Spatial and Temporal Analysis of Tornado Fatalities in the United States: 1880–2005

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(Manuscript received 10 January 2007, in final form 26 February 2007)

ABSTRACT

A dataset of killer tornadoes is compiled and analyzed spatially in order to assess region-specific vulnerabilities in the United States from 1880 to 2005. Results reveal that most tornado fatalities occur in the lower–Arkansas, Tennessee, and lower–Mississippi River valleys of the southeastern United States—a region outside of traditional "tornado alley." Analysis of variables including tornado frequency, land cover, mobile home density, population density, and nocturnal tornado probabilities demonstrates that the relative maximum of fatalities in the Deep South and minimum in the Great Plains may be due to the unique juxtaposition of both physical and social vulnerabilities. The spatial distribution of these killer tornadoes suggests that the above the national average mobile home density in the Southeast may be a key reason for the fatality maximum found in this area. A demographic analysis of fatalities during the latter part of the database record illustrates that the middle aged and elderly are at a much greater risk than are younger people during these events. Data issues discovered during this investigation reveal the need for a concerted effort to obtain critical information about how and where *all* casualties occur during future tornado and hazardous weather events. These new, enhanced data, combined with results of spatially explicit studies exploring the human sociology and psychology of these hazardous events, could be utilized to improve future warning dissemination and mitigation techniques.

1. Introduction and background

Tornadoes are nature's most violent windstorms and are a significant hazard to life and property throughout the United States. Approximately 800–1400 tornadoes are reported in the United States in any given year, with only a small percentage of these events producing casualties. Although there have been numerous advances in tornado detection, warning dissemination, and public awareness, tornado casualties cannot be prevented entirely as evidenced by recent individual killer tornado events (e.g., 6 November 2005) and outbreaks of killer tornadoes (e.g., 3 May 1999 and 4 May 2003) (AMS 2006). Although tornado fatalities during the past 50 yr have declined, it is suggested that fatalities within vulnerable housing stock continue to provide a major obstacle in reducing overall tornado death rates in the United States (Brooks and Doswell 2002).

A multitude of studies have investigated tornadoes as a hazard. Boruff et al. (2003) examined the overall trends in tornado hazards and their density in the United States, while Brooks and Doswell (2001) normalized tornado damage tallies by accounting for adjustments in inflation and wealth, revealing that the costs of individual tornadoes have not increased through time. A study by Aguirre et al. (1993) revealed that urban counties have significantly higher probabilities of tornado occurrence than rural counties. However, much of this disparity found between urban and rural counties is likely due to reporting biases (Doswell and Burgess 1988; King 1997; Brooks et al. 2003a; Anderson et al. 2007). A number of event-specific investigations have yielded insight into how individuals within a single tornado or tornado outbreaks were killed (e.g., Legates and Biddle 1999; May et al. 2000; Brown et al. 2002; Hammer and Schmidlin 2002, among others). Simmons and Sutter (2005a) analyzed casualties from F5 tornadoes, illustrating that fatalities from the most damaging tornadoes have decreased significantly over the course of the twentieth century. Simmons and Sutter (2005b) also assessed the impact of the deployment of Next-Generation Doppler Radar on the tornado casualties and warning lead time. Other inves-

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DOI: 10.1175/2007WAF2007004.1

tigations have examined the specifics of vehicles and tornadoes (Hammer and Schmidlin 2001) and tornado safe houses (Merrell et al. 2002). A number of analyses have focused on the climatology of tornadoes (e.g., Grazulis et al. 1993; Brooks et al. 2003a; Verbout et al. 2006, among others), a fundamental component to any risk analysis of atmospheric phenomena.

Sims and Baumann (1972) attempted to quantify the human perception and response to the threat of tornadoes across the United States (so-called coping styles), specifically focusing on the regional difference between the psychology of persons living in the American south (Alabama) and midwest (Illinois). Their research suggested that culturally dependent psychological dimensions, such as a southerner's tendency for fatalism, passivity, and lack of trust in organized warning systems, were partially responsible for the distribution of tornado fatalities in the United States. Biddle (1994) further explored this topic by surveying persons on warning behavior, risk perception, and other behavioral characteristics in Alabama, Illinois, and Oklahoma. His research, along with others (Cohen and Nisbett 1998), discounted some of the regional-cultural specific theories advanced by Sims and Baumann (1972). Biddle (1994) suggests that complacency (the "It can't happen here!" mindset) and detachment from the natural environment, in addition to a general failure to embrace warning information, may be more important in explaining behavior during tornado disasters.

Despite the large amount of research into tornado hazards, very little of this work has explored a spatial synthesis of tornado fatalities in the United States. Rather, past studies have consolidated fatalities with injuries and damage data in order to provide a broad examination of tornado hazards, limited analysis to specific tornado magnitudes, investigated statistical determinates of fatalities without regard to spatial distribution, or illustrated analyses from only specific states.

A number of factors impact the amount of risk faced by individuals during a tornado. As described by Hammer and Schmidlin (2001), these factors include technology (e.g., detection and warning systems), tornado characteristics (e.g., magnitude, intensity, duration, time of day, and geography), social aspects (e.g., population trends and urbanization), personal attributes (e.g., perception and preparedness), and location (i.e., type of shelter or lack thereof). The following investigation assesses, both spatially and temporally, the fatalities produced by all tornadoes in the contiguous United States since the late nineteenth century. In doing so, this study seeks to evaluate a portion of the factors that affect an individual's risk in terms of killer tornadoes, using a spatially explicit approach. A more thorough analysis of fatalities associated with tornadoes is essential to improving education and mitigation efforts concerning these extreme atmospheric hazards.

2. Methodology

The contiguous U.S. tornado fatality dataset utilized in this study was transcribed and compiled from two primary sources: 1) a long-term study of U.S. tornadoes by Grazulis (1993, 1997, hereafter Grazulis dataset) and 2) the National Climatic Data Center's *Storm Data* (NCDC 1959–2005) and "Storm Events" database (available online at http://www4.ncdc.noaa.gov/cgi-win/wwcgi.dll?wwEvent~Storms). The Grazulis dataset includes "significant" tornado events, including all events that are known to have produced a fatality, from 1680 to 1995. *Storm Data* reports from 1959 to 2005 were utilized to supplement the existing record of killer tornado events documented by Grazulis.

This study focuses on tornado fatalities beginning in 1880 and examines primarily three overlapping temporal periods: 1880–2005, 1950–2004, and 1985–2005. The commencement of analysis for the period after 1879 was chosen because 1) prior research illustrates (Brooks and Doswell 2002) that the late 1870s period contains an apparent break in the number of tornadoes with at least 10 fatalities, 2) the fact that this period is at the start of a large increase in the number of reported killer tornadoes (cf. Brooks and Doswell 2002, their Fig. 1), and 3) because this is the period of time when John Park Finley began his work collecting detailed information on U.S. tornadoes (Grazulis 1993; Brooks and Doswell 2002). A number of issues and caveats with the tornado and tornado fatality data have been described elsewhere (e.g., Doswell and Burgess 1988; Grazulis 1993; Brooks and Doswell 2001; Brooks and Doswell 2002). As a whole, the fatality data associated with tornadoes are likely the most complete aspect of historical record—although this may be subject to some debate for individual events and for those events during the first half of the historical record (primarily from 1880 to 1960). Only those deaths caused directly by tornado winds are counted within this study. Indirect or "secondary" tornado fatalities, due to, for example, heart attacks and debris cleanup, are not included in this analysis.

Both *Storm Data* and the Grazulis dataset include verbal text descriptions of damage and how casualties occurred during most tornado events. This additional information was utilized to refine further the dataset to include descriptions of age, gender, geographic location, and how and where fatalities occurred. These types of data were defined in the latter parts of the investigation, in particular, from 1985 onward. However, prior to this period, determining personal attributes and where and how the fatalities occurred becomes more difficult. Locational information of where fatalities occurred was derived on two different geographic scales: 1) a county (or parish) or town of the death and 2) information regarding the shelter (or lack thereof) where the fatality occurred (e.g., permanent home, mobile home, outside, boat, other structure, etc). In most cases, the descriptions within the two datasets incorporated a report of the closest nearby town to where the fatality occurred; though there are many cases where only a county name was provided. If a town or nearby city was known, the latitude and longitude for this municipality was chosen as the geographic location of the fatality. If this city information was unknown, the county seat for the county in question was utilized to obtain the geographic coordinates.

In several cases, the coding of the structure or location of where a fatality occurred was incorrectly entered into *Storm Data* (e.g., coded as a permanent home, yet description provided indicated it was a mobile home). In these cases, a judicious decision was made based on the data provided to place the fatality within the correct structure or location classification. Researchers and government entities should utilize caution when employing the fatality code information provided by *Storm Data* without examining the text description to confirm the location or structure suggested by the coding.

To reveal the spatial patterns of these data, a set of 60 km × 60 km grids of various tornado and fatality variable counts were produced. In several cases, these gridded data were smoothed using a Gaussian (3 × 3) lowpass filter in order to reveal the broad patterns in the data. Readers should use caution when evaluating these filtered data because 1) a slight underestimation of the distributions may occur near the edge of the conterminous U.S. boundary because no data points are available outside this domain in which some of the grid cells overlay and 2) many of the details in the filtered maps are smoothed out and the resulting patterns should be viewed as conservative depictions of the distribution of the variables displayed (i.e., details and high-frequency variations tend to be smoothed while broad patterns are retained) (Brooks et al. 2003a; Doswell et al. 2005). The gridded data are preferred by this author because they not only illustrate the overall distribution (albeit at a somewhat "noisier" rate), but also highlight the variability inherent in the data.

3. Results

a. 1880–2005 period

Tornadoes have occurred in all 50 states of the United States, including Alaska and Hawaii. However, because Alaska and Hawaii had no reported killer tornado events for the 126-yr period of record, this analysis is restricted to the conterminous United States. Only four states within the conterminous United States—California, Nevada, Rhode Island, and Vermont—have not experienced a killer tornado event during this period (Table 1). Three southern states—Mississippi, Alabama, and Arkansas—lead in terms of standardized fatalities (deaths per square kilometer × 1000) and standardized number of killer tornadoes (deadly events per square kilometer × 1000). Most states within the southeast United States have standardized fatality rates that are higher than the mean for the country, illustrating the enhanced tornado vulnerability of this region. It is likely, albeit difficult to confirm, that tallies in most southern states are higher than indicated as many African Americans may not have been counted in "official" tallies during earlier portions of the period of record (Grazulis 1993).

As illustrated in Brooks and Doswell (2002, cf. their Figs. 2 and 3) and reiterated here (Fig. 1), killer tornado events and their associated fatalities have decreased significantly since the 1930s. Doswell et al. (1999) and Brooks and Doswell (2002) discuss a number of possible reasons for this decline, including the initial development and, thereafter, advancement of the tornado forecasting process, improved communication, spotter networks, better construction techniques, deployment of radar, and the development of the watch–warning process. As hypothesized by Brooks and Doswell (2002), data suggest that the decreasing trend in the rate of tornado deaths per million U.S. population is unlikely to continue to decline, despite improved detection methods, communications, and watch–warning operations. For example, the mean number of fatalities for the period 1976–85 (58.6 fatalities per yr) is roughly the same as the 1996–2005 period (58.5), the latter period occurring *after* the "modernization" of the National Weather Service (NWS) (Friday 1994). The stalled decline in tornado fatality rates is not likely because of shortcomings in the forecast and watch–warning process, but rather may be because of the growing vulnerability brought about by demographic changes (e.g., Brooks and Doswell 2002; Hall and Ashley 2007, manuscript submitted to *Nat. Hazards Rev.*, hereafter HA).

During the period of record, "violent" tornadoes (F4

TABLE 1. State tornado fatalities, standardized fatalities (deaths per square kilometer × 1000), killer events, and standardized killer events (events per square kilometer × 1000) for 1880–2005. Italicized text indicates states that rank in the top five for the respective categories.

State	Deaths	Normalized fatalities (deaths per square kilometer × 1000)	Killer events	Normalized killer events (events per square kilometer × 1000)
AL	*1440*	*10.957*	*261*	*1.986*
AZ	3	0.010	2	0.007
AR	*1488*	*11.034*	*298*	*2.210*
CA	—	—	—	—
CO	32	0.119	12	0.045
CT	4	0.319	2	0.159
DE	4	0.790	3	0.593
FL	179	1.281	73	0.522
GA	1070	7.134	187	1.247
ID	2	0.009	1	0.005
IL	1169	*8.120*	173	1.202
IN	723	7.783	90	0.969
IA	592	4.091	119	0.822
KS	696	3.285	161	0.760
KY	467	4.539	86	0.836
LA	715	6.337	157	1.392
ME	2	0.025	2	0.025
MD	48	1.896	13	0.514
MA	116	5.713	10	0.492
MI	354	2.406	63	0.428
MN	493	2.391	102	0.495
MS	*1672*	*13.763*	*234*	*1.926*
MO	*1402*	*7.858*	213	1.194
MT	5	0.013	4	0.011
NE	279	1.401	88	0.442
NV	—	—	—	—
NH	5	0.215	3	0.129
NJ	14	0.729	7	0.364
NM	4	0.013	3	0.010
NY	32	0.262	25	0.204
NC	198	1.569	71	0.563
ND	81	0.453	30	0.168
OH	357	3.366	88	0.830
OK	1333	7.495	*262*	*1.473*
OR	6	0.022	2	0.007
PA	189	1.628	49	0.422
RI	—	—	—	—
SC	305	3.911	79	1.013
SD	104	0.529	51	0.259
TN	711	6.660	159	*1.489*
TX	*1812*	2.672	*366*	0.540
UT	1	0.005	1	0.005
VT	—	—	—	—
VA	70	0.683	26	0.254
WA	6	0.035	1	0.006
WV	116	1.860	9	0.144
WI	411	2.922	97	0.690
WY	7	0.028	5	0.020
Tot	18 717	—	3688	—
Avg	374	2.727	74	0.537

and F5) accounted for 66.3% of all fatalities, while significant tornadoes (F2+) were responsible for 98.8% of all fatalities. During 1950–2004, a period of time during which tornado tallies were officially recorded, violent tornadoes were responsible for 67.5% of all tornado deaths in the United States, yet *only* accounted for 2.1% of all tornadoes. Since the 1970s—the decade when postmortem damage classification via the Fujita

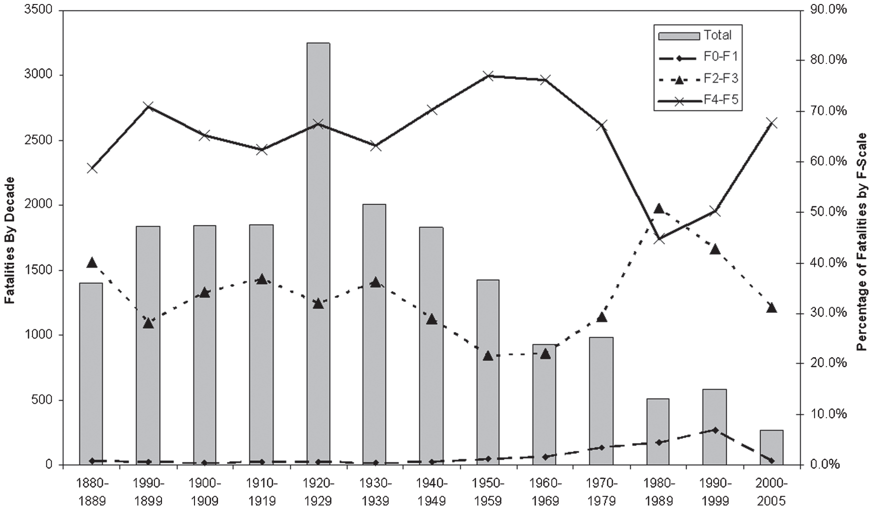

FIG. 1. Total number of tornado fatalities (solid bar) by decade (except for 2000–05) during the period of record and percentage of fatalities due to weak, significant, and violent tornadoes by decade (lines).

scale was implemented officially by the NWS (McDonald 2001)—the percentages of total fatalities due to F0–F1 and F2–F3 tornadoes have increased (Fig. 1). Nevertheless, violent tornadoes continue to account for more fatalities than all other Fujita damage classifications.

Similar to trends in overall seasonal tornado frequency (cf. Fig. 9 in Verbout et al. 2006), the 3-month period from mid-March through mid-June has more tornado deaths (not shown) and tornado death days (a day in which a U.S. tornado fatality was recorded) than any other period during the year (Fig. 2). During the 126-yr period, 3 April had 91 tornado-death days, at least 20 more than any other day. Although likely an artifact of the small sample size of the dataset (e.g., see Doswell 2007), these data suggest that during any given year there is over a 72% chance that a U.S. tornado fatality will be recorded on 3 April. The March–June transition season contains the climatological maximum in the collocation of supercell ingredients that support the development of killer tornadoes and tornado outbreaks across the Great Plains and southern United States (Miller 1972; Doswell 1987; Rasmussen and Blanchard 1998; Brooks et al. 2003b). The fall season corresponds to a secondary maximum in tornado fatalities and death days—albeit this maximum is relatively small in magnitude. This secondary maximum is due to killer events that occur primarily within the American south (Fig. 3).

A spatial analysis of the number of tornado fatalities

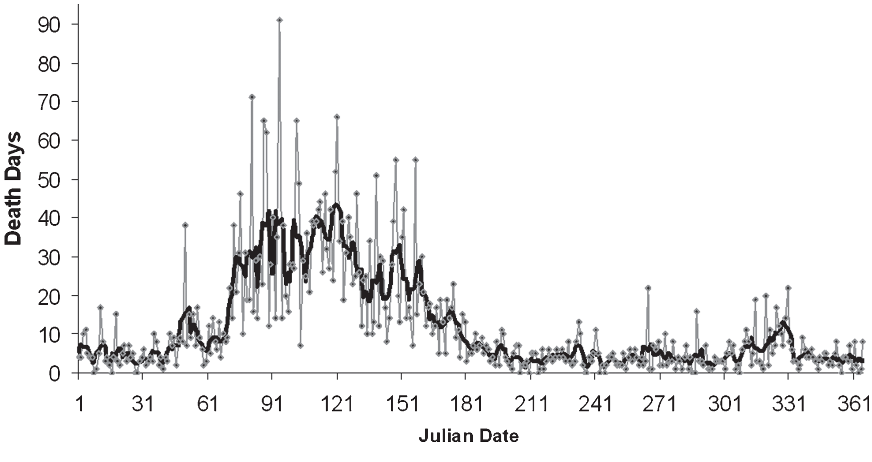

FIG. 2. Number of killer tornado days by Julian date for the period 1880–2005. Includes 5-day moving-average trend line (thick line).

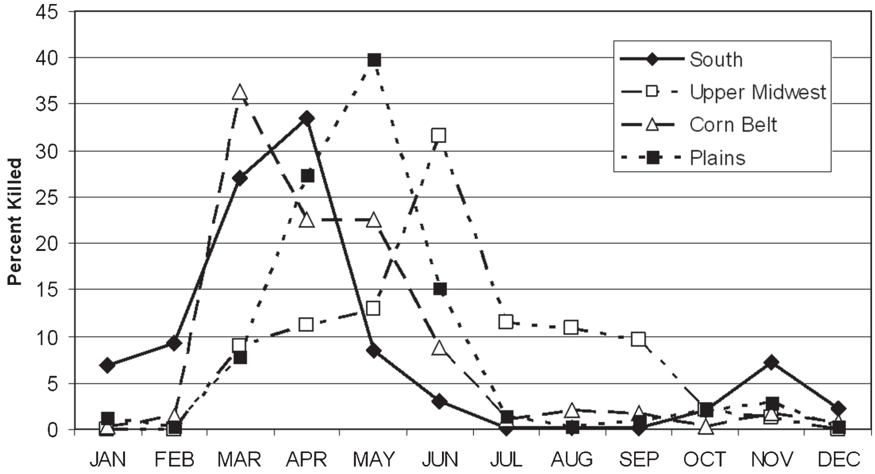

FIG. 3. The 1880–2005 monthly percentages of tornado fatalities by region illustrating the seasonality associated with tornado fatalities in the South (AL, AR, and MS), upper Midwest (IA, MN, and WI), Corn Belt (IL, IN, and OH), and the Great Plains (KS, NE, and OK).

and killer tornado events from 1880 to 2005 reveals a large region-specific maximum; in particular, the southeast and south-central portions of the United States have the greatest concentration of both fatalities and killer events (Fig. 4). The highest fatality tallies tend to stretch from Oklahoma and northeast Texas to Georgia, encompassing most of the Red River (of the South), Tennessee, and lower–Mississippi River Valley regions. Although this maximum does encompass some of the southeastern portions of the traditional "tornado alley" (Kelly et al. 1978; Brooks et al. 2003a, cf. their Fig. 11), as a whole tornado alley incurs a relative minimum in fatalities compared with other regions of the United States. This comparative lack of fatalities is unique considering the notably higher numbers of tornadoes (Fig. 5a), including violent tornadoes, that frequent the tornado alley region because of climatologically favorable atmospheric conditions (Brooks et al. 2003a; Brooks and Dotzek 2007). Some of this comparative fatality minimum could be because of the relatively low population of the Great Plains region during the early portions of the period of record. However, as illustrated later, this population minimum does not explain fully the relative lack of fatalities in comparison to the South and the Corn Belt. There are additional smaller, yet relative, maximums (Fig. 4) that occur in the upper–Mississippi River Valley region, along the Illinois–Missouri border, and, more broadly, in the Corn Belt. Larger spatial minimums are linked to minimums in tornado activity, including areas west of the Continental Divide and along the spine of the Appalachian Mountains. The regional frequencies in fatalities found in Fig. 3 tend to follow the well-defined, seasonal cycle of tornado occurrence illustrated and discussed in Brooks et al. (2003a). Although it is difficult to ascertain, it is hypothesized that people in the South may not perceive the importance of the early season tornado hazard revealed in Fig. 3 because killer tornadoes in this region tend to occur *before* the national climatological peak in severe weather.

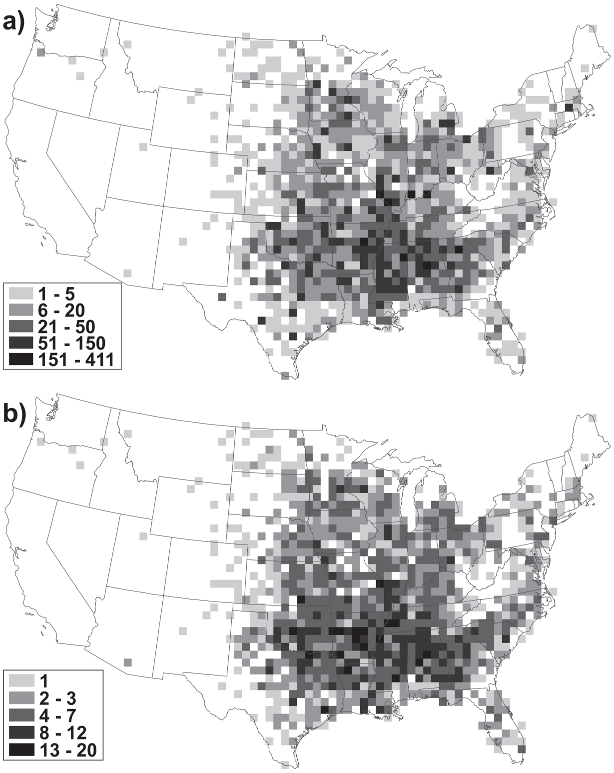

FIG. 4. Number of (a) tornado fatalities and (b) killer tornado events in a 60 km × 60 km grid for 1880–2005.

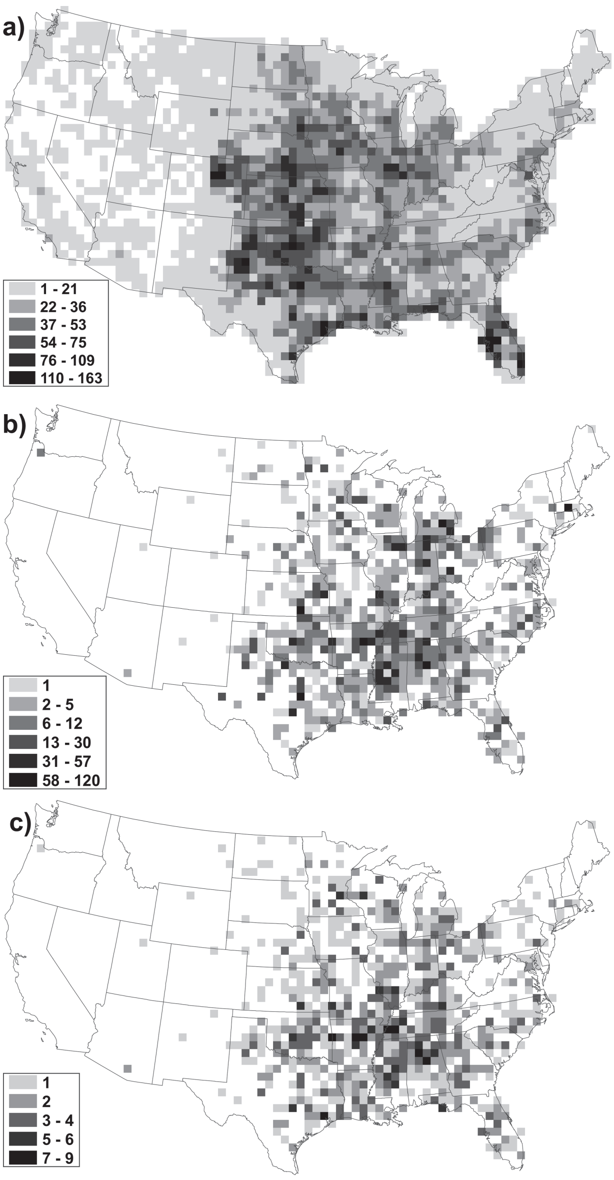

FIG. 5. Number of (a) tornadoes, (b) tornado fatalities, and (c) killer tornado events in a 60 km × 60 km grid for 1950–2004.

b. 1950–2004 period

During the early 1950s, the U.S. Weather Bureau began a concerted effort to count all U.S. tornadoes. In 1950, a list of tornadoes was provided in the *Climatological Data National Summary,* but it was not until 1953, the first full year of the issuance of Weather Bureau tornado watches, that the agency began to formally count all tornadoes. The *Climatological Data National Summary* document evolved into *Storm Data* by 1959, which, in addition to tornado data, included information on other storm perils such as severe hail, high winds, and floods (Grazulis 1993). Over the years, the tornado dataset has been formatted and adjusted by the National Severe Storms Forecast Center and Storm Prediction Center (SPC), and currently the National Tornado Database (http://www.spc.noaa.gov/climo/historical.html) is administered by the NWS Headquarters, SPC, and NCDC (McCarthy 2003). Issues related to the biases and trends in this dataset have been discussed elsewhere (e.g., Doswell and Burgess 1988; McCarthy 2003; Verbout et al. 2006). This study utilizes this tornado record, compiled from 1950 to 2004, as a basis for comparing the climatological distribution of tornado events and tornado fatalities.

An analysis of killer tornadoes in the United States during the 55-yr period continues to illustrate the high vulnerability of specific regions witnessed in the larger temporal analysis presented above (Figs. 5c and 6c). First, the interior South tends to have a larger total number of fatalities (Fig. 5b) and larger number of killer tornado events than any other region of the country during this period. In particular, the region centered on the lower–Arkansas, Tennessee, and lower–Mississippi River Valleys has the greatest concentration of tornado fatalities and killer events. It is improbable that this distribution is due to geographic shifts (or lack thereof) in favorable storm tracks considering the relatively long climatological record. However, it is likely that there is increased vulnerability within this region for several climatological and nonclimatological reasons, including 1) that although the overall frequency of tornadoes in this region is not as extreme as tornado alley (Fig. 6a), a large number of significant tornadoes do frequent the region (Fig. 6b); 2) that tornadoes within this region tend to occur during the cool and transition seasons (Brooks et al. 2003a) when day length is at a minimum, increasing the likelihood of nighttime tornadoes; 3) that because a greater fraction of tornadoes in this area occur during the cool and transition seasons, they tend to occur when flow is stronger and, hence, storm speeds higher, which may result in shorter warning response times; 4) that a large percentage of mobile home and weak-frame housing stock is in use in comparison to other parts of the country that experience tornadoes; 5) that the large percentage of forests and other land cover types reduces the visibility of both spotters and the public; 6) that there are higher low-level relative humidities in the South, resulting in haze and low cloud bases; 7) that there is a higher population density in the South in comparison to the Midwest and Great Plains; 8) that there is a lack of a focused "tornado season" in the South, which can lead to complacency (Doswell 2003); and 9) that other human vulnerabilities [education, coping styles; see

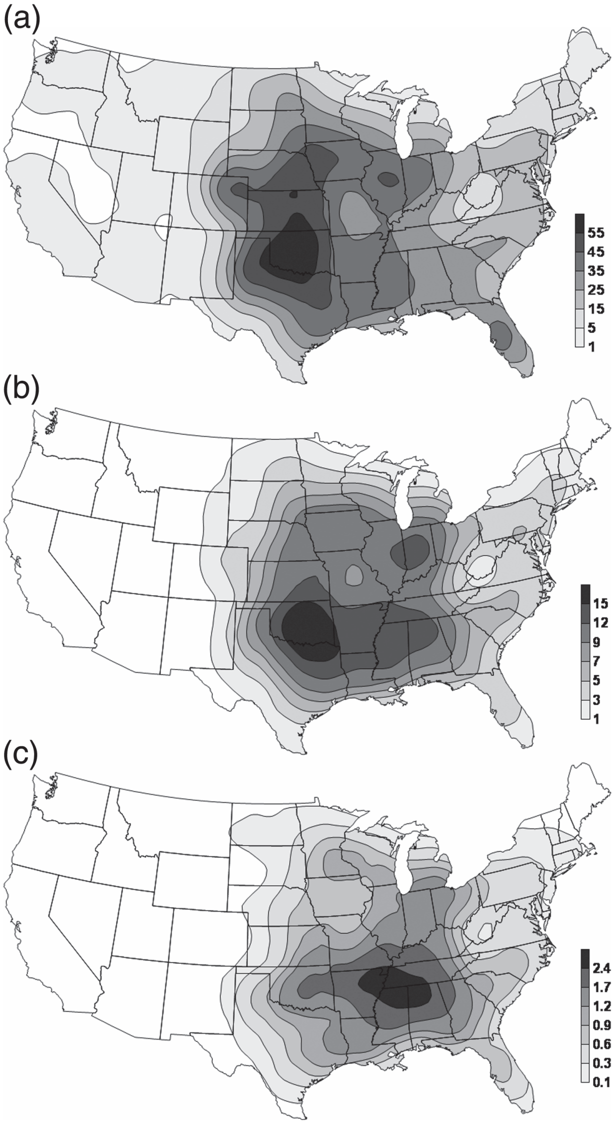

FIG. 6. Smoothed frequency of the number of (a) tornadoes, (b) significant (F2+) tornadoes, and (c) killer tornado events in a 60 km × 60 km grid for 1950–2004. Data smoothed using a Gaussian (3 × 3) lowpass filter. Associated caveats of these filtered data are discussed in section 2.

Sims and Baumann (1972); Biddle (1994)], warning distribution systems, etc.) tend to increase the fatality rates within this region. A portion of these hypotheses are addressed further in the subsequent section.

c. Fatality locations and the 1985–2005 period

An analysis of how and in what types of structures tornado fatalities have occurred is a critical step in improving future warning operations, amending (and, more importantly, enforcing) construction codes (Marshall 1994), and ascertaining the validity of regional insurance premiums. For this reason, descriptions of fatality locations from *Storm Data* and Grazulis (1993, 1997) were investigated to determine where and how (i.e., type of built structure or vehicle, not geographic location) people perished during these events. Unfortunately, detailed information on how the fatalities occurred is often not provided. In fact, in a couple cases, more information was provided about how chickens were killed in an event than humans. Lack of detailed information is of particular concern for a majority of the tornado fatality dataset. When detailed information is provided on how each fatality occurred, it often includes details on the type of structure, age, and sex of the victim. These types of data are more complete for the latter part of the killer tornado database record. For example, from 1950 to 1984, only 28.6% of descriptions provided in the datasets include enough information to determine explicitly the type of structure (or lack thereof) in which fatalities occurred, compared with 95.6% for 1985–2005. Thus, this portion of the analysis will focus on 1985–2005 because of the relative completeness of the data record for this period.

An analysis of killer tornadoes in the United States during the 21-yr period continues to illustrate the high vulnerability of specific regions revealed in sections 3a and 3b (Fig. 7). First, the interior South tends to have a larger total number of fatalities and number of killer tornado events than any other region of the county (Figs. 7a and 7b). During this period, the area from southwest Missouri though northern Georgia has a concentrated number of both killer tornado events and fatalities—with seven grid cells within this expanse containing four or more killer tornadoes during this relatively short time interval. In this case, how much of this concentration in the Tennessee Valley region and interior South is due to outbreaks or a geographic shift in favorable storm tracks is somewhat debatable, especially considering the short climatological record. For example, in examining the number of fatalities for 1985–2005, a number of high-frequency fatality grid cells are displayed relative to nearby cells. In most cases, these high-frequency cells are due to either tornado outbreaks (e.g., the 31 May 1985 outbreak in Ohio and Pennsylvania, the 3 May 1999 outbreak in Oklahoma and Kansas, and the 23 February 1999 outbreak in Florida) or exceptional solo killer tornado events (e.g., the 28 August 1990 event in Plainfield, Illinois, and the 27 May 1997 event in Jarrell, Texas). For this reason, the geographic distribution of killer tornadoes is more accurately displayed in the aforementioned maps in sections 3a and 3b, which illustrate a longer record.

The preceding discussion reveals a fundamental is-

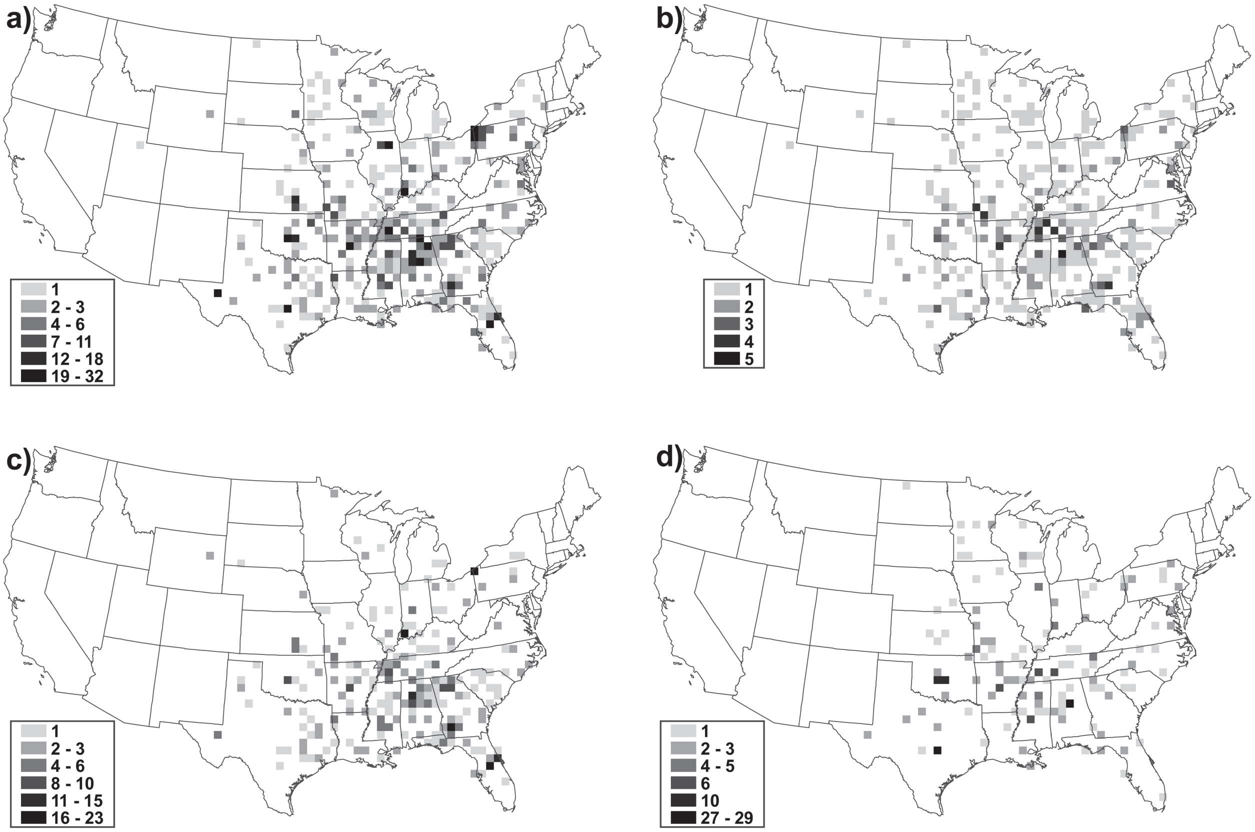

FIG. 7. Number of (a) tornado fatalities, (b) killer tornado events, (c) mobile home fatalities, and (d) permanent home fatalities in a 60 km × 60 km grid for 1985–2005.

sue, or problem, in describing tornado climatologies: sample size versus variability. Doswell (2007) demonstrates that with high variability, which is clearly evident in the tornado frequency and fatality climatologies illustrated in this manuscript, the sample size required to "smooth out" the random noise becomes much larger than that available. Doswell suggests that although we have many reported tornadoes, the sample size issue is generally underappreciated. Unfortunately, extending the period of record does not solve the problems associated with sample size and variability; after all, there are a number of nonmeteorological trends that can create further problems, especially the further back one incorporates these data. Therefore, caution should be exercised in drawing unwavering conclusions based on trends found within these data, especially for small temporal periods. With time, and better recording methods, the results found in this and other tornado climatology studies may become more convincing and definite. Unfortunately, as we wait for longer periods of record to transpire, fatalities will continue to occur and, therefore, it is imperative to examine trends and results from current datasets, despite their associated caveats.

Several additional variables were examined in order to scrutinize further the hypotheses proposed in section 3b. First, research by Brooks et al. (2003a, cf. their Fig. 7) has illustrated that the climatological tornado maximum for the South is during the winter and transition seasons, which suggests that nocturnal tornadoes are more likely to occur within this region. Nocturnal tornadoes present several problems for successfully mitigating a tornado event, including that 1) tornadoes at night are more difficult to identify by both spotters and the public, 2) the public is less likely to receive a warning during this period because the majority of people are sleeping, and 3) residents of mobile homes and other vulnerable housing stock are more likely to be in their homes during the night rather than in safer locations during the day (Simmons and Sutter 2005b). Analysis of sunset–sunrise data for all tornadoes during 1985–2005 illustrates that approximately 25.8% (42.5%) of U.S. tornadoes (tornado fatalities) occurred between sunset and sunrise. A result from a two-sample difference of proportion test [Rogerson (2001); 99% confidence interval] suggests that the percent of nighttime tornado fatalities is statistically greater than night-

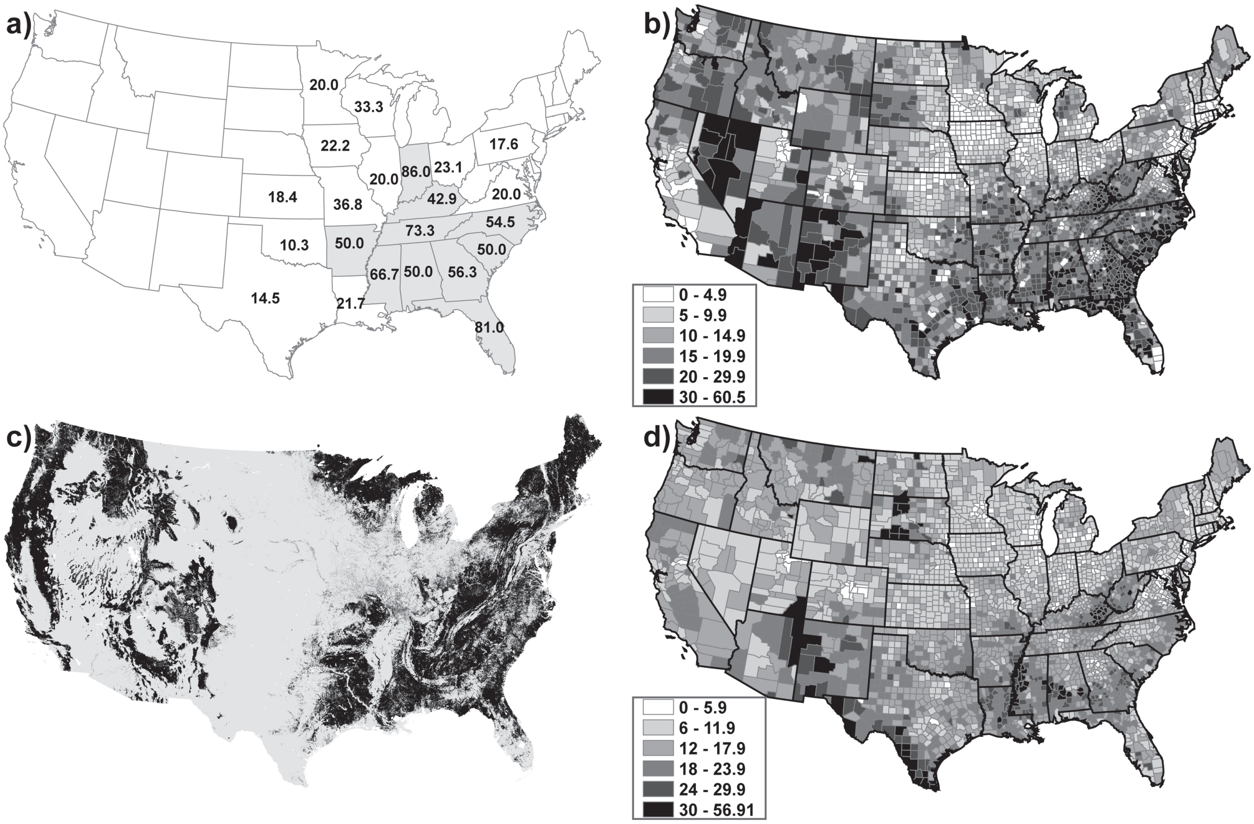

FIG. 8. (a) Percentage of nighttime tornado fatalities by state (illustrated for those states with greater than 10 tornado fatalities for 1985–2005; shaded states above the national average for nighttime tornado fatalities of 42.5%), (b) percentage of mobile homes by county (U.S. Census Bureau 2006), (c) forest cover (solid black) for the United States as determined by Advanced Very High Resolution Radiometer data (information online at http://nationalatlas.gov/articles/biology/a_forest.html), and (d) percent of county population in poverty (U.S. Census Bureau 2006).

time tornadoes for this period. This statistic substantiates the findings from a casualty regression model utilized by Simmons and Sutter (2005b), which indicated that expected fatalities are significantly lower for daytime tornadoes than for those that occur at night. The southeast United States has a higher likelihood of killer nighttime tornadoes, with most states within this region having greater percentages of tornado fatalities occurring at night than other states in the United States (Fig. 8a). Hence, lack of daylight is one variable restricting visibility of tornadoes in the South and, ultimately, leading to increased tornado vulnerability in this region.

Although the climatological tornado maximum in the South is during the winter and transition seasons, this "tornado season" is less clearly defined than in the plains region west of the Mississippi River (Brooks et al. 2003a, Doswell 2003). The tornado "season" in the plains and traditional tornado alley is much more concentrated and peaked (e.g., see Brooks et al. 2003a, their Fig. 8), which leads to an enhanced period of awareness and preparedness that will tend to reduce a person's overall vulnerability to a tornado hazard. Conversely, the South has a "low," albeit fairly constant, risk of tornadoes across a large portion of the year. As Doswell (2003) suggests, this overall low threat leads to the aforementioned "It can't happen here!" mentality that, in turn, reduces preparedness for these hazards. This complacent attitude, in combination with a nonvanishing threat of a significant tornado, enhances the vulnerability to persons living in the South.

Tornado fatalities are unique compared with flood (Ashley and Ashley 2008), lightning (Curran et al. 2000), convective straight-line wind (Ashley and Mote 2005), and nonconvective straight-line wind fatalities (Ashley and Black 2008) in that most tornado fatalities tend to occur *within* housing structures (71.3% from 1985 to 2005). For example, 62% of flood fatalities from 1959 to 2005 occur in or are associated with vehicles (Ashley and Ashley 2008); in addition, the primary location of nonconvective (42.8%) and convective straight-line (31.8%) wind fatalities from 1991 to 2005

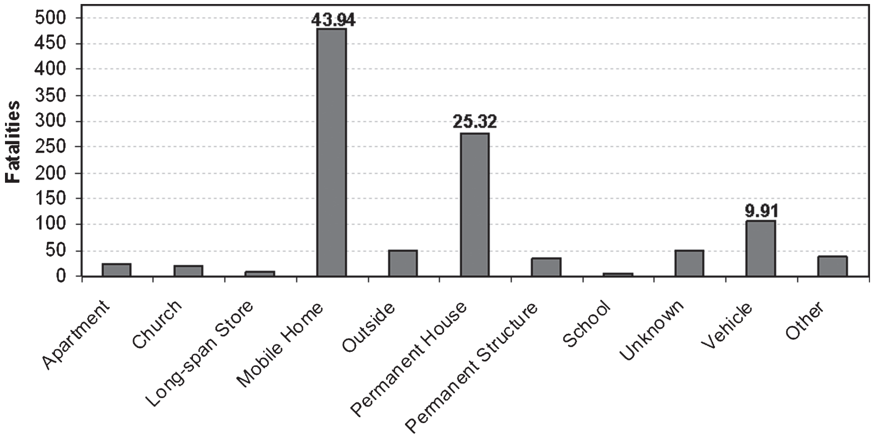

FIG. 9. Tornado fatalities by location of where the fatality occurred for 1985–2005. The three largest percentages are provided.

was also in vehicles. This illustrates that people are more likely to seek shelter in a tornadic situation in comparison with these other weather hazards. This also suggests that the type of housing stock where people are seeking shelter is very important in terms of reducing or increasing their vulnerability to tornadoes.

During 1985–2005, U.S. tornado mobile home fatalities accounted for 44% of all fatalities (Fig. 9). The percentage of fatalities within mobile homes has increased from just over 37% of all fatalities from 1986 to 1990 to nearly 57% of all fatalities from 2001 to 2005. During the same period, vehicular-related fatalities (9.9% of all fatalities) have tended to decrease, while fatalities within permanent homes (25.3%) have fluctuated between 20% and 30%. As illustrated in Brooks and Doswell (2002, cf. their Table 3), the mobile home fraction of U.S. housing has continued to increase, albeit at a slower rate between 1990 (7.2% of housing stock) and 2000 (7.6%) than previous decennial surveys (U.S. Census Bureau 2006). This increase in the mobile home housing stock in vulnerable areas of the South has led to the amplification of deaths in mobile homes (Brooks and Doswell 2002).

Exploring mobile and permanent home tornado fatalities from 1985 to 2005 indicates that the interior South contains a high distribution of both of these housing unit fatalities compared with the rest of the country (Figs. 7c and 7d). This is, in part, because of the overall higher fatality rates realized in this area. However, the spatial distribution of mobile home fatalities illustrates a clear maximum in the interior and deep South, further revealing the increased vulnerability of this region because of its higher percentage of "weak" housing stock. For example, 52.1% of all tornado fatalities in the region encompassing Arkansas, Alabama, Georgia, Mississippi, and Tennessee occurred in mobile homes. As suggested in Brooks and Doswell (2002), and confirmed in Fig. 8 and Table 2, deaths within mobile homes continue to present a significant problem to the future reduction of tornado fatalities in the United States. The southeast United States has the highest percentage of mobile home stock compared with any other region east of the Continental Divide (Fig. 8b). In most counties in the Southeast, the percentage of mobile home housing stock is well above 20%, indicating that a large portion of this region's populace incurs an enhanced vulnerability because of housing type.

Examining tree cover for the United States illustrates how forests and, therefore, lack of visibility may enhance the tornado vulnerability of particular areas, namely the Southeast (Fig. 8c). However, this argument fails when examining the Mississippi "Delta" region of Mississippi, Arkansas, and Louisiana. This flood-plain region is largely free of forests and has little topography, making daytime visibility better than surrounding forested regions. In fact, there are a number of high killer tornado event and fatality grid cells within the Mississippi Delta region (Figs. 4 and 5), an area that has some of the highest rates of social vulnerability in the country (Cutter et al. 2003). This suggests that tree

TABLE 2. Number of tornado fatalities and percentage of those fatalities in housing structures and vehicles for 1986–2005.

	Mobile home		Permanent home		Vehicle		
Years	Deaths	Tot (%)	Deaths	Tot (%)	Deaths	Tot (%)	Tot
1986–90	74	37.2	31	15.6	36	18.1	199
1991–95	93	44.1	46	21.8	18	8.5	211
1996–2005	158	43.6	127	35.1	36	9.9	362
2001–05	127	56.7	58	25.9	12	5.4	224

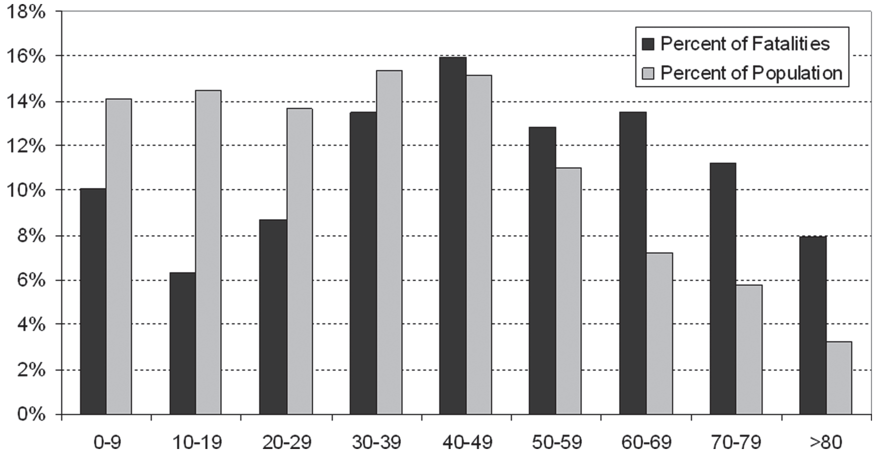

FIG. 10. Percent of tornado fatalities (1985–2005) and percent of population (U.S. Census Bureau 2006) by age segments. Fourteen percent of reported fatalities during this period did not contain age information and are thus not included in the graph.

cover and the associated reduction in the line of sight may not explain completely the enhanced vulnerability occurring in the Southeast. Other variables such as poverty (Fig. 8d; Phillips et al. 2005), weak-housing stock (Fig. 8b), greater population density east of the Interstate-35 (I-35) corridor (not shown) and a growing and sprawling Sunbelt population (Perry and Mackun 2001; Hobbs and Stoops 2002), lack of spotter activities and warning infrastructure earlier in the period, and psychology (Sims and Baumann 1972) may augment the vulnerability of the area. In addition, the region's close proximity to the Gulf of Mexico enhances low-level moisture availability and may make spotting tornadoes more difficult because of haze, lower lifting condensation levels, and a tendency for high-precipitation supercells that often contain "rain wrapped" and difficult-to-identify tornadoes. Conversely, the lack of forests and orography, when combined with a climatological maximum in daytime–evening (i.e., visible because of daylight) tornadoes in the Great Plains and Midwest, may help to reduce the overall vulnerability of these regions. Thus, it may be that the lack of trees, when combined with other climatological and sociological variables, is much more important in *reducing* vulnerability in some regions rather than *increasing* it in others.

It is also revealing that the regions that have the highest risk from tornadoes [Fig. 5a; also see Brooks et al. (2003a), their Fig. 4], in particular significant tornadoes [Fig. 5b; also see Concannon et al. (2000)], tend to have lower total numbers of fatalities and killer tornado events. This substantiates the position that seasonality, land cover, and weak housing stock contribute to the increased vulnerability in the South and decreased vulnerability in the traditional tornado alley. If one were to remove hypothetically the 3 May 1999 tornado outbreak, this lack of killer tornadoes would be even more substantial. Improved reporting of how and where fatalities occurred and a longer period of record will be required to confirm these unique geographic distributions found in the data.

Examining demographic data of fatalities for 1985–2005 illustrates the vulnerability of particular segments of the population (Fig. 10). The percentage of tornado fatalities stratified by age category shows that the middle-aged and elderly have a greater vulnerability to tornadoes; that is, each of the categories over 40 yr of age contain a higher percentage of fatalities compared with the percent of U.S. population in that category. Using the one-sample test for proportions (Rogerson 2001) reveals that all age categories above 60 (50) years of age are statistically different from the population at a 95% (90%) confidence interval. Conversely, the one-sample test for proportions indicates that age classes below 30 (40) are statistically different from the population at a 95% (90%) confidence interval suggesting that there is a reduced tornado vulnerability within younger segments of the population. The percentage of elderly population (>65) by county illustrates a definitive maximum in the Great Plains—in a belt from central Texas to North Dakota (not shown). However, there is a higher elderly population *density* that lives along and east of the I-35 corridor in the United States (not shown), suggesting that the region east of I-35 has a higher vulnerability because of the greater number of elderly living there in comparison to other parts of the country. There is no discernable difference in vulnerability between the sexes during this period: males account for 47.6% of all tornado fatalities, while 44.3%

were female, and 8.07% of victims were unclassified. Compared with other thunderstorm-related hazards (e.g., Curran et al. 2000; Ashley and Ashley 2008), this lack of difference in fatality rates between the sexes is unique.

4. Conclusions

A more complete analysis of the geographic patterns associated with tornado fatalities is essential to improving mitigation efforts toward tornado hazards. This study has highlighted particular vulnerabilities and impacts associated with reported killer tornadoes that have affected the United States over the 126-yr period of 1880–2005. During this period, nearly 19 000 people perished due to tornadoes. The *perception* of tornadoes as a hazard is much greater than the reality, with death rates per million remaining well below a value of 1:1 000 000 since 1975 (Brooks and Doswell 2002). Nevertheless, the potential for considerable loss of life and property due to tornadoes continues to exist, especially in highly vulnerable regions of the country. Further, the increasing population and migration patterns of this population (Perry and Mackun 2001; Hobbs and Stoops 2002) suggest that the overall vulnerability and risk to humans and their property may amplify in the future (e.g., Wurman et al. 2007; HA) despite improvements in forecasting, detection, and warning dissemination.

This investigation evaluated the unique spatial distribution of killer tornadoes across the United States, revealing that the southern tier of the United States—outside of the traditional tornado alley—has the greatest concentration of tornado fatalities and killer tornado events. Data suggest that the interior southeast and south-central United States have greater vulnerabilities to tornadoes because of the unique juxtaposition of a series of physical and sociological variables. For example, this region still has a relatively high frequency of tornadoes, with most of those tornadoes occurring during the night, in forested regions, in early season storms that are more likely to have high forward speeds, and before the "national" climatological peak in severe storm season—variables that may tend to catch people "off guard" during a tornado event. Sociologically, the southern-tier region has a greater concentration of mobile homes, percentage of population in poverty, and elderly population density—all factors that may enhance the vulnerability of this region. In contrast to the South, the Great Plains has a reduced vulnerability despite the region's large frequency of tornado and violent tornado events because of the concurrence of physical and social variables that are unlike to those in the South. Collectively, the Great Plains, which encompasses traditional tornado alley, has more visible tornadoes (daytime maximum in events and lack of trees), a relative minimum in vulnerable housing stock (low mobile home percentages), a comparatively small population density, and greater "experience" with tornadoes (because of their high frequency in tornado alley) leading to more awareness of what to do during a tornado situation.

A number of issues arose during this analysis because of the lack of completeness in the demographic and spatial data associated with the historical tornado records. Although *Storm Data* descriptions of how and where tornado fatalities occurred have advanced since the mid-1980s, there is still a need for a significant improvement in the information provided in future damage and casualty assessments. For example, with the NWS's recent adoption of the enhanced Fujita (EF) scale (see the Web site http://www.wind.ttu.edu/F_Scale), information on specific structure types (so-called damage indicators) of where tornado *casualties* occurred should be provided in *Storm Data*. Meteorologists and engineers verifying tornado damage should make a concerted effort to determine *casualty* location and the type of structure in which the fatality or injury occurred. Such information should be considered as important as, if not more important than, determining the EF scale ranking, track length, etc. Combining these improved future data resources with results from new investigations into the psychology of those impacted by these events [e.g., studies that investigate societal perceptions and "responses" like Sims and Baumann (1972) and Biddle (1994)] could improve our understanding of the human ecology of tornadoes.

Acknowledgments. This manuscript was partially supported by a Northern Illinois University Graduate School Research and Artistry grant. The author thanks Mr. Rick Schwantes for his help with data preprocessing; Dr. Rich Greene for his help with a raster data conversion routine; Drs. Sharon Ashley, Mace Bentley, and Chuck Doswell for providing comments and suggestions on early versions of this manuscript; and two anonymous referees who provided thoughtful and beneficial reviews.

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