

**Convective Mode Climatology of Tennessee Tornado Events and Effect on National
Weather Service Warning Processes**

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ABSTRACT

Tennessee resides in the Southeastern United States, a region prone to violent tornadoes on a year-round basis. With one of the highest tornado fatality rates in the country, and a climatology that varies across the state, analysis of storms resulting in Tennessee tornadoes is necessary for improving forecasting techniques and decreasing loss of life. This study analyzed convective modes responsible for Tennessee tornadoes from 2003 to 2014 to determine an association with fatalities, seasonality, day and night, tornado magnitude, regionality, and multiple-tornado days. Chi-squared tests were conducted to determine if these patterns were significant. National Weather Service forecasters from the Morristown, Tennessee, Weather Forecast Office (WFO) were interviewed to gain insight into how convective mode affects tornado forecasting and warning procedures.

Discrete supercells were the overwhelming producer of tornado-related fatalities, higher-magnitude ($\geq$ EF2) tornadoes, and multiple-day tornadoes. Quasi-linear convective systems (QLCSs) produced only non-fatal tornadoes with magnitudes of $\leq$ EF2 during the period; however, QLCS tornadoes were more frequent at night and in winter, when the public may have been more vulnerable. Spring was the most tornadic season, but approximately 37% of tornadoes occurred outside of this season. Multiple-tornado days were major contributors to tornado totals, with just over half of the 427 tornadoes occurring on ten days. I found no clear longitudinal gradient of convective mode or tornado characteristics across Tennessee. Chi-squared results indicated a relationship between convective mode tornado production and fatalities, seasonality, day and night, magnitude, and region of Tennessee. Forecasters commented on the relative ease associated with warning for discrete supercells, resulting in higher probability of detection, lower false alarm ratios, and longer lead times when compared to

QLCSs. Forecasters shared invaluable information concerning staffing considerations and warning decisions during severe weather events. This mixed-methods approach provided a comprehensive assessment of how convective mode affects tornado production and warning procedures, contributing to the emerging field of critical physical geography. Future work will include interviews with forecasters from the Memphis and Nashville WFOs, leading to a more comprehensive discussion of how modes differentially affect warning and forecasting procedures across Tennessee.

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Log of manually assigned convective modes	Radar_Log.pdf
National Weather Service interview guide	NWS_Interview_Guide.pdf

LIST OF ACRONYMS

CAPE	convective available potential energy
CMD	convective mode database
CSV	comma separated values
CWA	county warning area
EF	enhanced Fujita
F	Fujita
FAR	false alarm ratio
HSLC	high-shear, low-CAPE
IRB	Institutional Review Board
LCL	lifting condensation level
MIC	Meteorologist in Charge
NEXRAD	Next Generation Weather Radar
NOAA	National Oceanic and Atmospheric Administration
NWS	National Weather Service
POD	probability of detection
QLCS	quasi-linear convective system
RUC	Rapid Update Cycle
SOO	Science and Operations Officer
SPC	Storm Prediction Center
SWORPS	The Social Work Office of Research and Public Service
TVS	tornadic vortex signature
VORTEX(-SE)	Verification of the Origins of Rotation in Tornadoes Experiment (-Southeast)
WFO	Weather Forecast Office
WSR-88D	Weather Surveillance Radar-1988 Doppler

1. INTRODUCTION

The conterminous United States experiences more tornadoes than any other part of the world. The unique geography of the continent allows warm, moist air from the Gulf of Mexico to encounter cold, dry air from the Rockies and Canada, enabling convective instability necessary for tornadic storms (Jagger et al. 2015). Tornadoes are the fourth-largest weather-related killer in the United States, behind heat, hurricanes, and flooding (Hoekstra et al. 2011). Tennessee resides in the Southeastern United States, a region prone to nocturnal and killer tornadoes on a year-round basis (Ashley 2007; Ashley et al. 2008). As a result, the state has one of the highest tornado fatality rates in the country, further amplified by disproportionate concentrations of mobile homes, poverty, and elderly populations (Ashley 2007; Ashley et al. 2008).

A variety of storm types, referred to as convective modes, are capable of producing tornadoes. The public has a greater chance of being forewarned when meteorologists can accurately predict if a storm is likely to result in tornadoes during a severe weather event. This is especially important when the potential for tornadoes occurs at night, after the majority of the public has gone to sleep. While supercell thunderstorms are the most commonly known producers of tornadoes (Moller et al. 1994), quasi-linear convective systems (QLCSs) are also frequent tornado producers and present their own unique forecasting challenges (Trapp et al. 2005).

Previous work concerning convective modes and tornadoes has focused on the conterminous United States (Trapp et al. 2005; Schoen and Ashley 2011; Grams et al. 2012; Smith et al. 2012; Brotzge et al. 2013), the Midwestern United States (Duda and Gallus 2010), Oklahoma (Hocker and Basara 2008), and nocturnal-only tornadoes (Kis and Straka 2010).

Classification of convective modes is inescapably subjective and each of the researchers used slightly different specifications. While many of these studies discussed regional differences in tornado climatology and dominant storm modes, in-depth analysis on a Southeastern statewide level is lacking, as well as any discussion of how convective mode affects tornado-warning procedures in these areas, other than researcher speculation.

Brotzge and Erickson (2009) found that convective mode varies by region across the country, with cells dominating in the West and the Plains while quasi-linear modes are more prominent in the Southeast. Sherburn and Parker (2014) revealed that the lower Mississippi Valley and south-Atlantic regions are prone to more severe weather events that exhibit high wind shear and low convective available potential energy (CAPE) environments compared to other parts of the United States. These environments are abbreviated as high-shear, low-CAPE (HSLC). The shape and location of Tennessee afford opportunities to study effects of changing east-west topography on convective mode climatology in the Southeastern United States. The eastern portion of the state experiences less tornado risk than the central and western portions (Brown et al. 2016), and characteristics of tornado-producing convective modes may vary longitudinally as well.

Smith et al. (2012) found an association between convective mode and the enhanced Fujita (EF) ratings of tornadoes they spawn. Tornado damage is used indirectly to measure wind speed, resulting in a tornado intensity rating ranging from EF0 (weakest) to EF5 (strongest) (Doswell et al. 2009). The EF scale is a more specific scale that replaced the Fujita (F) scale in 2007, using 28 damage indicators rather than a single United States frame home to assess wind speed (Doswell et al. 2009). The two scales can be considered equivalent for climatological studies (Widen et al. 2013). Nationwide, discrete supercells are the dominant producers of

higher-magnitude (EF2 to EF5) tornadoes (Grams et al. 2012; Smith et al. 2012). Over 95% of the significant hail events and EF3 to EF5 tornadoes in the Smith et al. (2012) study were a result of supercells.

To notify the public of these tornadoes, local National Weather Service (NWS) Weather Forecast Offices (WFOs) issue tornado warnings based on radar imaging and spotter-confirmed sightings (Brotzge and Donner 2013). Warning polygons outline areas of potential risk based on the projected path of the tornado. These polygons replaced the county-based warning system in 2007 (Coleman et al. 2011; Brotzge and Donner 2013). The amount of time between an issued warning and tornado initiation is known as lead time (Bieringer and Ray 1996). Positive lead time occurs when a warning is issued before tornado initiation. A warning issued after tornado touchdown is associated with negative lead time (Brotzge and Erickson 2009). Tornado initiation that occurs simultaneously with a warning is referred to as zero lead time (Brotzge and Erickson 2009). Positive lead times are crucial in affording the public the best chance to seek shelter.

Brotzge and Erickson (2009) found that the Southeastern United States has the lowest proportion of warnings issued with zero and negative lead times, while the Plains region has the shortest (longest) average negative (positive) lead times. The Plains and Southeast typically experience more multiple-tornado events compared to the Midwest and the West (Brotzge and Erickson 2009). These events are often associated with stronger storm systems, allowing for higher probability of detection (POD) (Brotzge et al. 2013) and downstream tornado warnings issued earlier because of upstream tornadoes (Brotzge and Erickson 2009). This leads to greater positive lead times and lower proportions of zero and negative lead times (Brotzge and Erickson 2009). Forecasters use rotation within convective structures, known as tornadic vortex

signatures (TVSs) (Burgess et al. 1976), as clues to tornadic formation. Trapp et al. (1999) examined these TVSs and found that rotation within a QLCS is often less prominent aloft on radar scans, allowing an average of only five minutes of advanced warning to the public. Not all tornadic supercells display clear TVSs aloft, but the storms that do allow for an average of ten minutes extra lead time.

Understanding tornado climatology on a statewide level is crucial to future reduction in loss of life and property in the state of Tennessee. NWS WFO employees rely on their own knowledge of local warning areas to improve their forecasts (NOAA 2016). A study of the convective modes of storms that produce Tennessee tornadoes is necessary to alleviate forecasting challenges, improve POD, and decrease false alarms, wherein a tornado warning is issued and no tornado occurs. Additionally, a Tennessee-focused analysis will better inform policymakers responsible for storm preparation strategies and tornado shelters (Merrell et al. 2005) who operate on a statewide level. For the purposes of this study, I used the Tennessee convective mode database (hereafter referred to as the Smith database) and classification methods developed by Smith et al. (2012) to investigate the spatiotemporal qualities of convective modes spawning tornadoes in Tennessee. This database currently spans from 2003 to 2014. I also conducted interviews with NWS employees at the Morristown, Tennessee, WFO to obtain firsthand accounts of how these modes affect their decisions throughout the tornado warning process. This mixed-methods approach combines both quantitative and qualitative analyses and supports the emerging field of critical physical geography (Lave et al. 2014), which aims to better understand societal impacts in relation to physical geographic phenomena.

1.1 Research Objectives

This study used a mixed-methods approach to understand the convective mode climatology of tornadoes in Tennessee and its implications in tornado warning procedures. First, I examined spatiotemporal patterns of convective modes that have produced tornadoes initiating in or passing through Tennessee from 2003 to 2014. Then, I interviewed NWS employees in the Morristown, Tennessee, WFO to determine how these modes affect tornado forecasting and warning dissemination. The research was guided by the following objectives and supporting questions:

- Objective One: Determine the climatology and characteristics of tornadoes spawned from each type of convective mode (i.e., cell in cluster, cell in line, discrete supercell, QLCS).
 - What proportion of tornadoes is spawned from each convective mode?
 - How does the frequency of tornado production by each convective mode change from day to night?
 - Is there seasonality in the frequency of tornado production by each convective mode?
 - How does the climatology of tornado production by each convective mode vary between the western, central, and eastern portions of the state of Tennessee?
 - How does convective mode correspond to EF intensity?
 - Are specific convective modes more likely to contribute to multiple-tornado days or result in tornado-related fatalities?

- Objective Two: Improve our understanding of convective mode as part of the NWS tornado warning process.
 - How does convective mode affect tornado forecasting and warning procedures?
 - Does convective mode have diurnal effects on warning processes?
 - How may convective mode differentially affect the three WFOs in Tennessee?
 - How does convective mode affect forecasts on multiple-tornado days?
 - How do NWS forecasters view the role of convective mode in POD, false alarm ratios (FARs), and warning lead times?

2. BACKGROUND

A tornado is a vertical, rapidly rotating column of air in constant contact with a cloud base and the ground. Knowledge pertaining to tornadoes has increased substantially over the years as a result of improved radar and satellite data, improvements in computer modeling, and greater availability of in situ observations (Rasmussen et al. 1994; Trapp et al. 2005). However, a single theory on how tornadoes form has yet to be determined. A main focus of field research for the Verification of the Origins of Rotation in Tornadoes Experiment (VORTEX) was tornadic environments and the physics involved in tornado production (Rasmussen et al. 1994). Additional projects such as VORTEX2 (Wurman et al. 2012) and VORTEX-Southeast (VORTEX-SE) (Rasmussen 2015) continue to add to this knowledge. While specifics pertaining to tornadogenesis remain unknown, research suggests that vertical temperature and moisture gradients lead to instability and provide the energy needed for tornadic storms to form (Schultz et al. 2014). High humidity at the surface and wind shear are also necessary elements that aid in tornadogenesis (Schultz et al. 2014).

The transfer of heat through movement of fluid is known as convection (Doswell 2001). Moist convection, a necessary element for storm initiation, occurs in the atmosphere when air parcels near the surface lift, cool, and condense into clouds (Doswell 2001; Bluestein 2008). Lifting results when air masses are heated or come in contact with temperature or moisture surface boundaries, such as warm and cold fronts or drylines (Bluestein 2008). Many factors help determine whether convection will turn severe and which storm mode will develop, including air parcel buoyancy and wind shear (Moller et al. 1994; Doswell 2001).

2.1 Convective modes

2.1.1 Distinguishing between modes

Tornadoes are produced by a variety of convective storm types, which are referred to as convective modes. Understanding the evolution of convective modes leads to better severe weather forecasts (Thompson and Edwards 2000; Andra et al. 2002; Edwards et al. 2002; Dial et al. 2010). Unfortunately, classification of convective modes is unavoidably subjective because of radar resolution, focus of research, and unclear definitions of various storm modes (Gallus et al. 2008; Smith et al. 2012). Storms can morph from one mode to another or feature a mixture of mode characteristics within one system, especially in the cool season (Smith et al. 2012). Quantitative definitions of convective modes are not explicit, leaving researchers to select their own distinguishers during classification, including reflectivity thresholds and spatiotemporal qualities.

Examples of convective modes include the following: discrete supercells, cells in a cluster, cells in a line, and QLCSSs. Supercells, or simply “cells,” are distinguished by the presence of a persistent mesocyclone, a region of rising, rotating air extending through a great depth of the storm (Doswell and Burgess 1993). As the name implies, discrete cells are storms that are not attached to surrounding systems. Cells can also form in clusters or be embedded in lines of convection, consisting of separate mesocyclones connected by radar reflectivity (Gallus et al. 2008; Duda and Gallus 2010). Smith et al. (2012) chose an arbitrary 35 dBZ reflectivity threshold at the lowest radar elevation tilt to distinguish discrete cells from other nearby convection. Hook echoes, regions of low-level radar reflectivity located on the backside of some supercells, are commonly associated with tornado initiation (Markowski 2002) and, when present, help in identifying cellular convection. QLCSSs consist of continuous convection

oriented linearly, typically over 100 km in length (Trapp et al. 2005; Smith et al. 2012).

Differentiating between QLCSs and cells in lines can be very challenging, the biggest indicator being the depth of rotation within the structure (Smith et al. 2012). Unlike cellular mesocyclones, QLCSs tend to have much shallower areas of rotation, called mesovortices (Trapp and Weisman 2003; Weisman and Trapp 2003). Continuous reflectivity at or above the 35 dBZ threshold for at least 100 km, in addition to an aspect ratio of 3 to 1 or greater, was necessary for QLCS classification in the Smith database.

Despite variations in convective mode categories, the conclusions reached by Smith et al. (2012) resemble many previous studies, with the exception of one. Kis and Straka (2010) used a much broader definition for a QLCS that did not require continuous reflectivity for at least 100 km, leading to some discrete cells and cells in lines to be classified as QLCSs. The authors concluded that QLCSs are responsible for the majority of significant nocturnal events, while Smith et al. (2012) found diurnal qualities of cells and QLCSs to vary significantly by region. Studies also disagree on the seasonality of dominant storm modes. Trapp et al. (2005) claimed QLCSs were the dominant producer of tornadoes during cooler seasons across the United States, while Smith et al. (2012) described fairly equal chances of a tornado from discrete cells and cells in clusters compared to QLCSs and cells in lines from November through February. In addition to differences in storm mode classification, sample size may have produced these seasonal discrepancies. Trapp et al. (2005) used three years of data for their research while Smith et al. (2012) used nine years.

2.1.2 Forecasting challenges

Forecasting and warning procedures vary by convective mode. QLCSs offer unique forecasting challenges because of their size and lack of prominent rotation. Tornadoes have the potential to initiate rapidly at any point along their ≥ 100 km length (Trapp et al. 2005), making detection and warning dissemination very difficult. QLCSs produce tornadoes rather consistently throughout the year (Grams et al. 2012), so forecasters must always be alert when these modes are present. Trapp et al. (2005) suggested as many as 12% of QLCS tornadoes still go unreported, compared to only 1% from supercells. Convective mode causes a challenging tornado forecast in the Southeast during winter because of the equal distribution of tornadic QLCSs and supercells, and a fairly even chance of QLCS tornadoes throughout the day and night during the cool season (Grams et al. 2012).

QLCS and cluster modes are more common on single-tornado days whereas significant tornado outbreaks occur more frequently with discrete supercells (Grams et al. 2012). Providing a positive warning lead time is hardest for the first tornado of the day (Andra et al. 2002; Brotzge and Erickson 2009). Isolated tornadoes also prove challenging in regard to warning dissemination, while outbreaks or clusters of tornadoes allow for easier advanced warning (Brotzge and Erickson 2009). These cases stress the importance of high-resolution radar to differentiate between subtle characteristics in storm modes (Thompson and Edwards 2000) and highlight the challenge of tornado forecasting during QLCS and cluster modes. The nationwide installation of Next Generation Weather Radar (NEXRAD) Weather Surveillance Radar-1988 Doppler (WSR-88D) has alleviated some forecasting challenges (Simmons and Sutter 2005; Brotzge and Donner 2013).

Environmental parameters and synoptic patterns offer clues about future convection and tornado potential. Brotzge et al. (2013) determined that higher CAPE leads to higher POD and warning lead times. CAPE, storm-relative helicity, stability, veering, and wind speed vary by region and convective mode (Grams et al. 2012). Familiarity with the local climatology of these weather variables provides forecasters with a tool for more accurate severe weather forecasts. Grams et al. (2012) found that the Southeast tends to have more stability and less buoyancy compared to the Plains and Midwest. The authors also found greater 500-hPa height falls in the vicinity of Southeast tornadoes 12 hours prior to initiation. Throughout the mid-Atlantic and Southeast, QLCS tornadoes are more common in HSLC environments compared to environments without CAPE or shear restrictions (Davis and Parker 2012). Discrete-supercell tornadoes are less common in HSLC environments. Sherburn and Parker (2014) demonstrated that the Morristown, Tennessee, WFO has a much higher tendency for severe weather events associated with HSLC environments, particularly $\geq$ EF2 tornadoes, compared to the Memphis and Nashville WFOs. Tornado events associated with HSLC environments peak in the spring in the Southeast, with additional occurrence in the fall and winter months. HSLC severe weather events are essentially non-existent in the summer months in the Southeast.

The 3 May 1999 tornado outbreak in Oklahoma offers an example of the difficulties in forecasting tornadic storm modes and the importance of understanding their characteristics. The level of severe weather risk remained uncertain throughout the day because of issues discerning which type of convective modes would form and when storms would initiate (Edwards et al. 2002). Additionally, the weather turned severe around shift change, leaving newly arrived forecasters little time to assess the situation before the first severe weather watches were issued. Supercells proved to be the dominant storm mode for the Oklahoma outbreak, and the

consistency of convection and amount of tornadoes allowed for superior warning lead times. The local NWS office issued a warning or severe weather statement every 3.8 minutes for eight hours throughout the afternoon and evening (Andra et al. 2002).

2.2 Southeast vulnerabilities

Most people associate “Tornado Alley,” a loosely defined region of the Central Plains including Kansas, Oklahoma, and northern Texas, with the greatest tornado threat in the United States. While tornadoes do occur in greater numbers in the Plains, the Southeast experiences more killer and nocturnal tornadoes per year (Ashley 2007; Ashley et al. 2008; Gagan et al. 2010). Arkansas, Tennessee, and Mississippi are associated with the most tornado fatalities (Ashley 2007), and are located outside the traditional “Tornado Alley.” In their two-year study, Brotzge et al. (2013) found that 97% of tornado fatalities were associated with supercells across the United States, with supercells in lines responsible for the most deaths in the Deep South. Over 90% of tornado-related fatalities in a ten-year, nationwide study by Schoen and Ashley (2011) were the result of supercells, 78% of which were discrete cells. This study spanned from 1998 to 2007. During this time period, Tennessee was associated with the most deaths from QLCSs (17% of total statewide fatalities), with one bow echo responsible for half of these fatalities. The state also had another 17% of fatalities resulting from two storms with cell-in-line convection (Schoen and Ashley 2011).

While spring is typically regarded as “tornado season” in the Plains, the Southeast possesses a lower, year-round risk of tornadoes that can catch the public off-guard (Brooks et al. 2003). Dixon et al. (2011) found that, statistically, there is no reason to deem the Southeast, or “Dixie Alley,” separate from “Tornado Alley”; however, tornadoes in the Southeast tend to have

longer path lengths compared to those in the Plains. Tornado fatalities are highest in March through June throughout the Plains and South, but a secondary, smaller maximum occurs in the South during the fall (Ashley 2007). Cool season storms have a tendency to move faster than their warm season counterparts and, combined with the hilly, tree-lined terrain of the Southeast, can mean less lead time and POD of tornadoes (Gagan et al. 2010). Tornadoes that occur when the public is least aware, such as at night or in the cool season, possess a greater chance of going unwarned (Brotzge and Erickson 2010) and thus pose a specific risk to the Southeast. Regardless of the differences or similarities between the “Alleys,” the Southeast should be recognized as a place where tornadoes can and do occur with regularity if fatality rates are to be reduced.

2.2.1 Nocturnal tornadoes

While tornado-related deaths during the day have decreased over time, deaths attributed to nocturnal tornadoes have remained steady (Ashley et al. 2008). Nocturnal tornadoes are more difficult to spot, especially in the terrain of the Southeast, and occur when the majority of the public is sleeping. When tornado warnings are issued after the evening news, they are often unheard if the home is not equipped with a National Oceanic and Atmospheric Administration (NOAA) weather radio or cellphone emergency alerts. Nocturnal tornadoes are more common in the Southeast than the Central Plains, and comprise over 45% of tornadoes in Tennessee (Ashley et al. 2008). These nocturnal tornadoes are two times more likely to kill compared to their daytime counterparts (Ashley et al. 2008).

Studies that focus on nocturnal tornadoes are needed to better understand the diurnal differences in the environment that contribute to tornadogenesis (Kis and Straka 2010).

Environments deemed unfavorable for tornado development in the afternoon and early evening can give way to significant nocturnal tornadoes (Kis and Straka 2010). Nocturnal forecasters who rely on daytime tornado indicators can be misguided because of diurnal changes in boundary layer heights, convective stability, and low-level jets (Kis and Straka 2010). Most studies use a single sunrise and sunset time for nocturnal classification, even though sunset can vary by three hours in some locations throughout the year (Ashley et al. 2008). With this method, many tornadoes are misclassified and results are negatively affected. Proper assignment of tornadoes as nocturnal requires local sunrise and sunset times throughout the year (Ashley et al. 2008).

2.2.2 Mobile homes and language barriers

While tornado-related fatalities have declined over the years, the proportion of deaths in mobile homes has risen (Brooks and Doswell 2002). Sutter and Poitras (2010) reported that less than 8% of housing units consisted of manufactured homes between 1985 and 2007, yet 43% of tornado fatalities occurred within these structures. Ashley et al. (2008) found that over 60% of mobile home fatalities occurred at night, further emphasizing vulnerability of these units, especially to nocturnal tornadoes, and the necessity for proper warning systems. The Southeast in particular has seen a rise in mobile homes over the years, and improvements in warning lead times will do little to prevent tornado-related deaths in these structures at night. More adequate housing and shelters, along with better warning dissemination, must be implemented to reduce fatality rates (Brooks and Doswell 2002).

Language barriers also hinder the reduction of tornado-related fatalities (Donner et al. 2012). With most warnings being issued only in English, non-English speakers must rely on

other sources such as family and friends. Donner et al. (2012) found that Hispanics in one Missouri community seek information from a church leader during severe weather events. The higher fraction of poor and elderly throughout the South may also play a role in tornado-related fatalities (Ashley 2007). These groups could have limited access to warnings and proper shelter. Social science approaches are needed to better understand public access and response to tornado warnings across varied age groups, income brackets, and language barriers (Ashley et al. 2008; Gagan et al. 2010).

2.3 Warning the public

2.3.1 POD and lead time

POD and lead time are highly dependent on convective mode. Brotzge et al. (2013) found POD and lead time for supercells (85.4% and 16.8 minutes, respectively) to be much higher than for non-supercells (45.8% and 11.9 minutes, respectively). Negative lead times for non-supercells occur over three times more frequently than supercells (17.8% versus 5.2%, respectively) (Brotzge et al. 2013). Higher-magnitude tornadoes have a higher POD (92.2%) than lower-magnitude (EF0 to EF1) tornadoes (72.5%), and POD increases with tornado intensity regardless of convective mode. Lead times do not show the same improvement with intensity. Storms closer to the radar tend to have higher POD. QLCSs with farther radar proximity provide challenges because of their shallowness and lack of broad areas of circulation (Brotzge et al. 2013). POD increased by 10–15% with the installation of NEXRAD (Bieringer and Ray 1996), and mean lead times increased from 5.3 to 9.5 minutes (Simmons and Sutter 2005).

The Plains and Southeast, prone to multiple-tornado days, have higher average lead times compared to the Midwest and West (Brotzge and Erickson 2009). March and April tend to have higher negative lead times because of a nationwide spike in QLCS modes (Brotzge and Erickson 2009). Populated areas tend to have shorter average lead times compared to more rural areas (Brotzge et al. 2013). This can be attributed to the rise in zero and negative lead times on tornadoes reported by spotters that would otherwise have been missed in unpopulated locations (Brotzge and Erickson 2010). Once these lead times are removed, the average warning times are more uniform (Brotzge et al. 2013).

Simons and Sutter (2008) found that fatalities decrease as lead times approach 15 minutes, but lead times greater than 15 minutes are not effective in reducing fatality rates. The authors surmised that the public takes longer lead times less seriously, believing warnings to be false alarms when tornadoes do not appear right away. However, in a survey performed by Hoekstra et al. (2011), the average preferred lead time for tornado warnings was 34 minutes. If given lead times of one hour or greater, many participants claimed they would not feel as threatened by the situation, and some would choose to leave the area instead of taking shelter. This suggests that efforts to increase warning lead times may be detrimental to reducing fatality rates and communicating the seriousness of the situation to the public (Hoekstra et al. 2011; Brotzge et al. 2013). Furthermore, the most fatal tornadic storm modes already have the greatest lead times and POD, so further attempts to increase lead times on low-fatality, non-supercell systems may unintentionally increase overall FARs and reduce credibility in supercell warnings (Brotzge et al. 2013).

2.3.2 Warnings and FARs

In the United States, 122 NWS WFOs exist, three of which are in Tennessee (NOAA 2016). Located in Morristown, Nashville, and Memphis, each Tennessee office is responsible for forecasting weather in several counties across the state and bordering states, called county warning areas (CWAs) (Fig. 1) (All figures and tables are located in the Appendix). Forecasters in each WFO are familiar with localized weather patterns and topography, allowing for more accurate forecasts (NOAA 2016). Local WFOs issue a variety of weather watches and warnings, including tornado warnings (NOAA 2016), but all severe thunderstorm and tornado watches are issued by the Storm Prediction Center (SPC) in Norman, Oklahoma (NOAA 2015).

The likelihood of surveyed individuals to respond to weather warnings is positively associated with their perceived trust in their local NWS WFO (Ripberger et al. 2015a). Indirectly measuring public response to tornado warnings, Simmons and Sutter (2009) determined that injuries and fatalities increase as FARs increase. However, as Donner et al. (2012) pointed out, a false alarm is defined differently by the public and the NWS. If a warning is issued and a tornado occurs one county over, an individual may still view this as a false alarm because their neighborhood did not experience a direct hit. The NWS would consider the warning to be a success because a tornado occurred within a warning polygon. Using interviews of Louisiana, Missouri, and Tennessee residents, Donner et al. (2012) found that false alarms lead to an increase in the amount of time individuals take to seek shelter, but ultimately do not affect their choice of action. The Southeast and Midwest have higher FARs compared to the Plains and West. FARs increase as population density increases (within 50 km of radar) and decrease with distance from radar (due to fewer issued warnings) (Brotzge et al. 2011). FARs

are higher for isolated and weaker convective systems, and during non-peak times such as in winter and overnight (Brotzge et al. 2011).

These findings stress the importance of understanding diurnal and seasonal patterns in regional tornado-producing convective modes for the benefit of forecasts and warning dissemination. Clear communication between weather authorities and the public are crucial in explaining the severity of severe weather situations and eliciting the appropriate actions (Ripberger et al. 2015b). The public uses television and commercial radio as main sources for tornado warning information (Coleman et al. 2011). Telephone calls, sirens, and NOAA weather radios (Hammer and Schmidlin 2002) are also common resources, and more recently the internet, smart phone alerts, and social media have been used for warning dissemination (Brotzge and Donner 2013). Television and local radio cannot properly warn the public when they are sleeping, and sirens are not available in all communities. When tornadoes hit Jackson, Tennessee, overnight on 4 May 2003, some residents were awoken by sirens with minutes to spare while others slept through the alarm (Paul et al. 2003). Additionally, some towns use sirens for multiple purposes, which can lead to general confusion (Donner et al. 2012). A future reduction in tornado-related fatalities depends on improvements in warning dissemination (Paul et al. 2003; Ashley et al. 2008; Gagan et al. 2010) and an understanding of regional risk (Ashley 2007; Gagan et al. 2010) and vulnerability (Brooks and Doswell 2002; Ashley et al. 2008; Donner et al. 2012), especially as population density continues to increase nationwide (Brotzge and Donner 2013).

3. DATA

I obtained tornado data from the SPC (located online at <http://www.spc.noaa.gov/gis/svrgis/>). The dataset provides detailed information on each confirmed tornado in the United States from 1950 to the present day, including date, time, magnitude, track location and length, and fatalities (Schaefer and Edwards 1999). Issues with the tornado database are well documented; most notable is the apparent rise in frequency throughout the record. This is generally attributed to advancements in technology and reporting practices (Verbout et al. 2006), population sprawl (Elsner et al. 2013), and storm spotters (McCarthy 2003), which have allowed more tornadoes to be observed and recorded, as opposed to any significant physical increase in actual tornadoes. The detection of lower-magnitude tornadoes has increased nationwide as a direct result of NEXRAD technology detecting tornadoes that would have otherwise gone unreported (Angel 2002; Coleman and Dixon 2014). The implementation of NEXRAD in Morristown, Nashville, and Memphis, Tennessee, in 1995 has improved the detection of tornadoes occurring in forested areas, rough terrain, and at night (Gagan et al. 2010).

Another shortcoming of the SPC database is the lack of resolution in fatality information. Fatalities for each tornado are noted, but without regard to specific locations along the track. More detailed information about where these fatalities took place, along with information regarding gender, age, and building structure, can be found in the NOAA Storm Events database (located online at <https://www.ncdc.noaa.gov/stormevents/>), but as Ashley (2007) notes, more detailed fatality information is needed for the benefit of future research.

I downloaded the SPC dataset as a shapefile and manipulated it within ArcGIS before importing it into R. The shapefile contains complete tornado paths instead of county-segmented

data (wherein tornadoes crossing multiple counties are broken down into separate entries) found in other SPC tornado products. I selected all tornadoes initiating in or passing through the state of Tennessee from 2003 to 2014 based on the corresponding years within the Smith database, resulting in 427 total tornadoes (Fig. 2). By using data gathered after the statewide installation of NEXRAD, most of the aforementioned issues with the tornado database are essentially eliminated.

Bryan T. Smith of the SPC provided the Smith database that assigns convective modes to a portion of Tennessee tornadoes from 2003 to 2014. This database uses tornado data segmented by county and filtered hourly for the highest-magnitude report on a Rapid Update Cycle (RUC) model (Benjamin et al. 2004) 40-km horizontally spaced analysis grid (Smith et al. 2012). Not all Tennessee tornado events were assigned convective modes because of this filtering process. To create a complete dataset of observed tornadoes, I assessed the remaining entries in the SPC database manually. The Smith database distinguishes between six different convective modes: discrete supercell, cell in cluster, cell in line, cluster, QLCS, and bow echo. Some difficult cases were additionally labeled as linear hybrids when the convection possessed both supercell and QLCS characteristics, but in all cases a single convective mode was ultimately decided upon by Smith and his colleagues. The database contains additional information about nearby environmental conditions, including precipitable water, lifting condensation level (LCL) height, and CAPE, that are derived from a combination of gridded surface data and upper-air data and incorporated into the RUC model. These parameters will not be used in this study.

For my research, I used a slightly modified version of the convective mode classifications outlined in Smith et al. (2012). Very few storms in the Smith database were classified as bow echoes, which are subsets of QLCSs (Weisman and Trapp 2003; Trapp et al. 2005; Smith et al.

2012) composed of quasi-linear convection that “bows” into a comma-like shape due to low-level unidirectional winds (Trapp and Weisman 2003). I combined these entries with the QLCS category. Only one tornado during the period of study falls into the convective mode category of “cluster.” I labeled it as a “cell in cluster” for this study. This results in four separate convective mode classifications: cell in cluster (Fig. 3a), cell in line (Fig. 3b), discrete supercell (Fig. 3c), and QLCS (Fig. 3d).

Sunrise and sunset times for the cities of Knoxville, Nashville, and Memphis were necessary to determine which tornadoes were nocturnal. I obtained these times from the United States Naval Observatory (available online at http://aa.usno.navy.mil/data/docs/RS_OneYear.php).

I collected data concerning the impact convective mode has on the tornado forecasting and warning process in Tennessee through interviews with NWS forecasters from the Morristown, Tennessee, WFO. Open-ended questions related to tornado forecasting, warning procedures, and convective mode were posed and forecaster responses were recorded (with their consent) and transcribed.

4. METHODS

Because the Smith database used county-segmented data and did not contain all of the reported tornadoes in Tennessee between 2003 and 2014, the entries had to be manually matched to appropriate tornadoes in the SPC database. Using ArcGIS 10.3, I selected each tornado in the SPC tornado shapefile that intersected the state of Tennessee from 2003 to 2014. I exported the resulting attribute table of the dataset as a comma separated values (CSV) file. Each line of the resulting CSV file represented one tornado and consisted of the aforementioned information collected by the SPC. I matched convective modes from the Smith database to the corresponding tornadoes in the CSV file using date, time of initiation, latitude, longitude, and magnitude as guides.

I assigned convective modes to the tornadoes that were filtered from the Smith database with the aid of archived NEXRAD level II radar (obtained from Amazon Web Services at <https://s3.amazonaws.com/noaa-nexrad-level2/index.html>). The Gibson Ridge radar viewer (<http://www.grlevelx.com/>) was used to display the radar. I referenced scans from the radar site closest to each storm event. In cases where the nearest radar images were not available, or when additional imaging was needed to clarify convective mode, I also referenced other nearby radar sites. I determined convective mode at the starting location of the tornado using the radar scan occurring immediately prior to the time of tornado initiation. I also referenced preceding and subsequent radar scans in instances of convective mode ambiguity. By observing how the storm changed as it traveled, I obtained additional information about storm characteristics and the depth and strength of rotation that could be used to more accurately determine convective mode at the time of tornado initiation. The Smith database was used as a reference guide to ensure consistent storm classification. The filtering process used to create the Smith database meant

that there were often additional tornadic modes near the manually assigned storms. In many cases I could reference these storms to aid my classification. All 91 manually assigned convective modes are in the attached Radar_Log.pdf. I adjusted the time, and occasionally the date, of some of these tornadoes based on radar evidence, as did Smith et al. (2012).

Multiple radar elevation scans and products were referenced to arrive at a correct convective mode classification. Most important were the radar reflectivity product depicting rainfall intensity (as seen in Fig. 3), and storm-relative velocity product revealing areas of rotation, referred to as velocity couplets, within the storm (Fig. 4). Lowest-elevation radar tilts were given priority (typically 0.5° above the horizon) while subsequent higher scans were consulted as necessary, especially when distinguishing a cell in line from a QLCS. A clearly defined TVS appearing through multiple radar tilts was indicative of a mesocyclone and a cellular convective mode. The mesocyclone was always immediately surrounded by convection with reflectivity above the aforementioned 35-dBZ threshold. If this convection was completely isolated from other high-reflectivity convection by regions below 35 dBZ, I labeled the storm as a discrete supercell. Sometimes a hook echo was also present.

If a mesocyclone was connected to other areas of rotation by reflectivity above 35 dBZ, I labeled the storm as either a cell in line or cell in cluster. I labeled a storm as cell-in-line convection when areas of rotation and reflectivity were oriented in a linear fashion. Otherwise, I determined the mode as cell-in-cluster convection. In some cases, nearby rotation was not always present but the surrounding radar reflectivity indicated separate “clusters” or areas of intense rainfall that were connected to the mesocyclone by reflectivity above 35 dBZ. An additional radar product showing echo tops, or the top of the storm, was beneficial in these cases. Dominant storm updrafts were visible in this product, and I was able to determine if a storm was

discrete or accompanied by other cells, even when these cells did not exhibit clear rotation at the time. I labeled these storms as either cell in cluster or cell in line based on the orientation of the echo tops and reflectivity. I classified weaker rotation, and a line of convection with reflectivity above 35 dBZ for a distance of ≥ 100 km, as a QLCS. Rotation was much weaker and shallower than cell rotation, and sometimes not visible on the radar. An echo top exhibiting an updraft was either not present or much shallower and weaker than cell echo tops.

With each tornado properly assigned a convective mode, I loaded the CSV file (hereafter referred to as the convective mode database, or CMD) into R. I divided the tornadoes into three bins based on their point of origin, along longitudinal lines 87.5° W and 85.0° W, and appropriately labeled each as occurring in the eastern, central, or western region of Tennessee. Sunrise and sunset data for Knoxville, Nashville, and Memphis were used to determine if each event occurred at night or during daylight hours. Tornadoes that initiated along or west of 87.5° W were assigned Memphis sunrise and sunset times, tornadoes that initiated east of 85.0° W were assigned Knoxville sunrise and sunset times, and the remaining central tornadoes were assigned Nashville times. Any tornadoes that initiated outside of the state were still in reasonable proximity to these cities to not warrant separately assigned sunrise and sunset times. A tornado was considered nocturnal if the time of initiation fell between the sunset and sunrise times of its respective bin. This method allows for a more accurate classification of nocturnal tornadoes, as stressed by Ashley et al. (2008).

To complete Objective One, I used the R statistical programming language to calculate the proportions of tornadoes in the CMD belonging to each of the four categories of convective modes. Daytime and nocturnal ratios for each mode were calculated, in addition to percentages based on eastern, central, or western Tennessee tornado initiation. I isolated variations in

convective mode by season, using the following meteorological seasonal breakdowns: March through May for spring, June through August for summer, September through November for fall, and December through February for winter. I calculated percentages of each convective mode with respect to tornado magnitude, fatalities, and multiple-tornado days. Convective patterns among lower-magnitude and higher-magnitude tornadoes were evaluated, in addition to each EF rating individually. When analyzing the relationship between tornado fatalities and convective mode, I recognized that not all of these fatalities occurred within the state of Tennessee. This is because of tornadoes initiating or dissipating outside of the state, in particular the long-track tornado of 27 April 2011 that initiated in Alabama, resulting in 72 fatalities. Tornadoes that occurred on days where the total tornado count was ten or greater were examined for patterns in convective mode on especially active days. These are referred to as “multiple-tornado days.” A day was defined as a 24-hour period starting at 0000 UTC. I compared results with previous research to determine which nationwide and regional patterns of tornadic convective mode match Tennessee patterns. Differences and similarities between my results and previous research were identified and discussed.

I used Pearson’s chi-squared test for independence (McHugh 2013) to determine if a relationship existed between each tornadic convective mode and other categorical variables, consisting of fatalities, seasonality, day and night, magnitude, and regions of Tennessee. A contingency table was produced for each chi-squared test to determine the total number of tornadoes that resulted from the combination of each convective mode and each of the aforementioned categorical variables. The calculation of the chi-squared statistic is as follows:

$$\chi^2 = \sum \frac{(f_o - f_e)^2}{f_e}$$

where f_o = the observed tornado counts in each cell of the contingency table and f_e = the expected frequency of tornadoes in each cell (where no relationship exists between the variables). The expected frequencies are calculated with the following formula:

$$f_e = \frac{(\text{row total} * \text{column total})}{\text{total } N}$$

where $N = 427$ in this study. At least 80% of the expected frequencies must exceed five and all must exceed one in order for Pearson's chi-squared test to be valid for a table larger than two by two. The null hypothesis states that the two selected variables are independent of one another, suggesting no relationship occurs between convective mode and the other chosen variable with regard to tornado production. I rejected the null hypothesis when $p < 0.05$, indicating a relationship between the variables.

To accomplish Objective Two, Dr. Kelsey Ellis, Dr. Lisa Reyes Mason, and I interviewed three NWS forecasters in the Morristown, Tennessee, WFO. I completed Institutional Review Board (IRB) training and received IRB approval for human subjects research before recruiting interview participants. I sent an email to the Morristown WFO Meteorologist in Charge (MIC) and Science and Operations Officer (SOO), requesting three to five interview participants. They selected three interviewees based on availability and willingness to be interviewed. The interviews were conducted in-person at the Morristown NWS office. Each forecaster was interviewed independently, and interviews lasted 45 to 60 minutes. We posed open-ended questions, guided by the results of completed Objective One, related to tornado forecasting and warning dissemination with regard to different convective modes. An outline of topics covered can be found in the attached NWS_Interview_Guide.pdf.

Interviews were recorded with participant consent, and later transcribed by The Social Work Office of Research and Public Service (SWORPS) at the University of Tennessee, Knoxville. Transcribers signed a pledge of confidentiality. I used a thematic analysis approach (Braun and Clarke 2006) to analyze interview responses by reviewing the transcripts provided by SWORPS and noting common themes in convective mode forecasting techniques, challenges, and warning dissemination. I related these qualitative results to my results from Objective One and other published literature to provide a more thorough discussion about the climatology of tornado production by convective mode, and potential effects on NWS procedures and public safety.

5. RESULTS

I found 427 tornadoes reported in Tennessee during the study period (2003 to 2014). Cellular convective modes (including discrete cells and cells in clusters and lines) produced 79.6% of tornadoes (Table 1). The remaining tornadoes were produced by QLCSs. Cells in clusters were the top producers of tornadoes, and cells in lines produced the fewest tornadoes. A forecaster from the Morristown, Tennessee, NWS WFO stated that supercells are a “prime storm mode for tornado formation.” He said discrete supercells, in particular, are isolated and able to organize without interference from nearby convection. He noted that linear convection, such as a QLCS, has a harder time maintaining strong enough inflow to support rotation because nearby outflow can cut it off. As a result, a large tornado is much less likely to form.

5.1 Fatalities

A total of 200 fatalities were attributed to the tornadoes during this study period. Just under half of the total fatalities occurred nocturnally. Discrete-supercell tornadoes resulted in 173 deaths (86.5% of total). Sixty-five of these fatalities (37.6% of discrete-supercell fatalities) occurred at night. Cell-in-cluster tornadoes led to 16 fatalities, nine of which (56.3%) took place at night. Cell-in-line tornadoes were linked to 11 fatalities, all nocturnal. No deaths were reported in association with QLCS tornadoes.

I produced a contingency table as part of the Pearson’s chi-squared test for independence (Table 2). All expected fatality totals were greater than five (though some of the observed frequencies were less than five), supporting the use of a chi-squared test. Discrete-supercell tornadoes resulted in more fatalities than expected, while cell-in-line and QLCS tornadoes resulted in fewer than expected. The chi-squared test was significant, χ^2 ($df = 3$, $N = 427$) =

25.51, $p < 0.01$. The null hypothesis is rejected, suggesting that a relationship exists between the convective mode that produced a tornado and the likelihood of that tornado to cause fatalities.

5.2 Day and night

I found 203 nocturnal tornadoes in Tennessee from 2003 to 2014 (47.5% of total tornadoes). Of the cell-in-cluster tornadoes, 63.3% occurred during the daytime. This mode was the top producer of tornadoes during daylight hours (39.3% of total daytime tornadoes) (Fig. 5). Conversely, 65.5% of QLCS tornadoes occurred at night. This mode was the top producer of nocturnal tornadoes (28.1% of total nocturnal tornadoes). Cells in lines produced the fewest nocturnal tornadoes out of all convective modes (21.2 %). Convective mode was relatively evenly distributed at night compared to during the day, where cellular modes produced the majority of tornadoes.

These results are supported by my chi-squared contingency analysis (Table 3). QLCS tornadoes produced fewer (more) daytime (nocturnal) tornadoes than expected. Cell-in-cluster tornadoes produced more (fewer) daytime (nocturnal) tornadoes than expected. All expected tornado totals in the contingency table were greater than five and the test was significant, $\chi^2 (df = 3, N = 427) = 19.01, p < 0.01$. The null hypothesis is rejected, indicating an association between day/night tornado production and convective mode.

Morristown NWS forecasters discussed how tornado-warning procedures change between day and night. One forecaster stated that the eastern region of Tennessee often gets “leftover” convection from the rest of the state, as storms likely start during the day toward the west, reaching the Knoxville area at night. He said these storms are harder to warn because

forecasters must rely solely on their training and radar images without eyewitnesses reporting wall clouds or funnels.

The forecasters were concerned about the potential challenges associated with preparing for nocturnal events, both by the WFO and the public. Morristown forecasters work three shifts, alternating their schedules on a weekly basis. In the case of severe weather, these forecasters often show up early to shifts so they can be better prepared. It was mentioned that staffing can be difficult in the middle of the night in cases where the weather quickly turns severe, leading to stressful situations if extra forecasters cannot be reached. In efforts to increase public awareness and decrease loss of life from nocturnal tornadoes, Morristown forecasters provide statements via social media and the evening news to inform viewers of the likelihood of tornadoes overnight, giving the public time to prepare for the event instead of going to bed unaware.

5.3 Seasonality

Spring ranked highest in seasonal tornado totals (63.5% of total), and was the most tornadic season for each of the convective modes (Fig. 6). Winter ranked second in total tornado count (16.9% of total), and summer ranked lowest (6.1%). Cells in clusters and discrete supercells were responsible for 63.8% of all spring tornadoes (33.2% and 30.6%, respectively). Cells in lines and clusters produced 72.4% of fall tornadoes (39.7% and 32.8%, respectively). QLCSs and discrete supercells spawned 79.2% of tornadoes in winter (45.8% and 33.3%, respectively). Cells in clusters produced 73.1% of tornadoes during summer months.

Results from my chi-squared contingency analysis show that cell-in-cluster tornadoes occurred more (less) often in summer (winter) than expected (Table 4). Cell-in-line tornadoes occurred more (less) often in fall (winter) than expected. Discrete-supercell tornadoes occurred

more often in spring and winter than expected. This mode also produced less tornadoes than expected in the fall. QLCs underproduced tornadoes in the spring and overproduced tornadoes in the winter. All expected totals of tornadoes in the contingency table were above five and the test was significant, $\chi^2 (df = 9, N = 427) = 79.0, p < 0.01$. The null hypothesis is rejected, indicating that the tornadic capabilities of convective modes are associated with seasonality. I did not analyze the combined role of seasonality and convective mode on nocturnal tornadoes because of the small sample size after delineating into subcategories.

The majority of comments made by Morristown NWS forecasters on the combined effect of seasonality and convective mode on tornado-warning procedures were basic observations of seasonality of tornadoes in their CWA. They all stated that spring is the most active season, with a secondary season occurring in the fall and winter months. One forecaster said he felt the season started in November and continued through May, with activity increasing in late February and early March through the spring season. He recalled bad outbreaks occurring in November. He also mentioned that summer tornadoes can and do occur. Another forecaster stated that regions to the south of Tennessee have less seasonality and therefore have a higher potential for tornadoes throughout the year. He said winter tornadoes can occur in the eastern region of Tennessee but they are less common. He felt that March through May were the most tornadic months for the Morristown CWA, with another, smaller season in late fall.

Forecasters also discussed changes in the environment that will cause variation in convective mode throughout the year. One forecaster stated that the dominant weather patterns in late winter and early spring are synoptically driven, and high shear and low instability are often present in the Morristown CWA, leading to more cellular convection. From late May through summer, he said that shear decreases and instability increases, leading to more linear

convection. Later in the fall, he commented that more synoptically driven weather patterns return, along with cellular convection. Another forecaster also mentioned storms with a “strong wind structure” and less CAPE occurring in the spring, with high translational speeds that can be destructive even if they do not produce tornadoes. Forecasters did not mention how seasonal changes in convective mode may complicate their warning procedures.

5.4 Magnitude

The majority of tornadoes (339 out of 427, or 79.4% of total) were of low magnitude. Cells in clusters were responsible for approximately one-third of all lower-magnitude tornadoes (Fig. 7). The remaining lower-magnitude tornadoes were fairly evenly distributed among the other three modes. Discrete supercells were the top producers of higher-magnitude tornadoes (38.6% of EF2 to EF5 tornadoes), followed by cells in clusters (30.7%). QLCSs ranked lowest in the production of higher-magnitude tornadoes (11.36%) in this study. Only one EF5 tornado occurred in Tennessee between 2003 and 2014. The tornado was part of the 27 April 2011 outbreak. According to the SPC tornado database, this tornado was spawned by a discrete supercell in Alabama and resulted in 72 fatalities. QLCSs produced no EF3 to EF5 tornadoes.

Sample size was not sufficient to establish valid chi-squared significance among individual magnitudes (EF0, EF1, and so on) and convective mode. I grouped tornado totals by higher- or lower-magnitude before performing the chi-squared test (Table 5). QLCSs (discrete supercells) produced fewer (more) higher-magnitude tornadoes than expected. All expected tornado totals were above five, and the test was significant, $\chi^2 (df = 3, N = 427) = 9.39, p = 0.02$. The null hypothesis is rejected, suggesting that convective mode plays a role in tornado magnitude.

5.5 Regions of Tennessee

5.5.1 Regional differences

The central portion of the state had 212 tornadoes from 2003 to 2014 (49.7% of total tornadoes). The western portion had 129 total tornadoes (30.2%), and the eastern portion totaled 86 (20.1%). Tornadoes in the eastern region of Tennessee were mainly the result of discrete supercells (43.0%) and cells in clusters (41.9%) (Fig. 8). In the central region, QLCs and cells in clusters produced the most tornadoes (30.7% and 29.7%, respectively) and discrete supercells produced the least tornadoes (16.5%). In the western region, QLCs produced the fewest tornadoes (10.1%) while discrete supercells produced the most tornadoes (36.4%).

Cells in clusters and discrete supercells produced more tornadoes than expected in the eastern portion of Tennessee according to my chi-squared contingency analysis (Table 6). Cells in lines produced less tornadoes than expected in this region. Discrete supercells underproduced tornadoes in the central portion of the state but overproduced tornadoes in the eastern and western regions. QLCs produced more tornadoes than expected in the central region. All expected tornado totals in the contingency table were above five, and the chi-squared test was significant, $\chi^2 (df = 6, N = 427) = 57.02, p < 0.01$. The null hypothesis is rejected, suggesting that convective mode tornado production is associated with regional differences in Tennessee.

Forecasters from the Morristown NWS WFO discussed differences in the convective mode climatology across the state of Tennessee. One forecaster commented that the western and central regions, in contrast with the eastern region of the state, have a more active severe weather season with widespread events. Two forecasters mentioned that discrete cells may turn into multiple, transitioning modes or linear events, such as QLCs, as they travel east or as night falls, and with it the potential for tornadoes may turn to widespread winds and flooding. Storms

can also die out before reaching the Morristown CWA. Another forecaster speculated that outbreaks of QLCS tornadoes occurred more often in the western and central portions of Tennessee, as these linear systems tend to develop in Arkansas and travel west into Tennessee. He said the majority of tornadoes in the eastern region most likely result from discrete cells.

Forecasters commented on the benefit of being in the eastern part of the state, as they can watch storms upstream in western parts of the state or in Alabama, providing them with clues as to what kind of severe weather to expect when storms reach their CWA. One forecaster stated that new storms typically do not generate right over the eastern portion of Tennessee, but when convection does pop up overhead he looks at environmental variables to determine what and when to warn. He mentioned that once one warning is confirmed, subsequent warnings become easier because the forecast has been verified. Another forecaster said that the warning process should be fairly similar across the state, regardless of any differences in convective mode climatology.

5.5.2 Nocturnal differences

In western Tennessee, discrete supercells and cells in lines produced the most tornadoes at night (40.6% and 27.5% of total western nocturnal tornadoes, respectively), while cells in clusters produced the most daytime tornadoes (40.0%) (Fig. 9a). Cells in clusters also produced the most daytime tornadoes in central Tennessee (43.3%) (Fig. 9b). QLCSs were the most common producers of tornadoes at night (49.0%). In eastern Tennessee, cells-in-cluster tornadoes were most common at night (59.5%), while discrete-supercell tornadoes were most common during the day (56.8%) (Fig. 9c).

Morristown NWS forecasters discussed how the climatology of convective modes changes over the course of a day in Tennessee. They noted that the Southeast has a tendency to experience damaging storms nocturnally. Two forecasters were in agreement that the nighttime environment in the eastern region of Tennessee tends to favor the development of linear convective modes, such as QLCs, over cellular modes. They reasoned that heat is lost as the sun sets, CAPE decreases, and stability increases, often resulting in cellular modes merging into linear forms with embedded circulation. These storms can then produce tornadoes despite the lack of instability and CAPE. The forecasters have noticed that a warm frontal boundary over the Tennessee Valley is conducive to tornadoes, even in cases of nocturnal stability. They said discrete tornado and hail events during the day can give way to widespread linear wind events, or derechos, and flooding that can be more damaging and costly than tornadoes. One forecaster commented that, while this transition from cellular to QLCs between day and night is common, there are still plenty of fatalities in the eastern region of the state resulting from nocturnal supercells. Another forecaster believed cellular modes to be the dominant tornadic mode at night, because these systems tend to be more organized and therefore have the stamina to persist under nocturnal environmental conditions, especially when high shear is present.

5.6 Multiple-tornado days

Multiple-tornado days (days with ten or more tornadoes) were examined for patterns in convective mode, resulting in a subset of 215 tornadoes (50.4% of the original 427) that occurred on ten separate multiple-tornado days (Table 7). All QLCs tornadoes in the multiple-tornado day subset occurred on 27–28 April 2011 and 30 January 2013. The 21 QLCs tornadoes from the April event occurred during both day and night, while all 22 tornadoes from the January

event were nocturnal. Just over two-thirds of the QLCS tornadoes on multiple-tornado days took place nocturnally, while the remaining modes were relatively evenly dispersed between day and night.

The other convective modes produced tornadoes on at least six separate multiple-tornado days. None of these multiple-tornado days took place during summer months. Fifteen cell-in-line tornadoes and one cell-in-cluster tornado occurred on 15 November 2005. This was the only instance of a multiple-tornado day in the fall. Two cell-in-line tornadoes occurred during the aforementioned January QLCS event. One additional winter multiple-tornado event occurred on 6 February 2008, consisting of 16 discrete-supercell and three cell-in-cluster tornadoes. Spring was the most active season for multiple-tornado days with seven separate days consisting of ten or more tornadoes. Cell-in-cluster tornadoes occurred on all of these spring days, cell-in-line tornadoes occurred on three days, and discrete-supercell tornadoes occurred on all but one of the days.

Morristown NWS forecasters commented on convective mode with regard to multiple-tornado days or outbreaks, and how these modes affected their warning procedures. They stated that cells, particularly discrete supercells, were associated with the largest outbreaks. One forecaster mentioned that these multiple, discrete cells lead to better warnings and detection because of clear radar signatures with easily distinguishable rotation. He said that days with one or two tornadoes necessitate “high situational awareness,” requiring the forecasters to be more vigilant as to what the environment and radar are conveying. Another forecaster repeated this assertion, stating that single tornadoes are harder to warn, resulting in lower POD and higher FARs, since they can often occur in environments that are not conducive to tornadoes.

5.7 Tornado warning considerations

5.7.1 Warning procedures

Morristown NWS forecasters explained their warning procedures for various convective modes. Forecasters mentioned that a discrete cell has a clearer radar signature, with a highly visible TVS often accompanied by a hook echo. They said that a QLCS tornado is harder to detect. They look for a “bookend vortex,” defined as rotation at the end of a line of convection, or “nooks” within a line of convection that can exhibit a quick spin up of rotation and subsequent tornadoes. One forecaster stated that he referenced the reflectivity and velocity radar products equally for QLCSs, while he was able to mostly reference the velocity product for supercell rotation. He mentioned that a tornado from a QLCS is shorter-lived, smaller, and weaker compared to a cellular tornado. It can be harder to detect these tornadoes on radar because they can spin up and be gone within one five-minute scan of the radar.

Forecasters mentioned that their warning polygons may change based on convective mode. They agreed that tornado-warning polygons would be very similar regardless of convective mode because warnings are based on individual velocity couplets. For other severe-weather warnings, forecasters stated that they would tend to have a larger warning area for a QLCS to account for widespread winds and severe thunderstorms. (Severe thunderstorm warnings include a chance of tornadoes.) One forecaster said the process of warning for a QLCS is more complicated than a cell, because it is not uncommon to have a severe thunderstorm warning already in effect before a tornado warning is issued, resulting in some areas being under multiple warnings.

One forecaster recalled a situation where a QLCS tornado went unwarned, and could have possibly remained unverified if it had not been captured on a security camera. The funnel

was small and the radar showed no indication of rotation. He explained that rotation is harder to distinguish as distance from the radar increases, because the radar is “signaling higher up in the storms...[and] not getting good data at the lower levels.” He said information at low levels of the storm is crucial in identifying rotation of weaker tornadoes. Local topography also plays a role in these situations. The forecaster commented that radar coverage of shallow rotation in a QLCS is negatively affected by the Cumberland Plateau, an area in the eastern part of Tennessee with much higher elevation than surrounding areas. He suggested that the FAR is higher in these situations, since warnings were based on “partial evidence” and surrounding convection.

5.7.2 POD, FARs, and lead time

POD, FARs, and lead time were discussed by Morristown forecasters. One forecaster stated that tornadoes from slow-moving supercells have high POD and low FARs because they are “fairly well-behaved” on the radar. He said supercells allow for longer lead times, especially in cases where a cell is long-lasting and can provide areas downstream with advanced warning. He stated advanced downstream notifications are also possible in cases of outbreaks, where storm systems can be tracked and future regions prone to tornadoes can be identified. In these cases, he said the forecasters were “not putting out tornado warnings two hours ahead, but...planting the seeds” in the minds of the population for the possibility of future tornado warnings. He discussed how cases of clusters or lines of convection can be more challenging, as the interacting cells often feed off one another and may exhibit less clear rotation on radar, leading to lower POD and a higher FARs compared to discrete cells. Downdrafts from one cell can encourage formation of other cells, which may or may not become tornadic. Another forecaster commented on his experience with tornadoes from QLCSs, stating that they can pop

up quickly with little advance notice. In situations where these storms have a 50% chance of producing tornadoes, he was more likely to issue a warning so that he can provide the public with a better chance of seeking appropriate shelter. He said he was more concerned with POD compared to FARs because these storms often produce damaging winds that can cause injuries regardless of actual tornado formation.

6. DISCUSSION

6.1 Fatalities and nocturnal tornadoes

Almost half of the tornadoes in this study were nocturnal, aligning with findings by Ashley et al. (2008). Nocturnal tornadoes were fairly evenly distributed among all four modes, but QLCSs were the top producers during the study period. The majority of QLCS tornadoes happen at night. Forecasters mentioned forecasting and public communication challenges associated with nocturnal tornadoes and the weaker tornadoes that may spin up in a QLCS. Without the added benefit of spotter confirmations in these situations, the Morristown forecasters rely on local knowledge of environmental parameters (NOAA 2016) and radar imaging (Brotzge and Donner 2013). Forecaster comments were in agreement with the assertions of Kis and Straka (2010) that environments can change significantly between day and night, altering convection and tornado potential. It is critical that the severe weather potential is properly assessed before the public and off-duty forecasters go to bed. Early detection of nocturnal tornado potential helps guarantee sufficient staffing during severe weather events and increases the chances of the public taking protective action.

Forecasters acknowledge that the issues associated with communicating nocturnal severe weather threat to the public is an issue, leading to a large number of nocturnal fatalities. Contrary to Ashley et al. (2008), nocturnal tornadoes during the period used in this study did not produce more deaths than those that occurred during the day. This sample of tornadoes exhibited almost equal fatality rates between day and night tornadoes. Fatality statistics can be expected to change with the sample size of tornadoes and regions considered, especially since a large number of fatalities often come from a single outbreak event.

Previous research has highlighted the dangers of tornadic supercells, acknowledging them as the most fatal of tornadic convective modes (Schoen and Ashley 2011; Brotzge et al. 2013). The fatality statistics presented here support this claim, with 86.5% of total fatalities resulting from discrete-supercell tornadoes and the remaining deaths associated with cells in lines and clusters. While QLCSs resulted in zero fatalities in Tennessee from 2003 to 2014, this mode has produced deadly tornadoes in the state in the past (Schoen and Ashley 2011) and should not be dismissed as harmless.

Overall, the results highlight the fatal danger associated with tornadic discrete supercells and the unique forecasting challenges that arise with QLCSs. A highly disproportionate number of fatalities were attributed to discrete-supercell tornadoes in Tennessee from 2003 to 2014. While a QLCS is statistically much less likely to be fatal, the large spatial extent of this mode, coupled with communication and forecasting challenges, requires forecasters to be especially vigilant in predicting and warning for any potential tornadoes. This is particularly important for regions in Tennessee with high numbers of mobile homes and sleeping residents, which provide a dangerous combination leading to tornado injuries and fatalities.

6.2 Seasonality

The quantitative results and forecaster knowledge support the idea of year-round tornadoes in Tennessee and the Southeast. While individuals in the Central Plains generally experience a much more defined “tornado season” (Brooks et al. 2003), Tennessee residents must maintain a year-round awareness of tornado risk which can lead to complacency and unpreparedness. Approximately 37% of tornadoes in this study occurred outside of the spring season. QLCSs produced the most tornadoes in winter, as was the case with Trapp et al. (2005).

Winter tornadoes from discrete cells and cells in clusters versus cells in lines and QLCS were almost equal (35 and 37, respectively), aligning with the findings of Smith et al. (2012). Cool-season tornadoes pose extra risks to Tennessee. Shortened daylight hours mean tornadoes that occur after dark are harder to see in hilly, tree-lined terrain, causing public safety issues and providing extra challenges for forecasters. Winter was the second most active season across Tennessee in my analysis, with fall not far behind in third place. While the chi-squared results indicate tornadic convective mode is associated with seasonality, additional statistical analyses must be conducted to determine the degree of this association.

All interviewed forecasters have previous experience forecasting for multiple NWS WFOs in different regions of the United States, which means they have firsthand knowledge of the differences in tornado seasonality between the Plains and various locations in the Southeast. Morristown forecasters recognized the heightened cool-season risk of tornadoes in Tennessee, compared to the Plains. When comparing Tennessee to parts of the Deep South, the risk of cool season tornadoes is not as serious.

Two forecasters mentioned how the storm environment in the spring exhibits high shear, and one of these forecasters went on to say that summer environments have more CAPE. These comments align with the Southeastern seasonality of HSLC severe weather events outlined in the work of Sherburn and Parker (2014). These environmental changes affect the dominant convective modes that produce tornadoes. Perhaps more importantly, these shifts can lead to differences in severe weather threats. Throughout the interviews, risk of tornadoes was often discussed in tandem with risks of strong, straight-line winds and hail. Morristown forecasters associated QLCSs with damaging winds more often than tornadoes in their CWA. This may

vary across the Tennessee WFOs, and in different regions of the United States. Comparison of environmental differences across Tennessee regions is further discussed in Section 6.4.1.

6.3 Magnitude

Multiple studies (Grams et al. 2012; Smith et al. 2012) found discrete supercells to be the leading producers of higher-magnitude tornadoes across the country. Previous research (Trapp et al. 2005) has also noted that QLCSs tend to produce fewer higher-magnitude tornadoes compared to cellular modes. This assertion was also made by one of the Morristown forecasters, and supported by my climatological analysis. Discrete supercells (QLCSs) appear to be prone to more higher-magnitude (lower-magnitude) tornadoes across Tennessee. Cell-in-line and cell-in-cluster tornadoes are fairly evenly distributed between the two magnitude groupings.

The public may be tempted to dismiss danger associated with QLCS tornadoes because of the lack of fatalities and $\geq$ EF3 tornadoes associated with this mode in this study. However, this mode also exhibited a higher likelihood to produce tornadoes at night and during the winter months when the public is less aware of tornadic risk, demonstrating that forecasters and the public should be vigilant when this mode is present. Fatalities from QLCS tornadoes did not occur during this study period, but are a part of the tornado history in Tennessee.

6.4 Regions of Tennessee

The state was divided into three regions to investigate longitudinal changes in tornadic convective mode across Tennessee. Results did not display any clear longitudinal patterns of tornado frequency or convective mode. Almost half of the 427 tornadoes occurred in the central portion of Tennessee. The eastern portion of the state had the lowest number of tornadoes, in

line with the findings of Brown et al. (2016). Morristown NWS forecasters were aware of their CWA being the least tornadic region of Tennessee, and frequently mentioned their concern of other convective hazards, including high winds and hail. These concerns likely differ at the other Tennessee WFOs, where tornadoes are more common.

QLCSs and cells in clusters and lines produced many more tornadoes in the central region of Tennessee compared to the eastern and western regions. Discrete supercells were more evenly distributed, with slightly more tornadoes in the western region. These discrete-supercell tornadoes in the western region were more likely to occur nocturnally, and are more likely to produce higher-magnitude tornadoes, which may be a contributing factor to the higher fatality rates in western Tennessee seen in previous research (Brown et al. 2016). It would be interesting to look more closely at the spatiotemporal aspects of these fatalities with regard to convective mode with a larger dataset.

Care must be given when interpreting my results concerning convective mode across the different regions of Tennessee. I chose arbitrary longitudinal lines to divide the state into three sections to provide a preliminary look into patterns of tornadic convective modes across the state. Future work should assess a larger period and could analyze tornadic convective modes in the three Tennessee NWS WFO CWAs to provide forecasters information specific to their CWA.

6.4.1 Environmental differences

More than one Morristown forecaster commented that tornadoes occurred in their CWA in stable environments, which is more common in the Southeast compared to the Plains (Grams et al. 2012). One forecaster described high-shear, low-instability environments in the spring as conducive to cellular convection in the Morristown CWA. Low CAPE and low instability are

closely related, meaning the forecaster is referring to conditions similar to HSLC environments. His comments were in contrast to previous research (Davis and Parker 2012) which suggested that HSLC environments are more conducive to QLCSs in the Southeast and mid-Atlantic. Sherburn and Parker (2014) indicated that the Morristown CWA had a much higher tendency of HSLC severe weather events, including tornadoes rated $\geq$ EF2, compared to the Memphis and Nashville WFOs. Their work spanned from 2006 to 2011, a period that is included within my selected range of study. The eastern region of Tennessee reported a surprisingly low number of QLCS tornadoes, with the majority of tornadoes resulting from discrete supercells and cells in clusters. The discrepancy in expected QLCS tornadoes in this region prone to HSLC severe weather could be a result of underreporting of short-lived, lower-magnitude tornadoes (Trapp et al. 2005). There were only ten EF2 (and no EF3 to EF5) QLCS tornadoes reported in Tennessee from 2003 to 2014, and only one was in the eastern region of the state. Therefore, the majority of $\geq$ EF2 tornadoes highlighted in Sherburn and Parker (2014) in eastern Tennessee must be from cellular convection. This supports the comment made by the Morristown forecaster that high-shear, low-instability environments lead to cellular tornadoes in the eastern region of Tennessee. Analysis of convection responsible for hail and strong winds across Tennessee may reveal that QLCSs are present in these HSLC environments but are not producing tornadoes in the eastern part of the state.

Future analysis of convective mode in Tennessee should include the environmental information (including CAPE) contained within the Smith database to determine how these variables affect tornadic convective modes across the three CWAs in the state. This would allow for a more proper assessment of the comments made by Morristown forecasters concerning changes in mode as convection moves across the state. It is disappointing that there are not more

upper-air sounding data across the state to directly measure near-storm environments, as the only regular radiosonde launches take place at the Nashville WFO.

Morristown forecasters mentioned their benefit of being on the eastern end of storm events. It would also be interesting to compare POD, FARs, and lead times across Tennessee to see how Morristown may benefit from being downstream of more active regions of tornadic activity. While all forecasters benefit from assessing upstream weather before it reaches their CWA, Morristown forecasters believe they have a unique opportunity to gauge severe weather potential because activity often initiates in the Plains and reaches the western part of Tennessee the next day, before travelling east into the Morristown CWA.

6.4.2 Nocturnal differences

At first glance, QLCSs appear to produce many more nighttime tornadoes in the central region of the state while producing almost equal day and night tornadoes in the remaining two regions. However, all but three of the 22 QLCS tornadoes that took place nocturnally on 30 January 2013 were located in the central region of Tennessee. The 27–28 April 2011 outbreak produced nine discrete-supercell tornadoes during the day and 13 cell-in-cluster tornadoes at night in the eastern region of Tennessee. This event also included ten out of the 11 discrete-supercell tornadoes that took place nocturnally in the eastern part of the state from 2003 to 2014. Events like these show how much a single outbreak can affect results. The central region of Tennessee had a much higher number of cell-in-cluster tornadoes during daylight hours when compared to the rest of the state. Unlike the aforementioned tornado total discrepancies, which were in large part attributed to multiple-tornado day events, these cell-in-cluster tornadoes were

spread out among several different days. It would be interesting to isolate more multiple-tornado events to determine what role they play in the convective mode climatology across the state.

Multiple factors could be influencing convective mode tornado production across the state, including topography, and synoptic and mesoscale weather patterns. Further analysis of convective mode climatology in Tennessee will help NWS forecasters better forecast how convection can be expected to change as it travels through the state. Detailed knowledge of past tornado climatology aids forecasters in future situations exhibiting similar convective characteristics. The Memphis NWS office is responsible for forecasting for large parts of Arkansas and Mississippi, and including tornadoes from these areas in future work will offer better guidance in tornado forecasting and warning procedures for their CWA.

6.5 Multiple-tornado days

Just over half of the tornadoes in this study occurred on ten days with at least ten tornadoes, highlighting the effect of multiple-tornado days on the tornado climatology in the Southeast (Brotzge and Erickson 2009). Convective mode percentages on multiple-tornado days were similar to those of the entire 2003 to 2014 period, with the proportion of cell-in-cluster tornadoes differing the most between single- and multiple-tornado days (5.6% difference). Discrete supercells were responsible for the most tornadoes in the multiple-tornado day subset, a result in agreement with assertions by Morristown forecasters. This was also found to be the case in the work conducted by Grams et al. (2012).

QLCSs produced the lowest percentage of tornadoes on multiple-tornado days, but were also responsible for the two largest tornado totals attributed to a single mode on a single day. This mode was only 11.6% less likely to produce tornadoes on multiple-tornado days compared

to discrete cells. QLCSs also exhibited a higher likelihood of producing multiple tornadoes in a single night, during a time when the public is potentially less aware and prepared.

Morristown forecaster comments regarding POD and lead times on multiple-tornado days versus single-tornado days aligned with the findings of Brotzge and Erickson (2009), specifically that multiple-tornado days are associated with higher POD, greater lead times, and stronger convection. Forecasters mentioned that certain environments are more conducive to multiple-tornado events. Additional work should compare environmental parameters, such as instability and shear, to isolate key factors that trigger multiple-tornado days across Tennessee.

6.6 Tornado warning considerations

6.6.1 Warning procedures

Past research is in agreement with the comments by Morristown NWS forecasters concerning the relative ease of warning for tornadic discrete supercells and difficulties associated with identifying QLCS rotation (Trapp et al. 1999; Trapp et al. 2005; Smith et al. 2012). TVSSs (Burgess et al. 1976) and hook echoes (Markowski 2002) were specifically mentioned as key evidence forecasters look for to pinpoint tornado formation in a discrete cell. Shallow rotation in a QLCS provides a challenge in tornado identification, especially in the eastern region of Tennessee where local topography can interfere with radar signatures. This may allow tornadoes to go unwarned or unreported. Situations involving unclear radar signatures are handled slightly differently depending on the forecaster. One Morristown forecaster said he was “a little more likely than some to err on the side of giving mother nature the respect” by issuing warnings proactively instead of risking a missed warning. These decisions must be at the forefront of the minds of forecasters as they weigh each severe weather event, and specific knowledge of local

climatology is directly beneficial in these situations. Severe thunderstorm warnings allow forecasters some leniency in difficult QLCS situations. Forecasters can issue a larger severe thunderstorm-warning polygon along the front edge of a QLCS, providing advanced notice to the public of possible tornadoes, in addition to damaging winds and possible hail.

6.6.2 POD, FARs, and lead time

Morristown NWS forecaster comments regarding POD, FARs, and lead times were also well aligned with past research (Trapp et al. 1999; Brotzge et al. 2013). The same characteristics that allow for easy detection of tornadic cells on radar allow forecasters to provide extra lead time and less false alarms. POD for a QLCS decreases with greater distance from the radar (Brotzge et al. 2013), which is especially problematic in the Cumberland Plateau, where the terrain can cause additional radar interference. The aforementioned forecaster who errs on the side of issuing warnings in these situations acknowledged that his actions may lead to higher FARs. Every forecaster must weigh the decision to warn against the probability of injuries and fatalities resulting from unwarned tornadoes, and convective mode may complicate these decisions and cause more discrepancies between forecasters.

7. CONCLUSION

In this study, I evaluated the convective mode climatology of Tennessee tornadoes from 2003 to 2014. I assigned a convective mode to each tornado initiating in or passing through the state, using either the Smith database or a manual assessment of NEXRAD level II radar. I calculated proportions of tornadoes from each convective mode with regard to day and night, seasons, magnitude, fatalities, regions of Tennessee, and multiple-tornado days. Pearson's chi-squared tests for independence were used to determine if tornado production by convective mode is associated with day and night, seasonality, fatalities, magnitude, and longitude. I interviewed forecasters from the Morristown, Tennessee, WFO to gain insight into how their tornado warning and forecasting procedures are affected by convective mode. Information from these interviews was integrated with my climatology results and previous literature.

Previous research has shown that Tennessee is a region prone to nocturnal and fatal tornadoes, and my results support these claims. Almost half of the 427 tornadoes in Tennessee from 2003 to 2014 were nocturnal. Almost half of the 200 fatalities that resulted from tornadoes across the state during this period occurred at night. Discrete supercells caused the majority of tornado-related fatalities and were also the top producers of higher-magnitude and multiple-day tornadoes. QLCs produced only non-fatal tornadoes with magnitudes of $\leq$ EF2 during the 2003 to 2014 time period. However, these storms should still be taken seriously, as my results indicate that this mode has a higher tendency to produce tornadoes at night, while the public is sleeping and forecasters must rely solely on radar imaging to issue warnings, and in the off-season, when the public is less aware of potentially severe weather outbreaks. Examination of a larger period shows that QLCs have produced fatal tornadoes in Tennessee in the past.

Tennessee exhibits peak tornado activity in the spring, but tornado risk occurs year-round with a secondary, smaller peak in the cool season. Convective mode is associated with synoptic weather patterns across the United States on a seasonal time scale, and with environmental variables that affect convection as storms travel through the state. Future work should further analyze the environments in which Tennessee tornadoes form to determine how shear and CAPE affect convective mode throughout the year, especially in the eastern portion of the state where HSLC environments are common. These results could then be compared to tornadic environments in the Plains to more accurately assess differences in seasonal risk of tornadoes between the two major tornado regions of the country.

No clear gradient in tornado frequency or convective mode was found across Tennessee. The central region of Tennessee was the most tornado-prone, containing almost 50% of the 427 total tornadoes, and was more likely to have QLCS tornadoes. This region is surrounded by areas to the west and east with fewer tornadoes and a greater likelihood of tornadoes from supercell storms. Forecasters discussed how convection can change as it passes through the state, noting that cellular convection often consolidates into quasi-linear forms as day becomes night.

Multiple-tornado days were revealed to be an important consideration for tornado climatology studies. These days were major contributors to tornado totals, with just over half of the 427 tornadoes occurring on ten days. Discrete supercells were the top producers of tornadoes on these days. These cells are associated with clear radar signatures that allow forecasters higher POD, lower FARs, and longer lead times. QLCS tornadoes on multiple-tornado days were the result of two separate events (27–28 April 2011 and 30 January 2013), with about two-thirds of

the tornadoes occurring nocturnally, demonstrating the effect a small number of events can have on a climatological analysis.

All Pearson's chi-squared tests for independence were significant, suggesting a variety of factors, including day and night, seasonality, longitude, fatalities, and magnitude are associated with tornado production by convective modes in Tennessee. Additional statistical analyses must be conducted to determine the degree of influence between convective mode and each categorical variable. These analyses will provide more detail relating to the spatiotemporal characteristics of individual convective modes.

There were some challenges associated with the quantitative analyses in this study. The small sample size prevented analysis of seasonality and magnitude with regard to convective modes of nocturnal tornadoes. A larger sample size would allow for a more detailed understanding of dangerous nocturnal tornadoes, but would require a longer dataset of convective mode classifications. Analysis of the regional differences in Tennessee proved challenging because of the arbitrary longitudinal division of the state into three regions. While analysis of Tennessee is beneficial to policymakers who operate on a statewide level, future work should assess tornadoes in the three CWAs of the Tennessee NWS WFOs to provide a more robust discussion of regional differences in convective mode climatology and warning procedures between the three offices.

The in-depth interviews and qualitative analyses also provided challenges. Interview questions often led to conjectures of tornado and convective mode climatology in Tennessee because of individual forecaster experience and a lack of detailed convective mode statistics for the state. Forecasters shared important information regarding warning procedures and convective mode in their CWA, but their responses cannot be fully evaluated until interviews

with forecasters from the Memphis and Nashville NWS WFOs are completed. These interviews will be a part of the future work associated with the VORTEX-SE grant that funded this project, and will lead to a more in-depth qualitative analysis of regional differences in forecaster response. This analysis will reveal similarities and differences in warning procedures during tornadic events from differing convective modes across the state. These interviews should also reveal how each WFO in Tennessee views tornado risk relative to other severe weather risks in their CWAs. Questions that lead to additional insight during these interviews may be posed to the Morristown office in a follow-up meeting.

This research combined quantitative analysis of the convective mode climatology of Tennessee tornado events with qualitative analysis of in-depth interviews of Morristown NWS forecasters. While most the convective mode-related comments made by the Morristown forecasters aligned with my quantitative results, the interviews revealed additional invaluable information about staffing considerations and the internal dialogue that occurs when deciding whether or not to issue warnings. This mixed-methods approach provided a more comprehensive look into how convective mode affects tornado production and warning procedures, as part of the emerging field of critical physical geography. As populations grow and climate changes, it is imperative that scientific analyses not only study patterns in physical geographic phenomena, but the causes, effects, and implications concerning humans and their interactions with the environment must also be taken into account. This inclusion best ensures that policymakers have sufficient information to arrive at environmentally and economically sustainable solutions while implementing proactive safety measures and building new infrastructure. The work presented here will lead to future collaboration between the Morristown NWS WFO and geographers, climatologists, and social scientists at the University of Tennessee,

Knoxville, augmenting efforts to increase public awareness of severe weather threats across the region.

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APPENDIX

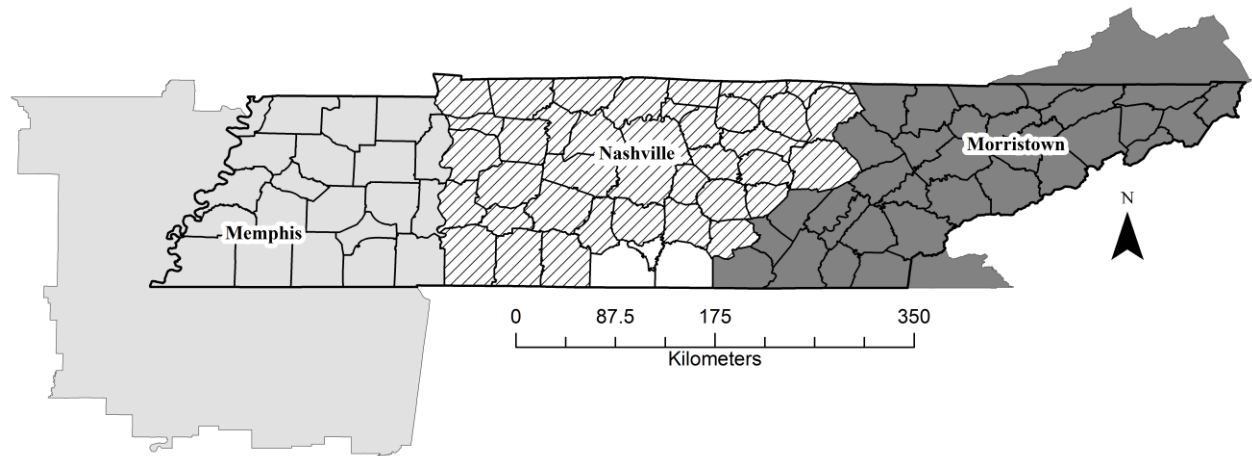


Fig. 1. CWAs for Memphis, Nashville, and Morristown, Tennessee, WFOs.

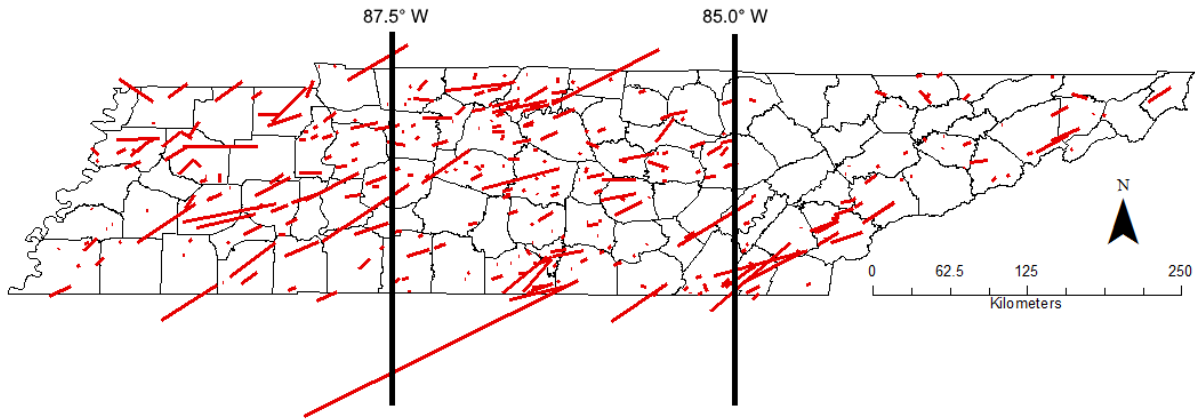


Fig. 2. Paths of tornadoes used in this study, including all 427 reported tornadoes originating in or passing through Tennessee from 2003 to 2014. Tornado starting locations were split into three bins based on longitudinal lines 87.5° W and 85.0° W to properly catalogue tornadoes as nocturnal, per sunrise and sunset times in Memphis, Nashville, and Knoxville, Tennessee. The resulting western, central, and eastern divisions were used for a regional analysis of convective mode.

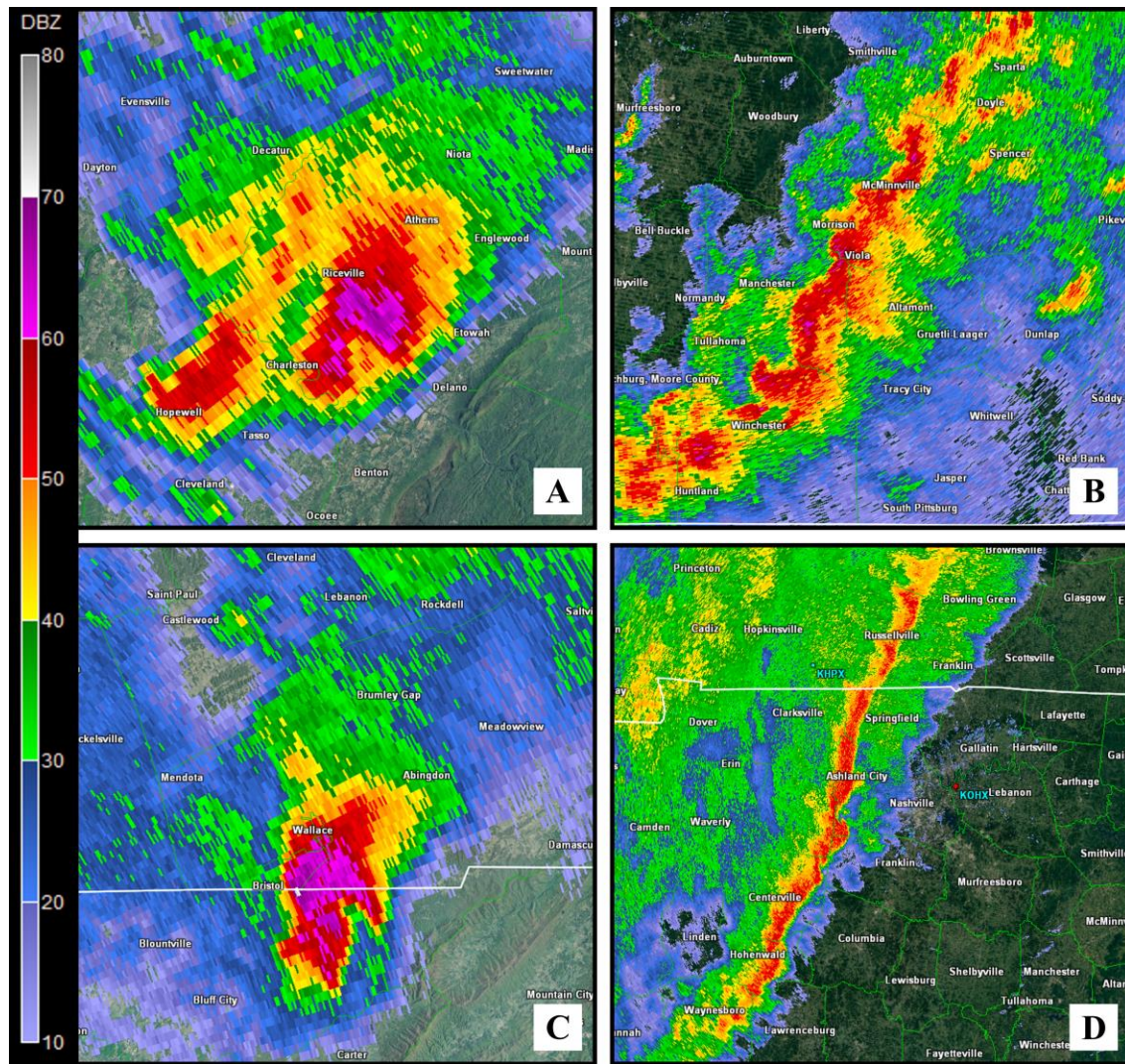


Fig. 3. Examples of convective mode classifications used in this study: (a) cell in cluster, (b) cell in line, (c) discrete supercell, (d) QLCS. Images depict radar reflectivity, or rainfall intensity, at the lowest elevation tilt (0.5° above horizon).

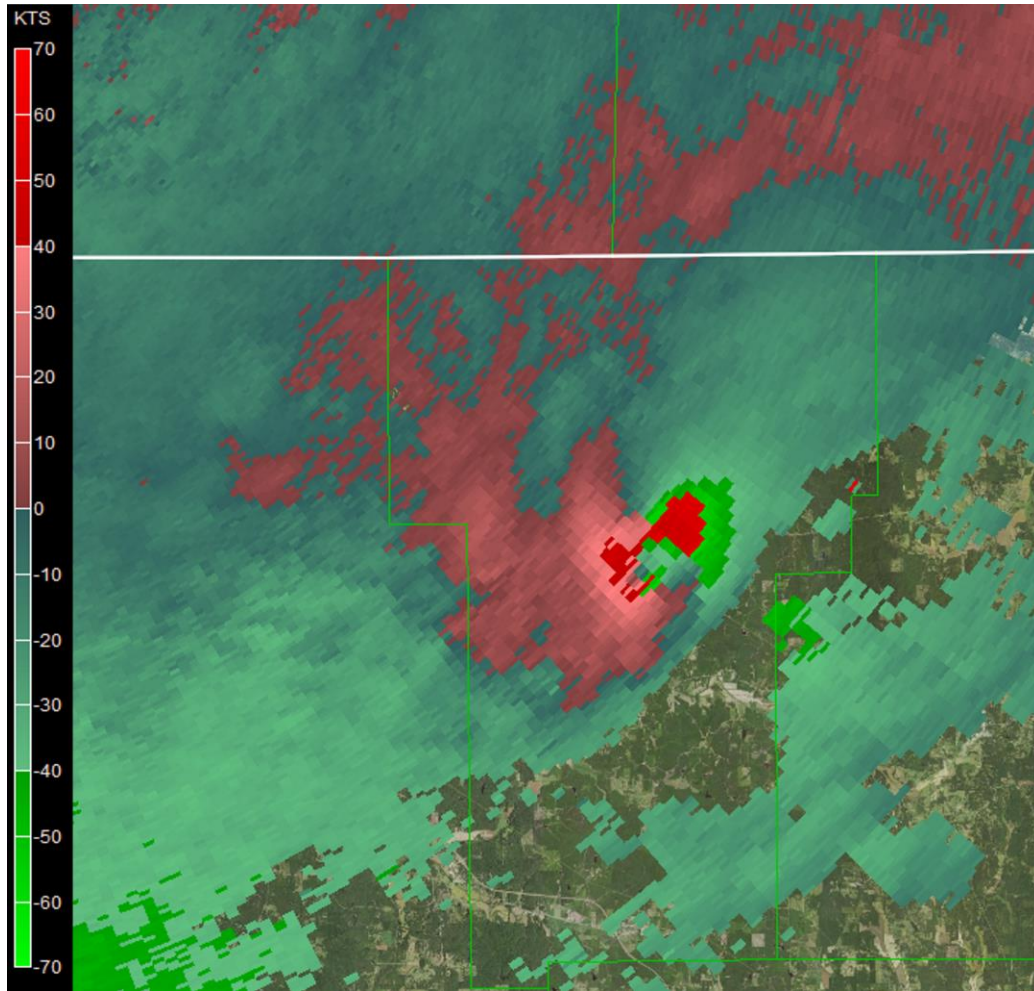


Fig. 4. Storm-relative velocity radar image (0.5° tilt) showing area of rotation within a supercell.

Table 1. Number of tornadoes produced by each convective mode, the percentage of total tornadoes produced by that mode, and the number of resulting fatalities.

Convective mode	Tornadoes	Percentage of total	Fatalities
Cell in cluster	139	32.6	16
Cell in line	83	19.4	11
Discrete supercell	118	27.6	173
QLCS	87	20.4	0
Total	427	100	200

Table 2. Chi-squared contingency table for convective mode and tornadoes fatalities. Table values represent the observed (O) and expected (E) number of tornadoes that were fatal and not fatal. O and E values with an observed count greater than expected are shown in bold text. Convective mode abbreviations here and in subsequent tables are as follows: cell in cluster (CC), cell in line (CL), discrete supercell (DS), and QLCS (QL).

	CC		CL		DS		QL		Total
	O	E	O	E	O	E	O	E	
Fatalities	8	9	1	5	18	7	0	6	27
No fatalities	131	130	82	78	100	111	87	82	400
Total	139		83		118		87		427

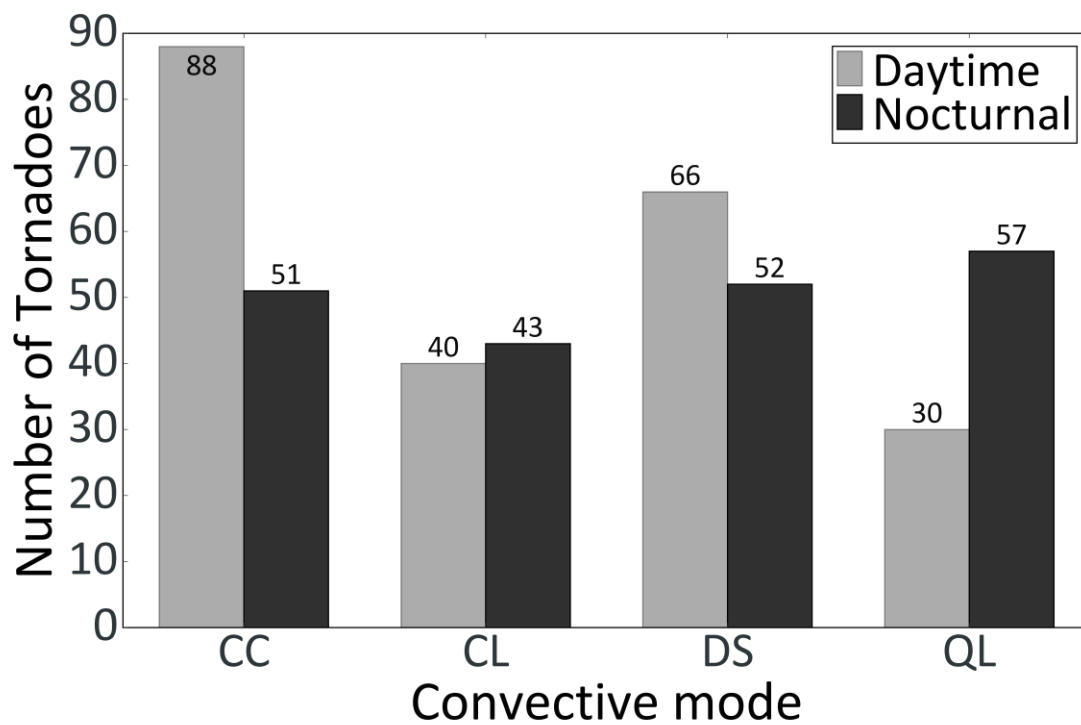


Fig. 5. Number of daytime and nocturnal tornadoes produced by each convective mode. Convective mode abbreviations here and in subsequent figures are as follows: cell in cluster (CC), cell in line (CL), discrete supercell (DS), and QLCS (QL).

Table 3. Chi-squared contingency table for convective mode and tornadoes by day and night. Table values represent the observed (O) and expected (E) number of tornadoes that occurred during the day or at night. O and E values with an observed count greater than expected are shown in bold text.

	CC		CL		DS		QL		Total
	O	E	O	E	O	E	O	E	
Day	88	73	40	44	66	62	30	46	224
Night	51	66	43	39	52	56	57	41	203
Total	139		83		118		87		427

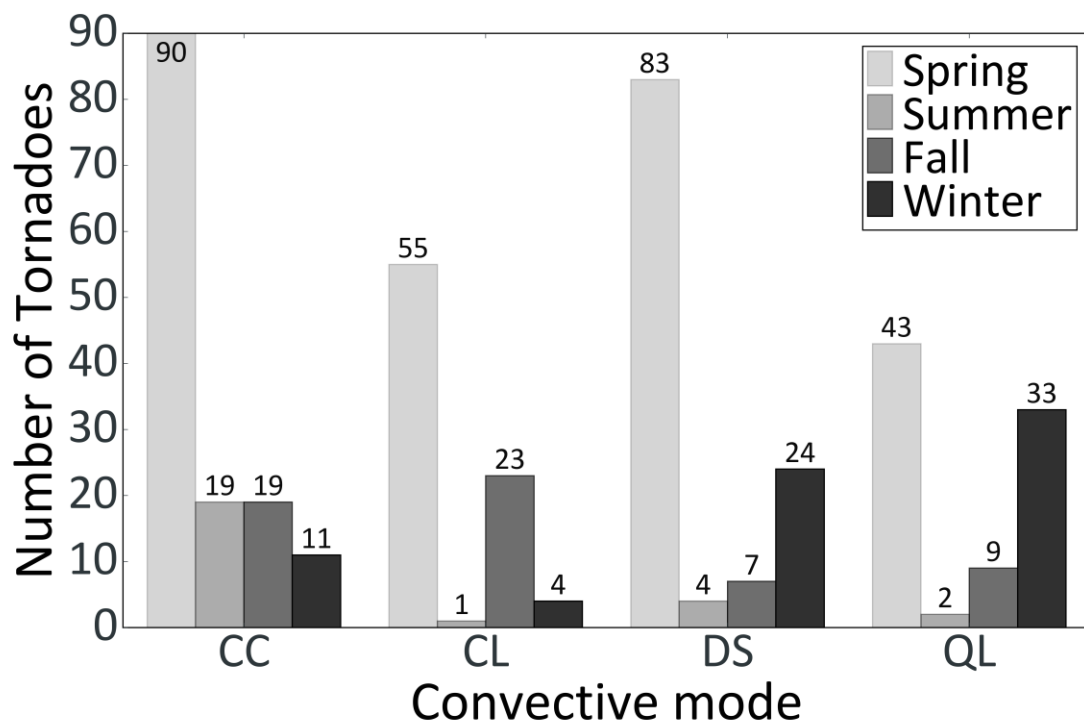


Fig. 6. Number of tornadoes produced by each convective mode, organized by season.

Table 4. Chi-squared contingency table for convective mode and tornadoes by season. Table values represent the observed (O) and expected (E) number of tornadoes that occurred in each season. O and E values with an observed count greater than expected are shown in bold text.

	CC		CL		DS		QL		Total
	O	E	O	E	O	E	O	E	
Spring	90	88	55	53	83	75	43	55	271
Summer	19	8	1	5	4	7	2	5	26
Fall	19	19	23	11	7	16	9	12	58
Winter	11	23	4	14	24	20	33	15	72
Total	139		83		118		87		427

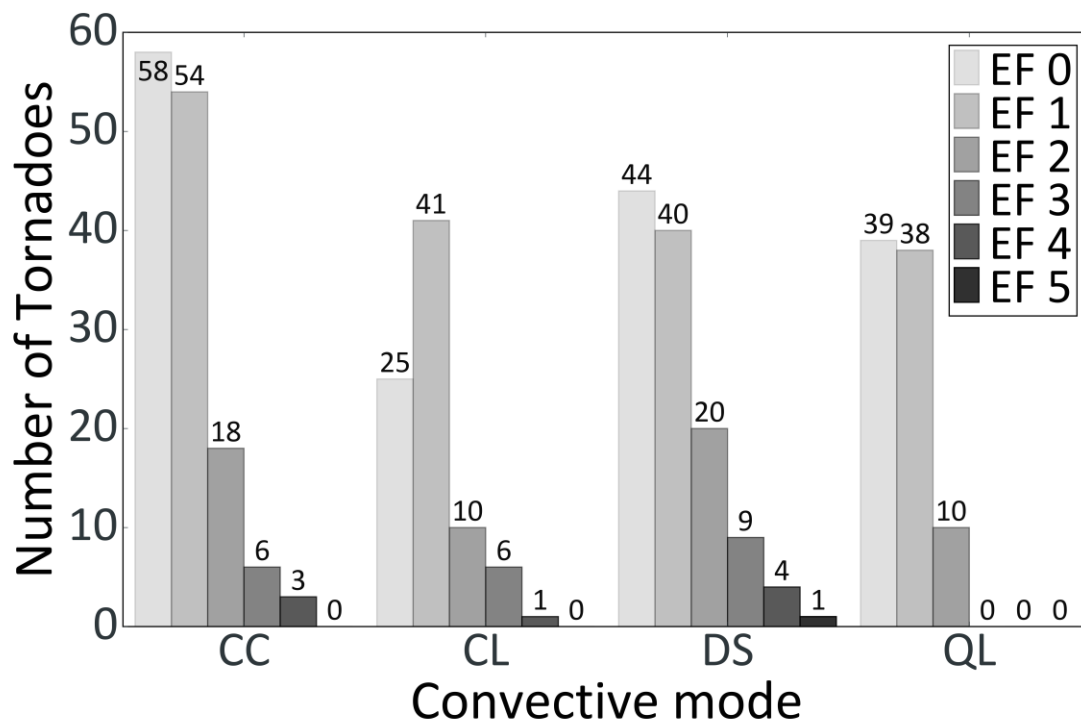


Fig. 7. Number of tornadoes produced by each convective mode, organized by magnitude.

Table 5. Chi-squared contingency table for convective mode and lower- or higher-magnitude tornado totals. Table values represent the observed (O) and expected (E) number of tornadoes that were lower- or higher-magnitude. O and E values with an observed count greater than expected are shown in bold text.

	CC		CL		DS		QL		Total
	O	E	O	E	O	E	O	E	
Lower-mag	112	110	66	66	84	94	77	69	339
Higher-mag	27	29	17	17	34	24	10	18	88
Total	139		83		118		87		427

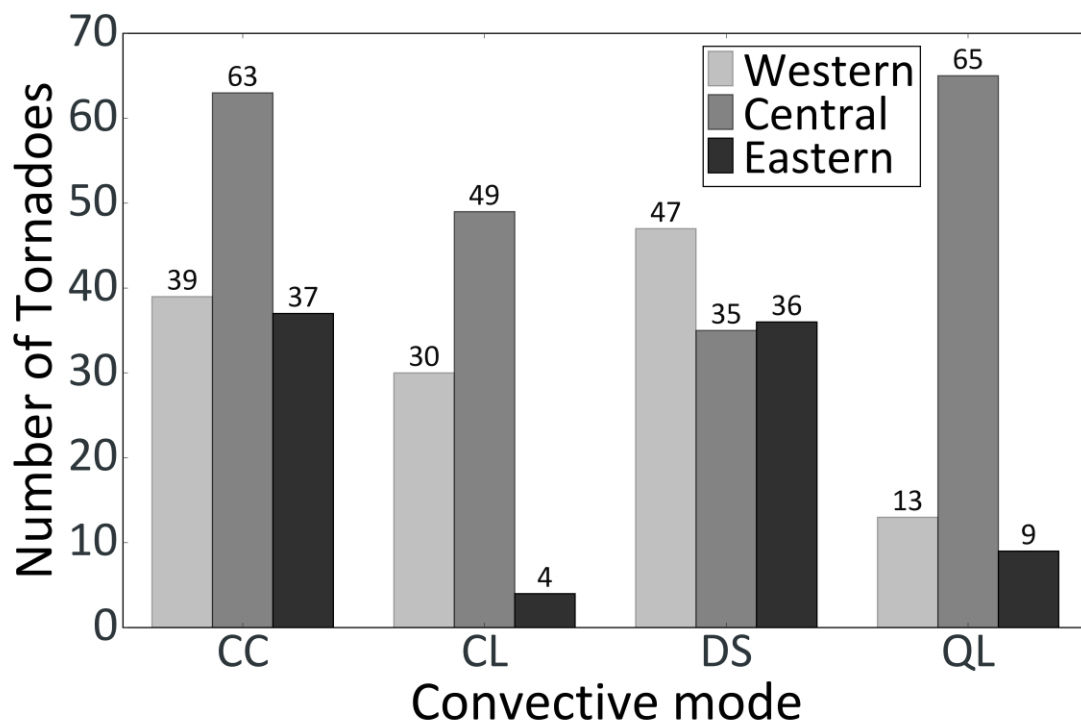
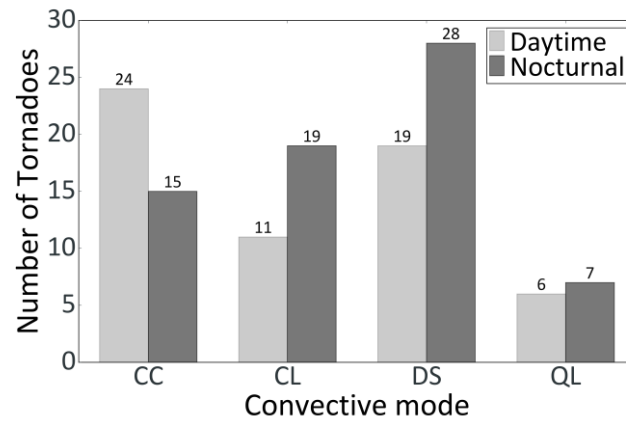


Fig. 8. Number of tornadoes produced by each convective mode in three regions of Tennessee.

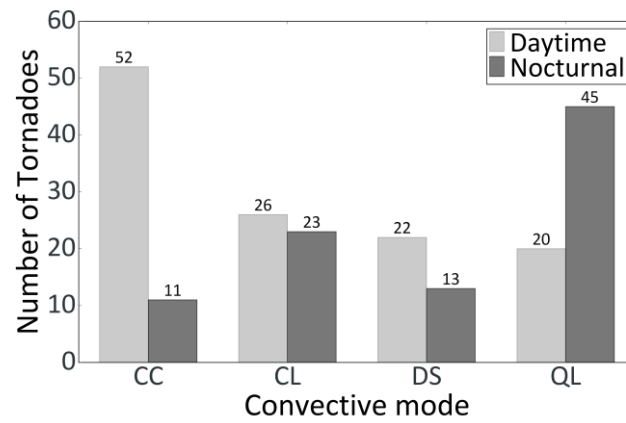
Table 6. Chi-squared contingency table for convective mode and tornadoes by region. Table values represent the observed (O) and expected (E) number of tornadoes that occurred in three regions of Tennessee. O and E values with an observed count greater than expected are shown in bold text.

	CC		CL		DS		QL		Total
	O	E	O	E	O	E	O	E	
Eastern	37	28	4	17	36	24	9	18	86
Central	63	69	49	41	35	59	65	43	212
Western	39	42	30	25	47	36	13	26	129
Total	139		83		118		87		427

(a)



(b)



(c)

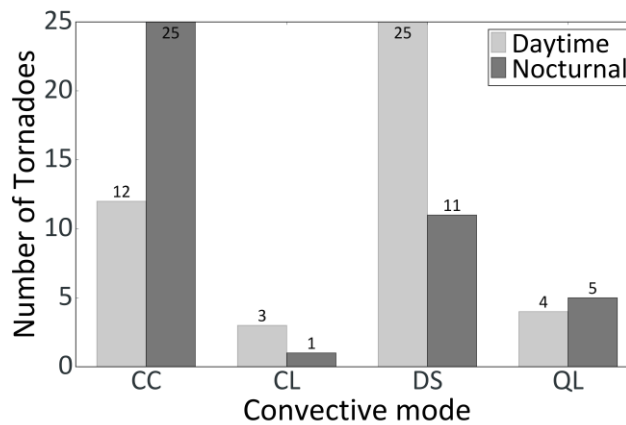


Fig. 9. Number of daytime and nocturnal tornadoes produced by each convective mode in the (a) western region, (b) central region, and (c) eastern region.

Table 7. Number and percent of tornadoes produced on multiple-tornado days by each convective mode.

Convective mode	Tornadoes	Percentage of total
Cell in cluster	58	27.0
Cell in line	46	21.4
Discrete supercell	68	31.6
QLCS	43	20.0
Total	215	100

VITA

Kelly Gassert was born in Cincinnati, Ohio. She obtained her first degree, a Bachelor of Fine Arts in Theatrical Design and Production with an emphasis in Costume Technology, from the College-Conservatory of Music at the University of Cincinnati in 2005. She returned to school to earn a Bachelor of Science in Atmospheric Sciences with an emphasis in Climatology from the University of North Carolina, Asheville in 2015. She received the Departmental Distinction in Academic Excellence, graduating with a 4.0 major GPA. While completing this second degree, Kelly held two internships at the Cooperative Institute for Climate and Satellites in Asheville, North Carolina. She presented an oral discussion of one of her projects at the American Geophysical Union Fall Meeting in San Francisco, California, in 2014. Kelly entered the Geography Department at the University of Tennessee, Knoxville in 2016 to pursue a Master of Science. She studied under Dr. Kelsey Ellis and was funded by two NOAA VORTEX-SE grants. She helped write the proposal for the second grant, which was based on the idea she formulated for her thesis. She worked as a Graduate Research Assistant, quantitatively calculating tornadic risk across the state of Tennessee and conducting qualitative interviews with residents to assess their perceived tornado risk. She presented preliminary findings of her thesis work at the Southeastern Division of the Association of American Geographers Annual Meeting in Columbia, South Carolina, in 2016 and was awarded Best Graduate Student Poster.