10-1-2010

A Climatology of Fatal Convective Wind Events by Storm Type

Walker S. Ashley

Joseph M. Schoen

Original Citation
Schoen, J. and W.S. Ashley, 2011: "A Climatology of Fatal Convective Wind Events by Storm Type" Weather and Forecasting 26, 109-121

A Climatology of Fatal Convective Wind Events by Storm Type

JOSEPH M. SCHOEN AND WALKER S. ASHLEY

Meteorology Program, Department of Geography, Northern Illinois University, DeKalb, Illinois

(Manuscript received 2 April 2010, in final form 1 October 2010)

ABSTRACT

There are still hundreds of casualties produced by thunderstorm hazards each year in the United States despite the many recent advances in prediction and mitigation of the effects of convective storms. Of the four most common thunderstorm hazards (wind, hail, flooding, and lightning), convective winds (tornadic and nontornadic) remain one of the most dangerous threats to life and property. Using thunderstorm fatality and Weather Surveillance Radar-1988 Doppler (WSR-88D) data, this research illustrates a spatial and temporal analysis of the storm morphological characteristics, or convective mode, of all fatal tornadic and nontornadic convective wind events from 1998 to 2007. The investigation employs a radar-based morphology classification system that delineates storm type based on an organizational continuum, including unorganized cellular, quasi-organized cellular (either a cluster of cells or a broken line of cells), organized cellular (supercells and supercells embedded in an organized linear system), and organized linear (either squall lines or bow echoes). Results illustrate that over 90% of the 634 recorded tornado deaths were associated with supercells, with 78% of the deaths due to isolated tornadic supercells and 12% linked to tornadic supercells embedded within an organized linear convective system. The morphologies responsible for the 191 nontornadic convective wind fatalities vary substantially, with bow echoes (24%), squall lines (19%), and clusters of cells (19%) the most prominent convective modes producing fatalities. Unorganized and quasi-organized convection accounted for nearly half (45%) of all nontornadic convective wind fatalities. Over half of all fatal tornadoes (53%) occurred between 0000 and 0600 UTC, and most (59%) fatalities from nontornadic convective winds occurred in the afternoon between 1800 and 0000 UTC. Two corridors of nontornadic convective wind fatalities were present: the lower Great Lakes region and the mid-South. Tornado fatalities were greatest in a zone extending from southeastern Missouri, through western Tennessee, northeastern Arkansas, Mississippi, Alabama, and Georgia. The methods employed and results found in this study are directly applicable in the further development of storm classification schemes and provide forecasters and emergency managers with information to assist in the creation and implementation of new convective wind mitigation strategies.

1. Introduction

Even though there have been many advances in the understanding and technology required to predict and mitigate the effects of convective storms, there are still many lives lost each year due to these events. Of the four most common thunderstorm hazards (wind, hail, flooding, and lightning), convective winds (tornadic and nontornadic) remain the most dangerous threat to life and property. Convective winds are responsible for an average of 84 fatalities per year in the United States—25 fatalities from nontornadic convective winds (Black and Ashley 2010) and 59 fatalities from tornadoes (Ashley 2007).

Corresponding author address: Walker S. Ashley, Meteorology Program, Dept. of Geography, Northern Illinois University, DeKalb, IL 60115.
E-mail: washley@niu.edu

DOI: 10.1175/2010WAF2222428.1

Many studies have analyzed the spatiotemporal characteristics of tornadic and nontornadic convective winds and their associated casualties. For example, the climatology of tornadoes has been well documented (e.g., Kelly et al. 1978; Concannon et al. 2000; Brooks et al. 2003; Ashley et al. 2008), and the distribution of tornado fatalities has also been investigated (Brooks and Doswell 2002; Brooks et al. 2003; Ashley 2007). Kelly et al. (1985) and Doswell et al. (2005) used archived severe thunderstorm wind report data to develop a climatology of nontornadic convective winds across the conterminous United States. Other studies have developed climatologies of particularly damaging and widespread convective wind events known as derechos (Johns and Hirt 1987; Bentley and Mote 1998; Coniglio and Stensrud 2004; Ashley and Mote 2005). Recently, work has begun to uncover the unique distributions and meteorological conditions associated with a variety of scales of nontornadic convective winds (Klimowski et al.

2003; Gallus et al. 2008; Black and Ashley 2010). Other investigations have examined and described the convective mode of specific storm types, including downburst-producing storms (Fujita and Wakimoto 1981), squall lines (Bluestein and Jain 1985), mesoscale convective systems (MCS; Parker and Johnson 2000), bow echoes (Fujita 1978; Przybylinski 1995; Weisman 2001; Klimowski et al. 2004), and supercells (Moller et al. 1994).

Several climatologies have sought to distinguish the radar morphologies, or modes, of storms producing tornadic and nontornadic convective wind events (Parker and Johnson 2000; Klimowski et al. 2003; Gallus et al. 2008). In general, most of these studies have encompassed limited spatiotemporal spans due to data and analysis restraints. For example, Gallus et al. (2008) examined all forms of convection that led to the production of severe-weather reports over just a single warm season in the Midwest yet still tallied 925 storm events for analysis. Some have tried to rectify this analysis limitation issue by constructing automated decision tree algorithms to classify each storm (Johnson et al. 1998; Lakshmanan et al. 2003, 2007; Gagne et al. 2009; Guillot et al. 2008), but work is still required to obtain acceptable accuracy from these programs (Gagne et al. 2009). No studies have focused on analyzing the convective morphologies of fatal tornadic and nontornadic wind events over an extended period of time.

The focus of this investigation is on analyzing all deadly wind events associated with convective storms in order to assess their radar morphologies at the time of each fatality. To accomplish this task, radar data were obtained, coordinated, and analyzed in correspondence with all fatalities that occurred during tornadic and nontornadic convective wind events from 1998 to 2007 over the contiguous United States. Using a similar thunderstorm classification system as developed in previous radar studies (e.g., Parker and Johnson 2000; Klimowski et al. 2003; Gallus et al. 2008; Ashley and Gilson 2009), fatal storms were categorized by their respective morphologies. In addition, the morphologies of fatal tornadic and nontornadic convective wind events were spatiotemporally compared and analyzed. This study seeks to confirm whether or not most convective wind fatalities occur as a result of organized convection (e.g., supercells, squall lines, and bow echoes).

2. Data and method

a. Source of data

The fatality data employed in this study were derived from the National Climatic Data Center (NCDC) *Storm Data* database. Many studies have discussed the inherent problems with *Storm Data* and the collection of hazard event data (e.g., Brooks and Doswell 2002; Brooks et al. 2003; Doswell et al. 2005; Trapp et al. 2005; Ashley and Black 2008). Since fatalities occur less frequently and generally attract more media attention than nonfatal events, it can be assumed that the numbers of fatalities reported in *Storm Data* are a reliable, if somewhat conservative, estimate of the number of fatalities due to convective windstorms. These data were used to determine the spatial and temporal information associated with each convective wind–related fatality in the United States from 1998 to 2007. This 10-yr time frame, which was selected because of the relative completeness of the radar and fatality datasets therein, was sufficient to construct a sample of hundreds of tornadic and nontornadic wind events.

For each fatal convective storm event, corresponding Weather Surveillance Radar-1988 Doppler (WSR-88D) level-III radar data were downloaded from NCDC's Hierarchical Data Storage System (HDSS; information available online at http://has.ncdc.noaa.gov/pls/plhas/has.dsselect). Unfortunately, 12 nontornadic convective wind events and 10 tornadic events had limited or no data available on the HDSS. Alternatively, lower-resolution radar data were consulted in these cases by examining the University Corporation for Atmospheric Research image archive (information available online at http://locust.mmm.ucar.edu) and/or the Storm Prediction Center's severe thunderstorm event index (information available online at http://www.spc.ncep.noaa.gov/exper/archive). The descriptions from *Storm Data* were also consulted to help to confirm the morphological characteristics of each of these unique cases.

b. Storm-type classification scheme

An analysis of the radar data before, during, and after the time of the fatality—usually about 30–60 min before and after the fatality—was conducted to determine the storm type responsible for the death. To eliminate some of the subjectivity inherent in trying to classify a storm that is constantly changing and evolving, the storm type was assigned based on its morphology at the time closest to the fatality occurrence. The classification scheme (Table 1) employed was consistent with and similar to those presented in previous studies examining radar morphology of convective storms (e.g., Parker and Johnson 2000; Klimowski et al. 2003; Gallus et al. 2008; Ashley and Gilson 2009). For this study, storms were classified as either unorganized cellular, quasi-organized cellular (cluster of cells or broken line of cells), organized cellular (supercells or supercells embedded in an organized linear system), or organized linear (squall lines and bow echoes).

Organized linear storms are defined as a conglomerate of convective storms with radar echoes greater than

TABLE 1. Descriptions of each storm category and storm type.

Storm category	Storm type
Cellular (unorganized) Not fulfilling any other category Radar echoes: no restriction Duration: typically <90 min Length: no restriction Cell proximity: cells with greatest reflectivity are ≥5 km	Unorganized cells (UO) Pulse-style convection Move and evolve independent of each other After Ashley and Gilson (2009)
Cellular (quasi organized) Individual, cluster, or line Representing the developing or dissipating stage in storms Moving, initiating, and evolving w.r.t. one another (merging and splitting) Radar echoes: ≥40 dB*Z* Duration: ≥30 min (Klimowski et al. 2003) Length: no restriction Cell proximity: some cells ≥40 dB*Z* are ≤5 km	Clusters of cells (CC) Nonlinear, nonsupercellular cluster of cells [after Gallus et al. (2008)] After ''areal'' morphologies (Bluestein and Jain 1985) Cells in broken squall lines (BL) As above, only arranged in a linear fashion [after Gallus et al. (2008)] After ''broken line'' and ''back building'' morphologies (Bluestein and Jain 1985)
Cellular (organized) Individual cell either isolated or embedded in an organized linear system (MCS or QLCS) Radar echoes: ≥40 dB*Z* Duration: ≥30 min (Klimowski et al. 2003) Length: no restriction for SC; SCL in organized linear system ≥75 km (Gallus et al. 2008) Cell proximity: no restriction for isolated supercells; embedded supercells are ≤5 km from a line of cells ≥75 km in length	Supercells (SC) Isolated cells containing NEXRAD level-III reflectivity features (inflow notch, hook echo, tight reflectivity, gradient, etc.) and persistent (≥6 radar scans or 30 min) mesocyclone in multiple elevation slices of storm relative velocity After Ashley and Gilson (2009) Consistent with type-I supercell from Agee and Jones (2009) Supercell embedded in an organized linear system (SCL) Bearing all supercell criteria but situated within an organized linear system as defined below After Miller and Johns (2000)
Linear (organized) Linear conglomerate of convective storms Consistent with linear MCS (Parker and Johnson 2000) or QLCS (Weisman and Davis 1998) Radar echoes: ≥40 dB*Z* Duration: ≥30 min (Klimowski et al. 2003) Length: ≥75 km (Gallus et al. 2008) Cell proximity: all cells ≥40 dB*Z* are ≤5 km and form a convective line ≥75 km in length	Squall lines (SL) Leading line has intensively reflective cells connected by moderately reflective cells Strong gradient on the leading edge With or without accompanying stratiform precipitation After Parker and Johnson (2000) and Gallus et al. (2008) Bow echoes (BE) Crescent-shaped radar echo Tight reflectivity gradient on the leading edge (convex side) Exhibits an increasing radius or a persistent arc Consistent with Fujita (1978) and Klimowski et al. (2003, 2004)

or equal to 40 dB*Z* connected by weaker radar echoes arranged in a linear (Parker and Johnson 2000), or quasi-linear fashion [i.e., quasi-linear convective systems (QLCS) or line-echo wave pattern; Weisman and Davis 1998], lasting greater than 30 min in duration (Klimowski et al. 2003), and having a length greater than 75 km (Gallus et al. 2008). Organized linear storms were further subdivided into bow echoes and squall lines. Bow echoes were defined, consistent with Fujita (1978) and Klimowski et al. (2003), as a crescent-shaped radar echo with a tight reflectivity gradient on the leading edge (convex side). These storms were required to exhibit an increasing radius with time or a persistent arc (distinguishing between linear organization and an unassociated, brief, arclike structure). For the purposes of this climatology, the different types of bow echoes that have been identified in Klimowski et al. (2004) were not used. Squall lines were defined, similar to the approach in Parker and Johnson (2000), as having a straight or minimally convex leading edge of intense cells connected by moderately intense cells. Squall lines have a strong reflectivity gradient on the leading edge and can, but are not required to, have stratiform precipitation following, leading, or traveling parallel to the leading convective line.

Organized cellular storms were those classified as either an individual isolated supercell (Moller et al. 1994;

Ashley and Gilson 2009) or a supercell embedded in an organized linear system [see Miller and Johns (2000) for examples]. Isolated supercells were defined after Ashley and Gilson (2009) as any cell meeting the following criteria: 1) one or more reflectivity features indicative of supercells present (e.g., radar echoes ≥40 d*BZ*; inflow notch, hook echo, tight reflectivity gradient, v notch, or storm splits), 2) a persistent (≥ six radar scans or 30 min) mesocyclone (or mesoanticyclone) as identified by the Next Generation Weather Radar (NEXRAD) mesocyclone detection algorithm (Stumpf et al. 1998), and 3) a persistent mesocyclone (or mesoanticyclone) as confirmed by multiple elevation slices of storm-relative velocity data (if available). An additional category of supercells, those embedded in an organized linear system, was used to accommodate those storms containing all the criteria listed previously for supercells but that were situated within an organized linear morphology such as a squall line or bow echo. From the perspective of our analysis, isolated supercells and supercells embedded in an organized linear system were mutually exclusive, that is, no "double counting" occurred since the storm fit into either the isolated supercell or supercell embedded in an organized linear system classification bin.

Quasi-organized cellular storms were those illustrating individuality within a larger area of convective storms that did not meet the specific criteria for supercells or organized linear storms. These storms usually represented the developing or dissipating stages of more organized convection. In addition, these morphologies were typically initiating and propagating in the same vicinity and direction, arranged in a linear (cells in a broken line) or nonlinear (cluster of cells) fashion (after Gallus et al. 2008), and moving and evolving with respect to one other, oftentimes merging and splitting. Since this category is a "cellular" category, storms in a quasi-organized cellular broken line, though having some similar characteristics to an organized linear system, do not have an assigned size limitation. Furthermore, because broken lines often represent the developing or dissipating stage of an organized linear system, the decision to classify a storm as a broken line or a squall line was, in some cases, challenging. For example, a developing squall line often takes the form of cells in a broken line connected by weak stratiform rain on the radar. In this stage, there was clearly a linear forcing mechanism creating the convection, but the cells had not developed enough to connect into a squall line. Since the higher reflectivity cells were still not connected on radar, these cells would be part of a "broken line" complex.

Clusters of cells were categorized as a collection of nonlinear multicells, such as those implied in the spectrum between unorganized cells and supercells. A cluster of cells was not organized enough at the time of the fatality to be called an organized linear or organized cellular storm, but it showed evidence of organization (e.g., development into, or dissipation from, a supercell, squall line, or bow echo) when viewed in the immediate period before or after the fatality. For these reasons, they were classified as "quasi organized."

The final storm type, cellular unorganized, was classified as a storm not meeting the criteria requirements associated with quasi-organized cellular, organized cellular, or organized linear convection. This was defined as individual cells displaying all of the following characteristics: pulse-style convection; initiating, propagating, and evolving independent of each other; and being arranged in a nonlinear fashion (Ashley and Gilson 2009). These storms differed from quasi-organized cellular or organized cellular storm morphologies since they were relatively short lived (0.5–1.5 h) and did not develop into or dissipate from a more organized convective mode (Ashley and Gilson 2009).

Thunderstorms have been traditionally thought of as occurring across a convective spectrum from unorganized, cellular convection on one end to highly organized supercells at the other end. This traditional spectrum view delineates thunderstorms by their degree of organization, with more organized thunderstorms tending toward greater hazard and risk. However, nature, especially the atmosphere, resists rigid boundaries found in taxonomies. Therefore, we sought to develop a storm classification system consistent with previous research and concomitant with the goal of this study, which was to determine the radar morphology of fatal convective storm events.

3. Results

a. Convective mode distribution

During 1998–2007, 825 fatalities in the conterminous United States were attributed to tornadoes or nontornadic convective wind events. Of the 825 recorded fatalities, 191 fatalities (23%) were due to nontornadic convective wind and 634 fatalities (77%) were due to tornadoes. Because many of the tornadoes during the period caused multiple fatalities, comparisons of the number of fatalities with the number of fatal storms were included in the figures. The convective mode with the most tornado fatalities was supercells, which averaged greater than three fatalities per fatal storm. This was followed by supercells in an organized line, which averaged greater than two fatalities per fatal storm (Fig. 1). The remaining fatal tornadic storm types had a near 1:1 ratio for fatalities per fatal storm; that is, these storm

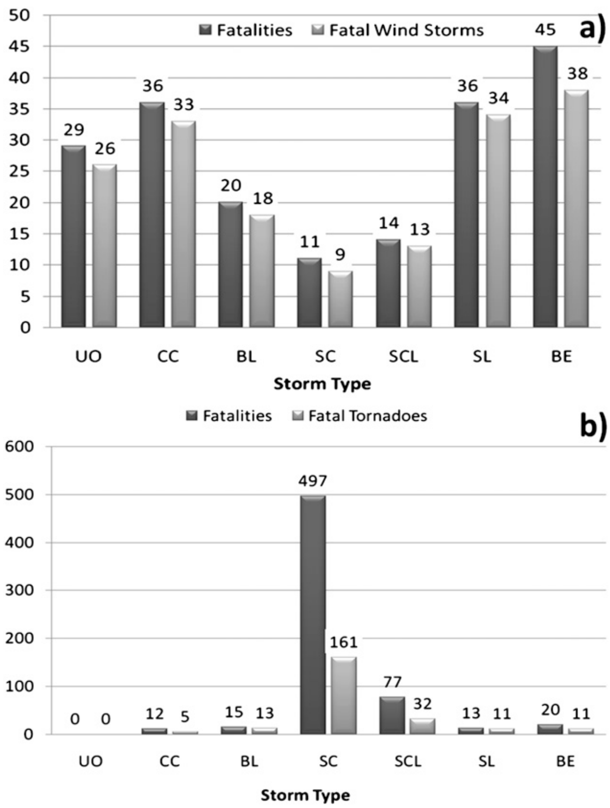

FIG. 1. Distribution of the total number of fatalities in comparison with number of fatal storms by storm type (1998–2007) for (a) nontornadic convective wind events and (b) tornadoes. See Table 1 for storm-type acronym definitions.

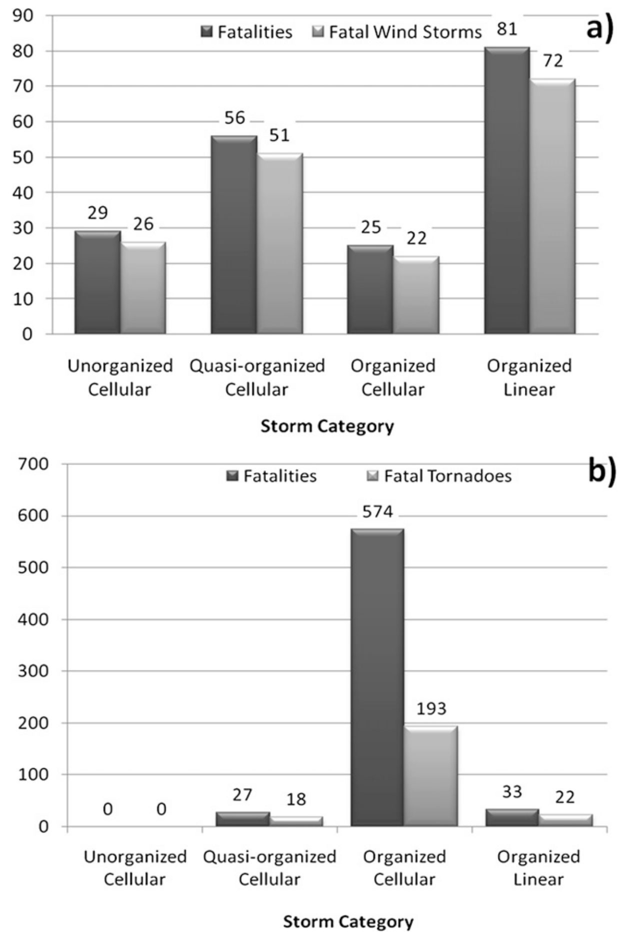

FIG. 2. Distribution of the total number of fatalities in comparison with number of fatal storms by storm category (1998–2007) for (a) nontornadic convective wind events and (b) tornadoes.

types rarely killed more than one person per event. This is illustrated in Fig. 1, which compares the number of tornado fatalities with the number of tornadoes that produced at least one fatality. The difference in fatalities (191) in comparison with fatal storm totals (171) was less apparent with nontornadic convective winds. Only 15 of the 171 (9%) nontornadic convective wind storms caused more than one fatality (Fig. 1).

Fatalities due to nontornadic convective winds were more evenly distributed across storm types as compared with tornadoes, albeit with some exceptions. Bow echoes were responsible for one-quarter of all nontornadic convective wind fatalities (Fig. 1). Squall lines and clusters of cells morphologies were the second-most fatal nontornadic convective storm types, causing 19% of the fatalities each. Thus, collectively, organized linear storms were the single largest source of nontornadic convective wind fatalities, causing 42% of the total number of fatalities (Fig. 2a). Since these storm-type percentages are associated only with fatalities, it is difficult to relate them to the storm-type tallies demonstrated in Klimowski et al. (2003) and Gallus et al. (2008). However, the percentages of fatalities caused by bow echoes and squall lines in this investigation are similar to the percentages of bow-echo and squall-line-generating severe-weather reports found in Klimowski et al. (2003) and Gallus et al. (2008).

Relatively few (only about 13%) of the nontornadic convective wind fatalities were caused by organized cellular storms. Quasi-organized cellular storms—that is, those storms that were classified as either cluster of cells and cells in broken squall lines—accounted for 29% of the total number of fatalities (Fig. 2a). Combining quasi-organized fatalities with the 15% of fatalities from unorganized cellular systems suggests that 45% of nontornadic convective wind fatalities were caused by weakly organized convection. This relatively large percentage of fatalities associated with unorganized or quasi-organized convection presents a unique mitigation problem since these storm types may be less likely to receive warnings in comparison with more-organized convective storms.

Most deaths from tornadoes were caused by supercells, with 497 (78%) of the 634 fatalities caused by isolated supercells (Fig. 2b). The organized cellular category of fatal storms—that is, supercells and supercells embedded in an organized linear system—accounted for over 90% of tornado fatalities (Fig. 2b). These fatality distributions are similar to the percentages of tornadoes formed from supercells found in Trapp et al. (2005). Trapp et al. (2005) attempted to quantify and compare the numbers of tornadoes produced by bow echoes and squall lines with those of tornadoes produced by isolated cells during a 3-yr period (1998–2000). Out of the three morphological categories in their study, ''cells'' (which would contain our ''supercell'' storm type) produced the most tornadoes (79%), whereas quasi-linear convective systems, within which our ''supercells embedded in an organized linear system'' storm type would be classified, were associated with 18% of the examined tornado events. Even though Trapp et al. (2005) evaluated tornadoes and not tornado fatalities, similarities in the distributions in the storm types of tornadoes and tornadoes that produce fatalities appear to exist.

b. Temporal results

From 1998 to 2007, the average number of fatalities due to nontornadic convective wind events was nearly 20 per year. There were two exceptional years for nontornadic convective wind fatalities: 1998 and 1999. The numbers of fatalities in both years were greater than 2 and 1 standard deviation σ above the mean, respectively (mean = 19.1 and $\sigma = 8.4$; Fig. 3a). Of the 38 fatalities in 1998 (Fig. 3a), just under one-half were from bow echoes (Ashley et al. 2007). Further, 21 fatalities in 1998 were attributed specifically to derechos, with 6 of those fatalities occurring during one event on 31 May (Ashley and Mote 2005; Ashley et al. 2007). Of the 28 fatalities in 1999 (Fig. 3a), 36% resulted from clusters of cells, and another 25% resulted from bow echoes.

The average number of tornado fatalities per year during the period of record was 63.4. This was slightly higher than the averages of around 58.5 (1996–2005) and 58.6 fatalities (1976–85) illustrated by Ashley (2007). Despite the higher annual variability of tornado *fatalities*, the annual number of *fatal tornadoes* during the period of record showed considerably less variability (Fig. 3b). The unusually high average number of fatalities can be partly explained by the fact that 1998 and 1999 were particularly deadly years. Similar to nontornadic convective wind fatalities, tornado fatalities during 1998 and 1999 fell 1.00 and 2.20 standard deviations above the mean, respectively (mean = 63.4 and $\sigma = 30.7$; Fig. 3b). In 1998, 125 of the 131 tornado fatalities (95%) occurred from only 25 isolated supercell storms; 41 of those fatalities occurred during an outbreak in central Florida on 23 February (National Weather Service 1998a), and another 34 people perished in an Alabama outbreak on 9 April (National Weather Service 1998b). In 1999, 76 of the 94 tornado fatalities (81%) were caused by isolated supercells, with 46 of those fatalities occurring in the Kansas–Oklahoma outbreak of 3 May (Brooks and Doswell 2002). Bow echoes resulted in an additional 13% of tornado fatalities that year.

In concurrence with severe thunderstorm climatologies (Kelly et al. 1985; Doswell et al. 2005), the greatest number of fatalities and fatal storms from nontornadic convective wind occurred in the warm-season months of May–August, with a peak in July (Fig. 3a). The morphologies associated with the nontornadic convective wind fatalities in these peak months were organized linear (38%), quasi-organized cellular (34%), unorganized (15%), and organized cellular (13%). Thus, nearly one-half of all fatalities from nontornadic convective wind storms come from nonorganized types of convection in the peak months for these storms. August was unique in that unorganized cellular storms produced nine fatalities as a result of events exclusively along the Gulf Coast. In examining the descriptions associated with these fatalities in *Storm Data*, no real patterns emerged to explain this phenomenon (e.g., five fatalities due to felled trees, two due to structure collapse, and two due to drowning).

The deadliest months for tornadoes were the spring transition season of February–May and the late-autumn month of November. April and May had the most fatalities: 138 and 136, respectively (Fig. 3b). The deadliest storm type for these months (February–May and November) was the isolated supercell morphology, comprising 82% of the fatalities during these periods. In general, the storm fatality rates in June and July were very low, averaging slightly over one fatality per storm (Fig. 3b). In contrast, February had the most fatalities per storm, averaging 6.2 fatalities per storm. The findings here are in agreement with the climatology for average monthly fatalities from Ashley (2007).

Over one-half of the nontornadic convective wind storms and their resulting fatalities occurred in the afternoon, with 37% of these fatalities occurring between 2100 and 0000 UTC (Figs. 3a and 4a). Between the hours of 1800 and 0000 UTC, the majority of fatal nontornadic convective wind fatalities were unorganized (22%), clusters of cells (19%), and bow echoes (18%). Collectively, 52% of these fatal nontornadic convective wind storms in the afternoon were due to nonorganized convection. This may be partly explained by the fact that more people are outdoors during this time of day and thus are more vulnerable to the hazards associated with a high-wind event.

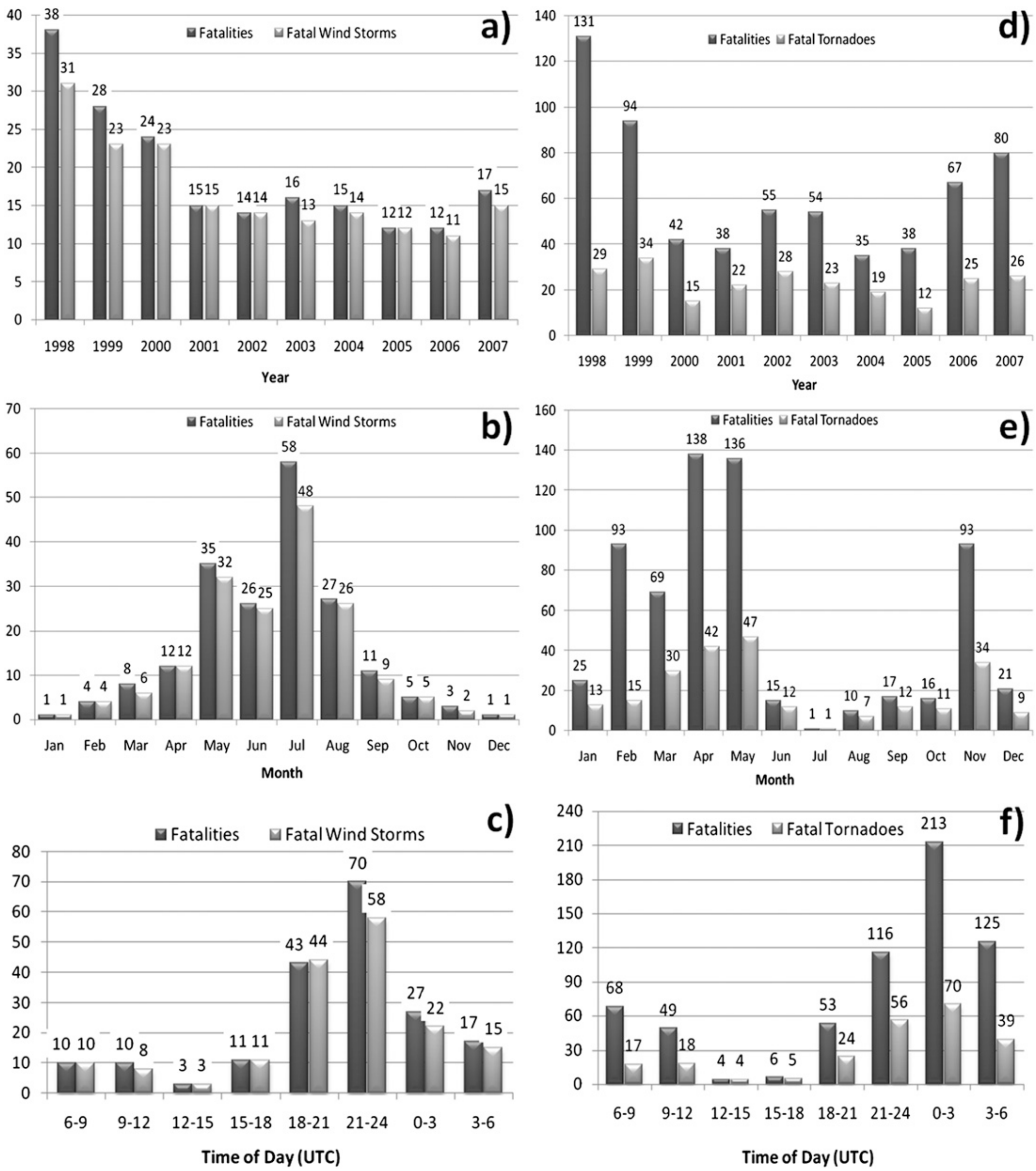

FIG. 3. Temporal results for number of fatalities in comparison with fatal storms during the period of record, 1998–2007, for (left) nontornadic convective wind events and (right) tornadoes by (a),(d) year, (b),(e) month, and (c),(f) time of day.

Recent results describing the locations of nontornadic wind fatalities illustrate that 50% of nontornadic convective wind fatalities (Black and Ashley 2010) and 69% of derecho fatalities (Ashley and Mote 2005) occur outdoors, in a vehicle, or in a boat. In addition, at least 43% of fatalities from nontornadic convective wind storms are related to a felled tree (Black and Ashley 2010). Last, Ashley and Black (2008) hypothesized that people are more likely to seek shelter in response to tornado warnings than in response to severe-thunderstorm warnings. This complacency issue could be a primary cause of the high fatality rate found for the warm-season afternoon—a period in which people tend to be engaged in outdoor activities.

In contrast to nontornadic convective wind, tornadoes were deadliest in the evening, with 34% of the fatalities occurring between the hours of 0000 and 0300 UTC and another 20% occurring between 0300 and 0600 UTC (Figs. 3b and 4b). The highest percentages of deaths per storm occurred during the period of time between 0300 and 0600 UTC and were most often associated with supercells embedded in organized linear systems. These

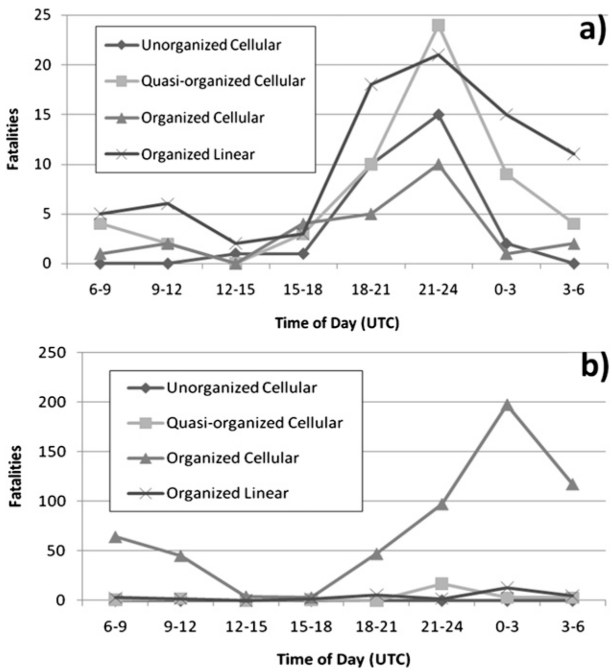

FIG. 4. Distribution of the total number of fatalities by time of day in UTC for each storm category (1998–2007) for (a) nontornadic convective wind events and (b) tornadoes.

temporal results are consistent with nighttime tornado statistics presented in Ashley et al. (2008).

c. Spatial results

Most nontornadic convective wind fatalities during the 10-yr record were concentrated east of the Continental Divide (Fig. 5, Table 2), which is concurrent with previous climatologies of severe thunderstorms (Kelly et al. 1985; Doswell et al. 2005). Two corridors are evident for nontornadic convective wind fatalities, similar to those found in Black and Ashley (2010). The first, and most significant, of these corridors appears in the Great Lakes region, extending in a belt from Wisconsin and Illinois eastward through Michigan, Indiana, Ohio, Pennsylvania, New York, and parts of northern Kentucky and West Virginia. The Great Lakes states of Michigan, New York, and Ohio contain 21% of all nontornadic convective wind fatalities (Table 3), with nearly one-half of these caused by organized linear morphologies. This distribution mimics the climatology of derecho fatalities illustrated by Ashley and Mote (2005), which suggests that derecho-producing convective systems could be the primary cause of fatalities in this corridor. There is a second high concentration of nontornadic fatalities in the mid-South, which extends from eastern Arkansas through Tennessee, Mississippi, Alabama, Georgia, and into South Carolina. Ashley (2007) illustrated that the mid-South region is an area that has a unique juxtaposition of risk and vulnerabilities that leads to elevated tornado fatality rates; it is possible that these risk (e.g., greater likelihood of nocturnal severe events in the mid-South) and vulnerability (e.g., mobile home density and forest cover in this region) characteristics may translate to other thunderstorm hazards, such as nontornadic convective wind events.

The morphologies of fatal nontornadic convective wind storms vary greatly in the Great Lakes region, with a large number of fatal storms classified as clusters of cells or bow echoes (Fig. 5, Table 3). A majority of the fatalities from nontornadic convective wind events in the mid-South and along the East Coast were from organized linear convection.

Most tornado fatalities during the period of record occurred in a zone covering Missouri, Tennessee, Alabama, and Georgia (Fig. 6, Table 2). This is consistent with the findings from Ashley (2007), which indicated a similar maximum of fatalities in the mid- and Deep South. Like Ashley (2007), this tornado fatality distribution is relatively inconsistent with the number of tornadoes and significant tornadoes, which show maxima that are farther west of the mid- and Deep South high-fatality corridor.

The dominant morphologies of the top 12 deadliest tornado states were overwhelmingly isolated supercells (Fig. 6, Table 4). One exception to this was Georgia, which, in comparison with the other top-12 tornado fatality states, had over one-half of the state's deaths occur in supercells embedded within an organized linear system. Note that 20 of the 33 fatalities from supercells embedded within an organized linear system came from a single night: 13 February 2000 and early morning 14 February 2000. Tennessee had the most tornado fatalities produced from organized linear convection at 17% (Table 4); over one-half of which resulted from a bow echo passing though on the afternoon of 17 January 1999. Tennessee also had a large share of tornado fatalities produced by supercells embedded within an organized linear system, with another 17% of the fatalities resulting from this morphology. These fatalities occurred from two storms: 4 May 2003 (11 of the 15 fatalities) and 10 November 2002 (the remaining 4 fatalities).

4. Conclusions

Thunderstorm hazards produce hundreds of casualties annually in the United States despite efforts to reduce and mitigate their associated risks. Among the most dangerous threats to life and property from convective storms are tornadoes and nontornadic convective wind

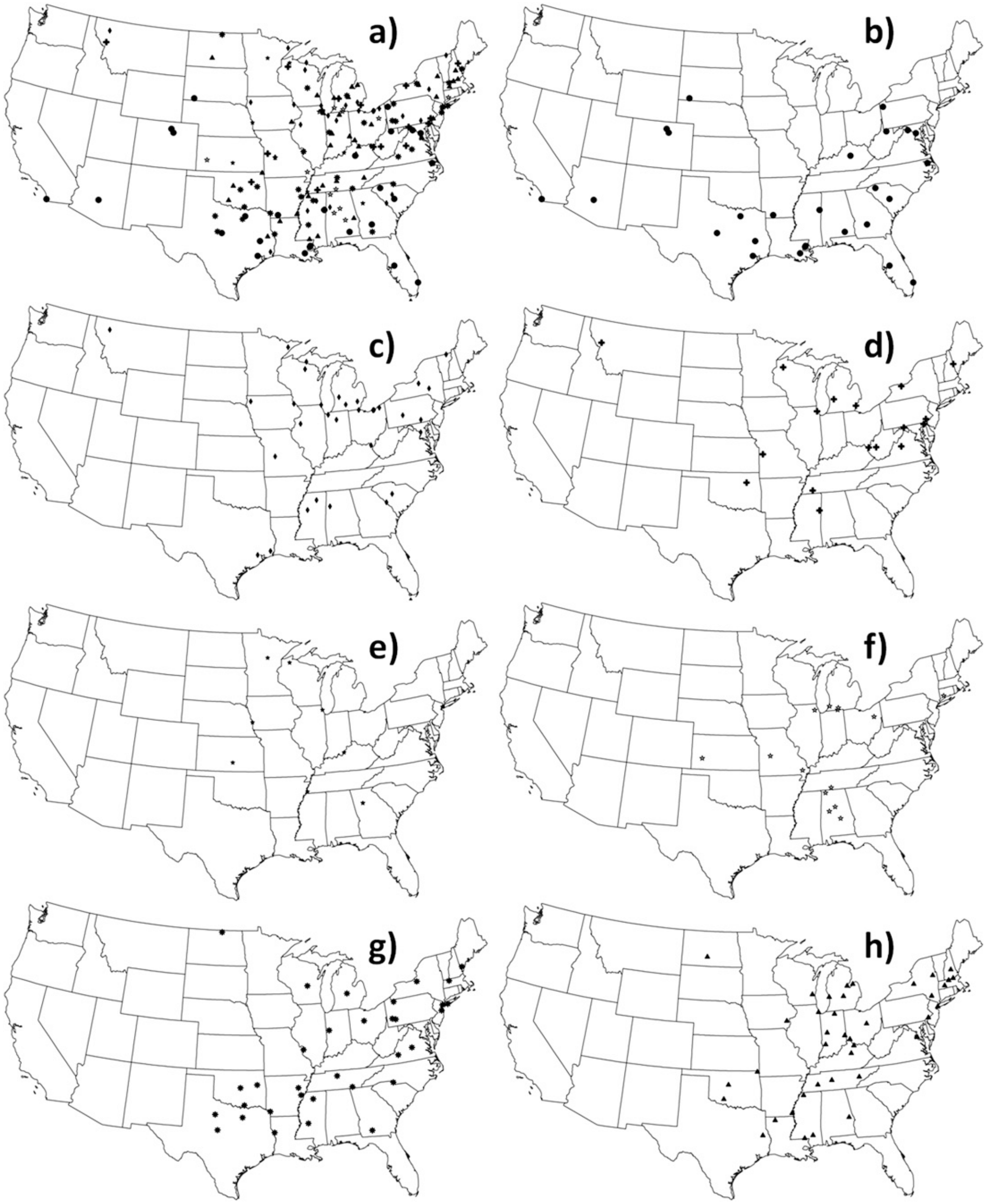

FIG. 5. Spatial distribution of fatalities caused by nontornadic convective wind events during the period of record (1998–2007) for (a) all storms combined, (b) unorganized storms (circles), (c) clusters of cells (diamonds), (d) broken lines (crosses), (e) supercells (filled stars), (f) supercells embedded in an organized linear system (open stars), (g) squall lines (asterisks), and (h) bow echoes (triangles).

events. Despite the many recent advances in prediction and mitigation of the effects of convective storms, much is still unknown about the morphological character of fatal storms. This study provided a climatology of all fatal tornadic and nontornadic convective wind events for 1998–2007. To facilitate this climatology, a radar-based classification system was developed, employing storm morphology delineation methods used in prior research. The results illustrate that

1) the morphologies of fatal nontornadic convective wind storms vary substantially, with bow echoes, squall lines, and clusters of cells being the most prominent;

TABLE 2. Number of fatalities and fatalities normalized for area (fatalities per square kilometer × 10 000) by state, during 1998–2007, for nontornadic convective winds and tornadoes. Counts and normalized values in boldface indicate the top five values for their respective categories.

	Nontornadic convective wind		Tornadoes	
State	Fatalities	Fatalities normalized for area	Fatalities	Fatalities normalized for area
AL	7	2.149	**78**	**23.945**
AR	5	1.513	19	5.750
AZ	1	0.141	0	0.000
CA	3	0.295	0	0.000
CO	3	0.464	2	0.309
CT	1	2.903	0	0.000
FL	3	0.806	**73**	**19.610**
GA	6	1.637	**60**	**16.375**
IA	3	0.858	7	2.002
IL	7	1.945	19	5.280
IN	8	**3.535**	27	**11.932**
KS	5	0.978	27	5.281
KY	6	2.390	8	3.186
LA	5	1.621	16	5.186
MA	4	**6.967**	0	0.000
MD/DC	5	**6.508**	5	6.544
ME	2	0.954	0	0.000
MI	**15**	2.496	3	0.499
MN	2	0.370	6	1.111
MO	5	1.154	**48**	11.082
MS	**10**	3.333	15	5.000
MT	2	0.219	0	0.000
NC	1	0.306	15	4.583
ND	2	0.455	1	0.228
NE	0	0.000	3	0.624
NH	2	3.468	0	0.000
NJ	1	1.959	1	1.959
NM	0	0.000	2	0.265
NY	**14**	**4.166**	1	0.298
OH	**11**	**3.949**	11	3.949
OK	7	1.612	45	10.361
PA	9	3.145	5	1.747
SC	4	2.064	6	3.096
SD	1	0.209	7	1.461
TN	9	3.437	**86**	**32.841**
TX	**10**	0.602	29	1.746
UT	0	0.000	1	0.190
VA	3	1.141	2	0.760
VT	1	1.674	0	0.000
WI	7	1.720	4	0.983
WV	5	0.823	0	0.000
WY	0	0.000	2	0.329

TABLE 3. Top 12 deadliest states from nontornadic convective wind events during 1998–2007. Listed for each state is the number of fatalities, the percent of the total number of fatalities for the period of record, and the number of fatalities from each storm type. See Table 1 for storm-type acronym explanations.

State	Fatalities	% of total	UO	CC	BL	SC	SCL	SL	BE
MI	15	7.7	0	4	3	0	3	1	4
NY	14	7.2	0	2	1	1	0	6	4
OH	11	5.6	0	6	0	0	1	1	3
MS	10	5.1	1	2	1	0	0	2	4
TX	10	5.1	4	2	0	0	0	3	1
TN	9	4.6	0	0	1	1	1	2	4
PA	9	4.6	1	2	2	0	0	3	1
IN	8	4.1	0	2	0	0	0	1	5
IL	7	3.6	0	2	1	1	1	1	1
WI	7	3.6	0	3	1	1	0	1	1
OK	7	3.6	0	0	1	0	0	3	3
AL	7	3.6	1	1	0	0	4	0	1

2) just under one-half of all fatalities from nontornadic convective wind were from unorganized or quasi-organized convection;
3) over one-half of nontornadic convective wind storms fatalities occurred in the afternoon between 1800 and 0000 UTC (52% of these afternoon fatalities were caused by nonorganized convection);
4) the majority of fatal nontornadic convective wind storms in the Great Lakes region were caused by clusters of cells or bow echoes, whereas in the mid-South most were from organized linear convection;
5) organized cellular convection (supercells combined with embedded supercells in organized linear convection) was the most fatal tornadic storm type, responsible for over 90% of tornado-related fatalities; and
6) most tornado fatalities occurred in a zone from southeastern Missouri through western Tennessee, northeastern Arkansas, Mississippi, Alabama, and Georgia and were caused by supercells or supercells embedded in organized linear systems.

These results suggest that deadly thunderstorm wind events can be generated from a variety of morphologies other than organized, typically "severe warned," convective forms such as supercells and linear systems. While the risk from organized convection remains relatively high because of the elevated probability of significant wind phenomena being engendered from these storm types, our results indicate a greater need for public awareness of the power of "ordinary," or unorganized, thunderstorms. Outreach programs should (re)attempt to inform the public of the dangers of unorganized and weakly organized convective storms, specifically the life-threatening nature of nontornadic convective wind events that may not appear to be overly intense from a radar perspective or perhaps may go unwarned because of a lack of formal "severe" criteria being met. While common sense should dictate the need for personal shelter in even an ordinary thunderstorm event, there are many fatal events that occur each year that illustrate that the seek-shelter message may need to be reiterated and reinforced.

FIG. 6. Spatial distribution of fatalities caused by tornadoes during the period of record (1998–2007) for (a) all storms combined, (b) clusters of cells (diamonds), (c) broken lines (crosses), (d) supercells (filled stars), (e) supercells embedded in an organized linear system (open stars), (f) squall lines (asterisks), and (g) bow echoes (triangles). Cellular unorganized (UO) storms are not illustrated since they were responsible for no fatal tornadic storms during the period of record.

Furthermore, the authors recommend that a more temporally comprehensive climatology that examines the morphologies of *all* severe convective events be pursued in the future. This would involve analyzing the storm types associated with thousands of severe reports over a decade or more. Unfortunately, the classification of hundreds or thousands of storms manually by an individual or team of researchers is a monumental—and likely impractical—task. The best solution for the advancement of a long-term climatology of storm types will involve the development of an effective automated storm detection and classification algorithm (e.g., see Gagne et al. 2009).

Up to this point, an assortment of classification schemes has been used to explain the various storm morphologies for purposes of spatiotemporal analyses (e.g., Bluestein

TABLE 4. As in Table 3, but for tornado fatalities.

State	Fatalities	% of total	UO	CC	BL	SC	SCL	SL	BE
TN	86	13.6	0	0	0	56	15	3	12
AL	78	12.3	0	0	1	72	1	2	2
FL	73	11.5	0	0	0	71	1	1	0
GA	60	9.5	0	3	1	23	33	0	0
MO	48	7.6	0	1	3	41	2	1	0
OK	45	7.1	0	0	0	44	0	1	0
TX	29	4.6	0	0	4	21	4	0	0
IN	27	4.3	0	0	0	25	0	0	2
KS	27	4.3	0	0	0	27	0	0	0
AR	19	3.0	0	0	1	16	2	0	0
IL	19	3.0	0	0	0	14	3	0	2
LA	16	2.5	0	2	1	9	3	1	0

and Jain 1985; Parker and Johnson 2000; Klimowski et al. 2003; Gallus et al. 2008). This study employed similar methods and definitions as outlined in these prior studies. In the future, the authors recommend that a universal classification system should be developed and adopted by the operational and research communities for the purposes of improving postevent analyses. Such a scheme, as well as resultant climatologies, could provide a wealth of information for the improvement of watch–warning systems, as well as the creation and implementation of new casualty-reducing mitigation strategies.

Acknowledgments. The authors thank Dr. Mace Bentley (NIU), Dr. David Changnon (NIU), and Mr. Victor Gensini (NIU) for providing feedback on earlier versions of this manuscript. In addition, we thank Drs. James LaDue (NOAA Warning Decision Training Branch), Les Lemon (Cooperative Institute for Mesoscale Meteorological Studies, University of Oklahoma), and Charles Doswell III (Cooperative Institute for Mesoscale Meteorological Studies, University of Oklahoma) for their comments and suggestions on the classification scheme presented in this work. We also appreciate the thoughtful and beneficial reviews provided by the referees.

REFERENCES

Agee, E., and E. Jones, 2009: Proposed conceptual taxonomy for proper identification and classification of tornado events. *Wea. Forecasting,* **24,** 609–617.

Ashley, W. S., 2007: Spatial and temporal analysis of tornado fatalities in the United States: 1880–2005. *Wea. Forecasting,* **22,** 1214–1228.

——, and T. L. Mote, 2005: Derecho hazards in the United States. *Bull. Amer. Meteor. Soc.,* **86,** 1577–1592.

——, and A. W. Black, 2008: Fatalities associated with nonconvective high-wind events in the United States. *J. Appl. Meteor. Climatol.,* **47,** 717–725.

——, and C. W. Gilson, 2009: A reassessment of U.S. lightning mortality. *Bull. Amer. Meteor. Soc.,* **90,** 1501–1518.

——, T. L. Mote, and M. L. Bentley, 2007: An extensive episode of derecho-producing convective systems in the United States during May–June 1998: A multi-scale analysis and review. *Meteor. Appl.,* **14,** 227–244.

——, A. J. Krmenec, and R. Schwantes, 2008: Vulnerability due to nocturnal tornadoes. *Wea. Forecasting,* **23,** 795–807.

Bentley, M. L., and T. L. Mote, 1998: A climatology of derecho-producing mesoscale convective systems in the central and eastern United States, 1986–95. Part I: Temporal and spatial distribution. *Bull. Amer. Meteor. Soc.,* **79,** 2527–2540.

Black, A. W., and W. S. Ashley, 2010: Nontornadic convective wind fatalities in the United States. *Nat. Hazards,* **54,** 355–366.

Bluestein, H. B., and M. H. Jain, 1985: Formation of mesoscale lines of precipitation: Severe squall lines in Oklahoma during the spring. *J. Atmos. Sci.,* **42,** 1711–1732.

Brooks, H., and C. A. Doswell III, 2002: Deaths in the 3 May 1999 Oklahoma City tornado from a historical perspective. *Wea. Forecasting,* **17,** 354–361.

——, ——, and M. P. Kay, 2003: Climatological estimates of local daily tornado probability for the United States. *Wea. Forecasting,* **18,** 626–640.

Concannon, P. R., H. E. Brooks, and C. A. Doswell III, 2000: Climatological risk of strong and violent tornadoes in the United States. Preprints, *Second Conf. on Environmental Applications,* Long Beach, CA, Amer. Meteor. Soc., 212–219.

Coniglio, M. C., and D. J. Stensrud, 2004: Interpreting the climatology of derechos. *Wea. Forecasting,* **19,** 595–605.

Doswell, C. A., III, H. E. Brooks, and M. P. Kay, 2005: Climatological estimates of local daily nontornadic severe thunderstorm probability for the United States. *Wea. Forecasting,* **20,** 577–595.

Fujita, T. T., 1978: Manual of downburst identification for Project Nimrod. University of Chicago Dept. of Geophysical Sciences Satellite and Mesometeorology Research Paper 156, 104 pp.

——, and R. M. Wakimoto, 1981: Five scales of airflow associated with a series of downbursts on 16 July 1980. *Mon. Wea. Rev.,* **109,** 1438–1456.

Gagne, D. J., II, A. McGovern, and J. Brotzge, 2009: Classification of convective areas using decision trees. *J. Atmos. Oceanic Technol.,* **26,** 1341–1353.

Gallus, W. A., Jr., N. A. Snook, and E. V. Johnson, 2008: Spring and summer severe weather reports over the Midwest as a function of convective mode: A preliminary study. *Wea. Forecasting,* **23,** 101–113.

Guillot, E. M., T. M. Smith, V. Lakshmanan, K. L. Elmore, D. W. Burgess, and G. J. Stumpf, 2008: Tornado and severe thunderstorm warning forecast skill and its relationship to storm type. Preprints, *24th Conf. on Interactive Information Processing Systems for Meteorology, Oceanography, and Hydrology,* New Orleans, LA, Amer. Meteor. Soc., 4A.3. [Available online at http://ams.confex.com/ams/pdfpapers/132244.pdf.]

Johns, R. H., and W. D. Hirt, 1987: Derechos: Widespread convectively induced windstorms. *Wea. Forecasting,* **2,** 32–49.

Johnson, J. T., P. L. MacKeen, A. Witt, E. D. Mitchell, G. J. Stumpf, M. D. Eilts, and K. W. Thomas, 1998: The Storm Cell Identification and Tracking (SCIT) algorithm: An enhanced WSR-88D algorithm. *Wea. Forecasting,* **13,** 263–276.

Kelly, D. L., J. T. Schaefer, R. P. McNulty, C. A. Doswell III, and R. F. Abbey, 1978: An augmented tornado climatology. *Mon. Wea. Rev.,* **106,** 1172–1183.

——, ——, and C. A. Doswell III, 1985: Climatology of nontornadic severe thunderstorm events in the United States. *Mon. Wea. Rev.,* **113,** 1997–2014.

Klimowski, B. A., M. J. Bunkers, M. R. Hjelmfelt, and J. N. Covert, 2003: Severe convective windstorms over the northern high plains of the United States. *Wea. Forecasting,* **18,** 502–519.

——, M. R. Hjelmfelt, and M. J. Bunkers, 2004: Radar observations of the early evolution of bow echoes. *Wea. Forecasting,* **19,** 727–734.

Lakshmanan, V., R. Rabin, and V. DeBrunner, 2003: Multiscale storm identification and forecast. *J. Atmos. Res.,* **67,** 367–380.

——, T. Smith, G. Stumpf, and K. Hondl, 2007: The Warning Decision Support System—Integrated Information. *Wea. Forecasting,* **22,** 596–612.

Miller, D. J., and R. H. Johns, 2000: A detailed look at extreme wind damage in derecho events. Preprints, *20th Conf. on Severe Local Storms,* Orlando, FL, Amer. Meteor. Soc., 52–55.

Moller, A. R., C. A. Doswell III, M. P. Foster, and G. R. Woodall, 1994: The operational recognition of supercell thunderstorm environments and storm structure. *Wea. Forecasting,* **9,** 327–347.

National Weather Service, 1998a: Central Florida tornado outbreak February 22–23, 1998. NOAA/NWS Service Assessment, 37 pp. [Available online at [http://www.nws.noaa.gov/om/assessments/pdfs/cntrlfl.pdf.]

——, 1998b: Southeastern United States tornadoes April 8, 1998. NOAA/NWS Service Assessment, 19 pp. [Available online at http://www.nws.noaa.gov/om/assessments/pdfs/setornad4-98.pdf.]

Parker, M. D., and R. H. Johnson, 2000: Organizational modes of midlatitude mesoscale convective systems. *Mon. Wea. Rev.,* **128,** 3413–3436.

Przybylinski, R. W., 1995: The bow echo: Observations, numerical simulations, and severe weather detection methods. *Wea. Forecasting,* **10,** 203–217.

Stumpf, G. J., A. Witt, E. D. Mitchell, P. L. Spencer, J. T. Johnson, M. D. Eilts, K. W. Thomas, and D. W. Burgess, 1998: The National Severe Storms Laboratory mesocyclone detection algorithm for the WSR-88D. *Wea. Forecasting,* **13,** 304–326.

Trapp, R. J., S. A. Tessendorf, E. S. Godfrey, and H. E. Brooks, 2005: Tornadoes from squall lines and bow echoes. Part I: Climatological distribution. *Wea. Forecasting,* **20,** 23–34.

Weisman, M. L., 2001: Bow echoes: A tribute to T. T. Fujita. *Bull. Amer. Meteor. Soc.,* **82,** 97–116.

——, and C. A. Davis, 1998: Mechanisms for the generation of mesoscale vortices within quasi-linear convective systems. *J. Atmos. Sci.,* **55,** 2603–2622.