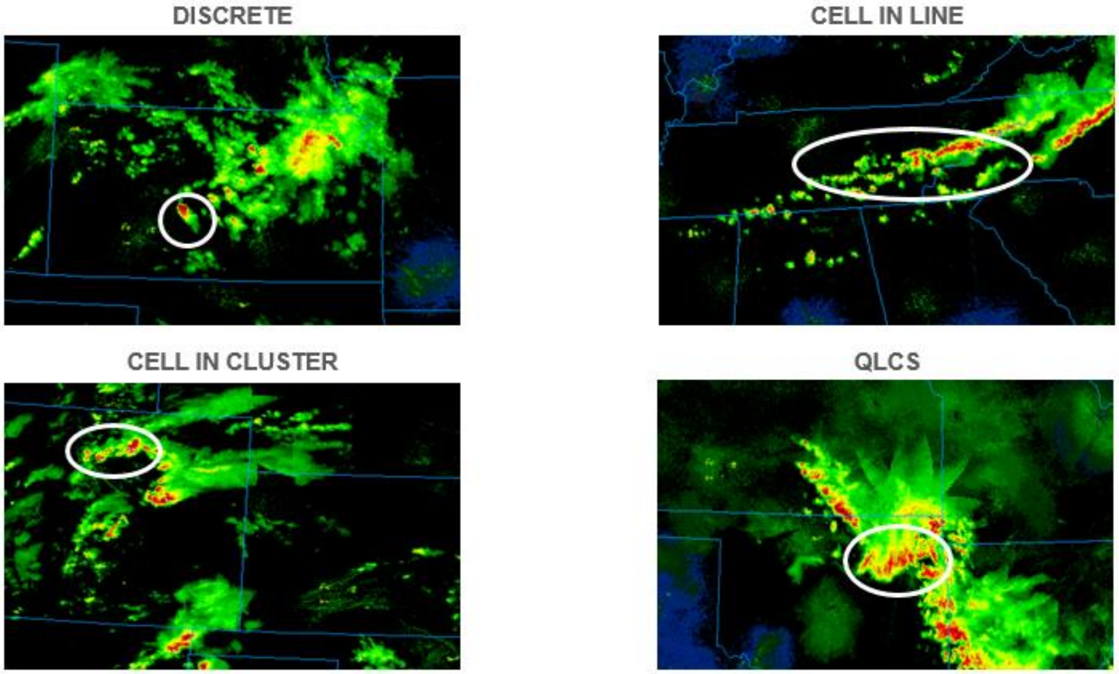
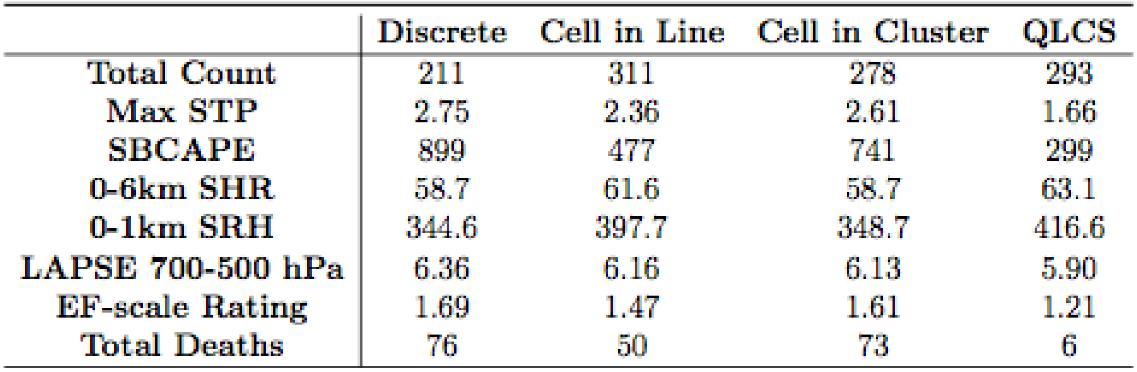


Figure 3.7: Radar imagery from NCAR's MMM archives (http://www2.mmm.ucar.edu/imagearchive/) of each of the four storm modes classified in SPC Storm Mode database.

Partitioning the SPC Storm Mode data into the appropriate season (NDJF), intensity (EF1+), and domain (25-42.5°N, 75-100°W) yields 1107 tornadoes for analysis. Additional analysis was performed on subsets of NDJF tornadoes of all intensities and across the entire CONUS, but results were similar to the smaller subset corresponding to the temporal and spatial domain used throughout this study. Despite the tendency for low-CAPE-high-shear cold-season tornado environments, which would tend to favor more linear rather than supercellular storm modes, in the twelve seasons analyzed here there is roughly an even distribution of tornadoes occurring under the QLCS, Cell in Line, and Cell in Cluster convective modes (Table 3.2). The smallest number of cold-season tornadoes occurs from discrete cells, yet still over 200 such tornadoes have occurred in these 12 years. The few tornadoes not accounted for in these four modes were either classified as a “hybrid” or were missing classification in the database. This finding suggests that cold-season tornadoes can occur quite commonly in all convective modes, thus adding to the complexity of forecasting their occurrence. Smith et al. (2012) makes the similar conclusion that the South shows the highest variability in convective mode in an annual sense.

It is also advantageous to compare known tornado parameters among the four convective modes, which the SPC Storm Mode database provides for each tornado occurrence. As such, Table 3.2 also gives averages of five parameters for each storm mode, as well as the average EF-scale rating and total number of casualties resulting from each mode. The parameters selected are conveniently also discussed above in the reanalysis data framework. It is seen that the ‘Discrete’ and ‘Cell in Cluster’ modes are associated with the highest maximum STP, highest SBCAPE, highest EF-scale rating, and the most deaths. This would suggest that isolated supercells, although slightly more uncommon in the cold season than other modes, produce more damaging and fatal tornadoes. However, these storm modes have lower vertical shear and SRH on average than the ‘Cell in Line’ or ‘QLCS’ tornadoes. In fact, QLCS tornadoes have the highest shear and lowest CAPE, and also the lowest EF-scale rating and number of deaths. This is not a surprising result, given the higher shear in wintertime, and accords well with Thompson et al. (2012) who show that 75% of winter QLCS tornadoes occur in high-shear environments with CAPE < 350 J kg^{-1}, whereas 75% of winter right-moving supercells (e.g. ‘Discrete’ category) have CAPE > 350 J kg^{-1}. Finally, it is interesting to note that the 700-500-hPa lapse rate increases from QLCS to Discrete modes, which is consistent with lapse rate tendencies for tornadoes in other parts of the year (Sherburn and Parker 2014).

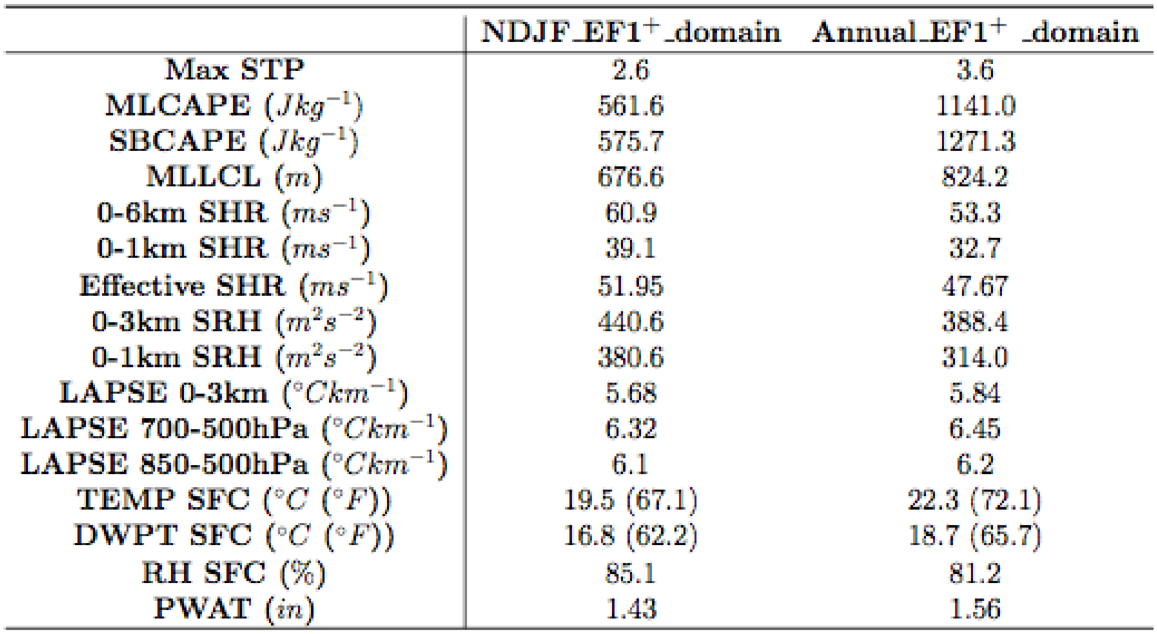
Table 3.2 Total counts and averages of various parameters among the four storm modes of NDJF EF1+ tornadoes (2003–2015) from the SPC Storm Mode database, and total deaths resulting from each storm mode.



	Discrete	Cell in Line	Cell in Cluster	QLCS
Total Count	211	311	278	293
Max STP	2.75	2.36	2.61	1.66
SBCAPE	899	477	741	299
0-6km SHR	58.7	61.6	58.7	63.1
0-1km SRH	344.6	397.7	348.7	416.6
LAPSE 700-500 hPa	6.36	6.16	6.13	5.90
EF-scale Rating	1.69	1.47	1.61	1.21
Total Deaths	76	50	73	6

Finally, it is valuable to look at average values of parameters in this data set across all storm modes during the cold season, and subsequently how they vary from tornadoes in an annual sense. Thus, Table 3.3 presents sixteen parameters averaged across all NDJF EF1+ tornadoes within the study domain. As expected, low CAPE and high shear is the rule for these cold-season tornadoes. For comparison, also shown in Table 3.3 are the parameter averages for annual EF1+ tornadoes in the domain. While lapse rates and moisture variables are comparable for NDJF and annual tornadoes, it is evident that cold-season tornadoes occur in more of a low-CAPE-high-shear environment with enhanced SRH compared to the annual average. Annual averages show much higher CAPE values (more than 500 J kg^{-1}), higher LCL heights, and lower wind shear than their cold-season counterparts. Also interesting is that cold-season tornadoes are associated with a high STP (2.6), not much below the annual STP average (3.6). Further, confirming results presented earlier in this chapter, the cold-season tornadoes in this limited sampling from the SPC Storm Mode database occur in very warm, moist environments, with surface temperatures and dew points averaging well over 60°F and within 5°F of the average annual values.

Table 3.3: Averages of various parameters for all NDJF and annual EF1+ tornadoes (2003–2015) from the SPC Storm Mode database.



	NDJF_EF1^{+}_domain	Annual_EF1^{+} _domain
Max STP	2.6	3.6
MLCAPE (Jkg^{-1})	561.6	1141.0
SBCAPE (Jkg^{-1})	575.7	1271.3
MLLCL (m)	676.6	824.2
0-6km SHR (ms^{-1})	60.9	53.3
0-1km SHR (ms^{-1})	39.1	32.7
Effective SHR (ms^{-1})	51.95	47.67
0-3km SRH (m^2s^{-2})	440.6	388.4
0-1km SRH (m^2s^{-2})	380.6	314.0
LAPSE 0-3km $(^{\circ}Ckm^{-1})$	5.68	5.84
LAPSE 700-500hPa $(^{\circ}Ckm^{-1})$	6.32	6.45
LAPSE 850-500hPa $(^{\circ}Ckm^{-1})$	6.1	6.2
TEMP SFC $(^{\circ}C\ (^{\circ}F))$	19.5 (67.1)	22.3 (72.1)
DWPT SFC $(^{\circ}C\ (^{\circ}F))$	16.8 (62.2)	18.7 (65.7)
RH SFC (%)	85.1	81.2
PWAT (in)	1.43	1.56

D. Discussion and Summary

Cold-season tornado environments have been evaluated and discussed using select parameters from the NCEP/NCAR Reanalysis dataset. Both monthly means and 6-hourly means over the NDJF season are assessed, with a focus on how a particular parameter differs in magnitude and spatial distribution between the ten most tornadic and ten least tornadic cold seasons in the study period (1953–2015). The SPC Storm Mode dataset supplements the general results by providing raw values for tornado parameters for cold-season tornado events over the period 2003–2015. This dataset also gives a glimpse as to the convective mode distribution of cold-season tornadoes.

Overall, the findings here reaffirm what is hypothesized, based on previous work, regarding the conditions that favor tornadoes during the NDJF time frame, but use a much larger and unique data record of tornadoes across the particular domain where they are most prevalent. Synoptically, seasons of enhanced NDJF tornado activity most prevalently occur in a regime characterized by a trough over the West and a ridge over the East and Atlantic Ocean. A jet streak across the Plains is also evident from the 0-6 km wind shear profile. The hot spot for severe weather in such a scenario would be the Mississippi Valley region, where in fact the majority of cold-season tornadoes occur overall. Kounkou et al. (2009) come to a similar conclusion with their smaller data set from Australia. The synoptic conditions found to be associated with active tornado cold seasons is also consistent with favorable teleconnection patterns from Chapter 2, with positive phase AO and NAO giving enhanced counts.

From a mesoscale perspective, NDJF tornadoes are indeed characterized by low values of CAPE, both surface-based and mid-level, with observations during tornado events rarely exceeding 1000 J kg^{-1}. Coupled with low CAPE is higher shear in winter than during other times of the year. Therefore, when the enhanced wind shear is accompanied by sufficient instability in the form of CAPE, cold-season tornadoes become more likely. Yet, the magnitude of CAPE during this time of year need not be as high (nor would we expect it to be during the winter) to still help yield strong tornadoes. As mentioned, this low-CAPE-high-shear paradigm is consistent with previous studies on cold or cool-season tornado environments. In addition to the CAPE and shear analysis, this study shows that in general, steep lapse rates accompany cold-season tornado activity, likely in part due to penetration of cold air aloft over the domain. While SRH does not appear to be the best discriminator between years of enhanced and reduced cold-season tornado counts, there is more SRH present during cold-season tornado activity compared to tornado activity in an annual sense.

Another major take-away, and perhaps the most important, from the meteorological analysis, is the key role that moisture plays in creating environments conducive to cold-season tornadoes. Whether on a coarse or fine temporal scale, it has been shown that variables like PWAT, specific humidity, relative humidity, and dew point temperature are all enhanced during cold-season tornado activity. Spatially, these variables are elevated along a southwest-to-northeast swath across the Mississippi Valley and Southeast, hinting at the influence of Gulf moisture, particularly from the warmer western Gulf waters revealed from SST reanalysis during most active tornado seasons. The reason why the western Gulf is warmer and the eastern Gulf is cooler during most active seasons is not entirely clear, and beyond the scope of this study, but the link between moisture advection from the western Gulf and cold-season tornado activity is not coincidental. In fact, this conclusion of the importance of moisture and moisture transport north and east stands the test of time. Early analysis of cold-season severe weather and tornadoes by Galway and Pearson (1981) shows a very similar conclusion regarding low-level moisture influence on cold-season outbreaks. Their postulation of a low-level jet influence is also consistent with the findings here, as Gulf moisture transport north and east helps to saturate an otherwise dry environment, that when coupled with shear, instability, and a trigger for lift, sets the stage for potentially dangerous tornado activity.

The patterns and conclusions drawn from reanalysis variables are further confirmed by the SPC Storm Mode database. When parameters are compared for cold-season versus annual tornado events, there is indeed a signal towards NDJF tornadoes having much lower CAPE and higher shear than when averaged across the entire year. Moisture variables are similar whether partitioning by cold season or the entire year, showing that wintertime tornadoes are occurring under moisture-rich conditions. Cold-season tornadoes have occurred over 200 times under each of the four main storm modes identified by Thompson et al. (2012), with a slight edge toward the more linear 'Cell in Line' and 'QLCS' modes. Although they occur least frequently, NDJF tornadoes classified as 'Discrete' or supercellular have the highest CAPE values and kill the most people over the 13-year SPC Storm Mode data set. Forecasting the correct convective mode of a particular tornado event, and consequently the risks associated with the event, however, remains a challenge.

Having a better understanding of spatial and temporal trends in NDJF tornadoes, and establishing the synoptic and mesoscale environments conducive to their occurrence, is of great worth to the weather and forecasting community. However, this study is incomplete without investigating how cold-season tornadoes are actually being perceived and communicated by meteorologists. Do professionals understand the potential risks of NDJF tornadoes? What barriers exist when communicating cold-season tornado risk and warnings to the public? What can be done to overcome these barriers, particularly during the cold season? These and other inquiries prompt the next chapter, which delves into the societal realm via a case study analysis. With the finding presented in Chapter 2 that NDJF tornadoes are increasing across much of the Mississippi Valley in recent years, and the possibility of more accurately predicting an active or inactive year from climate signals, there is great urgency to discover the current state of knowledge among the weather community and ensure that the public is being warned adequately for such events.

CHAPTER 4: SOCIAL PERSPECTIVE

The analysis and results presented in Chapters 2 and 3 are important in shedding light on climatological changes in the frequency and geography of cold-season tornadoes, and establishing possible links between enhanced tornado counts and various teleconnection patterns. Further, meteorological conditions and parameters have been investigated to help define an ideal set-up for cold-season tornado events. However, this physical scientific knowledge alone does not readily capture the societal impacts that cold-season tornadoes create; rather, it *motivates* the call to analyze the human aspect, which is often overlooked yet incredibly important in scientific research. After all, it is the human being who actually experiences and is impacted by a tornado. Assessment of how weather and climate information is communicated to the general public thus becomes vital, especially in a realm such as cold-season tornadoes that has not been studied previously from a social science perspective yet presents a plethora of risks to life and property. This chapter describes the outworking of this goal, namely developing and deploying a survey instrument in winter 2016–2017 to professionals within the weather and emergency management communities in the wake of major tornado events. First, the motivation for such an approach is described by highlighting many of the societal risks posed by cold-season tornadoes, with numerous references to past work. A review of how risk and warnings are disseminated by professionals and interpreted by the public, noting the importance of collaboration and clear communication, is also given in this section. Next, a Methodology section outlines the survey instrument preparation, research goals, and deployment strategies, as well as the qualitative and quantitative analysis methods used to draw important findings from the responses received. Results from four case studies are then presented with general themes and conclusions. Finally, future questions to address, propositions for improvement and limitations of the survey process close out the chapter.

A. Motivation

As discussed previously, cold-season tornadoes pose many societal risks. For example, their occurrence can catch the public off-guard because one typically does not expect severe weather and tornadoes during the winter months (Fike 1993, Simmons and Sutter 2007). People can also be unsuspecting of significant weather due to the bustle of holidays like Thanksgiving, Christmas, and New Year's, when many are concerned with family activities and not thinking about the weather. As found in Chapter 2, cold-season tornado spatial distribution is weighted toward the southern and southeastern U.S., which is a prime region for nocturnal tornadoes. Ashley et al. (2008) note that the southeastern U.S. region experiences almost half of its tornadoes after sunset, and Kis and Straka (2010) find that over half of the 70 significant nocturnal tornadoes from 2004–2006 occurred between October 15 and February 15, mostly over the Southeast and Gulf Coast. Surely some of the enhancement in nocturnal counts are due to shorter days in winter, but the meteorological conditions and more progressive storm systems that impact the Southeast during winter are also factors. Tornadoes occurring after dark add an additional risk of the public being unable to obtain warnings or see the ominous conditions (Paul et al. 2003), especially if they do not have adequate technology. In fact, Ashley et al. (2008) show that death from nocturnal tornadoes is twice as likely as death from daytime tornadoes (see also Coleman and Dixon 2011). Gagan et al. (2010) show that fatalities from tornadoes are much higher in the so-called “Dixie Alley” (which in their study includes the states of AR, LA, MS, AL, GA, and TN) than in the more well-recognized “Tornado Alley” across the Plains states. Further, they find that of all tornado fatalities in Dixie Alley, 64% occur during the October–March timeframe. Compounding the problem in the South is a variety of non-meteorological factors which increase risk of damage, injury, and death from tornadoes. These factors include a high mobile home density, a large and increasing elderly population, enhanced poverty, and forested areas (Ashley et al. 2007, Bergstrand et al. 2015, Ashley and Strader 2016). In fact, Emrich and Cutter (2011) do a principal component analysis of the Social Vulnerability Index (SoVI), a quantitative metric for assessing societal vulnerability (Cutter et al. 2003), and find elevated social vulnerability in the lower Mississippi River Valley. Figure 2 from Cutter et al. (2003), reproduced here as Figure 4.1, shows the enhanced SoVI across the Southeast, in particular in counties along the southern part of the Mississippi River.

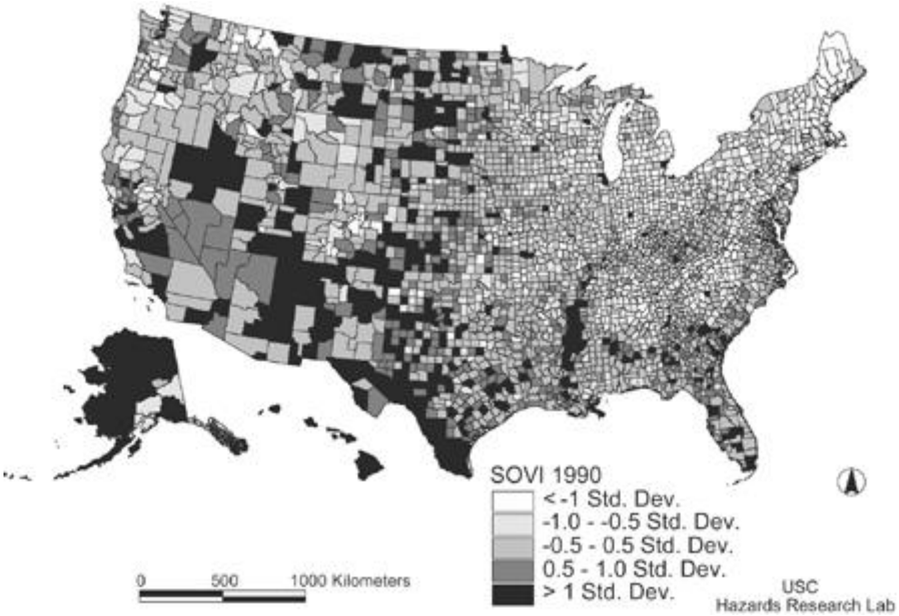


Figure 4.1: Figure 2 from Cutter et al. (2003) showing the comparative vulnerability of each U.S. county from the Social Vulnerability Index (SoVI).

Even beliefs in God (Sims and Baumann 1972) and the reliability (or lack there of) of tornado warning systems (Paul et al. 2014) can lead to passivity and ignorance of tornado risk in the South and beyond. Adding insult to injury, Sherburn et al. (2016) show that severe weather watch and warning issuance are the least accurate during the winter. As a good summary of the main overlapping threats present in the Southeast, Figure 8 from Ashley et al. (2007) is shown (Fig. 4.2). It is seen that nocturnal tornadoes, mobile home density, forested areas, and poverty are all enhanced across this region. All of these factors add up to cold-season tornadoes posing a greater risk for death and injury than spring and summer tornadoes across the U.S., perhaps by more than 15% (Simmons and Sutter 2008).

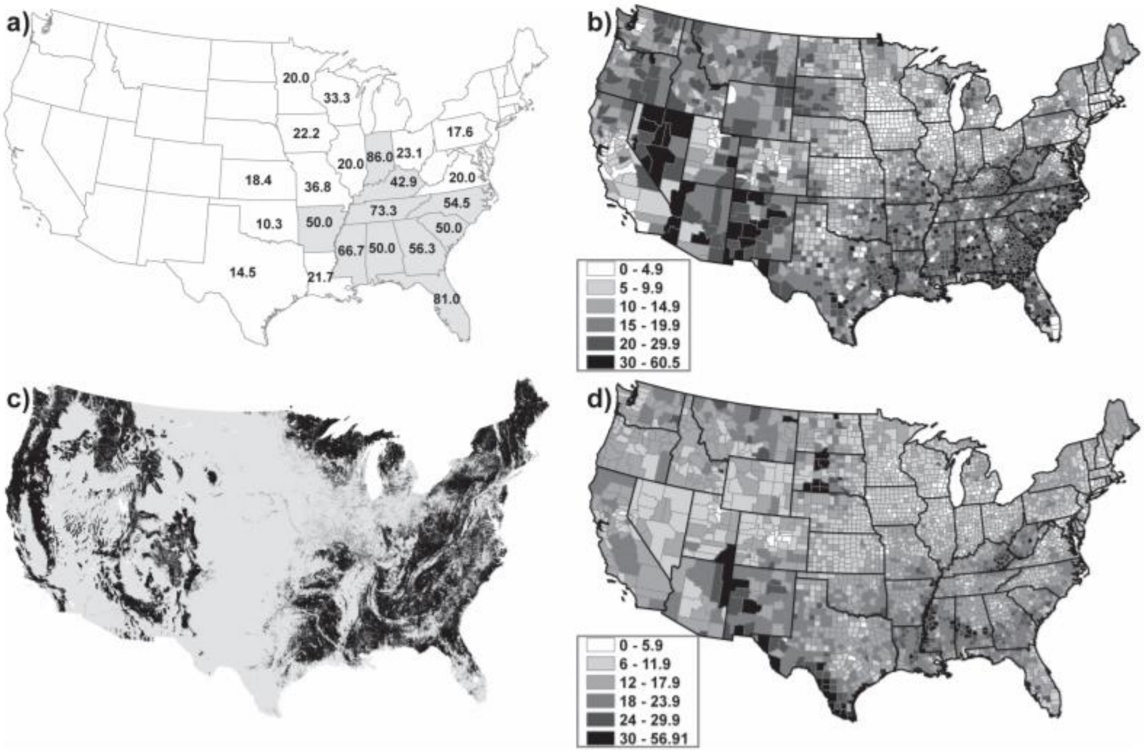


Figure 4.2: Figure 8 from Ashley et al. (2007), showing (a) percentage of nighttime tornado fatalities by state, (b) percentage of mobile homes by county, (c) forest cover, and (d) percent of county population in poverty.

Over the period 1953–2015 within the study domain (25-42.5°N, 75-100°W), some 937 people lost their lives as a result of NDJF tornadoes (Fig. 4.3). Some of these casualties occurred in major tornado outbreaks. Arguably the most prolific cold-season outbreak in modern history occurred on 21-22 February 1971 across the lower Mississippi Valley region. Nineteen confirmed tornadoes produced 123 deaths over these two days (Livingston 2012). Of these 19 tornadoes, thirteen of them were rated F2 or greater, but as mentioned in Chapter 2, it is possible that some of these tornadoes were overrated. The majority of the casualties are attributed to two tornadoes, one rated F4 and one rated F5, which struck Louisiana and Mississippi. The strength of these tornadoes was unprecedented for that day, and the F5 tornado in Louisiana is still the only (E)F5 tornado to strike that state in the modern record (Livingston 2012). A more recent and publicized cold-season tornado outbreak was termed the “Super Tuesday” tornado outbreak of 5-6 February 2008. This outbreak had fewer deaths (57) but more total tornadoes (87) than the February 1971 outbreak (NWS 2009). Even more recently, tornadoes that struck Mississippi and Texas around Christmastime in 2015 killed 26 people and injured more than 500 according to the Storm Data archives, and several rounds of deadly tornadoes struck the Southeast during the winter of 2016-17. Thus, although improvements in forecasting, safety, and awareness have occurred in recent decades, mass-casualty cold-season tornado events are still a very real and dangerous concern.

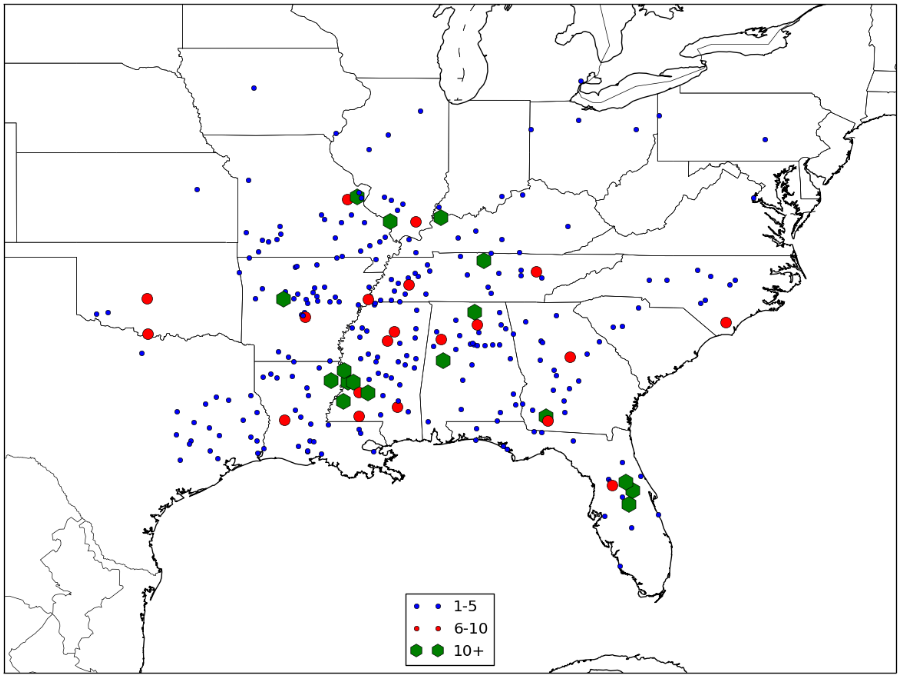


Figure 4.3: Geographical distribution of NDJF tornado deaths (1953–2015), categorized by number of deaths for a particular tornado.

Given this enhanced societal risk for cold-season tornadoes in the South, it is imperative that effective communication is had between local weather professionals – most notably National Weather Service Weather Forecasting Offices (WFOs) and television meteorologists – and the general public in advance of and during a cold-season tornado event (Reynolds and Seeger 2005). Local emergency managers (EMs) also play important roles in community preparation as well as recovery and resilience when a major tornado event occurs (Doswell et al. 1999, League et al. 2010). Baumgart et al. (2008) report that EMs use a variety of sources to attain severe weather information and make decisions based not only on their experience and training, but also on what information and products the NWS has already disseminated to warn the public. Therefore, interaction between local NWS and broadcast meteorologists and emergency managers is critical to distributing consistent and timely tornado risk information to the public.

Communication of the hazard and proper interpretation by the public can make all the difference in protecting lives and property, but unfortunately many issues in the communication pathway exist. Basher (2006) lists several barriers to effective communication of natural hazards, including dominance of the expert, public mistrust of warning systems or scientists, lack of community feedback on effective communication strategies, and an emphasis on the hazard itself rather than its societal risk. Efforts to overcome these communication barriers are especially pivotal in the South, the region that Bergstrand et al. (2015) found to be the least resilient region in the country due to various socio-economic factors (Emrich and Cutter 2011). Even with improvements in warning dissemination and communication methods, the public ultimately must decide whether and how to respond to the warning (Sorensen 2000). Thus, decision-makers play a key role in presenting not only an accurate, but also believable and action-initiating warning message in order to mitigate dangerous public impacts from a tornado event. It is in this vein that a survey instrument is developed to help gain understanding and areas for improvement using real-time cold-season tornado events.

B. Methodology

To specifically gauge how local meteorologists and emergency managers collaborate and communicate risk of cold-season tornadoes to the public, a post-event survey initiative is developed, with surveys deployed to these decision-makers in the wake of a major cold-season tornado events. Studies that assess tornado risk communication, and specifically those which employ quantitative methods such as surveys, are increasing in recent years (NOAA 2016). However, this study expands on merely quantitative results by offering experts a chance to answer open-ended questions about a specific cold-season tornado event, a realm that, to the author's knowledge, has never been explored via a social science investigation. The end goal of this analysis is to not only pinpoint unique factors and barriers in cold-season tornado risk communication, but also to search for ways to improve the public receptivity of such events, so that ultimately injuries and fatalities from such tornadoes can be reduced.

1. Selection of domain and participants

The spatial domain chosen for this societal impacts investigation is (30-37.5°N, 85-95°W) (Fig. 4.4). This domain is smaller than that of the climatological and meteorological portion of the study in order to capture the area where the vast majority of cold-season tornadoes occur and are increasing. Three groups of professionals were sought for participation, namely NWS meteorologists, television broadcast meteorologists, and emergency management officials. Morss et al. (2015) follow a similar strategy in their study of flash flooding risk perception and communication, interviewing professionals from these same three groups. There are twelve WFOs within the domain from which NWS meteorologists were contacted. Broadcast meteorologists were also sought from major television markets (i.e. network affiliates of ABC, CBS, FOX, and/or NBC) within the domain. In addition, local emergency management offices (initially from the same cities as where the broadcast meteorologists were sought, and later from counties where specific tornadoes occurred as part of the case studies) were contacted to solicit directors and personnel for potential participation. Figure 4.4 denotes the locations of the WFO offices and cities from which meteorologists and emergency management officials were initially sought.

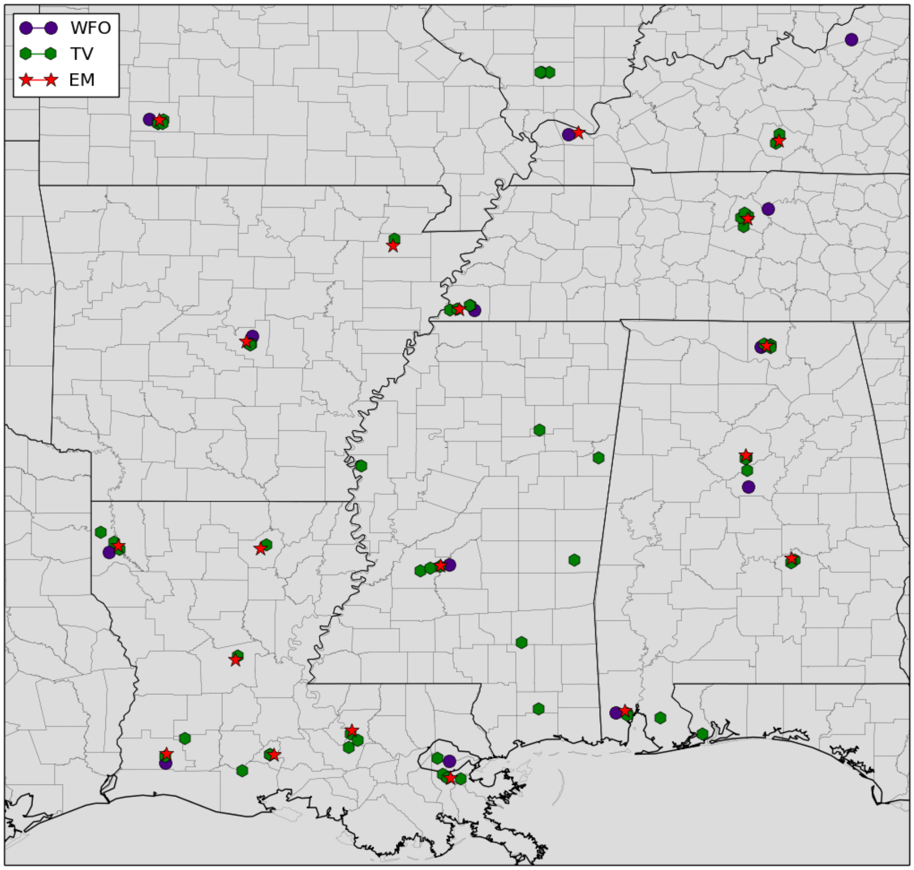


Figure 4.4: Locations of NWS WFO offices (circles), television stations (hexagons), and emergency management offices (stars) from which survey participants were initially sought.

In August and September 2016, potential research subjects were contacted via an initial e-mail (see Appendix A) that explained the research project and goals, as well as the value of participation. The e-mail asked potential participants to reply if he or she was interested and willing to participate. For ten of the twelve WFO offices, the informational e-mail was sent to the Meteorologist-in-Charge (MIC). The Warning Coordination Meteorologist (WCM) was contacted for the Shreveport office based on the contact preferences listed on the office website, and the Science and Operations Officer (SOO) was contacted for the Jackson office since the other lead positions were vacant at the time. For almost all of the broadcast meteorologists, the chief meteorologist at each of 63 television stations was sent the informational e-mail. Similarly, 24 emergency management offices (in most cases the director) were contacted with the informational e-mail. The e-mail also asked the professional to distribute the invitation among others in his or her weather team or office in order to acquire more willing participants.

By mid-October 2016, thirty-three people had responded to the initial call for participation, indicating their willingness if called upon. Of these 33, twenty were broadcast meteorologists, nine were WFO meteorologists, and four were emergency management personnel. Sixteen cities/areas were represented by the 33 willing participants; however, some of these areas only had one willing participant. Although this was an encouraging initial response rate, in order to gain value from the survey, the best scenario would be to have someone representing each sector available to take the survey. Thus, when a tornado occurred in a particular area, the project description and consent form (see Appendix A) were resent to professionals in the impact area who initially did not respond, with the hope of prompting their participation in light of a tornado event actually occurring. In addition, several county-level emergency management offices outside of major cities were contacted for the first time with the survey invitation and consent form after a tornado event impacted their county.

2. Survey composition and testing

Three similar but distinct surveys were developed for each of the three decision-making sectors: NWS meteorologists, television meteorologists, and emergency management personnel (see Appendix B for each survey). The online survey software QuestionPro (www.questionpro.com) was used to administer the surveys and collect responses. Through QuestionPro, each survey is given a unique Web address to add professionalism and ease of access (e.g. coldtornado-wfo.questionpro.com, coldtornado-tv.questionpro.com, and coldtornado-em.questionpro.com). In addition, to protect privacy, each survey is identified with a unique number rather than the respondent's name. This also prevents another person from taking or finishing a survey begun by another person. Upon completing his or her survey, the professional is sent a confirmation e-mail, and all survey results can instantly be seen on the QuestionPro reports dashboard. Survey reports are downloaded for both quantitative and qualitative analysis methods, to be described below. All survey data are stored within the QuestionPro interface and are only accessed and analyzed by the researchers in this study. Upon termination of the study and analysis period in Summer 2017, all results are deleted from the online interface.

The surveys consist of either 23 (WFO, TV) or 25 (EM) questions, a few with multiple parts, and are designed to take approximately 1 hour to complete. Some questions are open-ended and others ask the respondent to select a multiple-choice option or provide a 1-10 scale rating. Each survey begins by ensuring that the respondent is indeed familiar with and had a hand in decision-making for the tornado event in question.   Upon confirmation, the first few questions are open-ended and focus on the tornado event, addressing communication strategies the professional used, the challenges faced during the event, and his or her collaboration efforts with the other decision-making sectors. These questions are not meant to shame the professional if he or she is not satisfied with his or her performance in the case at hand, but simply to give him or her freedom to expose the nature of the methods used to communicate risk and the unique barriers to disseminating important warning information. Next come a series of closed-ended questions that ask the respondent to rate how he or she felt the community was warned, prepared for, and responded to the tornado event and its impacts, in light of the communication strategies and barriers described in the prefacing open-ended questions. Concluding the section on the particular tornado event, an open-ended question asks the professional to summarize what he or she learned from the event. Approximately the second half of the survey aims to paint a more complete picture by asking how the professional perceives the local vulnerability and public receptivity to tornadoes in general. Further, a question asks whether the professional is aware of the findings from Chapter 2, namely that there is an increasing risk from cold-season tornadoes in the South and Southeast (and also whether they perceive that the local public is aware). An important final question asks their opinion on what can be done to improve outreach and communication of cold-season tornadoes from their specific office/station and their decision-making sector as a whole. The survey ends by asking if the respondent would be willing to participate in a follow-up interview in order to delve further into his or her responses or discuss additional questions, if necessary. If willing, he or she is asked to provide his or her name and preferred contact information. In the end, no follow-up interviews were conducted on the basis of adequate written responses.

The survey structure and content were tested in August 2016 by meteorologists from the Cheyenne, Wyoming WFO, who provided affirmation of the content and a few structural enhancements. Personal communication with social science researchers Julie Demuth and Jen Henderson also led to improvements in the survey composition, such as the inclusion of questions about vulnerability. These researchers were also helpful in discussing the best qualitative analysis methods to implement.

3. Risk and confidentiality

In any human subject research endeavor, the goal is to minimize risk and adhere to strict confidentiality of personal information. As such, efforts are made in this survey analysis study to uphold these principles. No personally identifiable information is retained from the research subjects, and responses are kept separate from a respondent's information. That is, a survey participant's responses are not linked to his or her name. As mentioned, QuestionPro assigns each respondent a unique number, and that person's responses are kept under the password-protected database, only to be viewed by the researchers. Participants are told in the consent form that general phrases such as "WFO office", "TV meteorologist", "local emergency manager", etc. may be used in reporting results, and thus there is a possibility for an astute reader to narrow down which office or person is being referenced, given the small number of meteorologists and emergency managers working at a particular office or television market. However, participants are also assured that the goal of this study is not to pass judgment (good or bad) on decisions made by individuals, but rather to assess communication strategies, successes, and barriers with an eye toward improvement. If a participant chose to make himself or herself available for a follow-up interview, he or she was assured that the interview responses would be kept password-protected online or in a secure drawer (if written notes). All online data through QuestionPro are deleted at the conclusion of the survey analysis, and any other written personally identifiable data will be kept at Colorado State University for a maximum of three years, with access limited only to the PI and graduate research assistant. The Colorado State University Institutional Review Board approved this study in June 2016, noting that the risks involved were minimal.

4. Survey deployment

Risk for tornadoes within the study domain was monitored throughout the period November 2016–February 2017, the defined cold season for this study. When a tornado event occurred within this time frame, its significance was determined based on researcher discretion. In general, a tornado event was deemed worthy to warrant survey deployment if multiple tornadoes occurred within a small area, at least one significant tornado (EF2-EF5) occurred, or there was major damage, injury, or casualties (or a combination of these). When such a scenario transpired, an e-mail containing a link to the online survey was sent to those willing meteorologists and emergency managers from the impacted location (see Appendix A). In addition, the e-mail was resent to people who did not respond to the initial call for participation in the hopes of garnering new interest, and sent for the first time to county-level emergency management offices in the affected counties. In a couple rare instances, a phone call was made to an emergency management office after a period of no response in an effort to gain a sample from this third group of professionals (to unfortunately very little avail). Finally, one emergency management official who showed interest in the project was transferred to a new job before the survey period but still wished to share a few thoughts over the phone, to which the author obliged.

Attached to this e-mail was the consent form which explained once more the details of the study, rights of the respondent, and risks and benefits from participation. In all cases, this e-mail was sent 3-5 days after the tornado event to allow time for initial community response and recovery efforts. It should be noted that surveys given after an event may be suspect due to memory loss of the respondent, and, in this case, a bias toward local area demographics and culture that could distort a more general opinion (Simmons and Sutter, 2008). Since not every part of the domain was impacted by a major tornado event, many of the willing participants were never contacted (and their contact information subsequently destroyed), as explained in the consent form as a possible scenario. Effort was also made to refrain from sending a survey to the same research subject more than once during the cold-season, even if a particular area experienced more than one major tornado event. As described below, this requirement unfortunately resulted in a major tornado event in Hattiesburg, MS being bypassed. The research subjects were asked to complete and submit the online survey within one month, while the tornado event was still fresh in their minds and to prevent unnecessary delay of the data analysis. The initial contact e-mail, the e-mail containing the survey link, the three surveys, and the consent form are all contained in Appendices A and B.

5. Quantitative and qualitative analysis

Simple quantitative statistical analysis was done on the few closed-ended questions, such as comparing the means of responses given to the 1-10 scale questions. For qualitative analysis of the open-ended survey questions, the author breaks the survey into different categories based on the research questions, such as barriers to communication, receptivity and response of the public, relation to physical meteorology, vulnerability, and steps toward improvement. Next, a content analysis is performed by carefully combing the responses for similar words and phrases, in order to formulate common themes and factors which fall under one or more of the larger categories. These common threads are summarized, and the categories are then condensed into two main areas, to be discussed in the Results section below. A similar approach is taken in a flash flood survey analysis study by Morss et al. (2015). Suggestions for potential improvements and implementation of some of the ideas fleshed out in the surveys are then proposed.

C. Results

1. Summary of events

The winter of 2016-17 proved to be a very active tornado season in the U.S., which provided several opportunities for case studies. An amazing 317 total EF0-EF5 tornadoes touched down (SPC 2017), with the EF1-EF5 proportion of those still to be determined officially (but undoubtedly in the Top 10 of all cold seasons in the now-63-year data record). It should be noted the winter of 2016-17 was characterized by a positive-phase AO and a weak La Niña, which encouragingly affirm the climatological relationships found in Chapter 2. In all, four events were utilized for survey deployment, each of which included multiple tornadoes (some significant) resulting in either fatalities or multiple injuries. Figure 4.5 summarizes the locations of the tornado events used as case studies and the respective EF-scale ratings of each tornado.

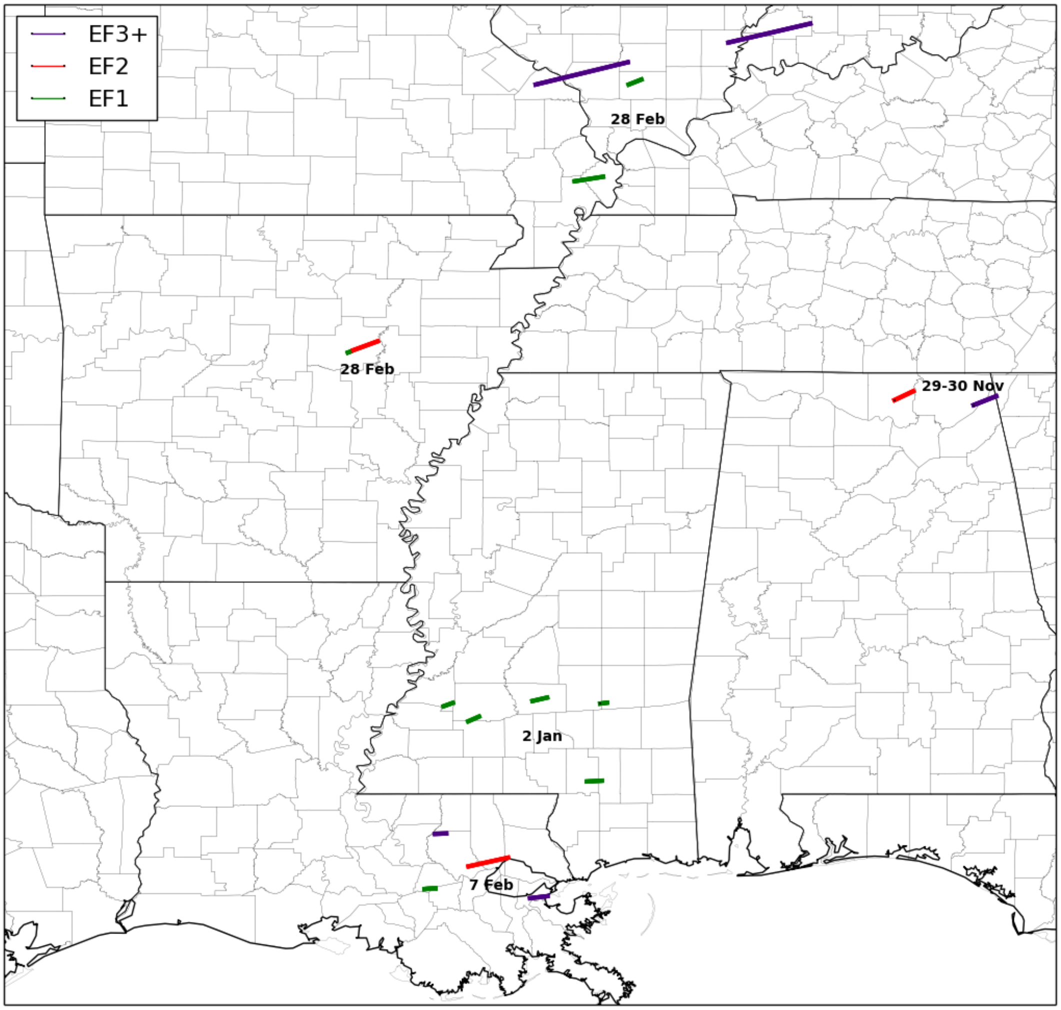


Figure 4.5: Tornado tracks for the four NDJF case studies, color-coded by EF-scale intensity.

The overall large-scale flow during the cold season of November 2016 – February 2017 is highlighted in Figs. 4.6-4.7, with Figure 4.6 showing monthly mean 500-hPa heights and Figure 4.7 showing monthly mean sea level pressure for the four months. November 2016 began with the continuation of a persistent ridge over most of the western and central United States (Fig. 4.6, upper left), with the storm track confining the only significant precipitation to the Northeast and Northwest. Abnormally warm temperatures were the rule over much of the country, and much of the southeastern United States began the study period in a severe drought. By the end of the November, the pattern began to shift toward more extratropical cyclones progressing across the country, leading to a stormier regime. Though outside of the study domain, tornadoes were reported in Nebraska and Iowa in late November before any appreciable activity in the Southeast, which is quite rare in these northern areas. The first Enhanced Risk for severe weather in quite some time was issued on both 28 and 29 November 2016 across Louisiana and Mississippi. On the 29th, a Moderate Risk also appeared for a 15% probability of significant tornadoes. A long-track EF3 killer tornado devastated the small communities of Rosalie and Ider, east of Huntsville, AL in the early morning hours (around 6Z) on 30 November, resulting in 3 fatalities. Another significant tornado tore a path through the eastern fringe of Madison County, where Huntsville is located. In all, 45 tornadoes were confirmed on 29-30 November across Mississippi, northern Alabama, and southern Tennessee, with many of those being of EF2 intensity. This case affirms the high vulnerability in the Southeast associated with nocturnal tornadoes over rural, forested areas (Paul et al. 2003, Ashley et al. 2008). As such, the 29-30 November killer EF3 Rosalie-Ider and Madison County tornadoes became the first case in which surveys were deployed.

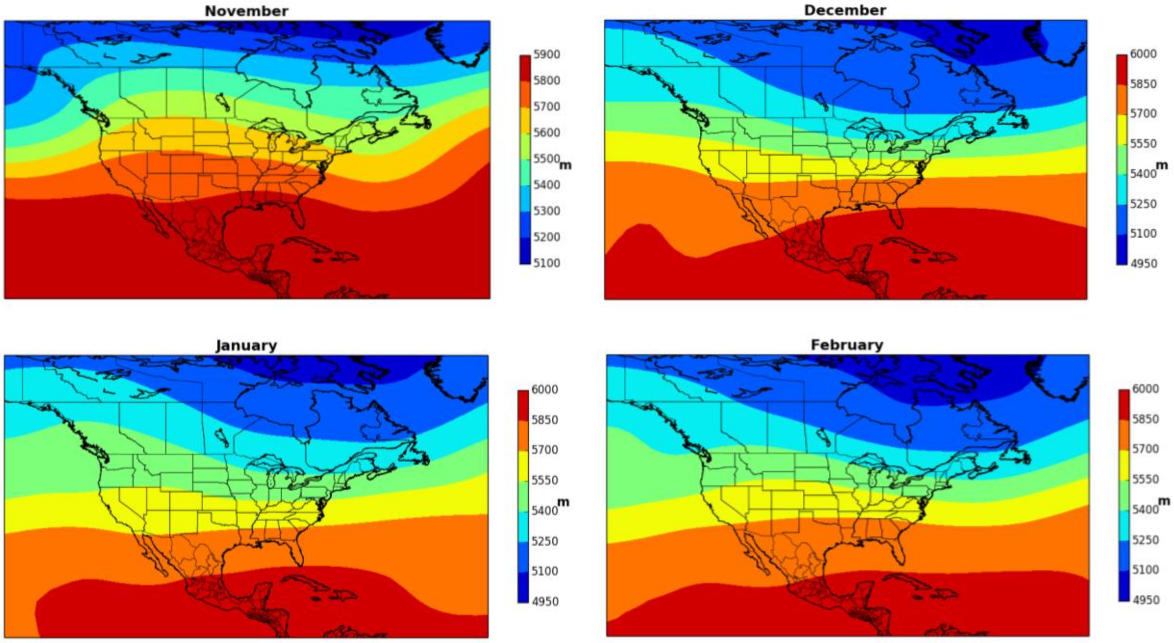


Figure 4.6: Monthly mean 500-hPa heights for November 2016–February 2017.

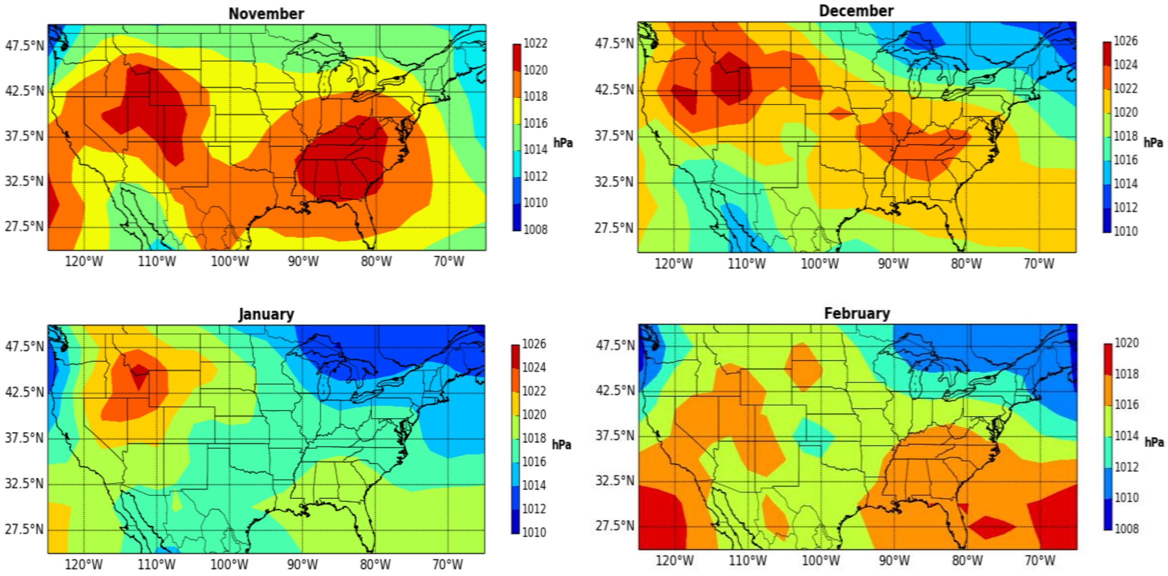


Figure 4.7: Monthly mean sea level pressure for November–February 2017.

The upper-level flow pattern for the months of December–February was similar in the mean (Fig. 4.7, upper right and bottom), with much lower heights in the northern tier of the U.S. compared to those in November and not much wave signal in the southern half of the CONUS, indicative of a more progressive pattern with both troughs and ridges affecting the study domain throughout the months. In addition, higher mean sea-level pressures in the domain during November and December (Fig. 4.7, top) gave way to lower pressures in January and February (Fig. 4.7, bottom), also affirming the shift to a stormier regime.

Following the late November outbreak was a quiet period with several surges of Arctic air penetrating southward into the U.S. While December proved to be a very inactive tornado month, January 2017 was just the opposite. On the 2nd, some 35 tornadoes were reported across the Deep South. A series of 8 strong and damaging tornadoes swept across southern Mississippi around midday. Although thankfully no casualties or injuries were reported, the localized nature of the tornadoes and the occurrence of one significant EF2 tornado prompted the second attempt at a case study. Additional tornadoes were reported in southern portions of Louisiana, Alabama, and Georgia. Although four casualties resulted from a tornado in far southeastern Alabama, this case was not examined due to its occurrence on the edge of the domain and under the Tallahassee NWS jurisdiction, which was not originally contacted about the study. A very active tornado week occurred from January 15 through January 22, with over 50 reports during this week. Of note, but officially outside of the study domain, were numerous killer tornadoes in southern Georgia on the 21st and 22nd. In addition, a large EF3 tornado killed four people and injured 56 in Hattiesburg, MS on the 20th. Unfortunately, this tornado was not included in the case study because the same area was impacted by the January 2 tornadoes, and the promise of no repeat surveys to the same group of decision makers needed to be upheld per the consent form. January 2017 ended up as the second most tornadic January since 1950, with 134 official tornado reports (SPC 2017).

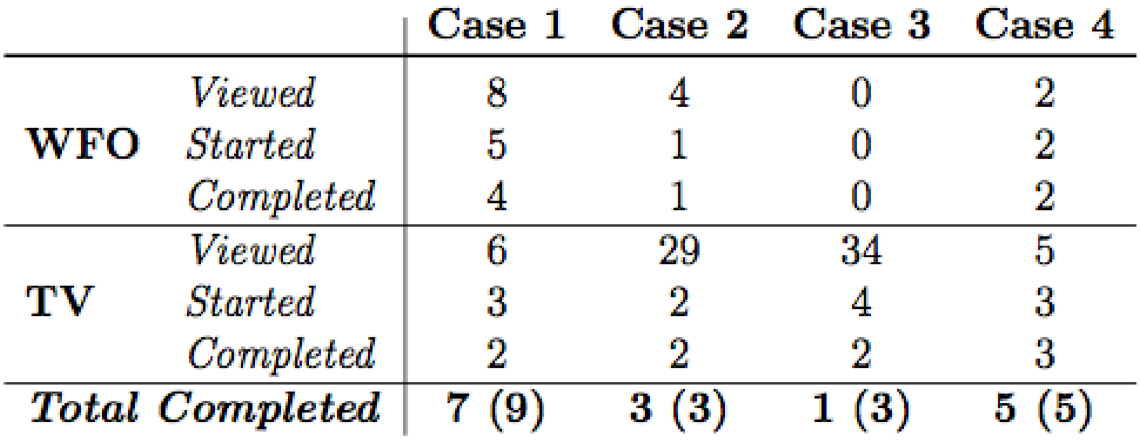
February 2017 provided the final two case studies. On the 7th, some 17 tornadoes were reported, scattered throughout the Mississippi Valley region. The greatest impacts were felt in southeastern Louisiana, where two EF3 tornadoes, one in East New Orleans and one in Livingston Parish, caused major damage, at least 30 injuries, but miraculously no fatalities. In fact, the EF3 tornado in East New Orleans was the strongest tornado ever recorded in Orleans Parish since records began in 1950. The middle part of February was fairly inactive within the domain, although a few rounds of tornadoes took place in Texas. Ironically, the very last day of the study period brought one more damaging tornado outbreak that spanned the two days of 28 February–1 March. Over 80 tornadoes were reported over these two days, with several significant tornadoes and three that unfortunately resulted in fatalities. These tornadoes primarily occurred from central Arkansas northeastward into Missouri, Illinois, Indiana, Kentucky, and Michigan. A final survey deployment was done for this day, specifically targeting two tornadoes in White County, Arkansas (just northeast of Little Rock) that injured four people and a swath of tornadoes stretching from southeast Missouri into southern Indiana and southern Illinois (in the Paducah, Kentucky WFO domain). This includes the only EF4 tornado of the 2016-17 winter season, which touched down in Perry County, MO and traveled northeastward across the Mississippi River into Illinois, responsible for uprooting thousands of trees, leveling dozens of structures, and killing one person. This tornado, which displayed multiple-vortex characteristics, was the longest track tornado in the Paducah NWS domain since 1981, traveling an astounding 50 miles before dissipation. Additional significant and killer tornadoes also struck this day in north-central Illinois but were not included in the survey analysis, being outside of the study domain. To summarize, the four cases that were subject to survey deployment are as follows: (1) Rosalie-Ider, AL, hereafter 29NOV-AL; (2) Southern Mississippi, hereafter 2JAN-MS; (3) Southeast Louisiana/East New Orleans, hereafter 7FEB-LA; and (4) Upper Mississippi Valley (AR/MO/IL/IN), hereafter 28FEB-UPMSV.

2. Survey demographics

Each case study yielded a different amount of interest and responses among the professionals. Given that the number of WFOs, TV stations, and EM offices sampled for each event was quite low, the number of responses received does not allow for robust statistics and determination of significance; however, for the limited population sampled, the number of professionals that did choose to participate in the survey is actually quite high. The repetition of similar themes expressed in the surveys affirm that the study has reached saturation, with a representative sample. Across the board, emergency management officials were least apt to respond, with only one complete response over the entire study period. As hypothesized below, the relative scarcity of EM personnel in the locations sampled combined with the busyness of post-event surveys and resiliency efforts may have precluded more participation from this group. In fact, it is not uncommon for rural counties to have only one or two people in an EM office, and their responsibilities can cover a wide range of services, from disaster surveys to volunteer coordination to city and county planning. Broadcast and NWS meteorologists responded in greater numbers for each case study, allowing for sufficient open-ended thoughts for analysis. Table 4.1

summarizes the demographics of the NWS and broadcast meteorologists for each of the four cases, highlighting the number from each sector that viewed, started (and dropped out), and finished the survey in its entirety. The total number of survey responses either completed entirely or partially (in parentheses) for each case is also given. Emergency management statistics are not included in Table 4.1 since only one EM completed the survey (although six viewed the survey across the four cases). Qualitative and quantitative analysis is performed on open-ended responses up to the point of drop out for partially completed surveys. Though it is not possible to know why, it is rather intriguing that many broadcast meteorologists viewed the survey (i.e. opened the link), but did not choose to start. Another interesting statistic generated by QuestionPro is the average amount of time taken by each decision-making sector in completing the survey. Time commitments ranged from an average of 14 minutes to one hour.

Table 4.1: Distribution of NWS and broadcast respondents viewing, starting, and completing surveys for Case 1 (29NOV-AL), Case 2 (2JAN-MS) Case 3 (7FEB-LA) and Case 4 (28FEB-UPMSV). The total number of completed surveys for each case is given as well as the total number of incomplete surveys in parentheses. EM participation is excluded due to only one complete response.



		Case 1	Case 2	Case 3	Case 4
WFO	*Viewed*	8	4	0	2
	Started	5	1	0	2
	Completed	4	1	0	2
TV	*Viewed*	6	29	34	5
	Started	3	2	4	3
	Completed	2	2	2	3
Total Completed		**7 (9)**	**3 (3)**	**1 (3)**	**5 (5)**

3. Survey results: Categories and common themes

Qualitative and quantitative analysis is performed on each set of responses for a case study according to the procedure outlined in the methodology subsection above. In so doing, five major categories, corresponding to the main research questions sought in the surveys, were defined, underneath of which many common themes emerged. These five categories are the following: (1) Barriers to Communication; (2) Public Receptivity and Response; (3) Meteorology; (4) Vulnerability; and (5) Next Steps. Upon analysis, it was found that many of the common themes expressed in the responses given had a link to more than one main category. It is not hard to imagine that a barrier to communication might directly relate to public receptivity, or be prompted by a struggle to grasp the physical meteorology set-up for the day. Similarly, a common theme expressed related to the perception of vulnerability of a community may directly relate to how receptive or aware the public is of an impending tornado threat. As such, the following two subsections present two main categories (with still some overlap), namely (1) 'Barriers to Communication', and (2) 'Vulnerability', through which survey responses are fleshed out and common themes are established. A flowchart is presented in Figure 4.8, which shows the two main categories for analysis with embedded factors and connections. Suggestions for improvement (e.g. 'Next Steps' category) are reserved for the Discussion section below, along with limitations. Through the survey analysis process, it became apparent, somewhat surprisingly, that there is not a large difference in perception of forecasting, barriers, and public response between the cold season and any other time of year. For example, for the four case studies combined, 59% of professionals said that the forecasting difficulty for cold-season tornadoes was similar to that of all tornadoes, and 88% of professionals believe the public shows similar receptivity for cold-season tornadoes as they do to tornadoes in general. Thus, while cold-season tornadoes definitely present unique challenges (which will be addressed), the following results will cater to tornadoes as a whole more so than the researcher initially anticipated.

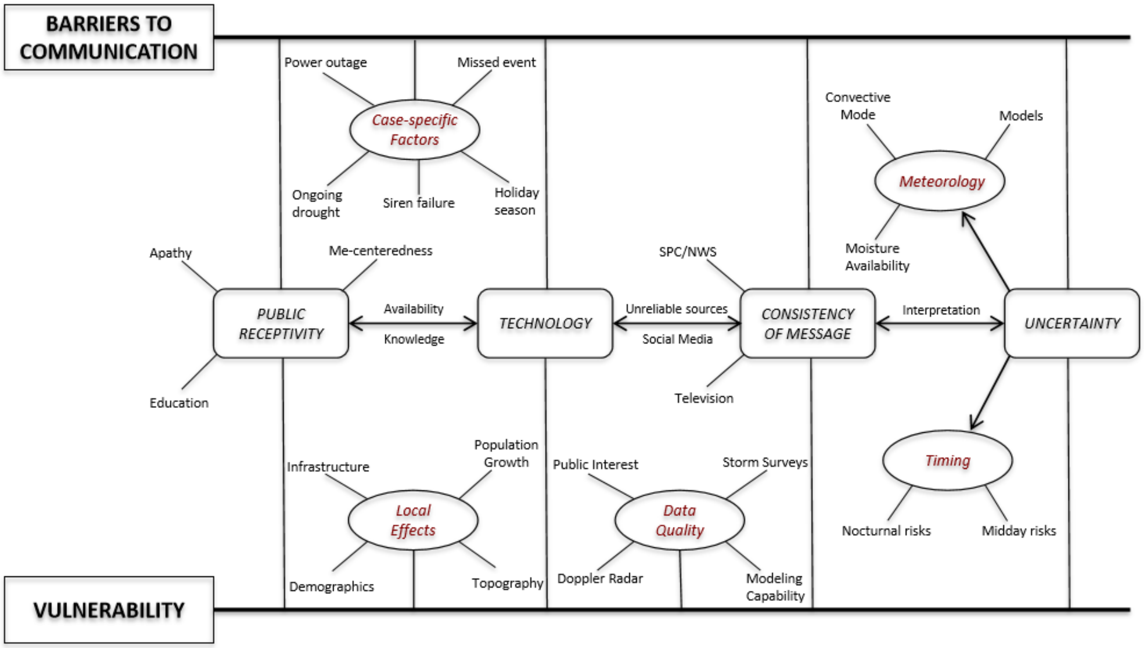


Figure 4.8: Flowchart showing common themes and pathways to open-ended survey results. The two large rectangles on the left represent two main categories of analysis ('Barriers to Communication' and 'Vulnerability'); the four rounded rectangles represent themes related to both of the categories (which are also interrelated via the double arrows) with straight-line appendages pointing to specific components within that theme; the ovals represent factors that play a role in only one of the categories, which also all have various, more specific components marked by the straight-line appendages; the ovals connected to the 'Uncertainty' theme represent factors related to Uncertainty which also play roles in both categories, with straight-line appendages similarly pointing to specific components of those factors.

(i) BARRIERS TO COMMUNICATION

A major research question from the survey instrument is what barriers exist in both the specific cold-season tornado case, and in tornado cases in general, to effective communication of the forecast, risk, and warnings to the public. Before addressing common responses across all cases, it is important to note the case-specific obstacles that arose, most of which are issues that could crop up for a tornado during any time of year. The 29NOV-AL case in particular presented unique communication problems for meteorologists. Several professionals mentioned the ongoing drought in the area (which led to a terrible wildfire nearby in Gatlinburg, TN) and cooler temperatures leading up to the event, so the forecast of rain and warmth may have led to more excitement rather than precautions against violent weather. In the words of one NWS meteorologist, "this was our first sizable rain event [in] months, so folks may have fixated on that first" (NWS1.1[1]). Originally, there was thought to be a greater risk of severe weather and tornadoes the day before in this area, which did not occur and as a result overshadowed the risk on the day in question. The 29NOV-AL case was also challenging for the professionals because of a triple whammy of electrical issues. First, a power outage limited television and Internet communication. Next, the local warning sirens failed to sound. Third, the power outage caused the Huntsville NOAA weather radio transmitter, which provides the best coverage for the affected counties, to go offline. Weather radios are usually touted as a good back-up during power outages, but in this case even this form of communication was eliminated. To make matters even worse, the tornadoes hit in the middle of the night, when most people

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[1] Hereafter, this nomenclature will be used to reference individual respondents. The citation will begin with either 'TV', 'NWS', or 'EM' to refer to the specific group of professionals, followed by a number 1-4 to refer to the specific tornado case, followed by another number indicating the individual. For example, NWS1.1 refers to the first NWS meteorologist respondent from Case #1.

had gone to bed. Thus, without electricity, people had to rely upon their phones to wake them up with weather alerts. Those who do not own Smartphones or have other advanced technological access to weather warnings therefore become more vulnerable to the effects of a tornado they do not realize is bearing down on them. As a result, one broadcast meteorologist commented that "the biggest thing to stress to the public is to have multiple ways to receive weather alerts" and check in on family or friends who may not be aware (TV1.3). As hypothesized earlier, the hustle and bustle of the holiday season can also cause people to let their severe weather guards down. This was the case for the 2JAN-MS case: as one broadcast meteorologist remarked, "coming out of a holiday weekend, it was most difficult just to get people's attention" (TV2.1).

Other barriers to communication were repeatedly expressed in the survey responses, which are interrelated and also connected to the second main research category of vulnerability. One major theme common throughout the cases is that of public receptivity. In other words, the professional does not have ultimate control over how or whether the public will receive the tornado risk information and warnings, which presents an opportunity for miscommunication and/or misinterpretation. In most surveys, the professionals expressed a view that the local public is well-educated and aware of the cold-season tornado risk in general, and therefore was not surprised at the specific tornado risk from this winter's events. For the 29NOV-AL case, many professionals acknowledged that a secondary severe weather season is well-known by residents of northern Alabama and southern Tennessee, so alerting the public of this tornado risk was not a huge barrier. For example, NWS meteorologists mentioned that "tornadoes are part of the fabric of this area" (NWS1.1), most people are "very aware of and prepared for tornadoes" (NWS1.3), and that the public is “keen on severe weather” (NWS1.2). This opinion is also shared by broadcast meteorologists in the Huntsville, Alabama market. According to one meteorologist, “most people who have lived in Alabama know that there is normally a ‘second’ severe weather season in the fall [and] I was pleasantly surprised by the amount of people who took the warnings seriously” (TV1.3). Meteorologists from the other cases also tended to share the opinion that the general public is aware of the risk and therefore able to heed warnings, even though the cases were in different geographical areas. TV2.1 from the 2JAN-MS case commented that “people down here take tornadoes seriously”, TV4.3 from the 28FEB-UPMS case relayed that “people are very interested in weather” and “viewers are used to nighttime/’cold-season’ outbreaks and know they can be serious”, and according to NWS2.1, “folks are not surprised when [cold-season tornadoes] happen.” Interesting, the one EM who completed a survey had a very different view on public receptivity. This EM expressed that “the biggest challenge we face is a lack of education with the public” and that “they just ignore our warning.” Further, he noted that “almost no citizen [has] any awareness of recovery resources, how to locate them, or how to use them.” He even gave a telling statistic that only 10% of the county population has opted into the mass warning communication system, with several people calling after this event to have their information removed “because [the system] woke them up.” Though there were no other EMs who responded who could have added more weight to this EM’s frustration, it is quite eye-opening to realize that EMs may have a very different view of public receptivity than meteorologists. One factor leading to differences in perspective may be an urban versus rural paradigm, since almost all broadcast and NWS meteorologists sampled work in urban areas, whereas many of the counties impacted by tornadoes during the study period are quite rural (and in fact the EM respondent is from a rural county). Thus, this may hint at a false sense of public awareness and receptivity by meteorologists in urban areas, while EM's in more direct contact with small, rural populations may sense that the public is not educated or receptive. These conflicting perceptions among professionals is potentially dangerous for safety of the public and yearns for a sampling of the public themselves to see how they actually receive and respond to cold-season tornado warnings.

Although there seems to be a general agreement among the meteorologists surveyed that the public is receptive to tornado risk and warning communication for both cold season and warm season events, several professionals did mention a large barrier that TV1.2 aptly called a "me-centered universe." Perhaps NWS1.4 sums this idea up with the quote that "I honestly feel like some people think we can look into a crystal ball and tell them precisely when a tornado will be in their neighborhood." Surely the public would want to know exactly if and when a tornado will strike their home, but the fact of the matter is that no meteorologist is able to deliver this level of precision. As a broadcast meteorologist in the 29NOV-AL case put it, "the main barrier is getting people information in the way they want it, which is basically impossible from a scientific perspective (TV1.2)." Thus, a barrier to communication arises when the public becomes frustrated by warning information that is not specific enough to them personally. This frustration in turn could lead to a lack of response, which could be interpreted by professionals as apathy or complacency. To address this issue, Morss et al. (2015) note the importance of professionals communicating that warning systems are unable to pinpoint where and when a tornado will strike.

The availability and understanding of technology in today's ever modernizing society also affects public receptivity and can itself be a barrier to communication. This is fleshed out mostly in the exorbitant number of options and pathways for communicating tornado risk and warnings, clearly confirmed by the variety of communication sources mentioned by professionals. For example, the EM who responded mentioned three mass communication options available to the public through his county and state EM agencies, and three major television markets in the county's listening area, each of which is served by a different WFO. Similarly, TV1.1 mentioned that "TORCON from the Weather Channel, the multi-tiered threat level information from local NWS offices . . . on top of the tiered SPC risks . . . muddy the water" for the public. With a plethora of options for receiving tornado warnings to choose from comes an enhanced risk for misinterpretation or frankly believing misinformation from unreliable sources. One is easily enticed to simply choose his or her favorite source based on things like aesthetically appealing graphics or the on-air weather personality, even if the message delivered is quite different from another source. This idea that the public develops relationships with television personalities is not new, as Horton and Whol (1956) originally coined the phenomenon "parasocial interaction", and it has been shown to play a big role in public receptivity (Schramm 2008, Schramm and Hartmann 2008). Applying parasocial relationships to meteorologists, a public survey conducted in the Memphis, TN market found that over time people form a relationship with their local television meteorologist and in turn trust him or her in times of severe weather (Sherman-Morris 2005). Thus arises the need to "work toward a single message, otherwise the public gets inundated with so much information they ignore it all," as the EM put it. Engaging the public in this discussion would be helpful to affirm whether or not this is indeed the case. It is revealing, however, that numerous professionals across multiple cases cited ‘consistency of message’ as a key barrier. The increasing social media influence is also affecting meteorologists in real time warning dissemination. When describing a challenge faced during the 7FEB-LA case, TV3.1 mentioned that “the added demands of on-air plus social media connectivity are stretching capabilities of meeting the expectations of timely posting of notices on all information platforms.” This is a real and concerning admission that warrants investigation as to how to avoid this issue. Again, probing the public to see how the majority of people receive their severe weather and tornado warning information in real time would be beneficial and lead to a more focused social media presence.

A final barrier repeated throughout survey responses by the professionals is that of uncertainty, which Morss et al. (2015) also showed to be a major player in risk communication. Here, uncertainty manifested itself primarily in two realms. First, there were uncertainties regarding the timing of the cold-season events. The nocturnal event of 29NOV-AL made it difficult to alert people as they slept; as TV1.3 put it, “The hardest thing was that we knew it was going to be an overnight event, and stressing to people to either stay up late or be aware.” In the 7FEB-LA case, TV 3.1 reported that the unique “mid/late morning timing of the outbreak . . . made connectivity to the public more difficult.” Uncertain timings of tornado events, whether in the cold-season or any time of year, also increase the vulnerability of the public, the other main category to be addressed next. A second uncertainty which presented itself in these cold-season events lies in the meteorology. While not directly asked in the survey, several professionals across all cases mentioned that communication of the tornado risk would have been made easier if there were a better understanding of, for instance, "how far north the warm moist air [would] make it" (TV2.1), and "the typical questions concerning boundary layer moisture return and instability that we have in the winter (NWS2.1)." These forecasting challenges affirm the importance of Gulf moisture and level of instability in cold-season tornado environments, as discussed in Chapter 3. Also of interest is the convective mode of the tornadic storms. NWS1.4 paints an important picture in assessing this challenge for the NOV29-AL case: "Forecasting the mode of convection and conveying our uncertainty was also a significant challenge. I think that we were a little unclear about whether we would be dealing with a linear band of convection or individual cells. When it became clear that we would see more supercellular-type convection in the open warm sector, the threat for significant tornadoes became more apparent." This again affirms findings shown in Chapter 3 above, namely that discrete cells do indeed kill many more people in the cold season than do QLCS tornadoes. Having a better handle on the expected storm mode would allow for more precise communication of the tornado risk. In addition to NWS1.4, when asked about general communication barriers, TV2.2 mentioned that "the public needs to have a better understanding of what the storm mode will be." Ultimately, a better understanding of convective mode (and severity) lies in the models, which was addressed by a few professionals. While TV3.2 described the 7FEB-LA case as "an event that models did not even notice", TV4.2 reported that "model agreement/consistency leading up the [28FEB-UPMSV] event made the event fairly easy to prepare for and led the public to being well prepared to take action."

(ii) VULNERABILITY

The second main category that surfaced in the survey is that of the perceived vulnerability of the communities impacted by the tornado event. As expected given the Southeast domain, many professionals mentioned various local area effects as contributing to public vulnerability. For the 29NOV-AL case, professionals commented on the "poverty/education/rural communication (NWS1.1)" of northern Alabama, and "substandard construction (NWS1.3)." Further, TV4.3 for the 28FEB-UPMSV case, referring to the Tri-State area of IL/KY/MO, mentioned that the "largely rural area with lots of manufactured housing [make the area] more vulnerable to damage." Indeed, these perceptions are in fact reality, as shown in recent studies which link non-meteorological factors to increased vulnerability in the Southeast (Ashley et al. 2007, Emrich and Cutter 2011, Ashley and Strader 2016). Little or no advanced warning also increases public vulnerability, as was the case for 7FEB-LA. In this event, TV3.1 learned "the dependence of first responders on our information delivery in real time" due to the lack of advanced warning.

Other sources of vulnerability include many factors already mentioned above which are related to communication barriers. For example, a lack of public education can lead to lower receptivity and thus make a community or particular sector of society more susceptible to cold-season tornadoes. While public response given a known tornado risk is hard to quantify, at least one study has shown that an awareness of tornado risk decreases demand for manufactured homes which do not provide adequate safety (Sutter and Poitras 2010). Related to education is the idea of an increasing population density, which a few professionals mentioned. For instance, TV2.1 expressed a concern that "a lot of people are moving here [i.e. southern MS] without the knowledge that tornadoes happen year-round." This perception is consistent with recent work which shows that as population density grows and cities and towns expand, more people are becoming exposed to tornado and natural hazards risk (Anderson et al. 2007, Donner and Rodriguez 2008, Ashley et al. 2014). Limited access to technology also makes one more vulnerable, as does misinterpretation of warning information due to belief in appealing yet unreliable sources. This again points back to a need for education to be able to help the public discern a reliable source. Uncertainties in the forecast and timing of the tornado event also leave a community more vulnerable. This is a particular challenge in the cold-season, with its propensity for nighttime tornadoes. As discussed earlier, overnight tornado events during the winter highlight the need for people to have available and reliable warning notification technology to alert them during these hours. If they do not, their susceptibility to dangerous tornado impacts will undoubtedly rise (Ashley et al. 2008).

One question the survey seeks to answer is whether or not the professionals view the public as being aware of the findings from Chapter 2, namely that there is an increasing threat of cold-season tornadoes in the Southeast and Mississippi Valley regions, and also whether the professionals themselves are aware. Interestingly, only 44% of the professionals reported that they were knowledgeable about the increasing risk during the cold season, and only 35% of professionals believe that the public is aware. In other words, there is not a clear understanding or belief that the findings from Chapter 2 are true.

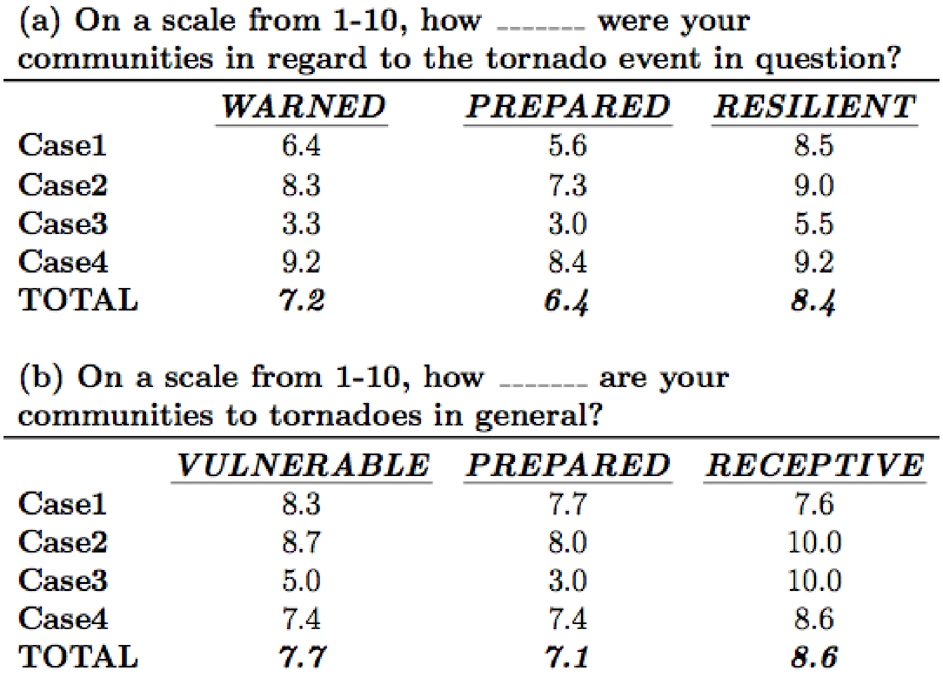
Another survey question asked professionals whether they believe their surrounding area is becoming more vulnerable to cold-season tornadoes over time. In the end, only 41% answered 'yes' to their areas becoming more vulnerable, despite reporting a high rating of vulnerability overall, to be discussed below. As a reason for the belief of non-increasing vulnerability, many professionals cited improving data quality and technology, including Doppler radar, modeling capability, public storm shelters, and more public interest and awareness. Though numbers of cold-season tornadoes are clearly up, as confirmed by Chapter 2, many believe that this is the result of, as TV3.1 puts it, "more frequent and aggressive post-storm survey efforts." Others mentioned "better reporting (TV1.1)" and "higher identification of cold-season and weaker tornadoes (TV2.2)." A few professionals also correctly cited the lack of pristine tornado data the further back in time one goes, yet data quality issues in this study are largely removed due to only retaining EF1+ tornadoes. Still, it is clear from the responses gathered that public vulnerability to tornadoes is high in the Southeast and Mississippi Valley regions and is further exacerbated during the cold-season.

D. Discussion

1. Summary of survey analysis

Quantitative results from survey questions which asked professionals to give a 1-10 rating of public awareness, preparedness, vulnerability, and receptivity provide a good summary of general opinions expressed by the professionals. Table 4.2 lists the average ratings from specific cases across all sectors as well as the overall averages across all cases. It is seen that although professionals view their communities as quite vulnerable to tornadoes (due to the variety of factors discussed above) and lacking in preparedness strategies, they are also very receptive to warning communication and resilient to impacts. These quantitative results were largely consistent between NWS and broadcast meteorologists, although the EM rated community preparedness (3/10) and receptivity (4/10) for tornadoes in general much lower than average, likely due to this professional's view that much of the local public is uneducated and not taking advantage of mass communication resources. The broadcast meteorologists in the 7FEB-LA case also reported lower-than-average ratings of public warning and preparedness due to the surprise nature of the event.

Table 4.2: Average ratings on 1-10 scale of professionals for (a) how warned, prepared, and resilient their communities were to the cold-season tornado event, and (b) how vulnerable, prepared, and receptive they perceive their communities to be to tornado warnings in general.



(a) On a scale from 1-10, how _______ were your communities in regard to the tornado event in question?

	WARNED	*PREPARED*	*RESILIENT*
Case1	6.4	5.6	8.5
Case2	8.3	7.3	9.0
Case3	3.3	3.0	5.5
Case4	9.2	8.4	9.2
TOTAL	***7.2***	***6.4***	***8.4***

(b) On a scale from 1-10, how _______ are your communities to tornadoes in general?

	VULNERABLE	*PREPARED*	*RECEPTIVE*
Case1	8.3	7.7	7.6
Case2	8.7	8.0	10.0
Case3	5.0	3.0	10.0
Case4	7.4	7.4	8.6
TOTAL	***7.7***	***7.1***	***8.6***

Several barriers to effective cold-season tornadoes surfaced in the survey responses. Many were case-specific, such as a power outage, an ongoing drought and cold spell, the vacation and holiday season, and the overnight timing. Meteorologists and EM's use a variety of tools to communicate the cold-season tornado risk, with more and more attention given to social media outlets, although the approaches taken in the cold season are not much different from those of the warm season. A major barrier to overcome is the “me-centeredness” of those people who desire to know exactly when and where a tornado will hit and whether he or she will directly be impacted. There is a massive amount of communication options available to the public, be it multiple local television stations, The Weather Channel, the local NWS office, telephone alerts, local EM-sponsored services, weather bloggers, or other online social media sources, each with their own graphics and color schemes, risk and outlook categories, and even opinions regarding the tornado threat, which leads to inconsistent tornado messages and in turn creates a threat to public safety. Uncertainties in the convective mode of the tornado was also repeatedly mentioned as a concern in warning communication. Most professionals expressed a public awareness of a secondary severe weather season in the cold months and that cold-season tornadoes are quite common, which led to a general sense that the public is not becoming more vulnerable over time. However, there is a view that the public is indeed quite vulnerable thanks to the local topography, poverty, prevalence of manufactured homes, and under-educated sectors of the population.

2. Limitations

The obvious limitation in this survey analysis is the relatively small and focused sample size. Only 17 professionals completed the entire survey, with only one of those being an emergency management official. Despite this sample size, many of the professionals gave extended and thoughtful responses, and it was revealing to see the relative consistency amongst the professionals surveyed for a specific case. More participation could have yielded additional findings, but for the most part respondents from a particular case shared similar thoughts; moreover, similar opinions from one case to the next were also prevalent, even with differing geographical locations. Thus, it can be asserted that a representative sample was indeed achieved. The dearth of emergency management response is disconcerting, but it was found in the author's attempts to contact this sector that these public officials are engrained in intense work for weeks after a tornado event. In addition, in one phone call the author made to an EM office seeking participation, it became clear that the office had no more than three staff and that their duties included much more than disaster response. Many counties in which the cold-season tornadoes of 2016-17 hit are small and rural, and therefore EM staff are few and very occupied with numerous county services, possibly preventing more participation.

Another limitation of the study lies in the survey instrument itself. While effort was taken to be clear, and initial testing was done before the study period began, the fact remains that these are human subjects with potential to have different interpretations for certain questions or terminology. For example, NWS1.1 confessed, "I don't know enough about the definition of vulnerability to understand how all those factors come together." Indeed, terminology such as 'vulnerability', 'preparedness', and 'resiliency' are known to be amorphous and carry a variety of interpretations. Additional limitations include the lack of public input, as addressed in the next section, and the sizeable time commitment necessary for thorough responses. On the whole, however, the amount of participation and quality of thoughts provided exceeded expectations.

3. Next steps: Implementation and future work

The final open-ended survey question asked respondents to suggest areas of improvement among the professional sectors in communication of cold-season tornado risk. A variety of helpful and revealing thoughts were given, mostly in response to the barriers and challenges presented earlier. A major theme going forward is that of educating the public. Several professionals mentioned the need for education at multiple levels, from elementary school children to adults. TV1.2 called for improved "education and helping people who need it most," and NWS4.2 called for cold-season tornado education to elementary students that focuses on "letting them know it could happen, what to do, and not to panic." One pathway towards education is that of outreach events, which a couple professionals mentioned are either happening currently in their office with much press and success or would be beneficial to have more of.

Educating the professionals is arguably just as important as educating the public. This can be harnessed in part through building connections among sectors within and outside of the meteorological community. As NWS1.1 aptly wrote, "[we must] continue to build better partnerships with the media" and "work more with social scientists because we don't know this stuff as well as they do." There has been much hype in recent years regarding the social science arm of meteorology, and these results add weight to the call for social scientists to work with researchers for better warning dissemination. As such, more discussions with both of these groups together in the same room, and formal training of professionals in social science practices and recent findings, specifically related to warning communication, is a must. Given the issue of inconsistency among sources reporting tornado warning information that was raised multiple times by professionals, there is merit to look for ways to consolidate graphics and threat ranking systems into a consistent package throughout WFOs and television media. Testing this 'less-is-more' approach for specific tornado events, whether in the cold season or at other times of year, may be difficult but could shed light on how the public receives warnings. Other ideas for improvements included a better knowledge of effective social media platforms, more professional training, and continued refinements in modeling and forecasting convective mode.

As has been said, an absent piece of the risk communication puzzle in this study is the public perception. Perhaps NWS1.1 put it best by saying that professionals must "get a better understanding of how the public receives (or doesn't) our pre-event messages. We've had a lot of discussion inside the office about how to create graphics/briefings/etc. for our social media accounts – but it's a meteorologist echo chamber. True answers have to come from the customers." Interviews in the non-professional public realm can help validate (or provide an opposing view) the opinions shared by experts regarding the same extreme weather phenomenon (Morss et al. 2015, Lazrus et al. 2016). Employing a survey taken by residents of areas impacted by particular cold-season tornadoes would therefore be valuable in comparing the perceptions of the experts with those to whom their warnings and messages are being received. For example, it would be helpful to know if the public is receiving warnings for cold-season tornadoes from television, radio, Internet, or other media outlets (which would increase the necessity for consistency among these sources), or whether the public is more prone to respond to threat simply based on environmental cues they can see or sense. Further, if the public is deemed "inactive", is that inactivity a result of apathy or an uncontrollable factor such as a power outage? It has been shown that in some cases of extreme weather, the professional decision-makers may hold a faulty view of how the public is receiving and responding to risk and warnings (Demuth et al. 2017), which presents a barrier to effective communication. Studies have also shown that social factors, such as relationships with professionals and communicating uncertainty, can hold more weight in a person's eyes than his or her knowledge of the science and even the accuracy of the forecast (Sherman-Morris 2005, Wall et al. 2017). It would also be intriguing to ask additional questions of the public, such as whether there is an understanding of what to do in different convective mode regimes, whether cold-season tornadoes are known to be increasing, and whether people deem themselves as vulnerable (and for what reasons). An expanded survey analysis modeled after the one presented here, but which incorporates the public sphere, in future cold seasons would be an ideal next step to paint a larger picture of cold-season tornado risk.

Future work that could flow from this study includes taking a more focused look at emergency management perception of cold-season tornado risk since only one responded to this winter's call for participation. It would be revealing to see whether the inconsistency between the EM's view of public receptivity and education with that of the meteorologists shows up with a larger sampling of EM officials. In addition, an investigation into the differences in perception between urban and rural settings should also be fleshed out more thoroughly and efforts made to ensure that all members of society are being adequately equipped to face tornado risk. Of course, one could imagine many other avenues to explore from a qualitative perspective in future work, but this survey analysis has presented many profitable findings to bolster the current state of knowledge in tornado warning dissemination, with a new and particular focus on the cold season. In fact, the flowchart presented here could be explored deductively as a conceptual model and potentially operationalized within the community to give a current picture of the complexities related to communicating tornado and severe weather hazards and risk. Taken with the meteorological and climatological perspectives presented earlier, this social perspective helps form a more complete and advanced presentation of cold-season tornadoes.

CHAPTER 5: SUMMARY AND CONCLUSIONS

The present-day meteorological literature is saturated with tornado studies, as the phenomenon continues to intrigue scientists, “weather weenies”, and the general public alike. To be sure, the hype around tornadoes is in part due to a tornado’s eye-catching appeal, but the fear tornadoes evoke and the potential destruction they produce have scientists continually seeking to discover more of their dynamical properties and climate trends. Despite the wealth of recent work on tornadoes, there exists a relative absence of research regarding tornadoes which occur during the cold season of November–February. This study has taken the most comprehensive look at cold-season tornadoes to date, incorporating three very different yet interconnected areas of investigation. First, a climatological perspective (Chapter 2) has aimed to expose long-term trends in NDJF tornado counts, both temporally and spatially. In addition, climate-scale teleconnections are analyzed to show any statistical relationships to cold-season tornado counts. Next, a meteorological approach (Chapter 3) delves into reanalysis data to piece together which tornado ingredients may be at play during cold-season events, and which parameters provide a good discrimination between active and inactive seasons. An analysis of convective mode of NDJF tornadoes is also given in this Chapter. Finally, a survey instrument has been developed and utilized in real-time events during November 2016 – February 2017 in order to look at cold-season tornadoes from a social perspective (Chapter 4). Professional meteorologists and emergency management officials are sought to provide insights into communication barriers during cold-season tornadoes as well as to give their take on how their communities prepare for and respond to these events.

This concluding Chapter will first give a brief summary of key findings from each of the cold-season tornado perspectives investigated. Next, limitations of this study are presented along with opportunities for future work. The chapter ends with emphasizing the significance of this study to help not only professionals but also the public.

A. Key Results

1. Climatological perspective

In establishing a tornado climatology for use in this study, all NDJF (E)F1+ tornadoes from November 1953–February 2015 are selected within a spatial domain of (25-42.5°N, 75-100°W), which encompasses the areas where the vast majority of such tornadoes occur. These qualifications yield a total sample of 4293 tornadoes. The study domain is divided into a 2.5° X 2.5° grid for analysis of temporal and spatial trends in counts. When NDJF counts over two Periods are compared, it is found that there has been an increase of 353 tornadoes in Period II (1984–2015) compared to Period I (1953–1984). Most of this increase is attributed to individual monthly increases during November (+454) and January (+121) in the more recent Period II, while the month of December has seen a substantial decrease (-224) in NDJF tornadoes in Period II. Over the entire 62-year data record, there is an upward trend of ~0.5 more tornadoes per season, yet with much interannual variability. Although an increase of one tornado every two cold seasons does not seem like much, this trend is statistically significant and much higher than the overall annual trend of EF1+ tornadoes. All this to say, the occurrence of cold-season tornadoes as a whole is increasing through time at a statistically significant pace.

Spatially, cold-season tornadoes are most likely to occur across the Southeast and Mississippi Valley regions, and these are also the areas where they are increasing in the most in frequency of occurrence. The bulls-eye of increasing NDJF counts from Period I to Period II is located across northern Tennessee, with the surrounding states also seeing increases, while eastern Oklahoma has seen the greatest decrease in NDJF counts between the Periods. Gridded analysis of linear trend shows similar spatial results, with a grid box located over northeastern Tennessee and southern Kentucky showing the greatest trend over the 62-year data record. The greatest interannual variability is found to be further west across northern Arkansas and southern Missouri.

Spectral analysis is performed on NDJF tornado counts over time, and reveals notable spectral peaks at a few different frequencies. From an F-test, it is found that the months of November and February, as well as the seasons of DJF and NDJF, all have a statistically-significant spectral peak at a frequency corresponding to enhanced counts every 3-7 years. Given that this is close to the known period of the ENSO cycle, NDJF tornado counts are statistically compared to the average 4-month ONI value over the 62-year period. It is found that there are on average 30 more cold-season tornadoes during episodes of La Niña than during El Niño or Neutral conditions, and although the correlation is low, the mean count during La Niña is in fact significantly different than the mean counts during El Niño and Neutral phases. A stronger statistical relationship is found, however, when correlating NDJF tornado counts to the AO index. Many more tornadoes occur during positive phases of the AO and NAO, when there is lower pressure over the North Atlantic and Arctic regions that keeps colder air suppressed near the Arctic Circle and creates in general warmer temperatures over the United States and stronger trade winds. The correlation between NDJF tornado counts and AO index (r^2=0.168) shows the strongest statistical significance, albeit only explaining 17% of the variance in counts. Thus, while teleconnection indices may not provide a crystal-clear indication of the severity of a particular cold season, there is evidence presented here that a high NDJF tornado count is more probable during La Niña and positive-phase AO conditions. As forecasting for these teleconnections becomes more reliable, this finding can prove quite helpful for alerting the public about more favorable conditions for an active cold season.

2. Meteorological perspective

The atmospheric parameters and environmental conditions favorable for tornadogenesis are a much-studied research topic, with some breadth of understanding in the present age for what is required to have a damaging tornado event. Through use of the NCEP/NCAR Reanalysis dataset, an investigation into the parameters contributing to cold-season tornado events has been performed. The ten most tornadic and ten least tornadic cold seasons are extracted to compare monthly mean values of several meteorological variables during these seasons. Though monthly means are a rather coarse resolution, there is found to be warmer, more unstable, and more moist conditions across the Southeast and Mississippi Valley during most active seasons. Further, surface pressure is lower across much of the domain during most active years, indicating more frequent passages of extra-tropical cyclones, while higher pressure off the East Coast is indicative of positive-phase AO conditions, consistent with the findings of Chapter 2. Gulf of Mexico SST's are enhanced from New Orleans westward during most active seasons, while cooler waters are noted further east. One hypothesis is that warm, moist Gulf air is transported northward into Texas and western Louisiana and interacts with a low-level jet and other propagating disturbances, thus advecting it northeastward into the areas of greatest cold-season tornado increase.

A more fine-scale approach using 6-hourly observations of a variety of tornado parameters yields similar results, confirming the importance of instability and especially moisture in prime cold-season tornado environments. Comparison of most active to least active seasons reveals enhanced CAPE and specific humidity in the most tornadic seasons (though CAPE is much lower on average than other times of the year), but wind shear variables do not show as pronounced an influence. However, when taken with the mean upper-level height patterns for the most tornadic seasons, an anomalous trough is in place over the western U.S. with an anomalous ridge in the eastern U.S. An associated jet streak aloft is found near the trough axis during most active seasons, which places the Mississippi Valley in the right exit region of the jet, a location which has been shown to be favorable for tornadoes, although not as favorable as the left exit region (Rose et al. 2004, Clark et al. 2009). A low-CAPE-high-shear regime known to be associated with cool or cold-season tornadoes shows up when looking at the frequency of observations that exceed a set threshold. For example, about twice as many instances of high CAPE (>1000 J kg^{-1} or >2000 J kg^{-1}) are observed during most tornadic cold seasons, albeit the numbers of these observations are much lower in the winter than in other times of the year. Steeper lapse rates and higher STP values are also revealed in most tornadic seasons, while SRH proves not to be the best discriminator, at least for the cold season. It is also interesting to note the differences that arise when multi-ingredient parameters are analyzed compared to their individual constituents. Both STP and a combination of MLCAPE and 0-6 km shear give different spatial patterns of frequency of exceedance and are arguably better discriminators than their individual components.

Finally, an analysis of the SPC Storm Mode database for NDJF EF1+ tornadoes occurring between 2003 and 2015 reveals that cold-season tornadoes are common under all four convective modes, with a range of 211 (Discrete) to 311 (Cell in Line) total instances during these years. Tornadoes within the Discrete mode cause the most fatalities during the cold season and are associated with a higher CAPE, while QLCS tornadoes during the cold season have the lowest average CAPE values but highest low-level wind shear. When this NDJF subset is compared to all EF1+ tornadoes within the study domain in the SPC Storm Mode database, it is affirmed that higher CAPE and lower shear within cold-season environments is the rule, along with very warm and moisture-rich conditions which are strikingly not too dissimilar from tornadoes on an annual basis. In summary, it can be concluded that cold-season tornado environments are characterized, most notably, by a wealth of Gulf moisture, unseasonably warm surface temperatures, low yet sufficient CAPE, steep lapse rates (perhaps due to penetration of cold air aloft), higher wind shear, and an occurrence downstream of an upper-level trough and jet streak.

3. Social perspective

In light of the amplified societal risks throughout the Southeastern U.S. associated with cold-season tornadoes, a survey instrument was developed to probe professional broadcast meteorologists, NWS meteorologists, and emergency management officials in a domain that encompasses the Southeast and Mississippi Valley regions. Whenever a major tornado event occurred between November 2016 – February 2017, surveys were deployed to willing participants. The surveys were designed to answer several research questions, such as what challenges plagued communication of the risk and warning for the tornado event in question, how the professional perceived the preparedness and resiliency of the impacted communities, what barriers to communication exist for tornadoes in general in the area, how vulnerable is the area to tornado impacts, and whether the professionals and the public are aware of the increasing risk of cold-season tornadoes. Potential improvements in warning dissemination and collaboration between sectors were also sought from the professionals. Four cases were selected throughout the study period in which significant tornadoes caused major damage and/or fatalities.

From the sampling of surveys completed by the professionals, several recurring themes surfaced. In regard to barriers to communication, cold-season specific challenges arose when trying to communicate risk, such as nighttime occurrence and the tornado event occurring immediately following a holiday. Other barriers professionals faced were more applicable to tornado cases in general. A major factor relayed was that of public receptivity. In general, meteorologists viewed their surrounding communities as very aware of cold-season tornado risk and prepared to tackle the impacts; however, the one emergency management official who responded had a very different perception, saying that the public in his rural county is neither educated nor equipped with disaster resources and few choose to receive mass communication warning notifications. Technology is indeed a major barrier, and even professionals themselves knowing how to best take advantage of the ever-increasing social media capability can be an obstacle. Another repetitious remark made by the professionals was a call for greater consistency in the messages given by media outlets. There seems to be a general opinion that too many options with too many varied (and thus confusing) graphic and color schemes are muddling proper and accurate communication. A 'less is more' approach would be more favorable to ensure the public is all receiving consistent and timely information. Uncertainties in timing of the tornado event, as well as in the physical meteorology, present difficulties as well. As shown in Chapter 3, it can be difficult to discern what the convective mode of a storm system might be, yet having a better idea of whether discrete cells or a line of storms is expected can make a big difference in what tornado risk messages are communicated. Professionals also confirmed forecasting challenges of cold-season tornado ingredients such as CAPE, shear, and moisture advection from the Gulf of Mexico.

Most professionals believe that their communities are very vulnerable to tornadoes, no matter what time of year, yet they also conclude that their communities are prepared for them and able to recover quickly. There is a general perception that their areas are not becoming more vulnerable over time, with several professionals citing improvements in data quality techniques such as storm surveys helping raise awareness and perhaps inflate tornado counts. As was expected, several professionals mentioned the well-documented vulnerabilities specific to the Southeastern U.S. increasing tornado risk there, such as poverty, elderly population, rural topography, and substandard housing. Of course, vulnerability of a population is also affected by technology, education, which media sources are used for receiving warnings, and uncertainty in timing of the event. Several calls for continuing or initiating public education for all age groups in tornado science and safety were made by the professionals, as well as a call for better collaboration among themselves and with the social science sector. These findings affirm the need for continued tornado risk communication refinements, in particular for cold-season events, although it is also imperative to receive a public perspective on such events.

B. Limitations and Future Work

This study on cold-season tornado events, albeit unique and fresh, does not come without limitations and opportunities for future refinements. The mere fact that the study focuses on the cold season months means that the sample size of tornadoes is quite small relative to the tornado database as a whole. This study has subjectively defined the cold season as comprising the months of November–February. While these are the four months with the least numbers of tornadoes in the annual average, one could argue that the month of November (or at least the first half of it) is more like spring than winter when it comes to severe weather and tornado environments. When the cold season is partitioned as the months of DJF in some of the climatological analysis in Chapter 2, there is indeed a change in sign of tornado count frequency trends across much of the domain due to the decreasing tornado counts through time in December. When the month of November is added, the trend becomes quite positive to produce the results presented here. A more in-depth of analysis for DJF tornadoes and November tornadoes only could be done to see if additional climatological and meteorological relationships hold, but the tornado sample size would be even more limited. When the month of November is retained, there is a more plausible sample size for analysis, and it is the opinion of the author that this month is still looked at as "cold" in the eyes of the public and not a month known for high tornado activity.

As mentioned in Chapter 2, there are numerous and well-documented issues with the current SPC tornado database that must be addressed. This data record for this study begins in 1953, which has been the year of choice for starting tornado climatology work by others who note that before this year there is enhanced uncertainty regarding data quality. Until F-scale implementation in 1974, there was not a standard way of rating tornadoes, but efforts to apply F-scale ratings to pre-1974 events are generally regarded as acceptable. However, an overcount (undercount) of F2 (F1) tornadoes is apparent in the data record before 1974, so efforts have been taken to apply the correction from Agee and Childs (2014) when discussing cold-season tornado intensities. The advent of Doppler radar in the 1990s made tornado observation easier, and as a result inflated the F0 tornado count compared to previous decades. This high number of F0 (and eventually EF0) tornadoes has continued since, leading to a large discrepancy between pre-Doppler and post-Doppler eras. This study avoids this issue by only extracting (E)F1-(E)F5 tornadoes for analysis, which has been shown by Verbout et al. (2006) to provide a better representation of tornado count trends through time. Further, this study is limited by its focus on tornado counts rather than other metrics such as tornado days or numbers of tornadoes on tornado days. The logic behind this decision was that the sample size would be much too small if tornado days were analyzed, given that (E)F1+ tornadoes occur on relatively few days during winter months.

Defining and implementing teleconnection indices for statistical investigation with tornado counts is also limited by subjectivity. A variety of ways to slice teleconnection indices could have been used, so taking a four-month (NDJF) average of ONI, AO, and NAO indices for each year may not necessarily be the best. For example, a transition from a negative to positive ONI that could have occurred over those four months would be washed out to a near-zero value in the mean. A more fine-scale approach would be to compare teleconnection index values to tornado counts on an individual monthly basis to see if the relationships found still hold, especially for the month of November given its large increase in tornadoes over time. AO and NAO indices are not as impacted by the choice of averaging because they typically do not change drastically over the course of four months. Given the statistically-significant correlations between La Niña, positive-phase AO, and positive-phase NAO with NDJF tornado counts, an exciting future endeavor could be to introduce a probabilistic tornado risk forecast sometime during the summer for an upcoming cold season according to the projections of teleconnection patterns. In fact, establishing seasonal forecasts of tornadoes is a growing ambition among the weather community (Allen et al. 2015, Elsner et al. 2015, Elsner and Widen 2016). Knowing whether or not the upcoming winter has a high chance of being tornadic is of great worth, as it can help the public stay aware and reduce their chances of being negatively impacted, as well as help city and county officials in resource allocation plans. In addition to using these particular teleconnection patterns to forecast for cold-season tornadoes, other teleconnection patterns not investigated here could be explored to see if similar correlations exist.

A major limitation of the meteorological investigation is the use of NCEP/NCAR Reanalysis, with its coarse spatial domain and limited number of parameters available for analysis. This reanalysis was chosen over other more modern options such as ERA-Interim, MERRA, or NARR due to its data record which extends backward into the 1950s to align with the tornado data time range. However, a future investigation using similar techniques with these more modern reanalyses with finer resolution capability would be valuable to either affirm the findings shown here or reveal new meteorological patterns. While the use of monthly mean values is supplemented by the more fine-scale 6-hourly data of tornado parameters, there still exists opportunity for analysis with higher resolution data. Perhaps doing a mesoanalysis study for cases of well-known cold-season events would help affirm the results presented here or even add more knowledge as to what characterizes a typical cold-season tornado environment. From the findings shown in Chapter 3, a plausible hypothesis would be that there is enhanced moisture, higher CAPE than is usually seen in the wintertime, and relatively high wind shear in significant cold-season tornado events.

The small sample size, especially among the emergency management community, limits the results of the survey instrument used to investigate the social perspective of cold-season tornadoes. Obtaining a greater population of EMs could potentially be had through efforts such as an in-person or phone interview rather than an online survey. The public sector is also entirely excluded from this study, so a major avenue for future work would be to develop a similar survey for a sampling of the population in the Southeast in Mississippi Valley region in regard to cold-season tornado cases. Bridging the communication and education gap between professionals and the public will only go so far if the public is not engaged and solicited for their feedback of warning and risk communication strategies; thus, a survey or interviews that include the public sphere is imperative. In-person interviews would also be helpful in overcoming the unavoidable subjectivity introduced by interpretation of open-ended responses in a written survey. Putting the main findings and suggestions given in this survey into action is another next step toward improving awareness and saving lives. For example, continuing work to consolidate and standardize the graphical aesthetics and rating scales communicated by various sectors would help lead to a more consistent message received by the public. It is also important to take the results of this study to the public and professionals alike in order to increase the current state of knowledge and explore ways of educating the public, from school children to the elderly, on the increasing cold-season tornado risk. One way to do this would be to refine the conceptual model presented into an operational product to be used for educational purposes in the weather risk community. As the 2016-17 season showed, people are still vulnerable and unfortunately can lose their lives from tornadoes in the cold season, so efforts to mitigate impacts should be a top priority.

C. Significance

The multi-faceted approach taken in this endeavor is the first of its kind in cold-season tornado research. Therefore, while it is difficult to confirm all of the results of this study with past work, there is great potential to use the findings presented here to not only vastly increase the current state of knowledge of cold-season tornadoes, but more importantly to work toward mitigating their impacts. The significant increasing trend found in tornado counts across parts of the Southeast and Mississippi Valley regions is alarming and provides motivation to help ensure public education and availability of resources in these areas. These results provide potential opportunities for seasonal forecasting of tornadoes and give forecasters a better idea of what parameters are typically present in cold-season tornado events. The need for improved modeling, especially in regard to convective mode, is also confirmed here, as it has been shown here that very different parameters and very different potential for fatalities exist between the four main convective modes, but all are common to be associated with cold-season tornadoes. Finally, the known societal risks associated with tornadoes during the cold season are fleshed out and expanded through the societal piece of this study, exposing the need for timely and effective risk and warning communication. There is already an understood communication gap between professionals and the public in severe weather and tornado risk, but this study goes further to reveal that the perceptions of what strategies to engage the public and how prepared and vulnerable the public actually is may vary among professionals. A consistent message and shared understanding between all sectors of society is pivotal, and the work presented here provides a call to have professionals interacting more with social scientists and the public interacting more with their decision-makers to achieve these goals. Emanating above all is the drive to prevent human casualty from tornadoes, and this study imparts an impetus toward that end for the little-studied yet vitally important phenomenon of cold-season tornadoes.

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APPENDIX A

SURVEY E-MAILS AND CONSENT FORM

(a) Initial Informational E-mail

This e-mail template was sent in August-September 2016 to seek participation in the survey.

Dear [NAME OF PROFESSIONAL],

My name is Samuel Childs, and I am a second-year Master's student in Colorado State University's Department of Atmospheric Science. My research focus is on cold-season tornado climatology and their associated societal impacts. A major aim of my work is to evaluate communication strategies and community response during a cold-season tornado event from the perspective of local meteorologists and emergency managers. Along with my advisor Dr. Russ Schumacher, we are seeking your participation in our project, entitled ***Communication Strategies and Community Preparation for Cold-season Tornado Events*.**

My initial research reveals that tornadoes occurring during the months of November through February (NDJF) are increasing, especially in the South and Mississippi Valley regions. Tornadoes occurring during this time of year may be more likely to catch people off-guard, and their propensity to occur in the South brings additional societal risks due to high mobile home density, forested terrain, and a high elderly population. Given these risks, and the increasing trend in NDJF tornado frequency, it is imperative to study communication efforts between local meteorologists and the public to mitigate risk and protect life and property. As such, we are seeking to study the social aspects of tornado events that occur from November 2016 – February 2017 in a domain encompassing the South and Mississippi Valley regions (including all or parts of AL, AR, KY, LA, MO, MS, and TN). By the time the study period begins in November, our goal is to acquire a pool of at least 10 participants from each of three decision-making sectors within the states mentioned who would be willing to participate in a post-event survey. These three groups include National Weather Service meteorologists, broadcast meteorologists, and emergency managers. A similar but distinct survey has been developed for each group, which aims to explore the communication strategies used by meteorologists and emergency managers before, during, and after cold-season tornado events, see what communication barriers exist, and assess community preparation and resilience. The survey will be administered using Question Pro, an innovative online survey analysis software. After a major tornado event occurs during November 2016 – February 2017, the surveys will be sent to willing participants responsible for the impact area. Thus, it is possible that you would agree to participate but not be contacted if your area does not receive a major tornado event during this upcoming cold season. From an initial test of the survey, it should take you approximately 1 hour to complete. Despite this time commitment, we hope you agree that this study is worth the time due to its penetration into the largely unknown but important realm of societal impacts of cold-season tornadoes. We truly believe your feedback will prove to provide great benefit in increasing awareness and improving communication of cold-season tornado risk to the public.

If you would be willing to take part in the survey, please respond to this e-mail with your name and best method of contact *before October 15*. I also ask that you forward this explanatory e-mail to others in your office who might be interested and willing to participate, and have him or her also respond via e-mail to me with name and contact info. Should your local area experience a substantial tornado event between November 2016 and February 2017, we will send willing participants their unique survey link along with an official consent form. This consent form is mandated by Colorado State University, but it is also our moral responsibility to ensure that you know the details of the study and clearly state your rights and protection as a participant. Filling out the survey will serve as your official consent. There are no major risks in this study, and we will take care to refrain from using any personally identifiable information in resulting articles or reports.

Please do not hesitate to contact us if you have any questions. Thank you in advance for your time and participation. Have a wonderful day!

Samuel Childs
Graduate Research Assistant
Colorado State University
sjchilds@rams.colostate.edu

Russ Schumacher
Associate Professor
Colorado State University
russ.schumacher@colostate.edu

(b) E-mail containing survey

**This e-mail template was sent to professionals after a tornado event occurred.*

Hello [NAME OF PROFESSIONAL],

I'm contacting you in regards to my cold-season tornado study. In light of the recent tornadoes near [PLACE OF TORNADO EVENT], I would appreciate your feedback in my survey. Your responses will remain confidential and secure, and the survey should take you no more than one hour to complete. Feel free to forward this to [OTHER METEOROLOGISTS/OTHERS] at your [STATION/OFFICE] who played a role in forecasting this event or who may have an interest in the study now that a tornado event has occurred. The more responses received, the better! Also attached is the official consent form mandated by Colorado State University for your reference. If you could finish the survey within a month while the event is still fresh in your mind, that would be great.

We have contracted with QuestionPro, an independent research firm, to field your confidential survey responses. Please follow this link to complete the survey:

[INSERT QUESTION PRO LINK]

Also feel free to contact me via sjchilds@rams.colostate.edu with any questions.

Thank you so much [NAME OF PROFESSIONAL] for your time and your help toward the public in these scary situations. Your input (and that of other decision makers in the [PLACE OF TORNADO EVENT] area) will help to shed light on and improve communication strategies for cold-season tornado events.

Samuel Childs
Graduate Research Assistant
Colorado State University
sjchilds@rams.colostate.edu

(c) Consent Form

This consent form was attached to the e-mail containing the survey link. Only the consent form for the meteorologists is shown (a nearly identical consent form was sent for the emergency managers).

DEPARTMENT OF ATMOSPHERIC SCIENCE
COLORADO STATE UNIVERSITY
1371 CAMPUS DELIVERY
FORT COLLINS, CO 80523-1371
(970) 491-8682 PHONE
(970) 491-4889 FAX
http://www.atmos.colostate.edu

Colorado State University

Hello,

We are seeking your participation in a current research project aimed at assessing communication strategies and community preparation and resilience to cold-season tornado events. Given that cold-season severe weather and tornadoes pose many societal risks, we hope to learn how you as a meteorologist are able to communicate risk and work with the public during a dangerous situation during the winter months. This study is intended to lead to potential improvements in communicating cold-season tornado risk in the future, not to blame or credit any past decisions or strategies.

With your consent, we invite you to participate in the survey, accessed via the link in the e-mail, regarding the recent cold-season tornado in your local area. The online survey consists of 23 questions about how you prepared for the tornado threat on that day, what strategies you employed to communicate the risk to the public, including your interaction with local emergency managers, and how you approached community response and resilience after the tornado event. We are also interested in learning your opinions on the vulnerability, preparedness, and resiliency of your local community. The survey should take approximately 1 hour of your time, depending on how thorough you make your responses. If you would like to give further input via e-mail or a phone call, you will have that opportunity at the end of the survey as well.

While there are no direct benefits to you for your participation in this study, the hope is that the information you provide will help identify potential improvements in future communication strategies of cold-season tornadoes and mitigate the destructive societal impacts among people in your community. There are no major sources of personal risk in this study, but we will be careful to minimize any release of personal information. Your responses to the survey are anonymous; however, the name of your community may be used for comparison between different approaches to cold-season tornado communication among regions. If you agree to provide additional information via e-mail or phone, this communication will be kept confidential at Colorado State University, and your name will not be used in any written reports that result from this research. If you give consent to participate but then are not contacted by us during the study period, your contact information will be kept confidential at Colorado State University, and subsequently destroyed at the end of the study period (February 2017).

Your participation in this study is completely voluntary. You may also choose to withdraw your consent at any time without penalty. Your consent and acknowledgment that we have provided you with appropriate information via this document and that you have decided to voluntarily participate is given by filling out the survey. You may start and stop the survey at any time without losing your progress, and you may omit any questions you choose. There is no penalty for incomplete surveys or blank responses.

If you have any questions or concerns before, during, or after taking the survey, please contact Prof. Russ Schumacher or Samuel Childs. If you have any questions about your rights as a volunteer in this research, contact Janell Barker, Human Research Administrator, at 970-491-1655.

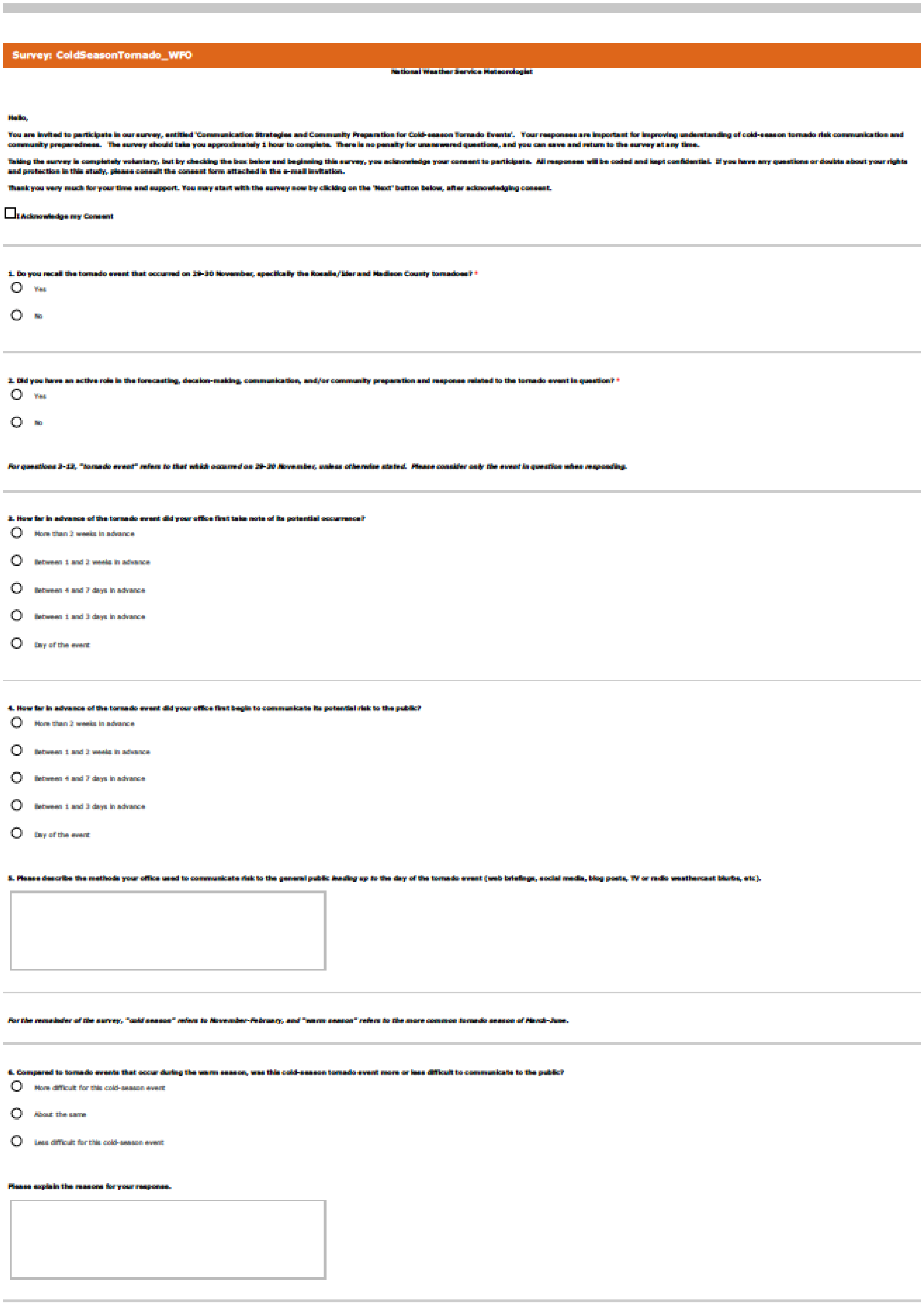
Researcher Contact Information
Samuel Childs, Graduate Research Assistant, sjchilds@rams.colostate.edu
Russ Schumacher, PI, russ.schumacher@colostate.edu, 970-491-8084

APPENDIX B

SURVEY INSTRUMENT

The three surveys from QuestionPro sent to NWS meteorologists, broadcast meteorologists, and emergency management for the first analyzed case (November 29-30) are reproduced here. There are a few differences in wording in some of the questions between the different sectors, and 2 additional questions in the emergency management survey. Surveys sent for the other 3 cases are identical except for a few small text changes to reflect the specified event.

(a) NWS Meteorologist Survey



Survey: ColdSeasonTornado_WFO

National Weather Service Meteorologist

Hello,

You are invited to participate in our survey, entitled 'Communication Strategies and Community Preparation for Cold-season Tornado Events'. Your responses are important for improving understanding of cold-season tornado risk communication and community preparedness. The survey should take you approximately 1 hour to complete. There is no penalty for unanswered questions, and you can save and return to the survey at any time.

Taking the survey is completely voluntary, but by checking the box below and beginning this survey, you acknowledge your consent to participate. All responses will be coded and kept confidential. If you have any questions or doubts about your rights and protection in this study, please consult the consent form attached in the e-mail invitation.

Thank you very much for your time and support. You may start with the survey now by clicking on the 'Next' button below, after acknowledging consent.

☐ **I Acknowledge my Consent**

1. Do you recall the tornado event that occurred on 29-30 November, specifically the Rosalie/Ider and Madison County tornadoes? *

○ Yes

○ No

2. Did you have an active role in the forecasting, decision-making, communication, and/or community preparation and response related to the tornado event in question? *

○ Yes

○ No

For questions 3-13, "tornado event" refers to that which occurred on 29-30 November, unless otherwise stated. Please consider only the event in question when responding.

3. How far in advance of the tornado event did your office first take note of its potential occurrence?

○ More than 2 weeks in advance

○ Between 1 and 2 weeks in advance

○ Between 4 and 7 days in advance

○ Between 1 and 3 days in advance

○ Day of the event

4. How far in advance of the tornado event did your office first begin to communicate its potential risk to the public?

○ More than 2 weeks in advance

○ Between 1 and 2 weeks in advance

○ Between 4 and 7 days in advance

○ Between 1 and 3 days in advance

○ Day of the event

5. Please describe the methods your office used to communicate risk to the general public leading up to the day of the tornado event (web briefings, social media, blog posts, TV or radio weathercast blurbs, etc).

For the remainder of the survey, "cold season" refers to November-February, and "warm season" refers to the more common tornado season of March-June.

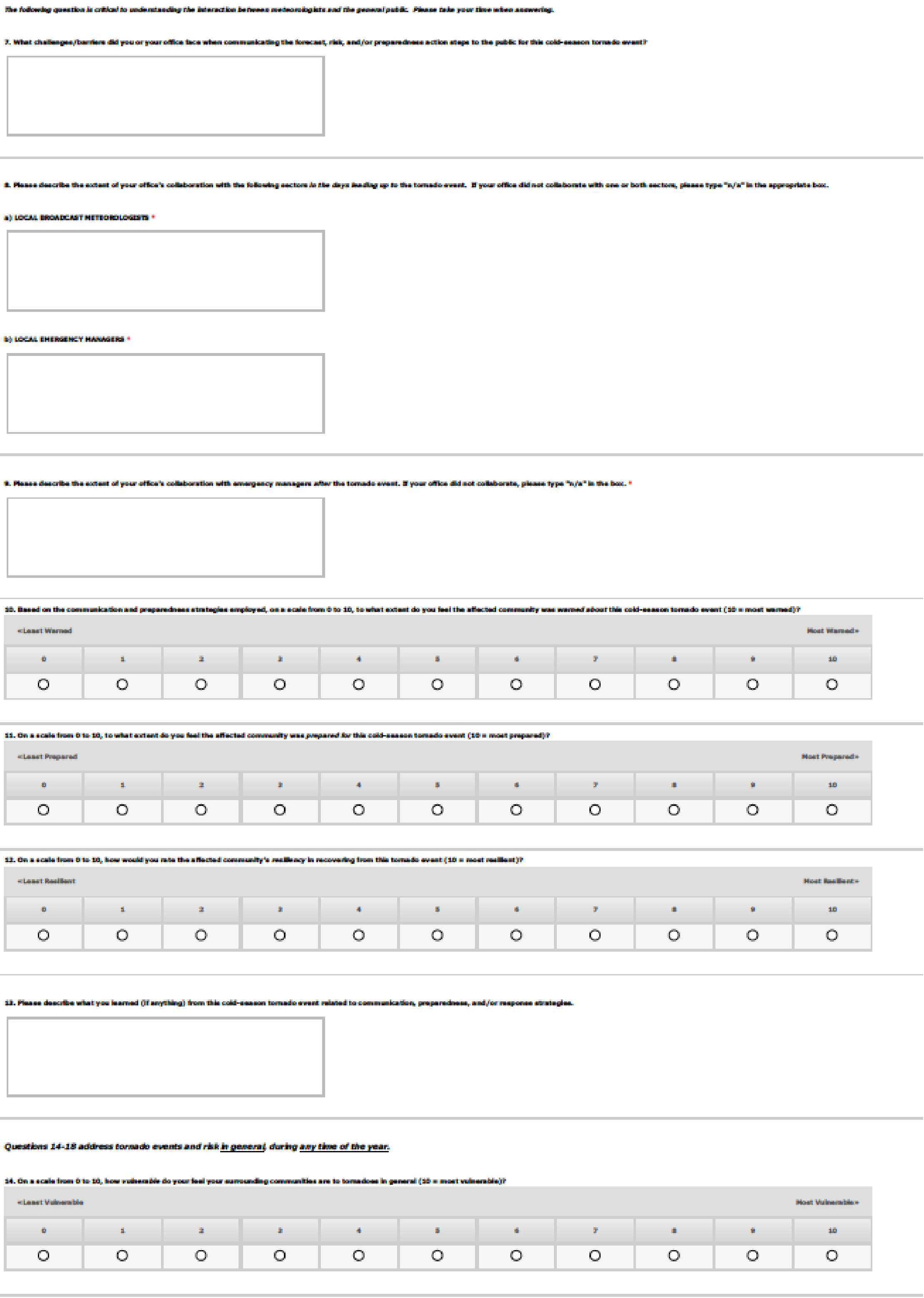
6. Compared to tornado events that occur during the warm season, was this cold-season tornado event more or less difficult to communicate to the public?

○ More difficult for this cold-season event

○ About the same

○ Less difficult for this cold-season event

Please explain the reasons for your response.



The following question is critical to understanding the interaction between meteorologists and the general public. Please take your time when answering.

7. What challenges/barriers did you or your office face when communicating the forecast, risk, and/or preparedness action steps to the public for this cold-season tornado event?

8. Please describe the extent of your office's collaboration with the following sectors *in the days leading up to* the tornado event. If your office did not collaborate with one or both sectors, please type "n/a" in the appropriate box.

a) LOCAL BROADCAST METEOROLOGISTS *

b) LOCAL EMERGENCY MANAGERS *

9. Please describe the extent of your office's collaboration with emergency managers *after* the tornado event. If your office did not collaborate, please type "n/a" in the box. *

10. Based on the communication and preparedness strategies employed, on a scale from 0 to 10, to what extent do you feel the affected community was *warned about* this cold-season tornado event (10 = most warned)?

<Least Warned										Most Warned>
0	1	2	3	4	5	6	7	8	9	10
○	○	○	○	○	○	○	○	○	○	○

11. On a scale from 0 to 10, to what extent do you feel the affected community was *prepared for* this cold-season tornado event (10 = most prepared)?

<Least Prepared										Most Prepared>
0	1	2	3	4	5	6	7	8	9	10
○	○	○	○	○	○	○	○	○	○	○

12. On a scale from 0 to 10, how would you rate the affected community's *resiliency* in recovering from this tornado event (10 = most resilient)?

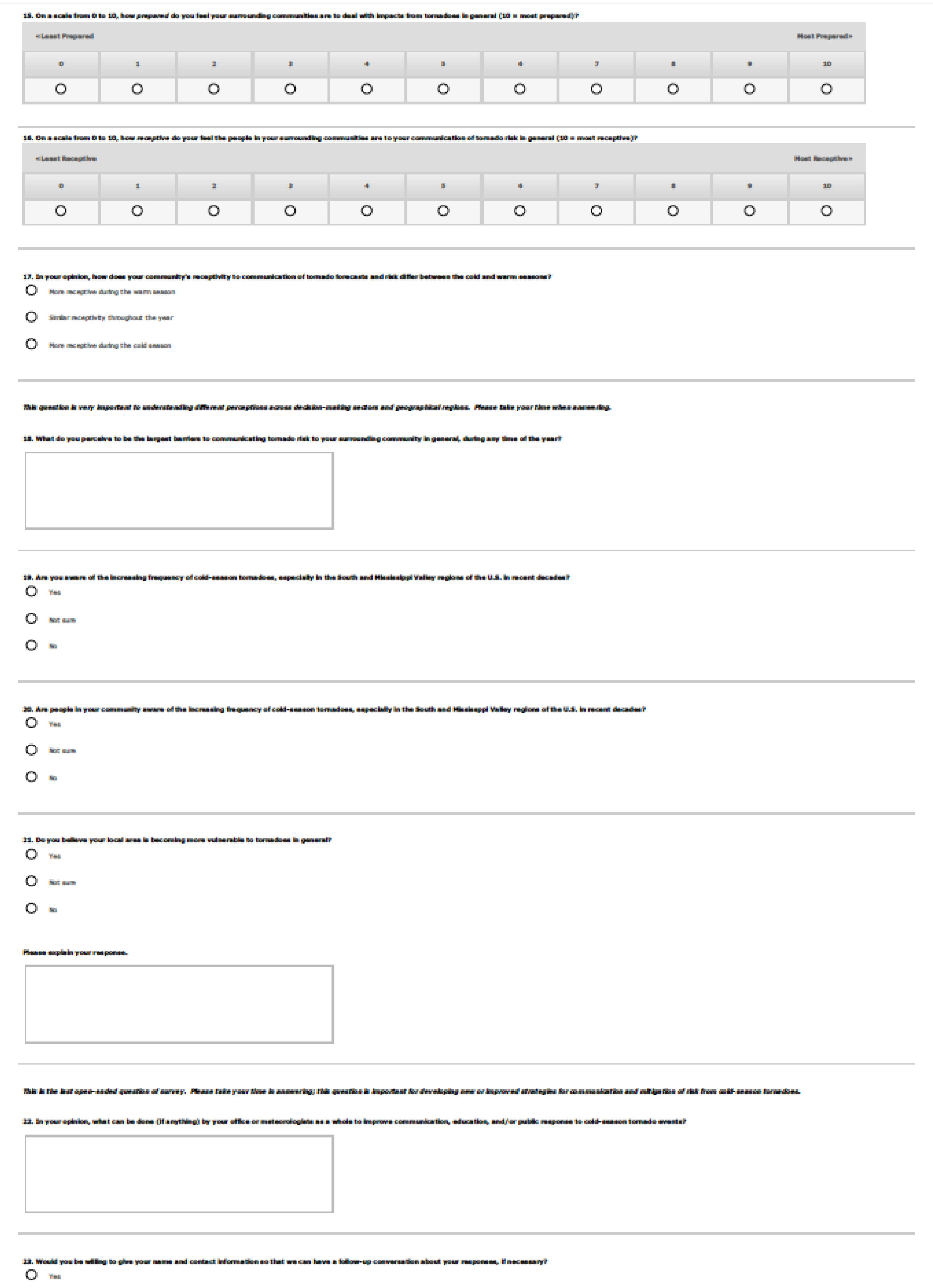
<Least Resilient										Most Resilient>
0	1	2	3	4	5	6	7	8	9	10
○	○	○	○	○	○	○	○	○	○	○

13. Please describe what you learned (if anything) from this cold-season tornado event related to communication, preparedness, and/or response strategies.

Questions 14-18 address tornado events and risk <u>in general</u>, during <u>any time of the year</u>.

14. On a scale from 0 to 10, how *vulnerable* do your feel your surrounding communities are to tornadoes in general (10 = most vulnerable)?

<Least Vulnerable										Most Vulnerable>
0	1	2	3	4	5	6	7	8	9	10
○	○	○	○	○	○	○	○	○	○	○



15. On a scale from 0 to 10, how *prepared* do you feel your surrounding communities are to deal with impacts from tornadoes in general (10 = most prepared)?

<Least Prepared										Most Prepared>
0	1	2	3	4	5	6	7	8	9	10
○	○	○	○	○	○	○	○	○	○	○

16. On a scale from 0 to 10, how *receptive* do your feel the people in your surrounding communities are to your communication of tornado risk in general (10 = most receptive)?

<Least Receptive										Most Receptive>
0	1	2	3	4	5	6	7	8	9	10
○	○	○	○	○	○	○	○	○	○	○

17. In your opinion, how does your community's receptivity to communication of tornado forecasts and risk differ between the cold and warm seasons?

○ More receptive during the warm season

○ Similar receptivity throughout the year

○ More receptive during the cold season

This question is very important to understanding different perceptions across decision-making sectors and geographical regions. Please take your time when answering.

18. What do you perceive to be the largest barriers to communicating tornado risk to your surrounding community in general, during any time of the year?

19. Are you aware of the increasing frequency of cold-season tornadoes, especially in the South and Mississippi Valley regions of the U.S. in recent decades?

○ Yes

○ Not sure

○ No

20. Are people in your community aware of the increasing frequency of cold-season tornadoes, especially in the South and Mississippi Valley regions of the U.S. in recent decades?

○ Yes

○ Not sure

○ No

21. Do you believe your local area is becoming more vulnerable to tornadoes in general?

○ Yes

○ Not sure

○ No

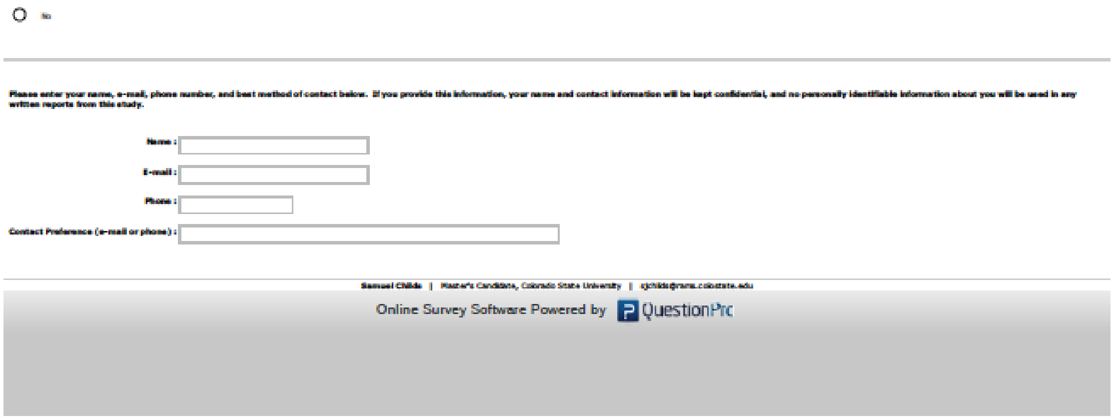
Please explain your response.

This is the last open-ended question of survey. Please take your time in answering; this question is important for developing new or improved strategies for communication and mitigation of risk from cold-season tornadoes.

22. In your opinion, what can be done (if anything) by your office or meteorologists as a whole to improve communication, education, and/or public response to cold-season tornado events?

23. Would you be willing to give your name and contact information so that we can have a follow-up conversation about your responses, if necessary?

○ Yes



○ No

Please enter your name, e-mail, phone number, and best method of contact below. If you provide this information, your name and contact information will be kept confidential, and no personally identifiable information about you will be used in any written reports from this study.

Name :

E-mail :

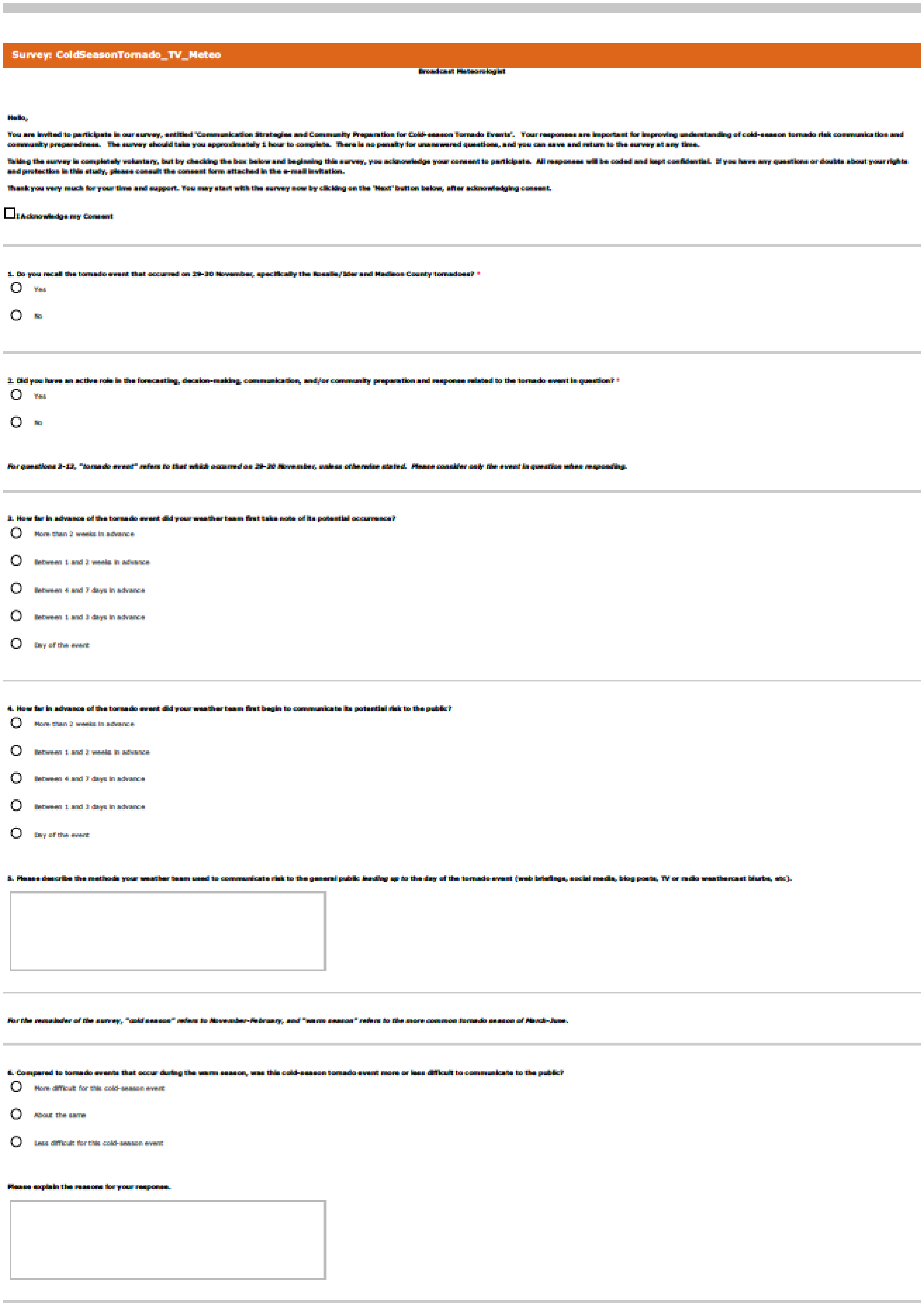
Phone :

Contact Preference (e-mail or phone) :

Samuel Childs | Master's Candidate, Colorado State University | sjchilds@rams.colostate.edu

Online Survey Software Powered by QuestionPro

(b) Broadcast Meteorologist Survey



Survey: ColdSeasonTornado_TV_Meteo

Broadcast Meteorologist

Hello,

You are invited to participate in our survey, entitled 'Communication Strategies and Community Preparation for Cold-season Tornado Events'. Your responses are important for improving understanding of cold-season tornado risk communication and community preparedness. The survey should take you approximately 1 hour to complete. There is no penalty for unanswered questions, and you can save and return to the survey at any time.

Taking the survey is completely voluntary, but by checking the box below and beginning this survey, you acknowledge your consent to participate. All responses will be coded and kept confidential. If you have any questions or doubts about your rights and protection in this study, please consult the consent form attached in the e-mail invitation.

Thank you very much for your time and support. You may start with the survey now by clicking on the 'Next' button below, after acknowledging consent.

☐ **I Acknowledge my Consent**

1. Do you recall the tornado event that occurred on 29-30 November, specifically the Rosalie/Ider and Madison County tornadoes? *

○ Yes

○ No

2. Did you have an active role in the forecasting, decision-making, communication, and/or community preparation and response related to the tornado event in question? *

○ Yes

○ No

For questions 3-13, "tornado event" refers to that which occurred on 29-30 November, unless otherwise stated. Please consider only the event in question when responding.

3. How far in advance of the tornado event did your weather team first take note of its potential occurrence?

○ More than 2 weeks in advance

○ Between 1 and 2 weeks in advance

○ Between 4 and 7 days in advance

○ Between 1 and 3 days in advance

○ Day of the event

4. How far in advance of the tornado event did your weather team first begin to communicate its potential risk to the public?

○ More than 2 weeks in advance

○ Between 1 and 2 weeks in advance

○ Between 4 and 7 days in advance

○ Between 1 and 3 days in advance

○ Day of the event

5. Please describe the methods your weather team used to communicate risk to the general public *leading up to the day of the tornado event* (web briefings, social media, blog posts, TV or radio weathercast blurbs, etc).

For the remainder of the survey, "cold season" refers to November-February, and "warm season" refers to the more common tornado season of March-June.

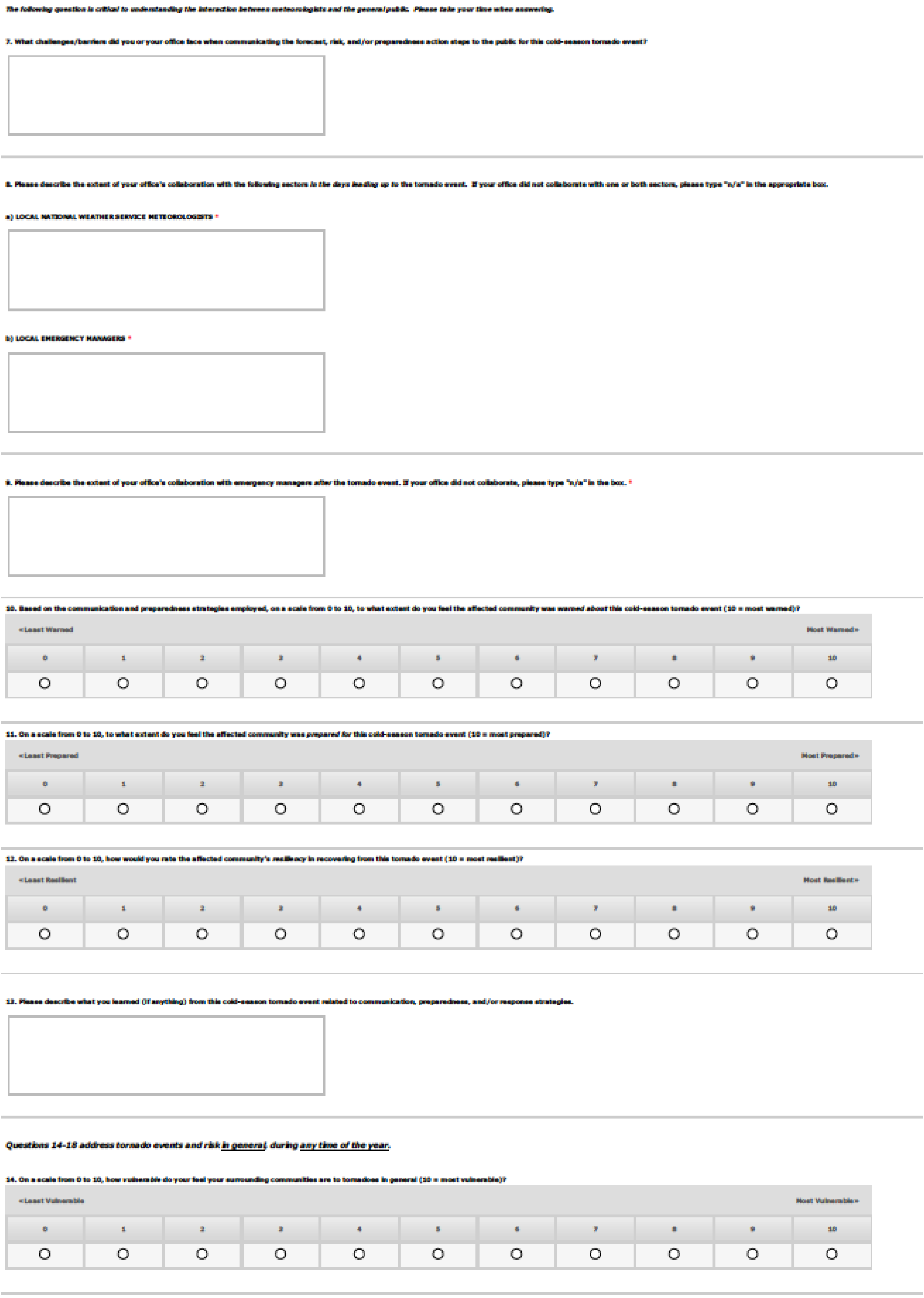
6. Compared to tornado events that occur during the warm season, was this cold-season tornado event more or less difficult to communicate to the public?

○ More difficult for this cold-season event

○ About the same

○ Less difficult for this cold-season event

Please explain the reasons for your response.



The following question is critical to understanding the interaction between meteorologists and the general public. Please take your time when answering.

7. What challenges/barriers did you or your office face when communicating the forecast, risk, and/or preparedness action steps to the public for this cold-season tornado event?

8. Please describe the extent of your office's collaboration with the following sectors *in the days leading up to* the tornado event. If your office did not collaborate with one or both sectors, please type "n/a" in the appropriate box.

a) LOCAL NATIONAL WEATHER SERVICE METEOROLOGISTS *

b) LOCAL EMERGENCY MANAGERS *

9. Please describe the extent of your office's collaboration with emergency managers *after* the tornado event. If your office did not collaborate, please type "n/a" in the box. *

10. Based on the communication and preparedness strategies employed, on a scale from 0 to 10, to what extent do you feel the affected community was *warned about* this cold-season tornado event (10 = most warned)?

<Least Warned										Most Warned>
0	1	2	3	4	5	6	7	8	9	10
○	○	○	○	○	○	○	○	○	○	○

11. On a scale from 0 to 10, to what extent do you feel the affected community was *prepared for* this cold-season tornado event (10 = most prepared)?

<Least Prepared										Most Prepared>
0	1	2	3	4	5	6	7	8	9	10
○	○	○	○	○	○	○	○	○	○	○

12. On a scale from 0 to 10, how would you rate the affected community's *resiliency* in recovering from this tornado event (10 = most resilient)?

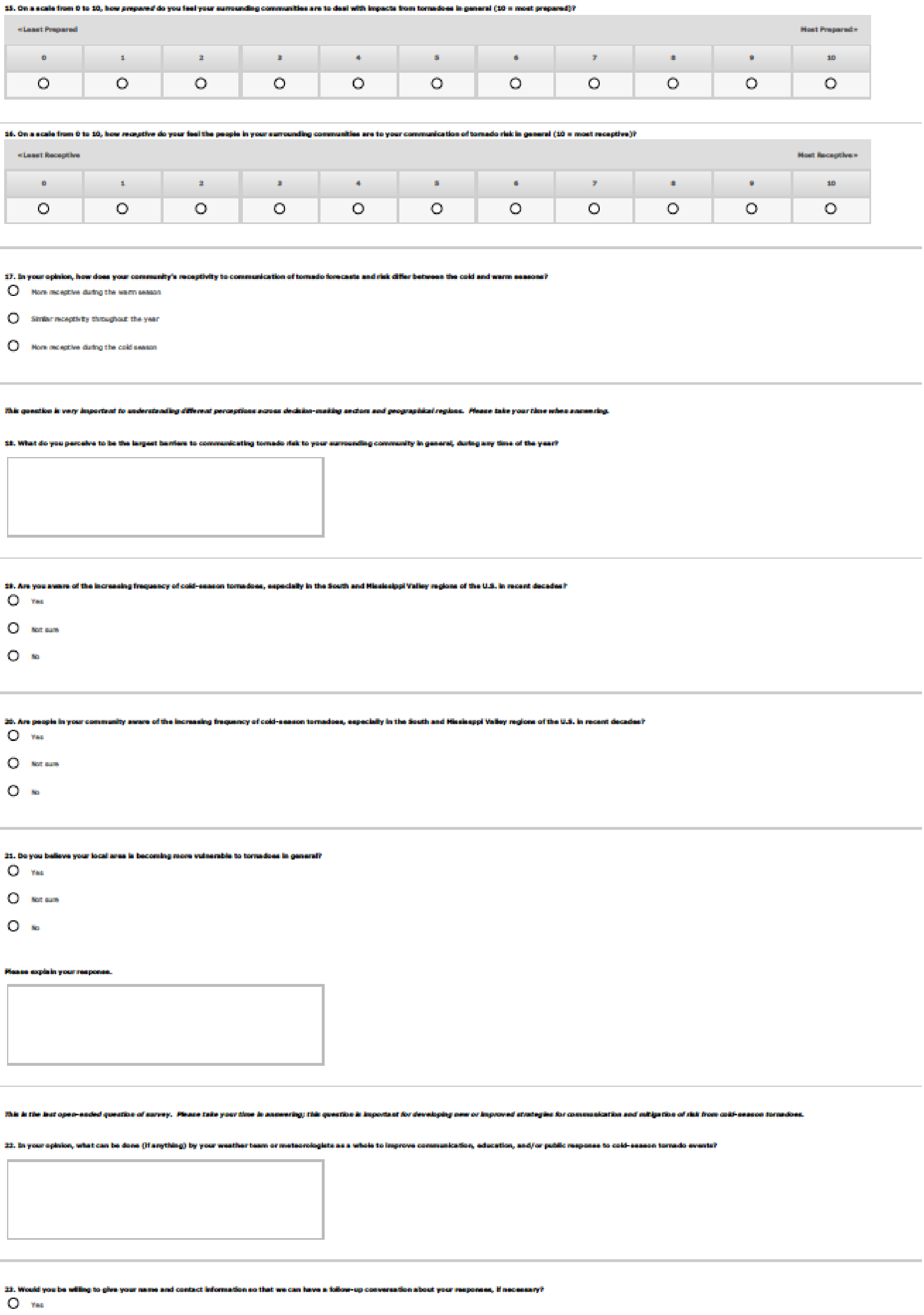
<Least Resilient										Most Resilient>
0	1	2	3	4	5	6	7	8	9	10
○	○	○	○	○	○	○	○	○	○	○

13. Please describe what you learned (if anything) from this cold-season tornado event related to communication, preparedness, and/or response strategies.

Questions 14-18 address tornado events and risk <u>in general</u>, during <u>any time of the year</u>.

14. On a scale from 0 to 10, how *vulnerable* do your feel your surrounding communities are to tornadoes in general (10 = most vulnerable)?

<Least Vulnerable										Most Vulnerable>
0	1	2	3	4	5	6	7	8	9	10
○	○	○	○	○	○	○	○	○	○	○



15. On a scale from 0 to 10, how *prepared* do you feel your surrounding communities are to deal with impacts from tornadoes in general (10 = most prepared)?

<Least Prepared										Most Prepared>
0	1	2	3	4	5	6	7	8	9	10
○	○	○	○	○	○	○	○	○	○	○

16. On a scale from 0 to 10, how *receptive* do your feel the people in your surrounding communities are to your communication of tornado risk in general (10 = most receptive)?

<Least Receptive										Most Receptive>
0	1	2	3	4	5	6	7	8	9	10
○	○	○	○	○	○	○	○	○	○	○

17. In your opinion, how does your community's receptivity to communication of tornado forecasts and risk differ between the cold and warm seasons?

○ More receptive during the warm season

○ Similar receptivity throughout the year

○ More receptive during the cold season

This question is very important to understanding different perceptions across decision-making sectors and geographical regions. Please take your time when answering.

18. What do you perceive to be the largest barriers to communicating tornado risk to your surrounding community in general, during any time of the year?

19. Are you aware of the increasing frequency of cold-season tornadoes, especially in the South and Mississippi Valley regions of the U.S. in recent decades?

○ Yes

○ Not sure

○ No

20. Are people in your community aware of the increasing frequency of cold-season tornadoes, especially in the South and Mississippi Valley regions of the U.S. in recent decades?

○ Yes

○ Not sure

○ No

21. Do you believe your local area is becoming more vulnerable to tornadoes in general?

○ Yes

○ Not sure

○ No

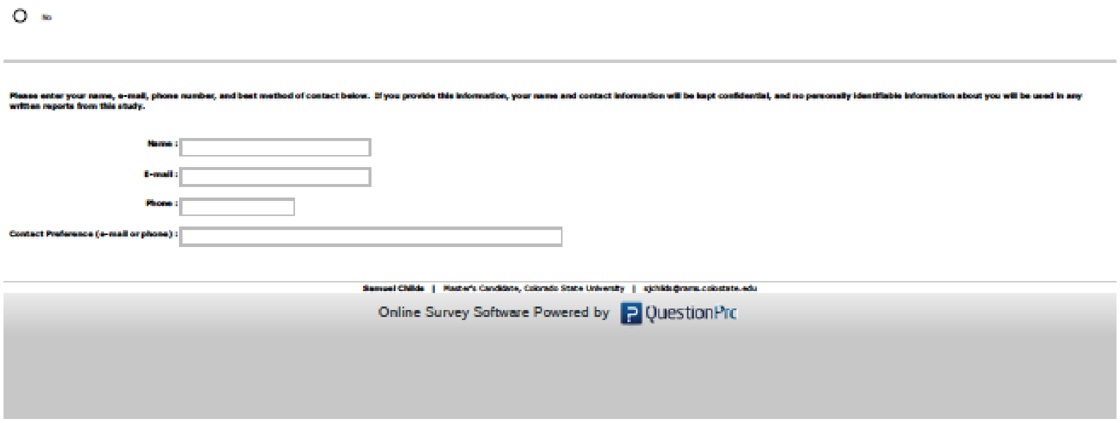
Please explain your response.

This is the last open-ended question of survey. Please take your time in answering; this question is important for developing new or improved strategies for communication and mitigation of risk from cold-season tornadoes.

22. In your opinion, what can be done (if anything) by your weather team or meteorologists as a whole to improve communication, education, and/or public response to cold-season tornado events?

23. Would you be willing to give your name and contact information so that we can have a follow-up conversation about your responses, if necessary?

○ Yes



○ No

Please enter your name, e-mail, phone number, and best method of contact below. If you provide this information, your name and contact information will be kept confidential, and no personally identifiable information about you will be used in any written reports from this study.

Name :

E-mail :

Phone :

Contact Preference (e-mail or phone) :

Samuel Childs | Master's Candidate, Colorado State University | sjchilds@rams.colostate.edu

Online Survey Software Powered by QuestionPro

(c) Emergency Management Survey

Survey: ColdSeasonTornado_EM

Emergency Management

Hello,

You are invited to participate in our survey, entitled 'Communication Strategies and Community Preparation for Cold-season Tornado Events'. Your responses are important for improving understanding of cold-season tornado risk communication and community preparedness. The survey should take you approximately 1 hour to complete. There is no penalty for unanswered questions, and you can save and return to the survey at any time.

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Thank you very much for your time and support. You may start with the survey now by clicking on the 'Next' button below, after acknowledging consent.

☐ **I Acknowledge my Consent**

1. Do you recall the tornado event that occurred on 29-30 November, specifically the Rosalie/Ider and Madison County tornadoes? *

○ Yes

○ No

2. Did you have an active role in the forecasting, decision-making, communication, and/or community preparation and response related to the tornado event in question? *

○ Yes

○ No

For questions 3-13, "tornado event" refers to that which occurred on 29-30 November, unless otherwise stated. Please consider only the event in question when responding.

3. How far in advance of the tornado event did your office first take note of its potential occurrence?

○ More than 2 weeks in advance

○ Between 1 and 2 weeks in advance

○ Between 4 and 7 days in advance

○ Between 1 and 3 days in advance

○ Day of the event

4. How far in advance of the tornado event did your office first begin to communicate its potential risk to the public?

○ More than 2 weeks in advance

○ Between 1 and 2 weeks in advance

○ Between 4 and 7 days in advance

○ Between 1 and 3 days in advance

○ Day of the event

5. Please describe the methods your office used to communicate risk to the general public leading up to the day of the tornado event (web briefings, social media, blog posts, TV or radio weathercast blurbs, etc).

For the remainder of the survey, "cold season" refers to November-February, and "warm season" refers to the more common tornado season of March-June.

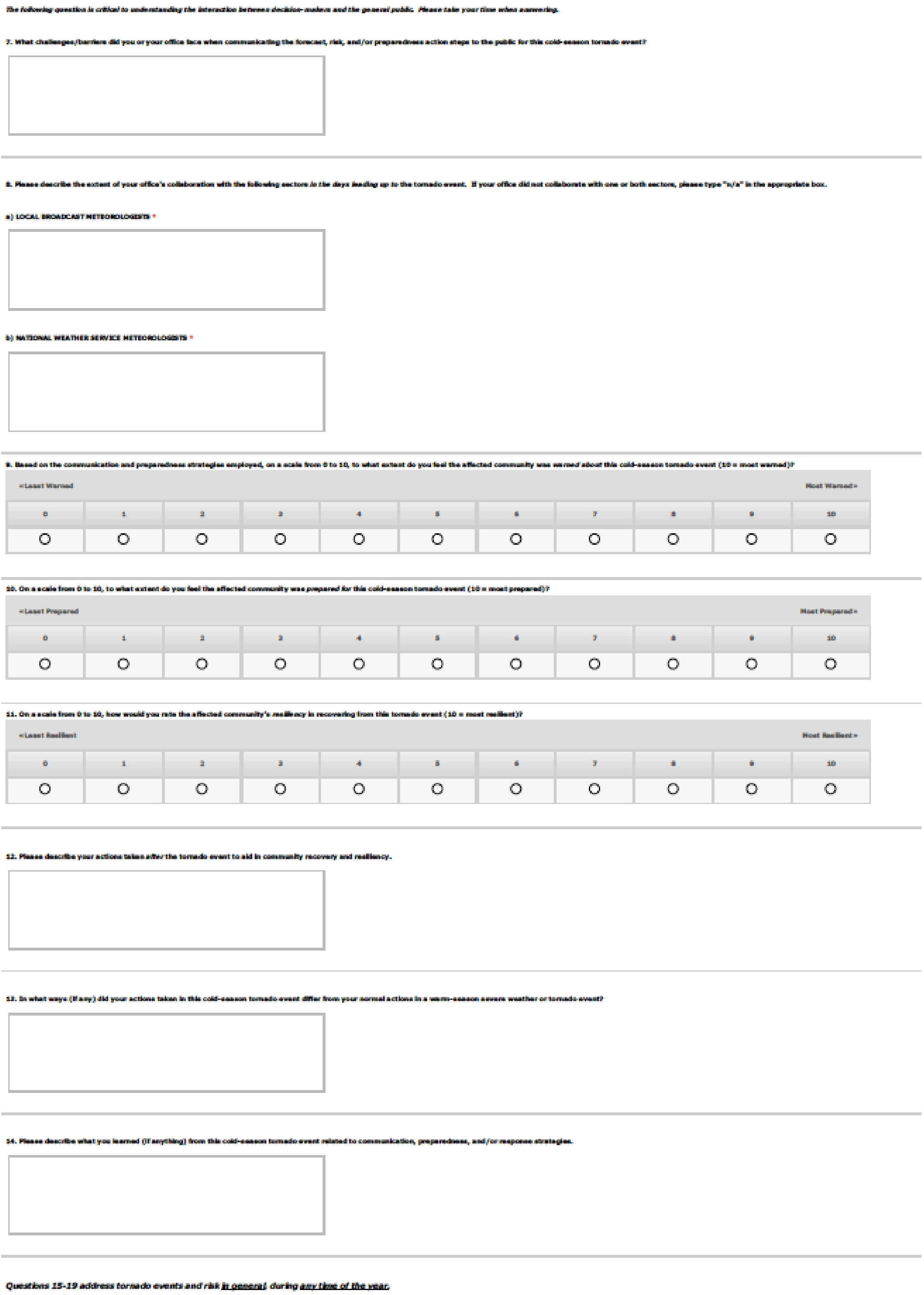
6. Compared to tornado events that occur during the warm season, was this cold-season tornado event more or less difficult to communicate to the public?

○ More difficult for this cold-season event

○ About the same

○ Less difficult for this cold-season event

Please explain the reasons for your response.



The following question is critical to understanding the interaction between decision-makers and the general public. Please take your time when answering.

7. What challenges/barriers did you or your office face when communicating the forecast, risk, and/or preparedness action steps to the public for this cold-season tornado event?

8. Please describe the extent of your office's collaboration with the following sectors *in the days leading up to the tornado event.* If your office did not collaborate with one or both sectors, please type "n/a" in the appropriate box.

a) LOCAL BROADCAST METEOROLOGISTS *

b) NATIONAL WEATHER SERVICE METEOROLOGISTS *

9. Based on the communication and preparedness strategies employed, on a scale from 0 to 10, to what extent do you feel the affected community was *warned about* this cold-season tornado event (10 = most warned)?

<Least Warned										Most Warned>
0	1	2	3	4	5	6	7	8	9	10
○	○	○	○	○	○	○	○	○	○	○

10. On a scale from 0 to 10, to what extent do you feel the affected community was *prepared for* this cold-season tornado event (10 = most prepared)?

<Least Prepared										Most Prepared>
0	1	2	3	4	5	6	7	8	9	10
○	○	○	○	○	○	○	○	○	○	○

11. On a scale from 0 to 10, how would you rate the affected community's *resiliency* in recovering from this tornado event (10 = most resilient)?

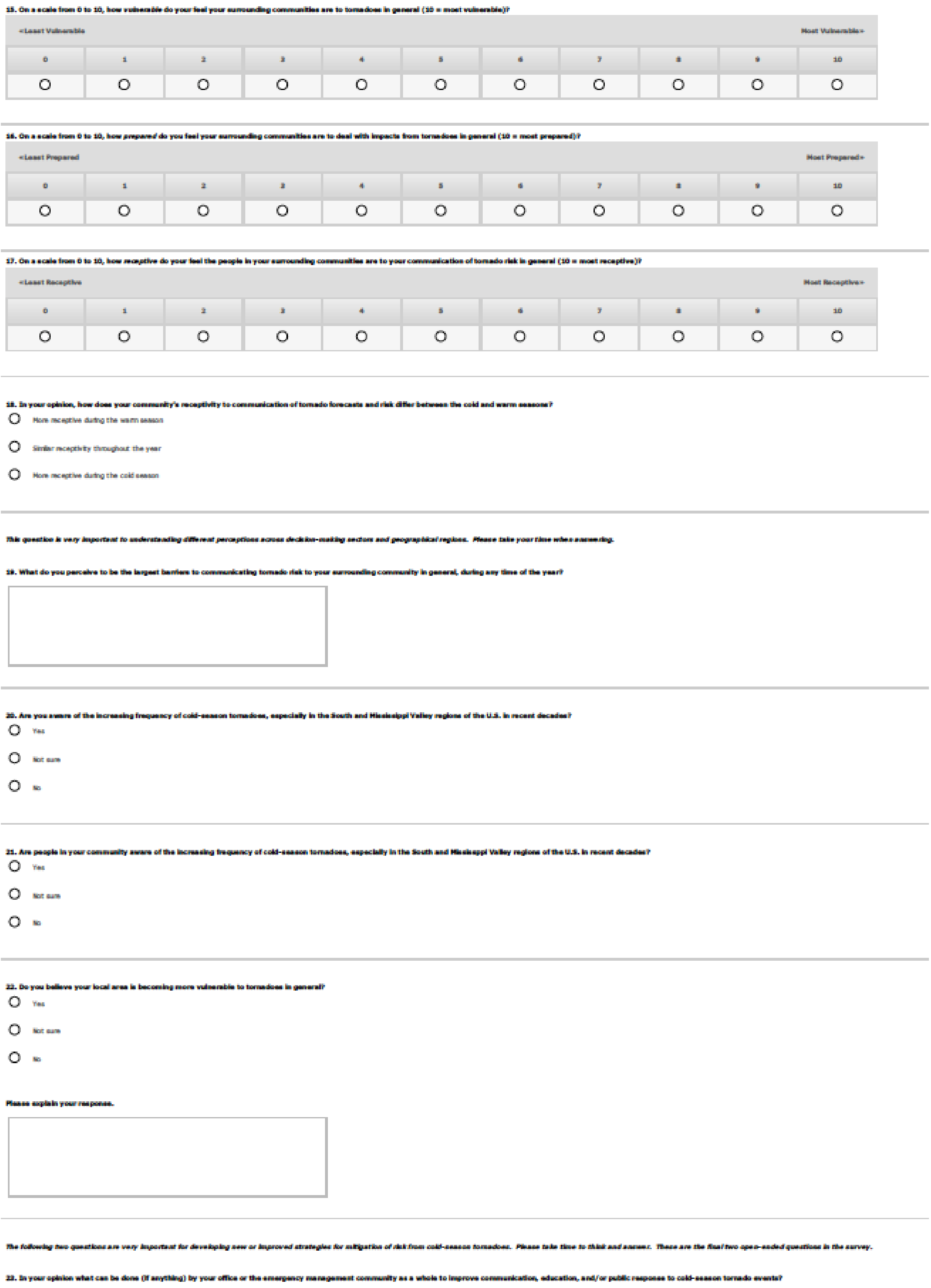
<Least Resilient										Most Resilient>
0	1	2	3	4	5	6	7	8	9	10
○	○	○	○	○	○	○	○	○	○	○

12. Please describe your actions taken *after* the tornado event to aid in community recovery and resiliency.

13. In what ways (if any) did your actions taken in this cold-season tornado event differ from your normal actions in a warm-season severe weather or tornado event?

14. Please describe what you learned (if anything) from this cold-season tornado event related to communication, preparedness, and/or response strategies.

Questions 15-19 address tornado events and risk in general, during any time of the year.



15. On a scale from 0 to 10, how *vulnerable* do your feel your surrounding communities are to tornadoes in general (10 = most vulnerable)?

<Least Vulnerable										Most Vulnerable>
0	1	2	3	4	5	6	7	8	9	10
○	○	○	○	○	○	○	○	○	○	○

16. On a scale from 0 to 10, how *prepared* do you feel your surrounding communities are to deal with impacts from tornadoes in general (10 = most prepared)?

<Least Prepared										Most Prepared>
0	1	2	3	4	5	6	7	8	9	10
○	○	○	○	○	○	○	○	○	○	○

17. On a scale from 0 to 10, how *receptive* do your feel the people in your surrounding communities are to your communication of tornado risk in general (10 = most receptive)?

<Least Receptive										Most Receptive>
0	1	2	3	4	5	6	7	8	9	10
○	○	○	○	○	○	○	○	○	○	○

18. In your opinion, how does your community's receptivity to communication of tornado forecasts and risk differ between the cold and warm seasons?

○ More receptive during the warm season

○ Similar receptivity throughout the year

○ More receptive during the cold season

This question is very important to understanding different perceptions across decision-making sectors and geographical regions. Please take your time when answering.

19. What do you perceive to be the largest barriers to communicating tornado risk to your surrounding community in general, during any time of the year?

20. Are you aware of the increasing frequency of cold-season tornadoes, especially in the South and Mississippi Valley regions of the U.S. in recent decades?

○ Yes

○ Not sure

○ No

21. Are people in your community aware of the increasing frequency of cold-season tornadoes, especially in the South and Mississippi Valley regions of the U.S. in recent decades?

○ Yes

○ Not sure

○ No

22. Do you believe your local area is becoming more vulnerable to tornadoes in general?

○ Yes

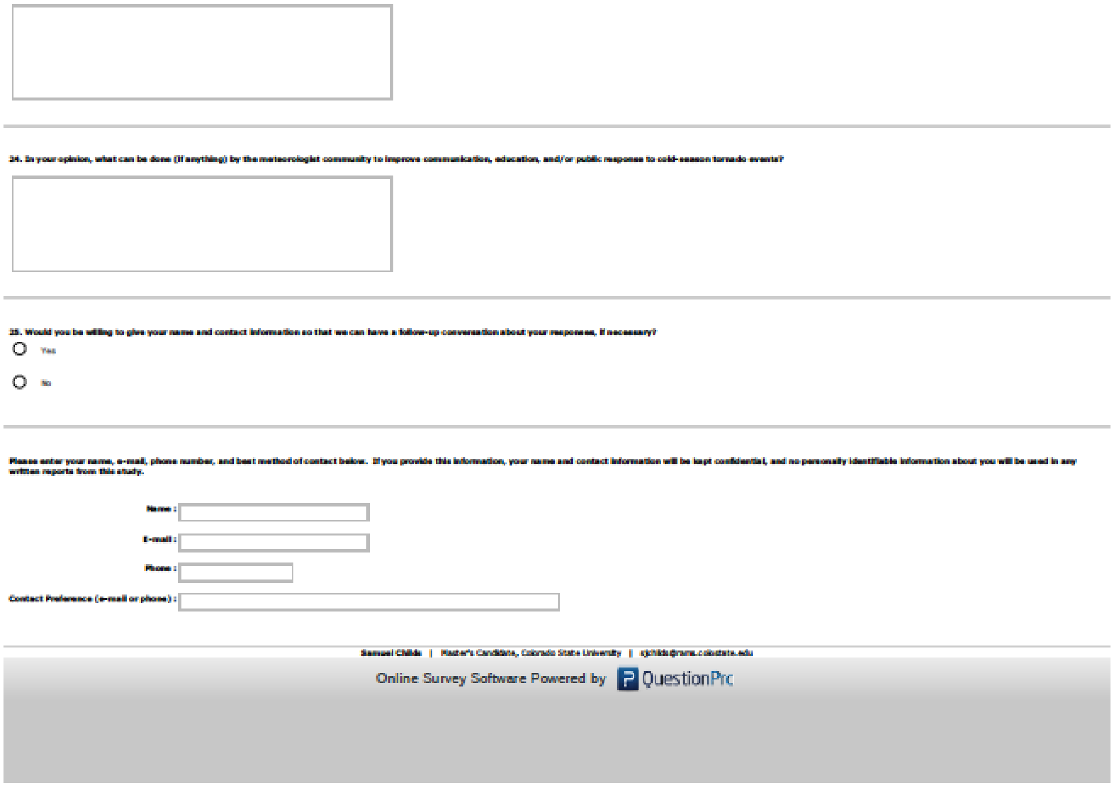
○ Not sure

○ No

Please explain your response.

The following two questions are very important for developing new or improved strategies for mitigation of risk from cold-season tornadoes. Please take time to think and answer. These are the final two open-ended questions in the survey.

23. In your opinion what can be done (if anything) by your office or the emergency management community as a whole to improve communication, education, and/or public response to cold-season tornado events?



24. In your opinion, what can be done (if anything) by the meteorologist community to improve communication, education, and/or public response to cold-season tornado events?

25. Would you be willing to give your name and contact information so that we can have a follow-up conversation about your responses, if necessary?

○ Yes

○ No

Please enter your name, e-mail, phone number, and best method of contact below. If you provide this information, your name and contact information will be kept confidential, and no personally identifiable information about you will be used in any written reports from this study.

Name :

E-mail :

Phone :

Contact Preference (e-mail or phone) :

Samuel Childs | Master's Candidate, Colorado State University | sjchilds@rams.colostate.edu