The Relationship between Tornadic and Nontornadic Convective Wind Fatalities and Warnings

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ABSTRACT

A database of tornado fatalities, nontornadic convective wind fatalities, severe thunderstorm warnings, and tornado warnings was compiled for the period 1986–2007 to assess the spatial and temporal distribution of warned and unwarned fatalities. The time of fatality and location as reported in *Storm Data* was compared to tornado and severe thunderstorm warnings to determine if a warning was in effect when the fatality occurred. Overall, 23.7% of tornado fatalities were unwarned, while 53.2% of nontornadic convective wind fatalities were unwarned. Most unwarned tornado fatalities occurred prior to the mid-1990s—coinciding with modernization of the National Weather Service—while unwarned nontornadic convective wind fatalities remained at a relatively elevated frequency throughout the study period. Geographic locations with high numbers of unwarned tornado and nontornadic convective wind fatalities were associated with one high-magnitude event that was unwarned rather than a series of smaller unwarned events over the period. There are many factors that contribute to warning response by the public, and the issuance of a severe thunderstorm or tornado warning is an important initial step in the warning process. A better understanding of the characteristics of warned and unwarned fatalities is important to future reduction of unwarned fatalities.

1. Introduction

When nontornadic convective winds or tornadoes are imminent or occurring, the primary method used by the National Weather Service (NWS) to alert the public to the hazard is the issuance of severe thunderstorm or tornado warnings. The goals of NWS warnings are to inform the public of hazardous weather situations and to encourage the public to initiate the appropriate mitigation response to protect life and property (Pifer and Mogil 1978); however, the public is ultimately responsible for taking action (Belville 1987). Warning performance improved greatly between the 1980s and early 1990s because of advances in radar technologies, forecasting methods, and meteorological knowledge (Brooks 2004). Brotzge and Erickson (2010) found that 73.6% of tornadoes in the 2000–04 period were associated with a NWS warning. Simmons and Sutter (2005) established that after the installation of the Weather Surveillance Radar-1988 Doppler (WSR-88D), the percentage of tornadoes warned increased to 60% from 35% prior to installation. A regression analysis of tornado casualties illustrated that expected fatalities were 45% lower for tornadoes occurring after installation of the new radar network. Further investigation by Simmons and Sutter (2008b) determined that tornado warnings do reduce fatalities, and increased lead times for tornado warnings up to approximately 15 min reduced casualties, while longer lead times resulted in increased fatalities compared to no warning. The greatest reduction in fatalities occurs at lead times of 10–15 min, possibly because of the public concluding that the warning is a false alarm if a tornado does not occur soon after the warning is issued (Simmons and Sutter 2006). Despite these advances, Doswell et al. (1999) note that even if forecasts were completely accurate and precise, the nonmeteorological aspects of the warning system—such

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as dissemination and public response—are largely out of the control of the NWS and are influenced by other warning response factors.

Warning response is a four-step process that includes identification of the risk, assessing if protection from the risk is necessary, determining if risk reduction is feasible, and finally the response of seeking shelter (Lindell and Perry 1992). Identification of the risk occurs when the public first becomes aware of the hazard through receipt of the warning or by seeing or hearing the threat. Many studies (e.g., Legates and Biddle 1999; Tiefenbacher et al. 2001; Hammer and Schmidlin 2002; Brown et al. 2002; Paul et al. 2003; Mitchem 2003; Comstock and Mallonee 2005; Hayden et al. 2007) note that the media and warning sirens are the most common dissemination methods used by the public to receive warnings. Sorensen (2000) found that the most rapid dissemination is through the use of reverse 911 telephone systems or tone-alert radios, both of which can alert about 90% of people within about 10 min, compared to 40% alerted by sirens and only 10% alerted by media in the same time frame. Dependence on television and sirens to receive warnings introduces issues that may hinder an appropriate response, as the approaching storm may disrupt electricity or communication, rendering media-based warnings or sirens useless. Media and sirens do little to alert those who are asleep, at work, in a vehicle, or not actively seeking weather information—these groups may have little or no warning of an approaching severe storm despite efforts to communicate a warning to them. Once the warning is received, the public still has to understand the contents of the warning and decide to take protective action.

Fatalities from tornadoes and nontornadic convective winds do not occur at random; rather, a high death rate occurs among people with high vulnerability. Many factors may explain increased or decreased vulnerability to these hazards, and an understanding of these factors is important to determine the relationship between warnings and fatalities. Factors that reduce vulnerability to these hazards include having a plan in place to address them, having a high school or college education attainment level, having a basement, and hearing sirens (Legates and Biddle 1999; Balluz et al. 2000; Brown et al. 2002).

Other factors can greatly increase vulnerability to these storms, such as housing type, the time of day, day of week, time of year, and/or age. In terms of housing type, the most vulnerable populations are those living in mobile homes (Brooks and Doswell 2002; Simmons and Sutter 2005, 2008a; Ashley 2007; Sutter and Simmons 2009; Chaney and Weaver 2010). Timing of the storm can increase vulnerability. Several studies have found that nocturnal tornadoes are particularly hazardous, as they are more difficult to identify, the public is less likely to receive a warning because people are sleeping, and residents of vulnerable structures are more likely to be home (Simmons and Sutter 2005; Ashley 2007; Ashley et al. 2008). Furthermore, tornado fatalities are affected by the day of the week of occurrence, as expected fatalities are about 70% higher on a weekend than a week day, again presumably because residents of vulnerable housing stock are more likely to be home rather than away at work (Simmons and Sutter 2008b). Previous research has also illustrated that the month of tornado occurrence has a large impact on the number of fatalities. Doswell (2003), Ashley (2007), and Simmons and Sutter (2008b) suggest that off-season tornadoes may be more deadly because people are more aware of the hazard during the traditional severe weather season (i.e., April–June) and less prepared during other times of the year. Finally, the age of victims has also been shown to have an effect on tornado fatalities. People over 40 years of age have a higher percentage of fatalities compared to the proportion of United States population in that age range (Ashley 2007).

Another possible factor in warning response is complacency, which may be the result of previous situations where warnings were issued and no severe weather occurred—the so-called cry wolf syndrome (Biddle 1994; Doswell et al. 1999; Roulston and Smith 2004). The role of the cry-wolf effect is not fully known and Barnes et al. (2007) found that an isolated false alarm may not be detrimental to warning response. Simmons and Sutter (2009) found that local, recent false alarms increased tornado fatalities and injuries. A one standard deviation increase in the false alarm ratio increased expected fatalities 12%–29% and expected injuries 13%–32% (Simmons and Sutter 2009). However, Simmons and Sutter (2009) note that since they used casualties as a proxy for warning response, they have no direct evidence that false alarms affect warning credibility. A further complication to public response is that the response is not independent of the decisions made by others (Roulston and Smith 2004). How the public reacts to multiple false alarms within a specific time period and the effects on warning response are also largely unknown (Barnes et al. 2007).

Each of these factors may contribute to the public response to warnings. As stated by Pifer and Mogil (1978), the goals of NWS warnings are to inform the public of hazardous weather situations and to encourage the public to initiate the appropriate responses to protect life and property. The nonmeteorological aspects of the warning system—such as dissemination and public response—are largely out of the control of the NWS and are influenced by previously mentioned warning response factors. However, issuance of a warning provides some of the information necessary for the public to reduce their exposure to the hazard. Ideally, there would be a warning issued for every severe event that causes a fatality, but that is not always the case. The results of this study will provide important information about the relationship between fatalities and warnings and identify parts of the warning process that may need improvement, ultimately reducing tornado and nontornadic convective wind fatalities.

2. Data and methodology

Information on fatalities caused directly by tornado or thunderstorm winds for 1977–2007 was gathered from *Storm Data* and the National Climatic Data Center's (NCDC's) Online Storm Events Database (http://www4.ncdc.noaa.gov/cgi-win/wwcgi.dll?wwEvent~Storms). Fatalities were singled out for investigation as they are less subjective and more reliable than injury information and monetary damage estimates. Fatality data acquired from *Storm Data* must be assessed with caution because of the difficulty in the collection of these types of data (Curran et al. 2000; Trapp et al. 2006). Research by Ashley and Gilson (2009) found that *Storm Data* underreported U.S. lightning fatalities by nearly 30% during 1977–2004 as compared to fatalities found by searching historical news sources through the online services of LexisNexis Academic and from the U.S. Centers for Disease Control's (CDC's) electronic record of death identification. Ashley and Mote (2005) note that fatalities due to derecho events may receive less media attention than large-impact events such as floods, tornadoes, or hurricanes, and it is hypothesized that nontornadic convective wind fatalities may be underreported in *Storm Data.* Despite issues with *Storm Data,* it remains the primary source for weather-related fatality information.

Similar to other recent atmospheric hazard fatality research (e.g., Ashley 2007; Ashley and Black 2008; Black and Ashley 2010), data were gathered from the descriptions of fatalities provided in *Storm Data* associated with nontornadic convective winds and tornadoes. Beyond basic information, such as the date and time of the fatality, most events in *Storm Data* include a narrative text description of damage and how casualties occurred. This supplemental information was recorded, along with information on the county, parish, and/or town of the death, as well as details on the circumstance of death or building structure type where the fatality took place (e.g., permanent home, mobile home, outdoors, vehicle, etc.).

The other key data component for this analysis is severe thunderstorm and tornado warning data. County-level severe thunderstorm and tornado warning data for 1986–2007 were acquired from the NWS (B. MacAloney 2008, personal communication). This period was chosen because information for warnings prior to 1986 was unavailable. First, the comparison between events and warnings was explored using the correlation between the two variables to quantify the strength of the relationship. The number of warnings was tabulated by state to evaluate which states experience the most warnings for tornadoes and severe thunderstorms. The number of warnings per year and per month for the period were calculated and compared to the number of events per year and per month. Warnings per county were mapped and compared to maps of tornado and severe thunderstorm climatologies constructed using the Storm Prediction Center Severe Weather geographical information service (SVRGIS) (http://www.spc.noaa.gov/gis/svrgis/) dataset to examine similarities and differences.

Since severe thunderstorm warnings can be issued for hail as well as nontornadic convective winds, both wind and hail events were mapped for comparison to severe thunderstorm warnings. However, examination of the NCDC's Storm Events database showed only two hail-related fatalities for the period 1950–2007 (one on 30 July 1979 in Fort Collins, Colorado, and the other on 28 March 2000 in Tarrant County, Texas). While it is possible for hail to cause a fatality, these account for fewer than 1% of deaths caused by nontornadic severe thunderstorms; as a result, hail events were excluded from the comparison of warnings to fatalities.

To explore the connection between fatalities and warnings, descriptive statistics and a GIS were used. Most nontornadic convective wind and tornado fatalities have information about date, time, and location of occurrence. The time of the fatality event as listed in *Storm Data* and county of each fatal event were compared to the time, date, and location of tornado and severe thunderstorm warnings; if either type of warning was in effect for the county at the time of the fatality, the storm was considered warned. If no warnings were in effect for the county at the time of the fatality or a warning was issued after the fatality occurred, the fatality was considered unwarned.

Each nontornadic convective wind event that resulted in a fatality was considered to meet the wind speed threshold set by the NWS to require a severe thunderstorm warning. However, it is possible that some of the nontornadic convective wind fatalities were caused by winds that did not meet this threshold and would not have had a warning issued. Only 48% of fatality-producing nontornadic convective wind events had any information about the wind speed associated with the storm and, of those, only 1% indicated that the gusts were measured and not estimated. Accurate estimates of severe wind speeds are difficult to obtain because of the lack of experience with high-wind situations (Doswell et al. 2005; Trapp et al. 2006). The lack of reliable wind speed information accompanying nontornadic convective wind events in *Storm Data* makes it impractical to determine if the winds that caused the fatality met the severe thunderstorm warning criteria of measured gusts of 25 m s^{-1}.

Tornadic and nontornadic convective wind fatalities and fatalities without warnings were mapped on an 80 km × 80 km grid; a grid cell of this size encloses the same area as a circle with radius 45.6 km (24.6 n mi), which is similar to the area under consideration by the National Oceanic and Atmospheric Administration (NOAA) Storm Prediction Center's thunderstorm outlooks (Doswell et al. 2005). The percentage of unwarned tornado and nontornadic convective fatalities was also mapped by state to better reveal the overall pattern of unwarned fatalities. Knowledge of the geographic patterns of warned and unwarned fatalities is important so that efforts to improve warnings can be targeted specifically toward the regions that would benefit.

Yearly and monthly trends in the number of tornado and nontornadic convective wind fatalities with warnings were explored to determine the variation between tornado and severe thunderstorm warnings. Because of the large amount of research on tornadoes and their formation, the probability of successful detection and warning are greater than for nontornadic convective wind events. This increased chance of successful detection is hypothesized to result in a greater percentage of tornado fatalities occurring during a warning as compared to nontornadic convective wind fatalities occurring during warnings. If true, this suggests that an enhanced focus on the severe thunderstorm warning process may be required and that improvements in severe thunderstorm warnings may have the potential to reduce fatalities compared to similar developments in tornado warnings. Doswell et al. (1999) note that public awareness is essential to reduce the number of severe weather fatalities. If a large percentage of tornado or nontornadic convective wind fatalities occur during warnings, it would indicate that while the warnings may be meteorologically sound, there is breakdown in the receipt, understanding, or response to the warnings. This lack of public awareness could illustrate a lack of receipt of the warning, complacency, or other socioeconomic factors that may have resulted in the fatalities.

3. Results

a. *Climatology of severe thunderstorm and tornado warnings*

Understanding the relationship between fatalities and NWS warnings is important because the most commonly stated issues with warnings is the fear of overwarning (the cry wolf syndrome) or underwarning and leaving the public with no notice of potentially hazardous conditions. Since warnings are one of the primary ways for the public to receive information about hazardous weather, it is necessary to examine temporal and spatial patterns in warnings and the relationship between warnings and events. From 1986–2007, there were 455 976 severe thunderstorm warnings and 59 621 tornado warnings issued at the county level in the conterminous United States. The number of severe thunderstorm and tornado warnings generally increased throughout the period (Fig. 1). The number of tornado warnings peaked during the months of March–June, while severe thunderstorm warnings were at their maximum from May to August. In both cases, these peaks coincide with the climatological maximum of occurrence of these hazards (Kelly et al. 1978, 1985; Brooks et al. 2003; Doswell et al. 2005; Ashley 2007). Tornado warnings were most frequent in May, while severe thunderstorm warnings were most common in July (Fig. 2).

To assess the relationship between tornado and severe thunderstorm events and their warnings, the Spearman's rho correlation (Rogerson 2006) is used, as each variable was found to be nonnormal using the one-sample Kolmogorov–Smirnov (K–S) test. The null hypothesis for the correlation is that there is no relationship, and the alternative hypothesis is that there is a relationship between events and warnings. Results of the Spearman's rho correlation for severe thunderstorm warnings and events showed a strong positive correlation ($r = 0.850$), and tornado warnings and events also showed a strong positive correlation ($r = 0.792$). Both correlations are significant at the 99% confidence interval. While correlation can explore the relationship between two variables, it does not imply causation. However, the sign and magnitude of the correlation values indicate that an increase in one variable results in an increase in the other and that there is a strong relationship between events and warnings.

To explore the spatial relationship between tornado and severe thunderstorm events and warnings, the number of tornado or severe thunderstorm warnings and the number of tornadoes or severe thunderstorms were mapped by county or parish. Reported tornadoes are most numerous in parts of Colorado, Texas, and Florida, with other areas of the Great Plains, Midwest, and Southeast also having a large number of reports (Fig. 3). Tornado warnings are most common in many of the same areas. Nontornadic convective wind and hail reports are most frequent across the Great Plains, in Arizona, and portions of the Southeast and, like tornadoes, appear to correspond well with severe thunderstorm warnings (Fig. 4).

Initial examination showed little difference in the geographic location of tornado, nontornadic convective wind, or hail reports and tornado or severe thunderstorm

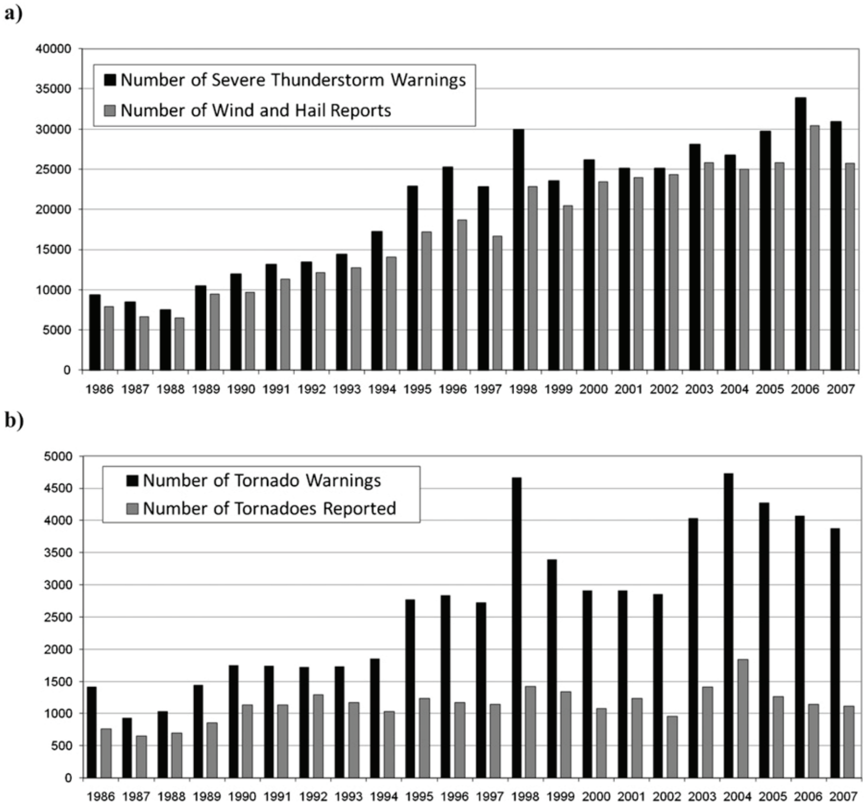

FIG. 1. Number of (a) severe thunderstorm warnings (dark gray) and total wind and hail reports (light gray) per year and (b) number of tornado warnings (dark gray) and tornado reports (light gray) per year, 1986–2007.

warnings. To better understand this relationship, the number of reports (tornado or nonconvective high wind and hail combined) by county was divided by the number of warnings (tornado or severe thunderstorm) by county and mapped (Fig. 5). Values greater than one indicate more reports than warnings, while values less than one indicate more warnings than reports. For tornado warnings and reports, the locations with more reports than warnings were found throughout the West, the upper Midwest, the Northeast, and parts of Florida. In contrast, the mid-South stands out as an area with more warnings than reports. Ashley et al. (2008) noted that many tornadoes in the mid-South occur at night when darkness can obscure tornadoes. In addition, the mid-South has large forested areas, hilly terrain, and higher low-level humidity that may reduce visibility of tornadoes and therefore reduce the number of reports.

Similar analysis for combined nontornadic convective wind and hail reports and severe thunderstorm reports yielded far different results. High values of the reports divided by warnings ratio are illustrated across the Midwest and throughout the Northeast. This may correspond to the high population densities found in these regions. The large populations of these areas make it more likely that nontornadic convective wind or hail will be seen and reported. Furthermore, the low population density of the Great Plains may result in many warnings being issued and few reports of severe weather being received, and explain the relatively low ratios found in that region, despite the Great Plains maxima of nontornadic convective wind and hail (Kelly et al. 1985; Doswell et al. 2005).

b. Temporal distribution of warnings and fatalities

From 1986 to 2007, there were 532 nontornadic convective wind fatalities and 1136 tornado fatalities. During 1986–2007, 53.2% of nontornadic convective wind fatalities were unwarned, while 23.7% of tornado fatalities were unwarned. To determine the significance of the difference in percentage of unwarned fatalities, the *t* test for equality of means (Rogerson 2006) was employed. Results of the test indicate that the difference in the percentage of unwarned tornado and unwarned nontornadic convective wind fatalities is significant at the 99% confidence interval ($p = 0.00079$).

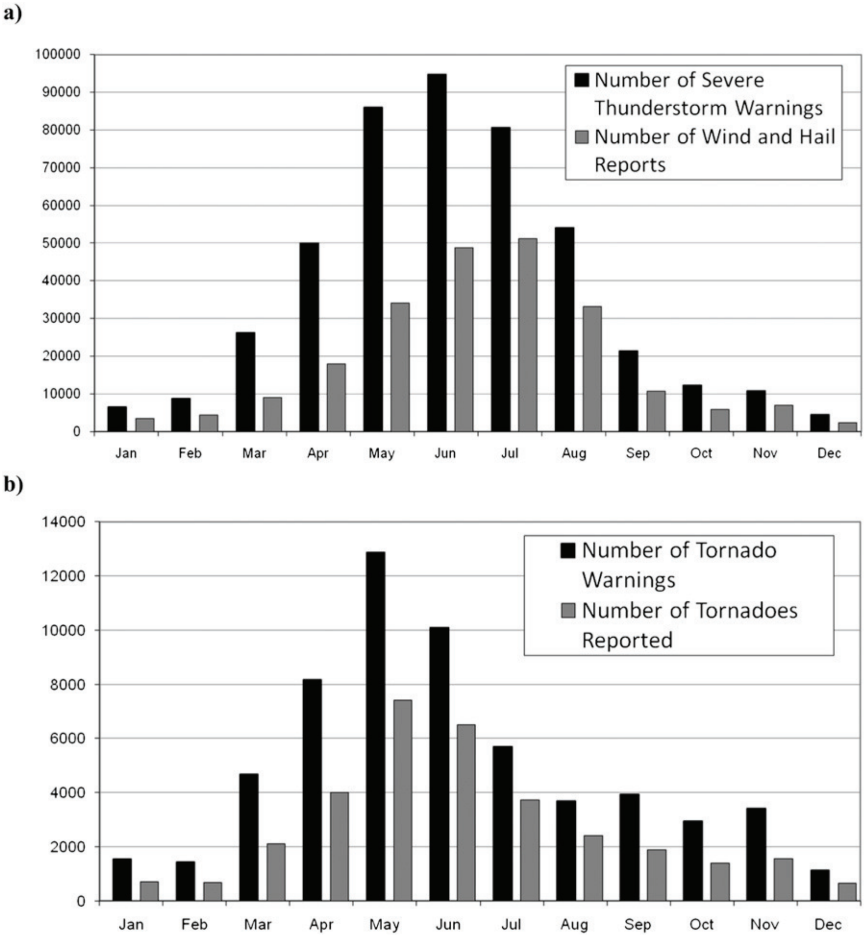

FIG. 2. As in Fig. 1, but by month.

The percentage of unwarned tornado fatalities ranged from 84.9% in 1990 to 3.2% in 1999 (Fig. 6; Table 1). The range of nontornadic convective wind fatalities without warnings during the period had a similar large variation: from 90% in 1992 to 5.9% in 2002. Despite the sizeable range in percentage of unwarned nontornadic convective fatalities, only 5 of the 22 years had less than 40% unwarned, while 14 out of 22 years had less than 40% unwarned tornado fatalities. Year-to-year examination of the percentage of unwarned fatalities reveals that most of the unwarned tornado fatalities were prior to the mid-1990s, while the percentage of unwarned nontornadic fatalities remained relatively high throughout the period. From 1986 to 1995, only two years had fewer than 30% unwarned tornado fatalities, but each year during the 12-yr period 1996–2007 had less than 30% unwarned tornado fatalities. Results of the Mann–Whitney U Test (Rogerson 2006) showed that the difference in the number of unwarned tornado fatalities between the 1986–95 and 1996–2007 periods is significant at the 99% confidence interval ($p = 0.00201$). While the percentage of nontornadic convective wind fatalities without warnings remained relatively high throughout both periods, the difference in the number of unwarned nontornadic convective wind fatalities between the periods was significant at the 95% confidence interval ($p = 0.01377$). The difference between the periods appears to coincide with the modernization of the NWS and technological advances that aided in the warning process such as the WSR-88D radar and Advanced Weather Interactive Processing System (AWIPS) (Friday 1994).

Most months during the period of analysis have less than 40% of tornado fatalities unwarned, and four months had less than 20% of tornado fatalities unwarned (Fig. 7; Table 2). One month that is conspicuous is August, when 83% of tornado fatalities were unwarned. August values are greatly influenced by the 28 August 1990 Plainfield, Illinois, tornado that was unwarned and killed 29 people. Nontornadic convective fatalities without warnings also illustrate similar characteristics. The

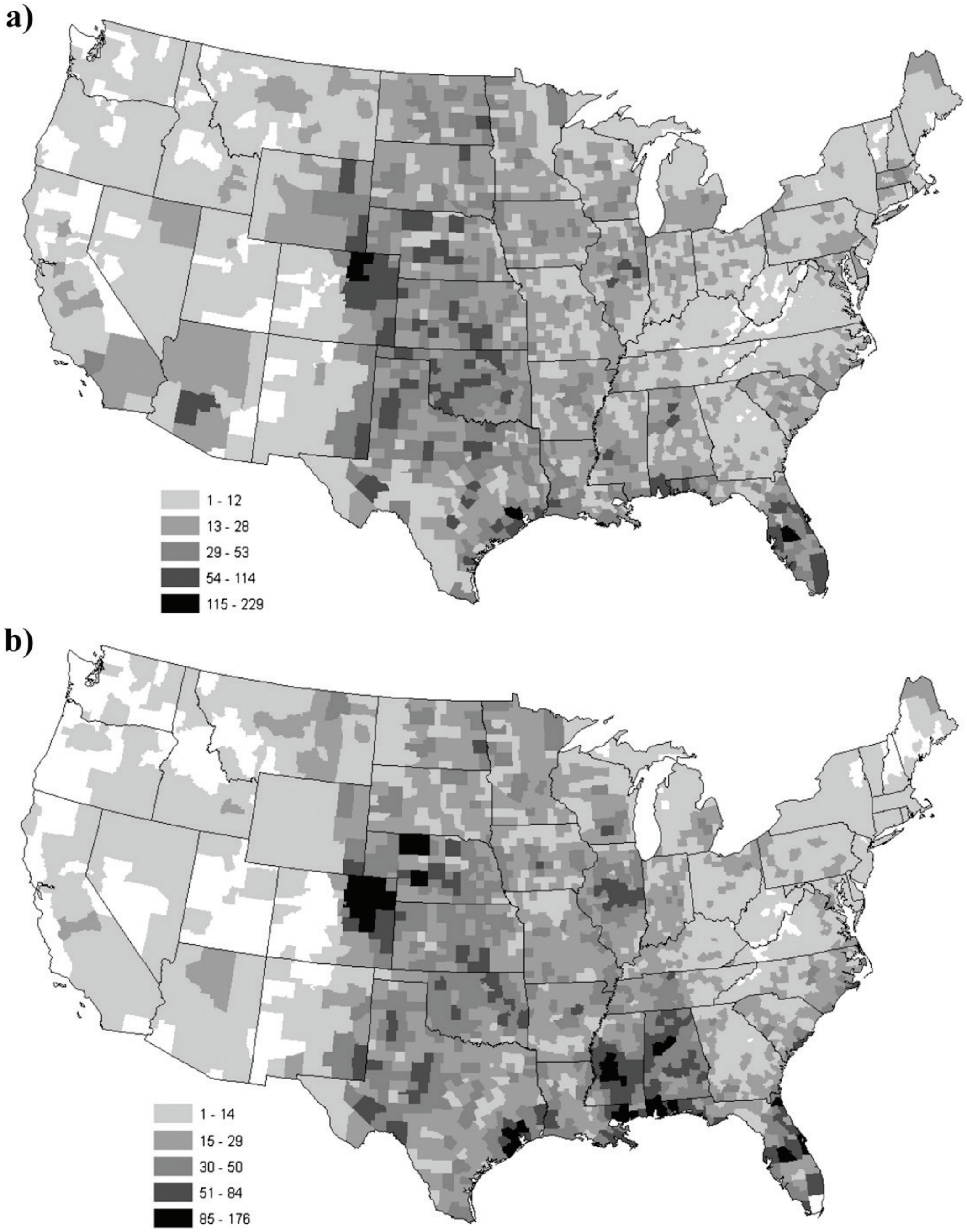

FIG. 3. Number of (a) tornado reports and (b) tornado warnings by county, 1986–2007.

month with the lowest percentage of unwarned fatalities was January, which had three warned and one unwarned nontornadic convective wind fatalities over the 1986–2007 period. However, most months had greater than 40% of nontornadic convective wind fatalities without warnings.

Examination of the percentage of unwarned nontornadic convective wind and tornado fatalities by hour revealed unique patterns (Fig. 8). Unwarned nontornadic convective wind fatalities are at their minimum during the 0600–0659 LST hour—coinciding with the climatological minimum of thunderstorm wind gusts (Kelly et al. 1985)—but increase rapidly in the late morning hours. The percent of unwarned fatalities ranges from 0% between 0600 and 0659 LST to as high as 90% between 1000 and 1059 LST with an average of about 55% through the entire 0700–2359 LST period. In contrast, the peak

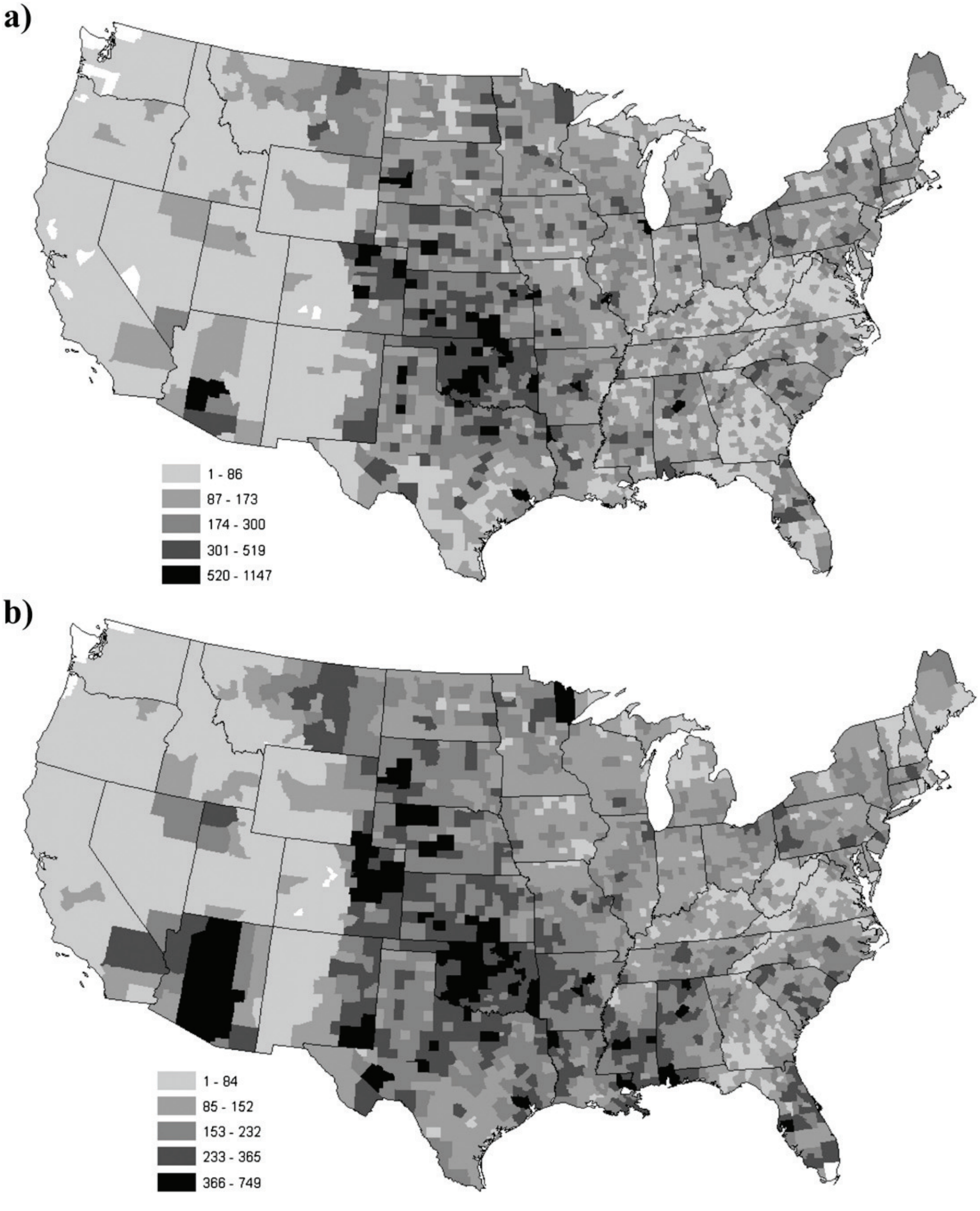

FIG. 4. As in Fig. 3, but (a) nontornadic severe convective wind and hail reports and (b) severe thunderstorm warnings.

in unwarned tornado fatalities is in the late morning, but the percentage of unwarned tornado fatalities drops off considerably during the afternoon. During the same 0700–2359 LST period, an average of 26% of tornado fatalities were unwarned, with a high of 67% between 1000 and 1059 LST and a low of 10% between 1800 and 1859 LST.

The percentage of both unwarned nontornadic convective wind and tornado fatalities is at its highest between 1000 and 1059 LST. Brotzge and Erickson (2010) note that in 44.2% of the cases they examined the first reported tornado of the day was not warned. Brotzge and Erickson (2010) suggest that some forecasters may hesitate to issue tornado warnings until a tornado has been spotted. This may prevent forecasters from issuing a warning and in part explain the high number of unwarned nontornadic convective wind and tornado fatalities during the 1000–1059 LST period.

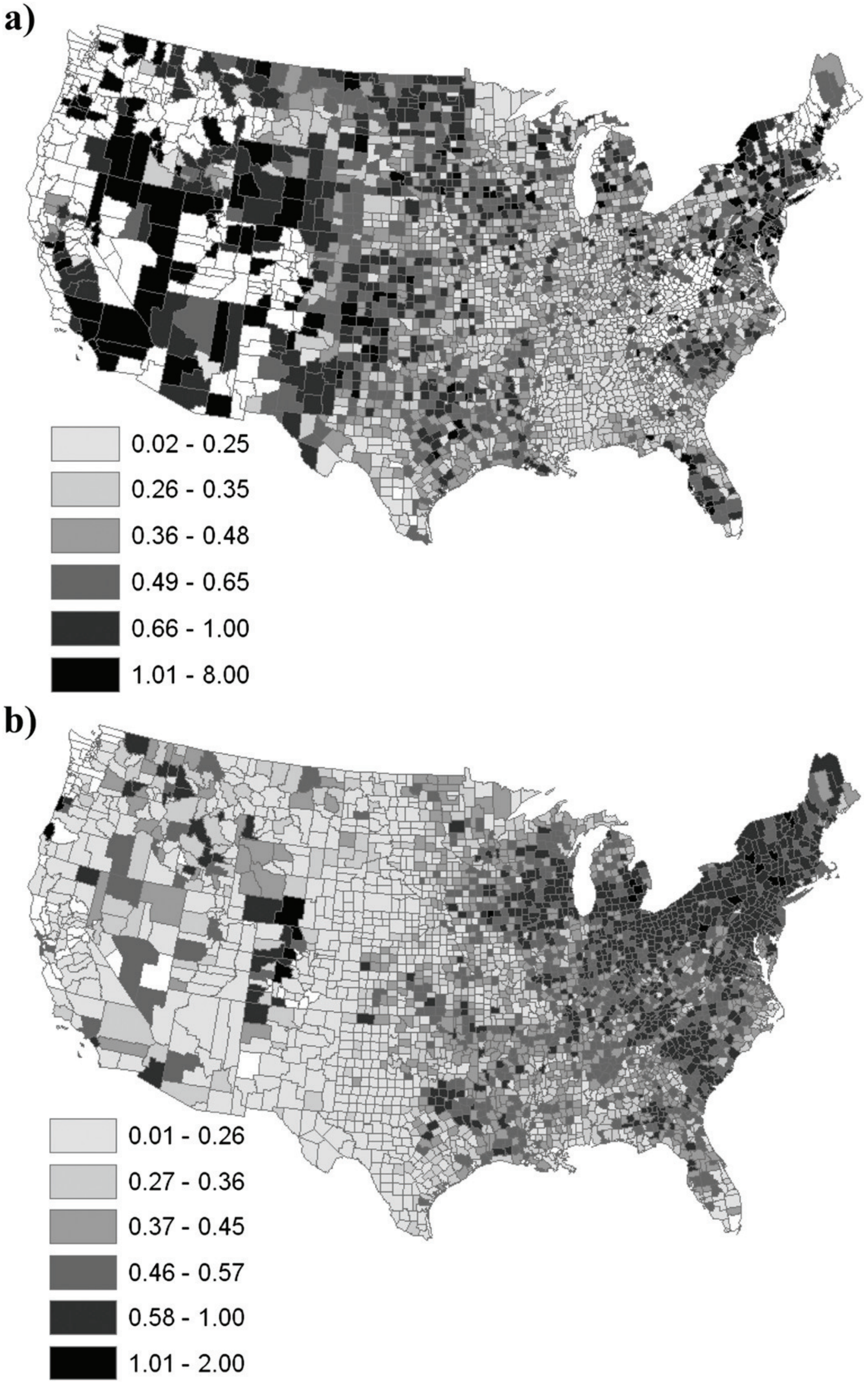

FIG. 5. Ratio of (a) tornado reports divided by tornado warnings per county, 1986–2007; and (b) combined nontornadic convective wind reports and hail reports divided by severe thunderstorm warnings per county, 1986–2007.

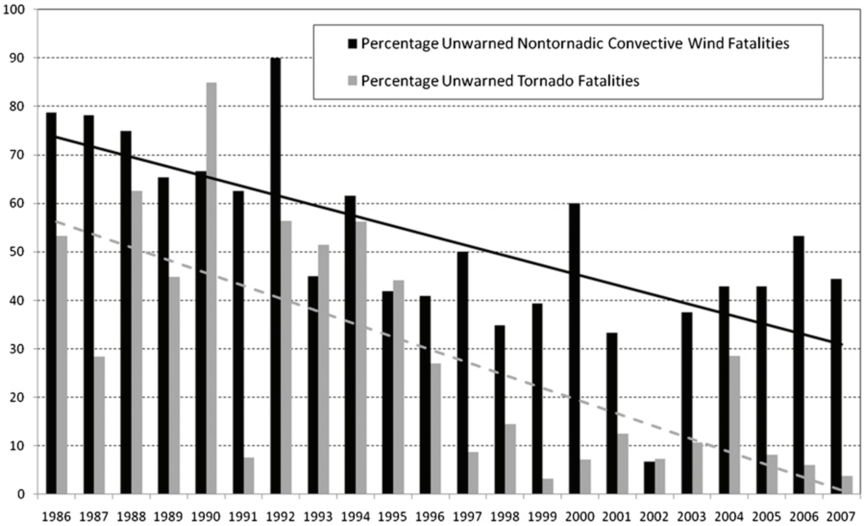

FIG. 6. Percentage of unwarned nontornadic convective wind fatalities (dark gray, with solid linear trend line) and unwarned tornado fatalities (light gray, with dashed linear trend line) by year, 1986–2007.

c. Spatial distribution of warnings and fatalities

Examination of warned and unwarned tornado fatalities reveals several unique patterns (Fig. 9; Table 3). High-fatality events such as the 1987 Saragosa, Texas, tornado; 1990 Plainfield, Illinois, tornado; and 1997 Jarrell, Texas, tornado are apparent. Overall, tornado fatalities are most common throughout the mid-South, consistent with previous research by Ashley (2007). Unwarned fatalities are most frequent through the mid-South, with relatively high counts found through the mid-Atlantic and Northeast. These regions also see high

TABLE 1. Number of total fatalities, warned fatalities, unwarned fatalities, and percentage of unwarned fatalities for tornadoes and nontornadic convective wind by year, 1986–2007.

	Nontornadic convective wind fatalities				Tornado fatalities			
Year	Total fatalities	Warned fatalities	Unwarned fatalities	Percent unwarned	Total fatalities	Warned fatalities	Unwarned fatalities	Percent unwarned
1986	33	7	26	78.8%	15	7	8	53.3%
1987	32	7	25	78.1%	60	43	17	28.3%
1988	20	5	15	75.0%	32	12	20	62.5%
1989	26	9	17	65.4%	49	27	22	44.9%
1990	42	14	28	66.7%	53	8	45	84.9%
1991	32	12	20	62.5%	40	37	3	7.5%
1992	10	1	9	90.0%	39	17	22	56.4%
1993	20	11	9	45.0%	33	16	17	51.5%
1994	13	5	8	61.5%	48	21	27	56.3%
1995	31	18	13	41.9%	34	19	15	44.1%
1996	22	13	9	40.9%	26	19	7	26.9%
1997	38	19	19	50.0%	69	63	6	8.7%
1998	46	30	16	34.8%	131	112	19	14.5%
1999	28	17	11	39.3%	94	91	3	3.2%
2000	25	10	15	60.0%	42	39	3	7.1%
2001	15	10	5	33.3%	40	35	5	12.5%
2002	15	14	1	6.7%	55	51	4	7.3%
2003	16	10	6	37.5%	56	50	6	10.7%
2004	21	12	9	42.9%	35	25	10	28.6%
2005	14	8	6	42.9%	37	34	3	8.1%
2006	15	7	8	53.3%	67	63	4	6.0%
2007	18	10	8	44.4%	81	78	3	3.7%
Totals	532	249	283	53.2%	1136	867	269	23.7%

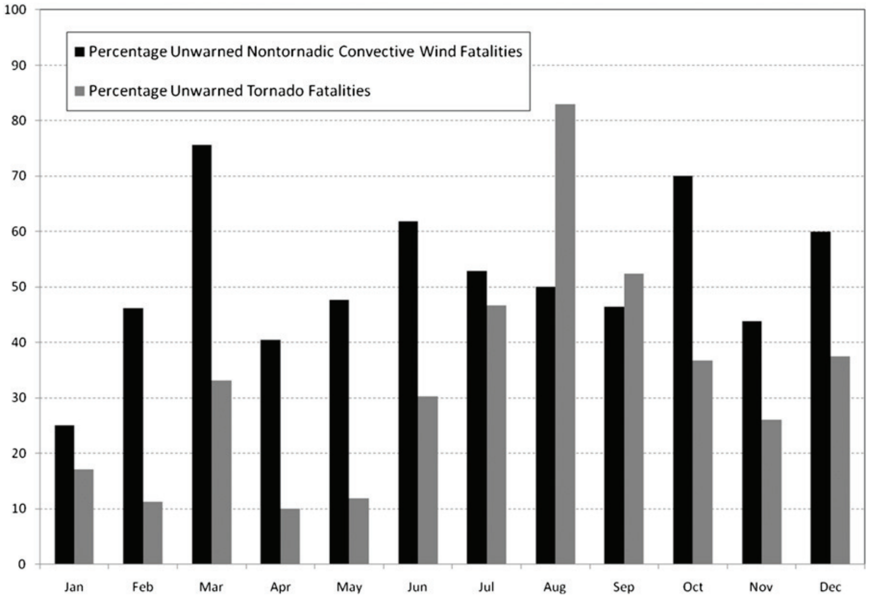

FIG. 7. Percentage of unwarned nontornadic convective wind fatalities (dark gray) and unwarned tornado fatalities (light gray) by month of occurrence, 1986–2007.

percentages of tornadoes caused by quasi-linear convective systems (QLCSs) (Trapp et al. 2005). This storm morphology is less likely to produce traditional radar-based indicators of tornado formation and offers little guidance for the issuance of a warning (Trapp et al. 2005). This may explain the relatively high number of unwarned tornado fatalities. Three locations—one in Illinois, one in Alabama, and one in Georgia—each have more than 10 unwarned fatalities during the period. In each case, the high number of unwarned fatalities is related to one event that was unwarned rather than an accumulation of unwarned fatalities over many events (the 28 August 1990 Plainfield tornado in Illinois, 27 March 1994 Cherokee County tornado in Alabama, and 20 March 1998 tornado in White and Hall counties in Georgia). Despite the elevated number of unwarned fatalities across the mid-South, the overall percentage of unwarned fatalities is low. New York, Massachusetts, Virginia, and Utah have the greatest percentage of unwarned fatalities, although Utah only had one fatality during the period of record. While tornado fatalities occurred in North and South Dakota, Wyoming, Colorado, New Mexico, Maryland, and New Jersey, none of these was unwarned.

Brotzge and Erickson (2009, 2010) suggest that the first tornado of the day and tornadoes as part of an

TABLE 2. Number of total fatalities, warned fatalities, unwarned fatalities, and percentage of unwarned fatalities for tornadoes and nontornadic convective wind by month, 1986–2007.

	Nontornadic convective wind fatalities				Tornado fatalities			
Month	Total fatalities	Warned fatalities	Unwarned fatalities	Percent unwarned	Total fatalities	Warned fatalities	Unwarned fatalities	Percent unwarned
January	4	3	1	25.0%	35	29	6	17.1%
February	13	7	6	46.2%	115	102	13	11.3%
March	41	10	31	75.6%	163	109	54	33.1%
April	47	28	19	40.4%	200	180	20	10.0%
May	86	45	41	47.7%	237	209	28	11.8%
June	89	34	55	61.8%	43	30	13	30.2%
July	121	57	64	52.9%	15	8	7	46.7%
August	72	36	36	50.0%	53	9	44	83.0%
September	28	15	13	46.4%	21	10	11	52.4%
October	10	3	7	70.0%	30	19	11	36.7%
November	16	9	7	43.8%	192	142	50	26.0%
December	5	2	3	60.0%	32	20	12	37.5%

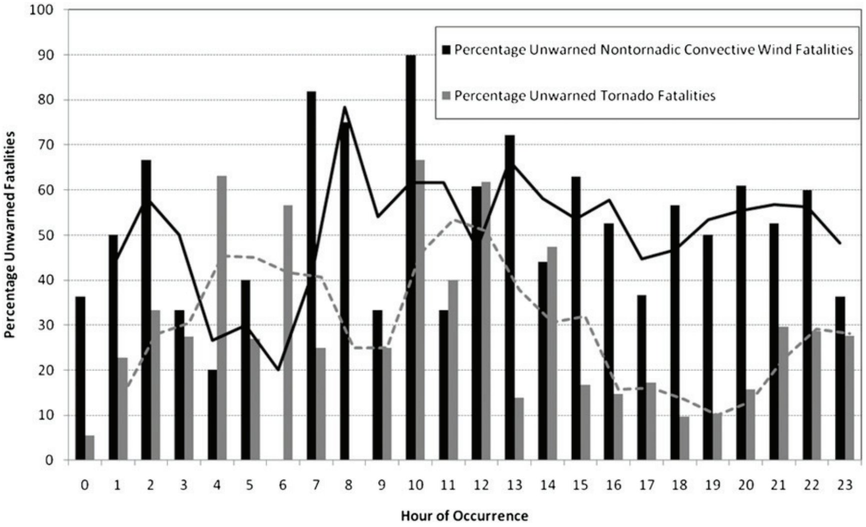

FIG. 8. Percentage of unwarned nontornadic convective wind fatalities (dark gray, with solid two period moving average trend line) and unwarned tornado fatalities (light gray, with dashed two period moving average trend line) by hour of occurrence in LST, 1986–2007.

isolated event rather than an outbreak have a greater likelihood of having zero or negative lead time or no warning. Unwarned tornado fatalities were analyzed further to determine if they were due to either the first storm of the day or part of an isolated event. Examination of tornado events illustrated that in many cases, tornadoes associated with storms from the previous day continued past midnight and into the day in question. Although these storms from the previous day would have been the first of the day, they were not related to the fatality-producing storms in question. To remove the effects of tornadoes from the previous day, the 24-h period used to evaluate if the tornado was the first of the day was adjusted from 0000–2359 to 0600–0559 LST. There is some debate about how many tornadoes must occur in a day to constitute an outbreak. Galway (1977) suggested that 10 or more tornadoes may constitute an outbreak. In their development of a severe weather ranking system, Doswell et al. (2006) did not define an outbreak explicitly but only considered days with seven or more tornadoes and noted that days with less than seven tornadoes would likely not be referred to as an outbreak in any part of their period of study from 1970 to 2003. For this reason, a threshold of seven tornadoes was used to determine if an unwarned tornado fatality occurred as part of an outbreak or an isolated event. In other cases, there were two or more regions of the United States experiencing tornadoes each day. In these situations, if the first tornado of the day was outside of the region of the unwarned tornado fatality, it was not considered. For example, if the first tornado of the day occurs in North Dakota and an unwarned tornado fatality occurs in Florida, it is unlikely that the meteorological conditions that produced the North Dakota tornado extend to Florida. In addition, forecasters outside of the northern Great Plains are unlikely to gain any situational awareness due to the North Dakota tornado that would assist in issuing warnings in Florida.

Overall, 49.8% of unwarned tornado fatalities were found to be part of isolated events, the first tornado of the day, or both. Of unwarned tornado fatalities, 22.7% occurred as an isolated event and 17.1% were a result of the first tornado of the day. An additional 10.0% of unwarned tornado fatalities were associated with both the first tornado of the day and with having occurred during an isolated event. The remaining 50.2% of unwarned tornado fatalities were not part of isolated events or the first tornado of the day. Of the unwarned fatalities that were not isolated and/or the first tornado of the day, 71.8% occurred in the 1985–95 period prior to NWS modernization in the mid-1990s. While isolated tornadoes and the first tornado of the day may have a greater likelihood of having zero or negative lead time or no warning (Brotzge and Erickson 2009, 2010), they only account for about half of unwarned tornado fatalities. The remaining unwarned tornado fatalities are due to tornadoes beyond the first of the day and/or on days with seven or more tornadoes.

Ashley (2007) found that nearly 99% of tornado fatalities between 1880 and 2005 were due to significant (F2+) tornadoes. Significant tornadoes accounted for 81% of unwarned tornado fatalities—fewer than expected given the findings of Ashley (2007)—with a much higher proportion of unwarned fatalities due to F0–F1

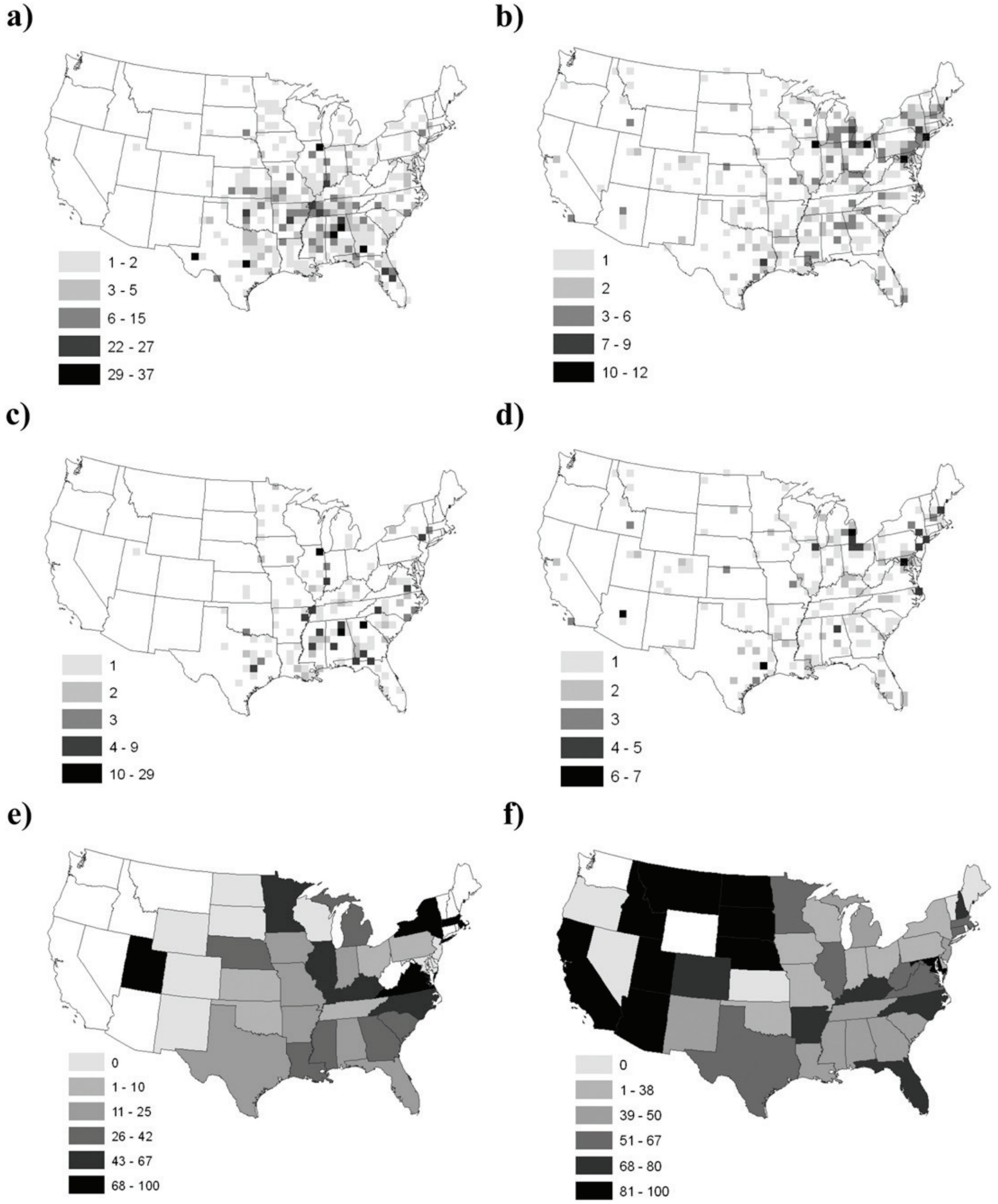

FIG. 9. Number of (a) tornado fatalities, (b) nontornadic convective wind fatalities, (c) unwarned tornado fatalities, and (d) unwarned nontornadic convective wind fatalities in an 80 km × 80 km grid 1986–2007. (e) The percentage of unwarned tornado fatalities by state, 1986–2007; (f) the percentage of unwarned nontornadic convective wind fatalities by state, 1986–2007.

tornadoes. Trapp et al. (2005) found statistically that more weak (F1) tornadoes were produced by QLCSs than cell-type thunderstorms. The difficulty of detecting QLCS-generated tornadoes may explain the relatively high number of unwarned fatalities due to F0–F1 tornadoes. This suggests that a focus on improving warnings for all tornadoes—not just the first tornado of the day or isolated tornadoes—has the highest likelihood of reducing unwarned tornado fatalities.

Nontornadic convective wind fatalities are most common throughout the Great Lakes, Northeast, and through parts of the Southeast (Fig. 9), a finding consistent with previous research by Black and Ashley (2010). These regions experience high vulnerability to

TABLE 3. Number of total fatalities, warned fatalities, unwarned fatalities, and percentage of unwarned fatalities for tornadoes and nontornadic convective wind by state, 1986–2007.

State	Tornado fatalities	Warned tornado fatalities	Unwarned tornado fatalities	Percentage unwarned tornado fatalities	Nontornadic convective wind fatalities	Warned nontornadic convective wind fatalities	Unwarned nontornadic convective wind fatalities	Percentage unwarned nontornadic convective wind fatalities
AL	147	114	33	22.45%	18	10	8	44.4%
AR	70	61	9	12.86%	11	3	8	72.7%
AZ	0	0	0	—	8	1	7	87.5%
CA	0	0	0	—	6	0	6	100.0%
CO	2	2	0	0.00%	10	2	8	80.0%
CT	0	0	0	—	3	1	2	66.7%
DC	0	0	0	—	4	3	1	25.0%
DE	0	0	0	—	3	0	3	100.0%
FL	98	82	16	16.33%	17	5	12	70.6%
GA	83	51	32	38.55%	20	10	10	50.0%
IA	8	6	2	25.00%	6	4	2	33.3%
ID	0	0	0	—	5	0	5	100.0%
IL	51	17	34	66.67%	22	9	13	59.1%
IN	43	34	9	20.93%	18	13	5	27.8%
KS	51	49	2	3.92%	5	5	0	0.0%
KY	14	5	9	64.29%	14	3	11	78.6%
LA	28	19	9	32.14%	19	10	9	47.4%
MA	3	0	3	100.00%	9	3	6	66.7%
MD	5	5	0	0.00%	12	1	11	91.7%
ME	0	0	0	—	2	2	0	0.0%
MI	7	4	3	42.86%	44	21	23	52.3%
MN	11	6	5	45.45%	3	1	2	66.7%
MO	54	48	6	11.11%	12	7	5	41.7%
MS	51	29	22	43.14%	17	8	9	52.9%
MT	0	0	0	—	2	0	2	100.0%
NC	30	14	16	53.33%	13	3	10	76.9%
ND	2	2	0	0.00%	2	0	2	100.0%
NE	5	3	2	40.00%	4	0	4	100.0%
NH	0	0	0	—	8	2	6	75.0%
NJ	1	1	0	0.00%	11	7	4	36.4%
NM	2	2	0	0.00%	2	1	1	50.0%
NV	0	0	0	—	1	1	0	0.0%
NY	16	3	13	81.25%	37	25	12	32.4%
OH	15	14	1	6.67%	38	23	15	39.5%
OK	59	56	3	5.08%	9	6	3	33.3%
OR	0	0	0	—	1	1	0	0.0%
PA	10	9	1	10.00%	21	15	6	28.6%
RI	0	0	0	—	0	0	0	—
SC	13	8	5	38.46%	13	7	6	46.2%
SD	7	7	0	0.00%	3	0	3	100.0%
TN	109	104	5	4.59%	10	6	4	40.0%
TX	121	101	20	16.53%	39	15	24	61.5%
UT	1	0	1	100.00%	3	0	3	100.0%
VA	10	2	8	80.00%	5	2	3	60.0%
VT	0	0	0	—	1	1	0	0.0%
WA	0	0	0	—	0	0	0	—
WI	7	7	0	0.00%	11	7	4	36.4%
WV	0	0	0	—	10	5	5	50.0%
WY	2	2	0	0.00%	0	0	0	—

nontornadic convective winds because they are adjoined to large bodies of water, are heavily forested, and have high population densities that expose larger numbers of people to the hazard. Most unwarned nontornadic convective wind fatalities also occur in these regions. Additional areas with high numbers of unwarned fatalities are located in Arizona and Texas. The percentage of unwarned nontornadic convective wind fatalities is highest in several Intermountain West states, in the northern Great Plains, and in Maryland, with each of these states having 100% of fatalities unwarned. However, only 16% of the total number of unwarned nontornadic convective wind fatalities occurred in these states. The states of California, Idaho, Montana, Nebraska, North Dakota, South Dakota, and Utah had 34 unwarned fatalities, or about 12% of the total. While *Storm Data* does not mention the circumstances surrounding most of the fatalities in these states, two of the cases do note that microbursts were responsible for the fatality-inducing winds. In the Intermountain West, microbursts are generally on the dry end of the microburst spectrum, with high cloud bases and little or no precipitation reaching the ground (Wakimoto 1985). These storms may be difficult to identify by radar and successfully warn for, as thunderstorms with reflectivity values of as little as 30 d*BZ* are adequate to produce dry microbursts (Wakimoto 1985). Furthermore, nontornadic convective wind is a relatively infrequent occurrence in the Intermountain West (Ashley and Mote 2005; Doswell et al. 2005). These meteorological and social factors may combine to explain the nontornadic convective wind fatalities in this region.

4. Conclusions

Many factors contribute to the occurrence of nontornadic convective wind and tornado fatalities, including the public's response to these events. The issuance of a severe thunderstorm or tornado warning is very important, as receipt of the warning is the often the first step in successful warning response. For the period 1986–2007, 23.7% of tornado fatalities were unwarned, while 53.2% of nontornadic convective wind fatalities were unwarned. There is a significant decline in the number of unwarned tornado fatalities and unwarned nontornadic convective wind fatalities between the early (1986–95) and late (1996–2007) periods. Differences between the early and late periods coincide with modernization of the NWS and the introduction of the WSR-88D radar system. Improvement of warnings was promoted as one of the main benefits of the WSR-88D radar (Simmons and Sutter 2005), and the findings presented in this research suggest that the percentage of unwarned fatalities decreased post-modernization. Despite the greater likelihood of negative lead time or no warning, only about 50% of unwarned tornado fatalities were caused by either the first tornado of the day or a tornado in an isolated event. Thus, a focus on improving warnings for all tornadoes has the best chance to reduce tornado fatalities.

This study found a significant difference in the percentage of unwarned tornado and nontornadic convective wind fatalities. Brooks and Doswell (2002) and Ashley (2007) note that tornado fatalities have decreased significantly since the 1930s, and there is little evidence of a similar trend in the number of nontornadic convective wind fatalities; however, the lack of a long-term dataset of nontornadic convective wind fatalities makes a direct comparison between tornadic and convective wind fatalities difficult. Brooks and Doswell (2002) and Ashley (2007) suggest that much of the decrease in tornado fatalities may be attributed to advances in forecasting, communication, and other technologies. Based on the lack of discernable trend in nontornadic convective wind fatalities and the relatively low number of warned nontornadic convective wind fatalities, it appears that a renewed focus on reducing nontornadic convective wind fatalities may be required. During the period of study, over half of nontornadic convective fatalities were unwarned, leaving the victims perhaps unaware of the hazard and with little time to seek appropriate shelter. However, it is possible that some of these nontornadic convective wind fatalities were caused by winds that remained below the arbitrary "severe" wind threshold and remained unwarned for that reason. Less than half of fatalities gathered from *Storm Data* had any information on wind speed, so it is difficult to address this possibility. The high percentage of unwarned fatalities is reflected further in the fatality locations, as most nontornadic convective wind fatalities occur in nonsheltering locations such as vehicles, boats, or outdoors (Black and Ashley 2010), while most tornado fatalities occur in permanent structures or mobile homes (Ashley 2007). While the NWS cannot control the public response or whether or not an individual seeks shelter, ensuring that a warning was issued would likely increase the number of people who do seek shelter and decrease the number of convective wind fatalities. Furthermore, it is outside the scope of this study to assess the difficulties and costs that may be encountered during improvement of the nontornadic convective wind warning process. The NWS should assess whether or not the communication, forecasting, and technological advances that are hypothesized to have led to the decrease in tornado fatalities over the last half century are being employed to their fullest potential to improve the nontornadic convective wind warning process and what other steps can be taken to reduce nontornadic convective wind fatalities.

The high number of tornado fatalities inside warnings is indicative of the quality of tornado warnings issued by the NWS. However, Brooks and Doswell (2002) and Ashley (2007) suggest that the decreasing trend in tornado fatalities is likely to slow or reverse because of changing demographic trends that put greater amounts of people at higher risk, despite improving warning performance. Therefore, it is important to continue the investigation of the psychological and societal aspects that factor into warning response and integrate these findings into education about the hazards of severe weather. Based on the results of this research, specific recommendations to reduce fatalities and improve the warning process include a renewed focus on the warnings and mitigation for nontornadic convective wind hazard, along with surveys of the public to assess their perceptions of hazardous weather and warning response. This information can be used to focus efforts in mitigation and reduce future fatalities. A better understanding of the public perception of these hazards and their response to these hazards, coupled with increased meteorological knowledge, offers the best opportunity to reduce nontornadic convective wind and tornado casualties in the future.

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REFERENCES

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.

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

Balluz, L., T. Holmes, J. Malilay, L. Schieve, and S. Kiezak, 2000: Predictors for people's response to a tornado warning: Arkansas, 1 March 1997. *Disasters,* **24,** 71–77.

Barnes, L. R., E. C. Gruntfest, M. H. Hayden, D. M. Schultz, and C. Benight, 2007: False alarms and close calls: A conceptual model of warning accuracy. *Wea. Forecasting,* **22,** 1140–1147.

Belville, J. D., 1987: The National Weather Service Warning System. *Ann. Emerg. Med.,* **16,** 1078–1080.

Biddle, M. D., 1994: Tornado hazards, coping styles, and modernized warning systems. M.S. thesis, Dept. of Geography, The University of Oklahoma—Norman, 143 pp.

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

Brooks, H. E., 2004: Tornado-warning performance in the past and future: A perspective from signal detection theory. *Bull. Amer. Meteor. Soc.,* **85,** 837–843.

——, 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. *Wea. Forecasting,* **18,** 626–640.

Brotzge, J., and S. Erickson, 2009: NWS tornado warnings with zero or negative lead times. *Wea. Forecasting,* **24,** 140–154.

——, and ——, 2010: Tornadoes without NWS warning. *Wea. Forecasting,* **25,** 159–172.

Brown, S., P. Archer, and S. Mallonee, 2002: Tornado-related deaths and injuries in Oklahoma due to the 3 May 1999 tornadoes. *Wea. Forecasting,* **17,** 343–353.

Chaney, P. L., and G. S. Weaver, 2010: The vulnerability of mobile home residents in tornado disasters: The 2008 Super Tuesday tornado in Macon County, Tennessee. *Wea. Climate Soc.,* **2,** 190–199.

Comstock, R. D., and S. Mallonee, 2005: Comparing reactions to two severe tornadoes in one Oklahoma community. *Disasters,* **29,** 277–287.

Curran, E. B., R. L. Holle, and R. E. Lopez, 2000: Lightning casualties and damages in the United States from 1959 to 1994. *J. Climate,* **13,** 3448–3464.

Doswell, C. A., III, 2003: Societal impacts of severe thunderstorms and tornadoes: Lessons learned and implications for Europe. *Atmos. Res.,* **67–68,** 135–152.

——, A. R. Moller, and H. E. Brooks, 1999: Storm spotting and public awareness since the first tornado forecasts of 1948. *Wea. Forecasting,* **14,** 544–557.

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

——, R. Edwards, R. L. Thompson, J. A. Hart, and K. C. Crosbie, 2006: A simple and flexible method for ranking severe weather events. *Wea. Forecasting,* **21,** 939–951.

Friday, E. W., Jr., 1994: The modernization and associated restructuring of the National Weather Service: An overview. *Bull. Amer. Meteor. Soc.,* **75,** 43–52.

Galway, J. G., 1977: Some climatological aspects of tornado outbreaks. *Mon. Wea. Rev.,* **105,** 477–484.

Hammer, B., and T. W. Schmidlin, 2002: Response to warnings during the 3 May 1999 Oklahoma City tornado: Reasons and relative injury rates. *Wea. Forecasting,* **17,** 577–581.

Hayden, M. H., S. Drobot, S. Radil, C. Benight, E. C. Gruntfest, and L. R. Barnes, 2007: Information sources for flash flood warnings in Denver, CO and Austin, TX. *Environ. Hazards,* **7,** 211–219.

Kelly, D. L., J. T. Schaefer, R. P. McNulty, C. A. Doswell III, and R. F. Abbey Jr., 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.

Legates, D. R., and M. D. Biddle, cited 1999: Warning response and risk behavior in the Oak Grove–Birmingham, Alabama, tornado of 08 April 1998. Natural Hazards Research and Applications Information Center Quick Response Rep. 116. [Available online at http://www.colorado.edu/hazards/research/qr/qr116/qr116.html.]

Lindell, M., and R. Perry, 1992: *Behavioral Foundations of Community Emergency Planning*. Hemisphere Publishing, 630 pp.

Mitchem, J. D., cited 2003: An analysis of the September 20, 2002 Indianapolis tornado: Public response to a tornado warning and damage assessment difficulties. Natural Hazards Research and Applications Information Center Quick Response Rep. 161. [Available online at http://www.colorado.edu/hazards/research/qr/qr161/qr161.html.]

Paul, B. K., V. T. Brock, S. Csiki, and L. Emerson, cited 2003: Public response to tornado warnings: A comparative study of the May 4, 2003, Tornadoes in Kansas, Missouri, and Tennessee. Natural Hazards Research and Applications Information Center Quick Response Rep. 165. [Available online at http://www.colorado.edu/hazards/research/qr/qr165/qr165.html.]

Pifer, B., and H. M. Mogil, 1978: NWS hazardous weather terminology. *Bull. Amer. Meteor. Soc.,* **59,** 1583–1588.

Rogerson, P. A., 2006: *Statistical Methods for Geography: A Student's Guide*. 2nd ed. Sage Publications, 320 pp.

Roulston, M. S., and L. A. Smith, 2004: The boy who cried wolf revisited: The impact of false alarm intolerance on cost-loss scenarios. *Wea. Forecasting,* **19,** 391–397.

Simmons, K. M., and D. Sutter, 2005: WSR-88D radar, tornado warnings, and tornado casualties. *Wea. Forecasting,* **20,** 301–310.

——, and ——, 2006: Improvements in tornado warnings and tornado casualties. *Int. J. Mass Emerg. Disasters,* **24,** 351–369.

——, and ——, 2008a: Manufactured home building regulations and the February 2, 2007 Florida tornadoes. *Nat. Hazards,* **46,** 415–425.

——, and ——, 2008b: Tornado warnings, lead times, and tornado casualties: An empirical investigation. *Wea. Forecasting,* **23,** 246–258.

——, and ——, 2009: False alarms, tornado warnings, and tornado casualties. *Wea. Climate Soc.,* **1,** 38–53.

Sorensen, J. H., 2000: Hazard warning systems: Review of 20 years of progress. *Nat. Hazards Rev.,* **1,** 119–125.

Sutter, D., and K. M. Simmons, 2009: Tornado fatalities and mobile homes in the United States. *Nat. Hazards,* **53,** 125–137.

Tiefenbacher, J. P., W. Monfredo, M. Shuey, and R. J. Cecora, cited 2001: Examining a "near-miss" experience: Awareness, behavior, and post-disaster response among residents on the periphery of a tornado-damage path. Natural Hazards Research and Applications Information Center Quick Response Rep. 137. [Available online at http://www.colorado.edu/hazards/research/qr/qr137/qr137.html.]

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.

——, D. M. Wheatley, N. T. Atkins, R. W. Pryzbylinski, and R. Wolf, 2006: Buyer beware: Some words of caution on the use of severe wind reports in postevent assessment and research. *Wea. Forecasting,* **21,** 408–415.

Wakimoto, R. M., 1985: Forecasting dry microburst activity over the high plains. *Mon. Wea. Rev.,* **113,** 1131–1143.