Vulnerability due to Nocturnal Tornadoes

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ABSTRACT

This study investigates the human vulnerability caused by tornadoes that occurred between sunset and sunrise from 1880 to 2007. Nocturnal tornadoes are theorized to enhance vulnerability because they are difficult to spot and occur when the public tends to be asleep and in weak building structures. Results illustrate that the nocturnal tornado death rate over the past century has not shared the same pace of decline as those events transpiring during the daytime. From 1950 to 2005, a mere 27.3% of tornadoes were nocturnal, yet 39.3% of tornado fatalities and 42.1% of killer tornado events occurred at night. Tornadoes during the overnight period (local midnight to sunrise) are 2.5 times as likely to kill as those occurring during the daytime hours. It is argued that a core reason why the national tornado fatality toll has not continued to decrease in the past few decades is due to the vulnerability to these nocturnal events. This vulnerability is magnified when other factors such as escalating mobile (or "manufactured") home stock and an increasing and spreading population are realized. Unlike other structure types that show no robust demarcation between nocturnal and daytime fatalities, nearly 61% of fatalities in mobile homes take place at night revealing this housing stock's distinct nocturnal tornado vulnerability. Further, spatial analysis illustrates that the American South's high nocturnal tornado risk is an important factor leading to the region's high fatality rate. The investigation emphasizes a potential break in the tornado warning dissemination system utilized currently in the United States.

1. Introduction

Nocturnal tornadoes appear to be particularly hazardous to humans as evidenced by recent killer tornadoes (Table 1) and tornado outbreaks. As an example, 80 tornado fatalities occurred during 2007, with 59 (or 73.8%) of those fatalities taking place between sunset and sunrise; moreover, 19 of 26 (or 73.1% of) 2007's killer tornadoes occurred at night. Nocturnal tornado events enhance human vulnerability and reduce the success of mitigation activities for several reasons. First, tornadoes are difficult to visually identify at night by both the public and trained spotters and, even if a warning is provided, the public is less likely to receive that warning at night due to normal sleeping patterns (Monk et al. 2000). In addition, the public has a tendency to be in more vulnerable housing and building structures (e.g., mobile or "manufactured" and single-family homes) during the night in comparison to safer locations (e.g., school or place of work in steel or reinforced-concrete buildings) during the day (Simmons and Sutter 2005a; Ashley 2007). Ashley (2007) found that 69.2% of all tornado fatalities from 1985 to 2005 occurred in either mobile or permanent homes, illustrating the enhanced vulnerability of these particular housing structures. Finally, tornado siren systems are deployed to mitigate tornado hazards during *outdoor* activities, making them less effective for mitigating nocturnal events when people have a greater tendency to be indoors.

Several studies have suggested, illustrated, or explicitly investigated the importance of nocturnal tornado vulnerability. Using a regression analysis of tornado casualties, Simmons and Sutter (2005a) established that expected casualties are significantly lower for tornadoes occurring during the "day" (between 0600 and 1759 local time) or "evening" (1800 and 2359 LT) than those occurring late at night (0000 and 0559 LT). Utilizing similar time of day delineations, Simmons and Sutter (2008) estimated regression models of tornado casualties employing tornado data from 1986 to 2002. Their results suggest that expected fatalities (injuries) are 64% (43%) lower for daytime tornado cases in

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TABLE 1. Top 10 killer nocturnal U.S. tornadoes from 1998 to 2007. The maximum damage ratings assessed using the Fujita scale (F) or enhanced Fujita scale (EF), which was implemented on 1 Feb 2007, are provided.

Rank	Date	City, state	Fatalities	Damage
1	8 Apr 1998	Edgewater, AL	32	F5
2	23 Feb 1998	Kissimmee, FL	25	F3
2	6 Nov 2005	Evansville, IN	25	F3
4	2 Apr 2006	Newbern, TN	16	F3
5	2 Feb 2007	Lake Mack, FL	13	EF3
6	23 Feb 1998	Osteen, FL	12	F3
7	4 May 2003	Jackson, TN	11	F4
7	13 Feb 2000	Camilla, GA	11	F3
9	4 May 2007	Greensburg, KS	10	EF5
10	2 Feb 2007	Lady Lake, FL	8	EF3
10	15 Nov 2006	Riegelwood, NC	8	F3

comparison to "overnight" events, while expected fatalities (injuries) are 40% (38%) lower for daytime than evening tornadoes. In a study examining specifically tornadoes causing F5 damage, Simmons and Sutter (2005b) found varied results on whether day, evening, or overnight violent tornadoes augmented human vulnerability. In a geographic synthesis of tornado fatalities, Ashley (2007) suggested that one of the primary reasons the American South has a greater fatality rate than other high-risk regions is because tornadoes in the South tend to occur during cool and transition seasons (as also illustrated by Brooks et al. 2003), when daylength is at a minimum. Ashley established that from 1985 to 2005 approximately 25.8% of U.S. tornadoes occurred between sunset and sunrise, while a much greater proportion (42.5%) of tornado fatalities happen at night.

Paul et al. (2003) examined the public warning response during the 4–5 May 2003 tornado outbreak in the central United States, finding that survey respondents who experienced nocturnal tornadoes in Tennessee (in comparison to the daytime tornadoes in Kansas and Missouri during that same event) were less likely to receive warnings because they were asleep. In another case study, which examined the 2007 Groundhog Day tornado outbreak in Florida (includes the Lake Mack and Lady Lake, Florida, events highlighted in Table 1), Simmons and Sutter (2007) suggested that since most watches and warnings occurred well after prime-time television and late local news during this event, many residents went to sleep unaware of the potential threat that night. This "break" in the warning dissemination chain ultimately reduced the response to the storms and likely enhanced vulnerability. Another similar late-night tornado and nocturnally induced "break" in warning dissemination was illustrated in the 22–23 February 1998 Kissimmee, Florida tornado (Schmidlin et al. 1998), the second most deadly tornado event in the recent decade (Table 1). Confirming the importance of seasonality, Simmons and Sutter (2007) also illustrated that fatalities per tornado are in fact *lower* during the "active" months of May and June in comparison to "off peak" months of November–April.

In general, while there is evidence that human vulnerability is enhanced by nocturnal tornado events, most of these studies have utilized arbitrary time range delineations for what constitutes "day" versus "night." Even the use of local time standards, as in the Simmons and Sutter studies, ignores geographic and seasonal variations in sunset and sunrise times and length of the local nocturnal period. To illustrate the magnitude of this difference, Tupelo, Mississippi [located in the middle of the South's killer tornado alley; see Ashley (2007), Fig. 6.c], can change almost 2.5 h [local standard time, (LST)] over the course of a year, while the Midwest's Chicago, Illinois, witnesses almost a 3.2-h (LST) variation in sunset time. The length of the nocturnal period can change over 4.5 h in Tupelo and nearly 6 h in Chicago. Thus, it is imperative that any study examining nocturnal tornado vulnerabilities control for the change in sunset and sunrise during calculations.

In addition, much of the past research examining vulnerability has accounted for temporal changes (e.g., seasonality), but little of this work has accounted for the complexity of vulnerability across space. For example, does the American South have a greater vulnerability due to a larger proportion of this region's tornadoes occurring at night, while the Great Plains have a reduced vulnerability since tornadoes in "Tornado Alley" occur more often during daylight hours and thus can be witnessed and mitigated against with greater success? Unlike most tornado vulnerabilities [see Ashley (2007) for a discussion of a variety of physical and social vulnerability types], time of day can be calculated and assessed using rigorous methods. Clearly, there are numerous physical and social factors that contribute to a fatality in any hazardous situation; however, this study seeks to analyze a single issue—nocturnal tornadoes—to determine to what extent these events contribute to the tornado vulnerability of the U.S. population.

2. Methodology

This study utilized several unique resources to acquire historical tornado event and fatality data, including the National Climatic Data Center's publication *Storm Data* (NCDC 1959–2007), NCDC's Storm Event Database (http://www4.ncdc.noaa.gov/cgi-win/wwcgi.dll?wwEvent~Storms), a long-term study of U.S. tornadoes by Grazulis (1993, 1997; hereafter, Grazulis), and the historical archives of event and fatality data provided by National Oceanic and Atmospheric Administration's (NOAA) Storm Prediction Center (SPC 2008). Ashley (2007) has discussed the primary methods for the acquisition of the tornado fatality and event data; therefore, the reader is asked to peruse this work for details and issues regarding these data. In addition, it is important to note that this investigation focuses solely on fatalities since this appears to be the most robust division of the reported casualty data.

Unlike most vulnerability factors, time of day can be calculated and assessed using precise methods. However, calculating sunrise–sunset times for the tens of thousands of records in the databases can be a daunting task considering the ever-changing daylength and the multitude of time zone and database issues involved in the reconciliation of the data. As an example of one of the many issues involved in coordinating times, all tornadoes in the SPC tornado database are cataloged in central standard time (CST) using decimal notation instead of hours and minutes, no matter where and in what time zone the event occurred. Such archaic "standardization" practices make investigation of these data more onerous and confusing than necessary.

Although many tornado events transpire across a set temporal window, only the start time and location for each tornado report in the historical SPC database were utilized in this study to assess the tornado sunset–sunrise climatology. We agree with Brooks et al. (2003) who state that a tornado's "touchdown" point is the most reliable data aspect of the spatial and temporal window associated with a typical tornado record. However, and in contrast to the SPC tornado report data, the tornado *fatality* data were further refined geographically since the descriptions in *Storm Data* and the Grazulis works often incorporated a report of the closest nearby town to where each fatality occurred. Thus, instead of simply employing the start point of the *killer* tornado for calculation purposes, fatality locations were determined to the closest municipality or county (parish) seat.

All times in the tornado databases were coordinated to LST. In addition, all sunset–sunrise calculations were based on a locale's LST. Converting time to LST removes the cumbersome influence of daylight saving time calculations, which can vary on a yearly basis and observance by some states.

Solar calculations of sunset and sunrise were based on the geometric equations from Meeus (1991), which were provided by NOAA (2008). Technically, sunset and sunrise occur when the upper edge of the disk of the sun is along the local, unobstructed horizon (U.S. Navy 2008). These calculations take into account 0.833° of atmospheric refraction and assume "average" atmospheric conditions. Clearly, this assumption is not necessarily robust during a tornadic storm environment; however, there is no other scientific way to determine the relative "darkness" of the thousands of events in the dataset occurring during these critical times of the day. Since visibility drops dramatically (outside of the effects of light pollution, power flashes, and lightning) in storm environments *prior* to a clear-sky evening period's normal sunset and twilight, this calculation method provides a conservative estimate of nocturnal sky conditions. We also chose not to utilize twilight in our calculations since illumination by the upper atmosphere assumes "clear" atmospheric conditions, which are not found in storm environments. Visibility in sunset, sunrise, and twilight situations is certainly dependent upon a multitude of factors, most importantly a person's position with respect to the sun and tornado. Since it is not possible to determine the relative darkness of these events, we uphold a simple day versus night demarcation for tornado events based solely on the above solar calculations of sunset and sunrise.

To reveal the spatial patterns of various tornado and fatality attributes, we counted data points on a set of 80 km × 80 km grids on an Albers equal-area conic projection. Similar to Brooks et al. (2003), we utilize this specific resolution because a grid cell of 80 km per side has the same area as a circle with a radius of 24.6 n mi, which closely approximates the area used in SPC probability forecasts.

3. Results

a. Temporal analysis

From 1880 to 2007, there were a total of 18 864 recorded tornado fatalities and 3650 killer tornado events equating to an average of 5.2 fatalities per killer tornado. Unfortunately, 148 fatalities associated with 83 killer events—occurring primarily during the early period of record—have undocumented times of occurrence and are therefore excluded from further analysis. Approximately 34.1% of fatalities (39.3% of killer tornadoes) took place between sunset and sunrise during this 128-yr period. Complete counts of reported tornadoes are not available for this entire period making a comparison between all tornadoes and killer events impractical. However, the SPC's tornado archive, which contains all recorded tornado events from 1950 to 2005 (Schaefer and Edwards 1999; McCarthy 2003; Brooks et al. 2003; Verbout et al. 2006), was employed for the latter period of record to illustrate differences between all tornado cases and those specific events that killed persons.

From 1950 to 2005, a *recorded* 48 165 tornadoes occurred throughout the United States; 143 of these events are subsequently removed from the analysis because they contained no location information or were in U.S. territories and states (e.g., Alaska and Hawaii) outside of the scope of this analysis. During this period, only 27.3% of tornado events were nocturnal. We hypothesize that the reporting efficiency for nocturnal tornadoes may be lower than daytime events, which would lead to larger undercounts for the nocturnal period. However, we have no competing dataset to provide the evidence necessary to support our hypothesis. In comparison to the nocturnal tornado event percentage, 39.3% of tornado fatalities and 42.1% of killer tornadoes from 1950 to 2005 took place during the night. Results from a two-sample difference of proportion test [Rogerson (2001); 99% confidence interval] indicate that the percentage of nocturnal tornado fatalities and the percentage of killer tornado events are both statistically greater than the percentage of nocturnal tornadoes for 1950–2005. This conclusion is similar to what Ashley (2007) found for nocturnal events during the shorter period 1985–2005 and reconfirms the findings from the casualty regression model reported by Simmons and Sutter (2005a), which indicated that expected fatalities are significantly lower for daytime tornadoes than for those that occur at night.

Just over 2.0% of all daytime tornadoes from 1950 to 2005 are killer events, while roughly 3.9% of nocturnal tornadoes produce fatalities. Despite the small percentages, the difference between the two proportions is statistically significant at a 99% confidence interval. Thus, tornadoes at night are almost twice as likely to kill as those during the daytime.

Simmons and Sutter (2005a) used three time of day delineations, including "day," "evening," and "overnight", in their investigations of tornado vulnerabilities. In this study, we examine the vulnerability of similar time periods, but use the specific sunset–sunrise information in our calculations rather than arbitrary temporal designations. Thus, our three time delineations include day (between local sunrise and sunset), evening (from sunset to LST midnight), and overnight (from LST midnight to sunrise). The demarcation of the nocturnal period into two separate periods follows the logic that most of the public would be sleeping, most likely passively *unwarned*, and therefore more vulnerable during the overnight hours in comparison to the other temporal segments. Moreover, persons asleep have a much greater tendency to be unaware of possible environmental cues, which in some cases are an important factor in the initialization of a successful warning process (Hayden et al. 2007). A recent poll (Harris Interactive 2007) illustrates that 61% of those surveyed acquired their weather forecasts from local television news or The Weather Channel, with an additional 23% of those surveyed acquiring weather forecasts from Internet sources. These information-*seeking* activities are used to acquire life-saving warnings while awake and it is therefore expected that vulnerability would be higher during the overnight hours when most persons are sleeping and not seeking warning or forecast information. We believe that this is a safe assumption considering that a relatively small proportion of American households[1] have, or use, the National Weather Service's (NWS) All Hazards Weather Radio, equipped with a tone alarm to alert and awaken persons during tornadoes. To what degree the public *uses* the All Hazards Weather Radio in their place of residence for nocturnal warnings is unknown, but we feel prudent with the assumption that it is more than likely less than 5% of the covered population. In addition, there will always be a segment of the All Hazards Weather Radio user population that will simply sleep through the tone alert for a variety of reasons (e.g., volume of tone alert too low, "heavy" sleeper).

Overall, only 9.3% (12.7%) of fatalities (killer events) occurred during the overnight period from 1950 to 2005, while 30.0% (29.4%) of fatalities (killer events) transpired during the evening period. The lower percentages in comparison with daytime tornadoes are expected considering that most tornadoes occur during the afternoon—or "daytime"—hours (Fig. 1). Despite the small fatality and killer event proportions for evening and overnight tornadoes, the *relative* threat from these nocturnal events is much greater than for daytime

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[1] There are no studies, to our knowledge, that have investigated the penetration of All Hazards Weather Radio into American *households*—the most likely structure of occupancy during nighttime hours. Hayden et al. (2007) found that 11% of Denver, CO, and 25% of Austin, TX, residents listed All Hazards Weather Radio as a source they used for weather information. However, the survey did not indicate how many of these residents have a radio plugged in (and with battery backup), with the tone alert turned on, and close to their place of sleep. In a recent investigation of winter storm warning information dissemination, Drobot (2007) found that 86% of survey respondents along the Colorado Front Range "rarely or never used" All Hazards Weather Radio as a source for weather information. A joint project between the Departments of Commerce, Education, and Homeland Security has provided All Hazards Weather Radios to nearly all public (and even most nonpublic) schools in the United States (M. Mack, 2008, personal communication). While this distribution of radios into schools is positive and suggests near-complete penetration into this structure type, it still does not indicate that large proportions of Americans have individually purchased and, more importantly, adopted the use of radios with tone alerts in their own households.

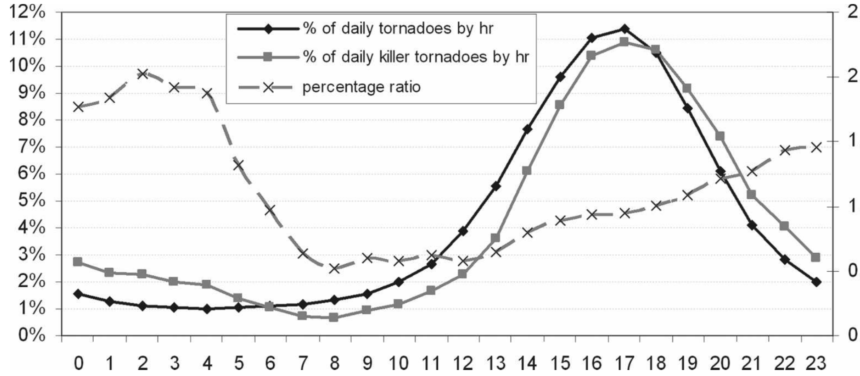

FIG. 1. The 3-h running mean of the percent of tornadoes by hourly distribution (LST) of occurrence for all tornadoes (black; diamonds) and killer tornadoes (gray; squares) by hour. Percentages are based on the total number of events or killer events over a day for the period 1950–2005. The dashed gray line represents the percentage of daily killer tornadoes by hour divided by the percent of daily tornadoes by hour. Left *y*-axis scale indicates percentage by hour, while right *y*-axis scale indicates ratio.

events. For example, 72.7% of tornadoes take place during the daytime but account for just 57.9% of killer events—much lower than expected. Conversely, overnight tornadoes only account for 6.6% of all events, yet produce proportionately nearly double that percentage (i.e., 12.7%) in killer tornado events. Overall, these relatively small proportions fail to truly reflect the enhanced vulnerability due to overnight tornadoes. As an alternative, consider that nearly 4.9% of all overnight tornadoes, or roughly 1 in 20 events, from 1950 to 2005 are killer events in comparison to 3.6% for evening tornadoes, and just 2.0% for daytime events. Hence, for 1950–2005, tornadoes during the socially sedentary and slumberous overnight hours were nearly *2.5 times* as likely to kill as those during the daytime.

To assess the statistical significance of the propensity for daytime, evening, and overnight killer storm events, a logit regression (Hamilton 1992) is fit to all tornadoes occurring through the United States from 1950 to 2005. The dependent variable for this model is a binary scaling of each event as either a killer tornado (=1) or nonkiller (=0). As our purpose here is to document the significance of the differences in the likelihood of killer tornadoes occurring in evening or overnight periods, as opposed to daytime, the treatment variables in the model are binary classifications denoting evening (yes = 1, no = 0) and overnight occurrence. The function of a logit regression is to model the probability of one data type (nominal scaled) relative to another. In this case, the model captures the probability of a killer tornado incident relative to the tornado being a nonkiller. The slope parameter estimates in Table 2 confirm the above descriptive conclusions: A given tornado event is more likely to be a killer if it occurs in the evening period than if it occurred during daylight hours, and a given tornado is more likely to be a killer if it occurs during the overnight period than if it occurred during the daytime. Both slope parameters are statistically significant. With the covariance matrix for these parameters (not shown), we can also test whether the evening and overnight slope parameters differ. The results of that test, $t = -1.98$ and $\Pr(>|t|) = 0.048$, indicate that the likelihood of an overnight tornado being a killer event is indeed greater than the likelihood of an evening tornado being a killer.

TABLE 2. Parameter estimates from logit regression: Prob(killer tornado) = *f*(time of day).

	Parameter estimate	Standard error	*T* value	Pr(>|*t*|)
Intercept	−3.1711	0.0506	−62.60	0.0000
Evening	0.2894	0.0325	8.88	0.0000
Overnight	0.3897	0.0469	8.30	0.0000

Brooks and Doswell (2002) have illustrated the substantial decrease in the rate of tornado deaths per million persons (DPM)[2] in the United States since 1925 (Fig. 2). They revealed that death rates prior to 1925 hovered near 1.7 DPM. Since that time, the rates have decreased to, for example, 0.22 DPM during 1997–2006 decade. Although the normalized fatality trend is negative since 1925, the DPM rate due to nocturnal tornadoes has not benefited from the same rate of decrease as all tornado fatalities. The significance of the differ-

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[2] We employed the same U.S. Census data and followed a method of population extrapolation identical to that used by Brooks and Doswell (2002) to estimate U.S. population tallies over the period of record.

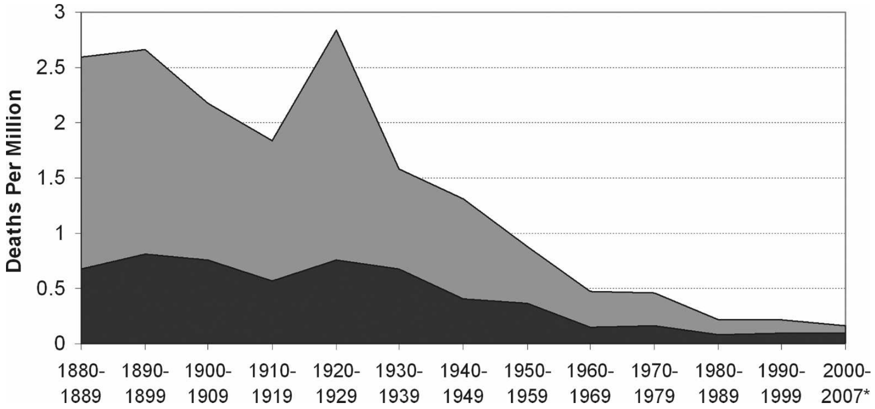

FIG. 2. Average decadal (except for the 2000–07 period; asterisk) tornado death rate for all (light gray) and nocturnal (dark gray) tornado records. The decadal values are based on the average of the 10 annual death rates (DPM yr^{-1}) for each corresponding decade.

ence between the rates at which DPM has decreased for nocturnal versus daytime tornadoes is documented by the regression shown in Table 3. To linearize the decadal plot of DPM after 1920, the DPM data are first rescaled by natural logarithms. The regression is a simple time trend model of the pooled day and night DPM data, with ln(DPM) as the outcome and decade as the predictor. A binary dummy variable differentiating night from day is added singularly to capture any difference between intercepts of the day and night trend lines, and as an interaction term with decade to capture differences in the slopes of these trends (Fig. 3).

Overall, the model is statistically significant ($F_{3,4} = 102$; $R^2 = 0.95$). However, the more important result is that both the intercept-shift and slope-shift terms are significantly different from zero. Taken individually, ln(DPM) changes at a rate of −0.0406 per decade for daylight tornadoes, while the rate of decrease per decade for nocturnal tornadoes is flatter by an amount equal to 0.0104. In other words, the rate of change in ln(DPM) per decade for nocturnal tornadoes is −0.0302 (=−0.0406 + 0.0104). That the intercept-shift and slope-shift parameters are significantly different from zero indicates that the decreasing trend of daytime tornado DPM from the 1920s to the present is fundamentally different than the decreasing trend of nocturnal tornado DPM over the same period.

The percentage of nocturnal fatalities and killer events per decade has increased since the 1925 era and, in fact, has increased greatly since 1960 (Fig. 4). The percentage of nocturnal tornadoes has decreased from 28.4% during the 1960s to 25.7% during 2000–05. Admittedly, it is difficult to identify if secular issues in the dataset (see Doswell 2007 for a discussion) are a cause for this decreasing trend. In comparison with the decreasing trend in nocturnal tornadoes, the percent of nocturnal fatalities (killer tornadoes) has *increased* from 32.4% (35.9%) during the 1960s to 63.0% (52.9%) from 2000 to 2007.

This increase in the percentage of nocturnal fatalities and killer events, coinciding with a decrease in the percentage of documented nocturnal tornadoes, illustrates a fundamental and increasing vulnerability due to nocturnal tornadoes in the United States, especially since the middle part of the twentieth century. Furthermore, this particular vulnerability, in combination with other primary vulnerabilities such as increasing mobile home stock (Brooks and Doswell 2002; Ashley 2007; Simmons and Sutter 2007) and expanding population (Hall and Ashley 2008), could lead to a hypothesized flattening and, more realistically, an increase in the fatality trend in the United States during the twenty-first century. In fact, this increase is likely taking place at present considering the fatality total during the most recent 10 yr on record, 1998–2007, is 11.1% higher than the 1978–87 tally and 48.0% higher than the 1988–97 sum. Although purely speculative, it is believed that without the improvements in tornado detection, tech-

TABLE 3. Linear regression of ln(DPM) against decade; differentiating day vs night occurrence.

	Parameter estimate	Standard error	*T* value	Pr(>|*t*|)
Intercept	78.6693	5.8478	13.4527	0.0000
Decade	−0.0406	0.0030	−13.6316	0.0000
Intercept shift (nocturnal)	−20.8987	8.2701	−2.5270	0.0242
Slope shift (nocturnal)	0.0104	0.0042	2.4728	0.0268

Model $R^2 = 0.9562$; $F_{3,14} = 102$; $\Pr(>F) = 0.0000$

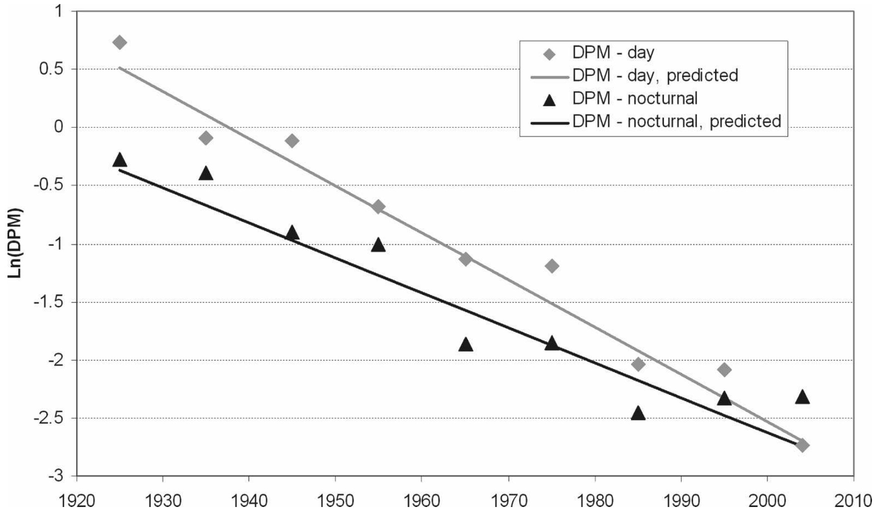

FIG. 3. Linearized plot of day and nocturnal DPM by decade, 1920–present, with fit regression lines.

nology, and warning operations and dissemination [see Doswell et al. (1999), Brooks and Doswell (2002), and Simmons and Sutter (2005a) for a discussion of these advances], this increasing trend would likely be more substantial.

Simmons and Sutter (2007, 2008) have illustrated that tornadoes during the late fall and winter (the so-called off season) are more dangerous, all else being equal, than tornadoes occurring in the late spring and summer. In their regression analysis, Simmons and Sutter (2008) found that expected fatalities are 15% lower for tornadoes from March to June. Simmons and Sutter (2007) suggest that the explanation for the above difference in expected seasonal fatality rates is because there is greater awareness by the public during the "national severe weather season," which spans, climatologically, the late spring and early summer. Such heightened awareness during this severe weather season is thought to lead to enhanced warning response and, all else being equal, a reduction in vulnerability. In addition, such reduced complacency by the public during this specific period has been discussed by Doswell (2003) as a possible reason for the discrepancy in vulnerability between Tornado Alley, where the tornado season and, therefore, risk is heightened across a relatively short window of time, and the South, which has a lower, yet constant, risk to tornadoes [see Brooks et al.'s (2003) Fig. 8 for examples].

We propose that the seasonality factor may be entwined with the nocturnal tornado issue. For example, the cool and spring transition season months of November–April have the highest nocturnal fatality rates (Fig. 5), despite having relatively few tornado events in comparison to the warm season and tornado climatological

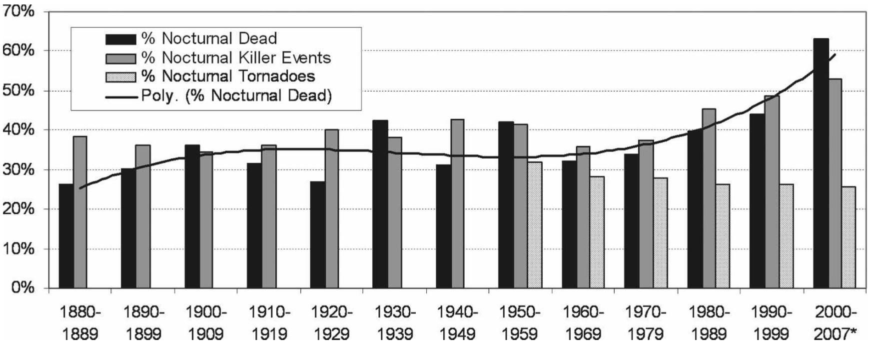

FIG. 4. Average decadal values of percent nocturnal tornado fatalities, percent nocturnal killer tornadoes, and percent nocturnal tornadoes. Asterisk in gray bars indicates 8-yr analysis for fatalities and killer events, and only 5 yr of analysis for the percent of nocturnal tornadoes. Third-order polynomial trend line is fit to the percent dead at night data.

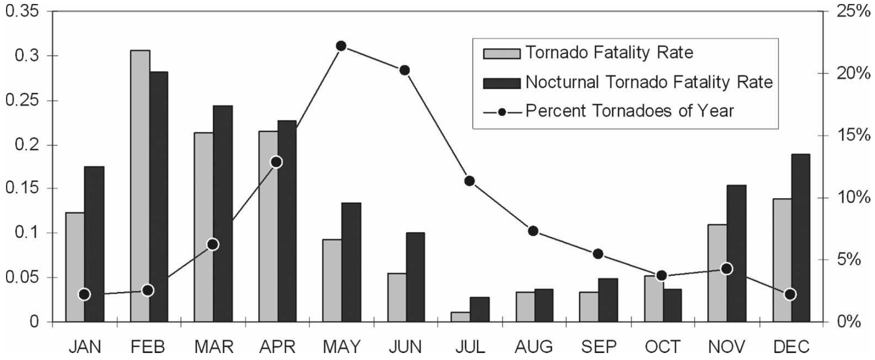

FIG. 5. Monthly percent of tornadoes during the year (line with circles), tornado fatality rate (light gray), and nocturnal tornado fatality rate (black) based on 1950–2005 data. The fatality rates are the number of fatalities for the period of interest divided by the number of tornadoes that occurred during that period. Left y-axis scale indicates fatality rates, while right y-axis scale indicates monthly percentage of tornadoes for the year.

peak months of May and June. Climatologically, tornadoes during this November–April period occur throughout the southern tier of the United States, from Texas, eastward through the Deep South and Florida (Brooks et al. 2003; NSSL 2008). As suggested by Ashley (2007), a potential significant reason for this area's high fatality rates in comparison to high-risk areas like Tornado Alley could be the prevalence of off-season, nocturnal tornadoes. This factor, combined with the forest cover, unique orography, and low cloud bases, make identifying tornadoes in this region especially difficult.

b. *Spatial analysis*

Examining the variety of nocturnal tornado proportions available in Table 4 illustrates the regional bias in vulnerability due to nocturnal events. For example, most of the top 15 states ranked by the percentage of

TABLE 4. Top 20 states ranked and sorted by greatest percentage of killer nocturnal (NT) tornado events from 1950 to 2005. This ranking of proportions only included states with a minimum of 10 killer events within individual state borders in order to remove small sample size effects on the percentages. Additional percentages, in no particular rank order, include nocturnal fatalities and tornadoes from 1950 to 2005 in the third and fourth columns, respectively, and nocturnal killer events and fatalities from 1880 to 2007 in the fifth and sixth columns, respectively.

	1950–2005	1950–2005	1950–2005	1880–2007	1880–2007
State	Killer NT events (%)	NT fatalities (%)	NT events (%)	Killer NT events (%)	NT fatalities (%)
NC	66.7	80.7	28.3	60.3	74.5
TN	61.4	77.9	45.8	60.2	70.2
LA	56.3	34.3	35.3	46.8	29.9
AR	52.4	37.2	42.5	48.4	45.4
SC	52.2	63.5	29.1	44.3	34.1
AL	50.0	46.3	36.1	52.7	46.0
KY	50.0	38.1	41.5	41.4	44.2
MS	47.9	34.6	39.6	51.5	43.0
FL	45.8	52.3	21.3	50.0	60.3
MO	45.3	53.2	36.3	42.2	18.4
OH	45.0	40.6	24.9	41.7	34.1
GA	42.4	46.2	33.3	44.7	36.7
TX	41.0	28.6	28.3	44.1	38.5
VA	40.0	20.0	20.9	29.2	21.5
IL	38.6	22.5	29.5	34.1	11.9
OK	37.0	38.1	36.7	39.5	28.9
IN	33.3	33.9	32.6	23.8	15.2
KS	32.4	43.0	24.9	36.3	41.0
NE	31.8	38.5	23.2	25.9	23.9
PA	31.8	19.5	23.2	20.8	10.1

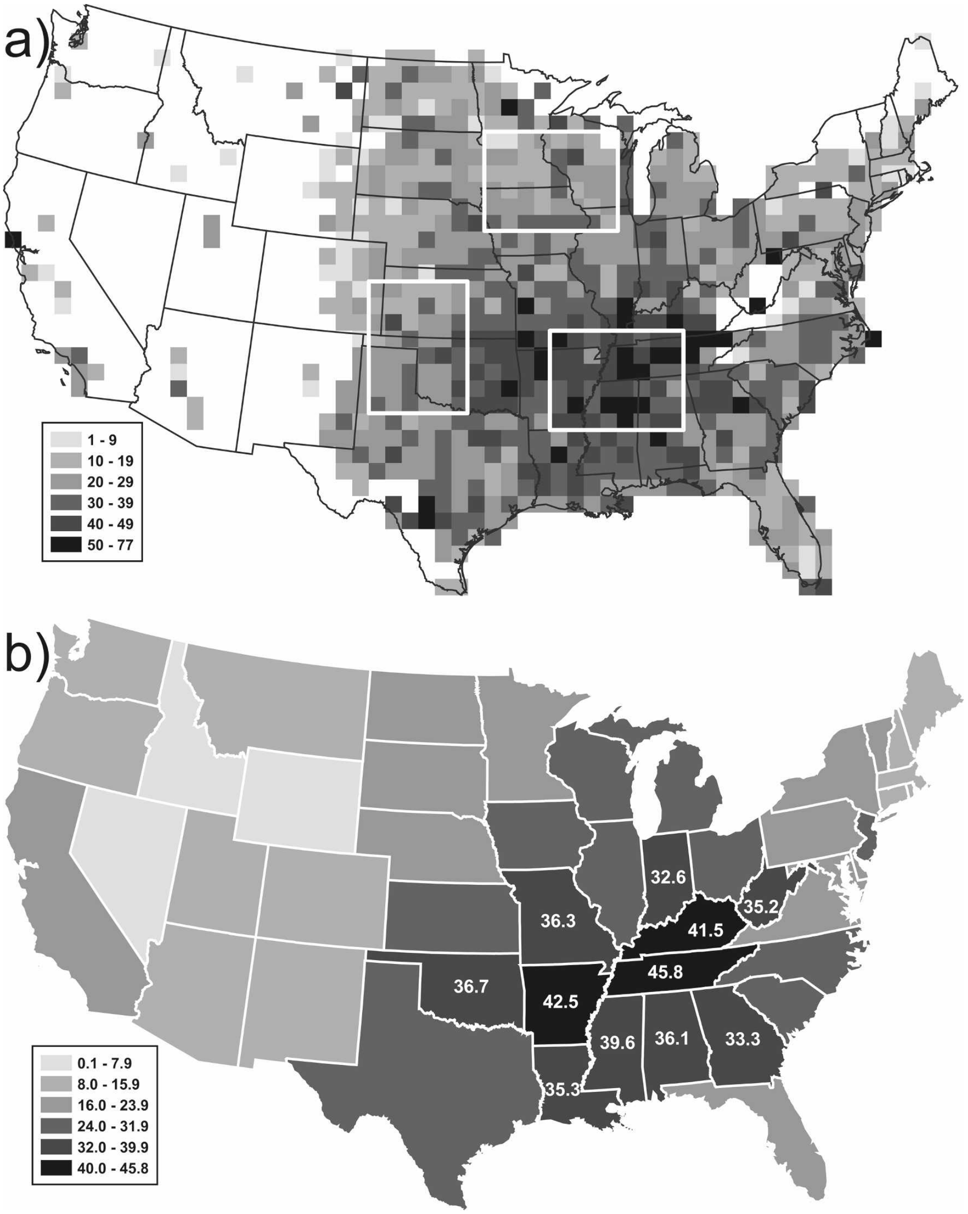

FIG. 6. (a) Percent of total tornadoes in an 80 km × 80 km grid cell from 1950 to 2005 that are nocturnal. Data are only displayed for grid cells with a minimum of 10 events occurring from 1950 to 2005. The panel includes three region-specific rectangles, each covering 48 grid cells. See text for explanation. (b) Percent of tornadoes that are nocturnal events by state. Only those states with greater ≥32% are labeled.

killer nocturnal tornado events are states in the Southeast. This regional vulnerability is not unexpected considering that most of the states in this southern region have some of the highest percentages of nocturnal tornadoes in the country (Fig. 6). In particular, the area of the American South, which contains the lower Arkansas, lower and mid-Mississippi, and Tennessee River valleys, has the highest percentages of nocturnal tornadoes (Fig. 6a), nocturnal fatalities (Fig. 7a), and number of nocturnal killer events (Fig. 7c) in comparison to all other regions of the United States. This area also has the highest *concentration* of percent killer events at night from 1880 to 2007 (Fig. 7d), revealing further this region-specific vulnerability. It is particularly interesting that these same geographic subregions were highlighted in Ashley (2007) as the most vulnerable in the United States, despite the greater risk for tornadoes (including significant events) in the southern and cen-

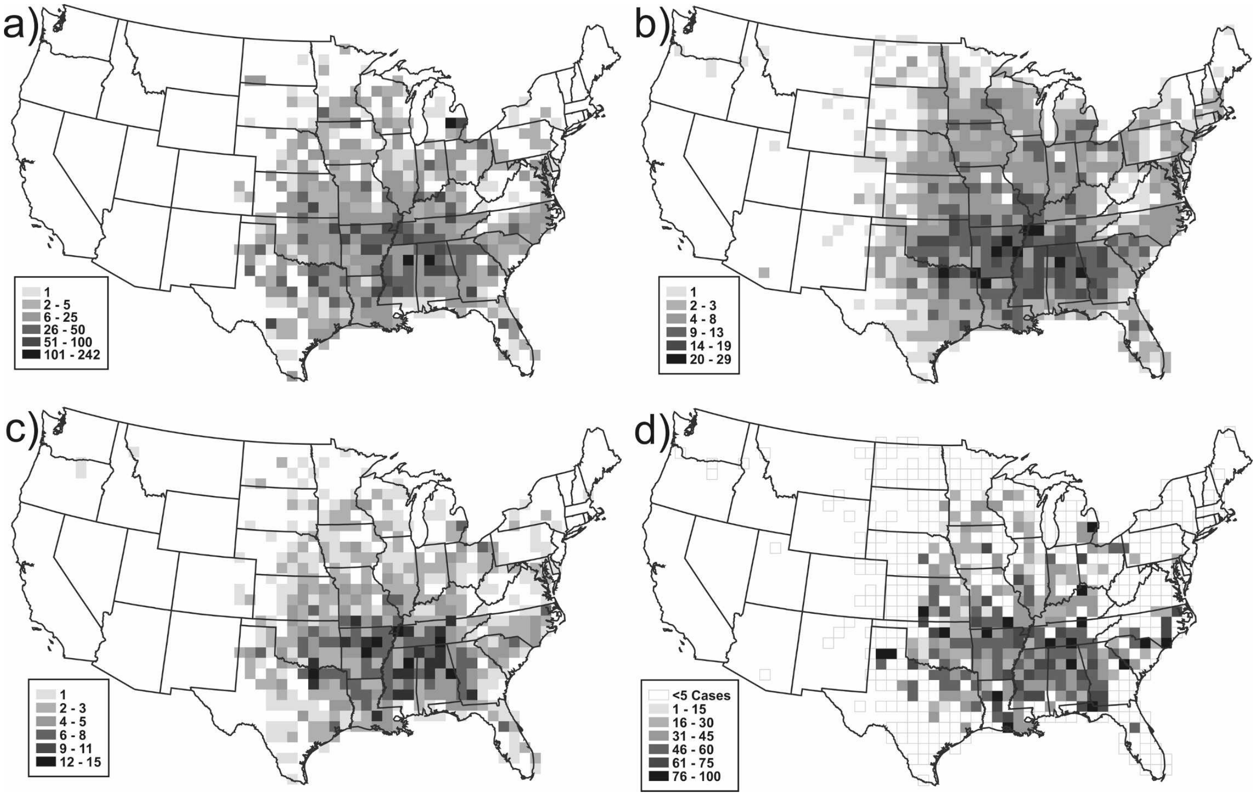

FIG. 7. Number of (a) nocturnal fatalities, (b) killer events, (c) nocturnal killer events, and (d) percent nocturnal killer events (in grid cells with greater than or equal to 10 fatalities during the period; an open cell indicates a grid cell that contained less than five killer events) from 1880 to 2007.

tral Great Plains—or Tornado Alley. Therefore, and as suggested by Ashley (2007), some of the enhanced vulnerability in the American South and lower relative vulnerability in Tornado Alley may be explained by differences in nocturnal tornado frequencies in these areas.

To test this hypothesis, we examined three separate areas represented by the rectangles placed across the existing 80 km × 80 km grid illustrated in Fig. 6a. Individually, these rectangles encompass 48 (or, 6 × 8) unique grid cells and are positioned in three specific areas that have a relatively high risk of tornadoes compared to the rest of the conterminous United States. Specifically, these three rectangular subregions epitomize 1) the American South, an area with the highest frequency of fatalities and killer tornado events (Ashley 2007); 2) the south-central plains, an area that is theoretically the center of Tornado Alley and contains the highest supercellular tornado frequencies in the United States and, arguably, in the world (Concannon et al. 2000; Brooks et al. 2003); and 3) the Upper Midwest, an area that theoretically may contain a mixture of risks and vulnerabilities found in the other two regions.

Nocturnal tornadoes account for 21.4% of all tornadoes across the grid cells in the Upper Midwest sample region, 26.6% of all tornadoes across the plains subregion, and 43.1% of tornadoes across the South subregion. While this certainly documents the greater vulnerability of the South to nocturnal tornado events, there is more to the story. The descriptive statistics for these three subregion samples are presented in Table 5. Notice that the variance within the Upper Midwest subregion is essentially equal to the variance within the plains subregion, but that the variance within the South subregion is significantly less. Since the spatial domain is of constant size across these three subregion samples, the coefficient of variation can be used as a measure of spatial variation. These data, therefore, show that not only is the expectation of a nocturnal tornado greater in

TABLE 5. Descriptive statistics of percent nocturnal tornadoes, by subregion. See text and Fig. 6 for regional illustrations.

	Midwest	Great Plains	South
Mean	0.2139	0.2662	0.4314
Variance	0.0068	0.0069	0.0055
Coef of variation	0.3876	0.3138	0.1722

TABLE 6. One-way ANOVA to test H0—there are no differences in mean percent nocturnal tornadoes by subregion. See text and Fig. 6 for regional illustrations.

ANOVA	Df	Sum of square	Mean square
Region	2	1.4332	0.7166
Error	140	1.1190	0.0079

Model $R^2 = 0.5615$; $F_{2,140} = 89.654$; $\Pr(>F) = 0.0000$

the South region as a whole, but that the expectation of a nocturnal tornado within the region is more uniform (less variable) than in the Upper Midwest and plains subregions.

The more important question is whether these differences in vulnerability are statistically significant. To test this, we employ a simple one-way analysis of variance (ANOVA; Hamilton 1992), with the percent nocturnal tornadoes as the outcome and region as the treatment. In cases where the dependent variable is measured as a percentage, or on a (0, 1) scale, it is common to rescale the data by the arcsin transformation. The results of this ANOVA are presented in Table 6. The model F is statistically significant at the 95% confidence level, meaning that there are significant differences by region. In these specific data, region explains only 56% of the variation in the dependent variable; the remaining 44% can be attributed directly to spatial variation within each subregion sample. Nevertheless, at least one of the differences in vulnerability to nocturnal tornadoes between regions is statistically significant. Figure 8 specifically identifies the mean and 95% confidence region about the mean for each of the subregions. As is clearly shown, the vulnerability of the South to nocturnal tornadoes is significantly different from both the Upper Midwest and plains. Less apparent is that the difference in vulnerability between the Midwest and plains subregions is also statistically significant.

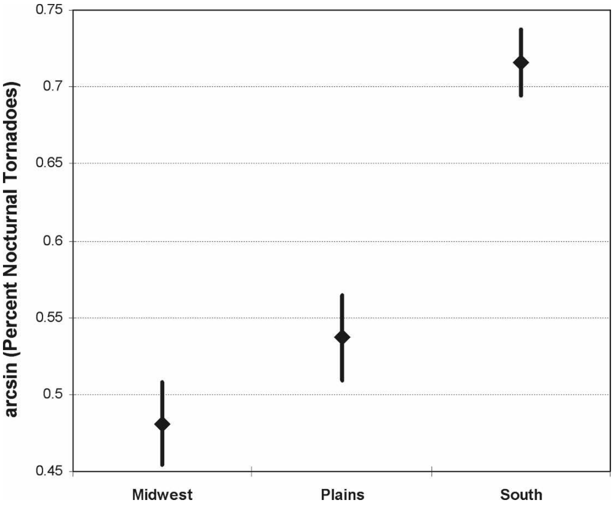

FIG. 8. Mean (diamonds) and 95% confidence region (vertical lines) for percent nocturnal tornadoes (arcsin transformation), by subregion. See text and Fig. 6 for regional illustrations.

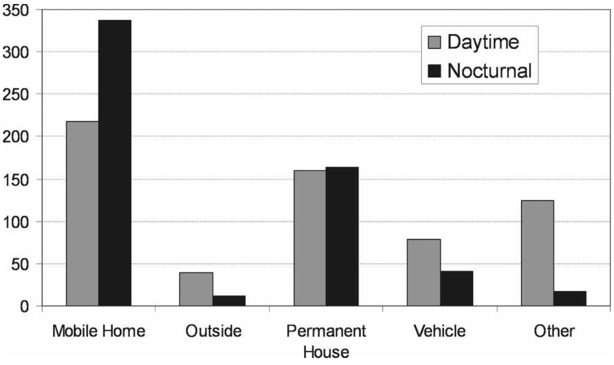

FIG. 9. Tornado fatalities by location of where the fatality occurred, subdivided by daytime or nocturnal incidence, for 1985–2005.

As Ashley (2007) illustrated, the American South has some of the highest mobile home stock in the nation, which tends to increase the vulnerability in this area. Examining the fatalities by location of occurrence during 1985–2007 reveals an interesting nocturnal division between housing fatality types (Fig. 9). Overall, mobile homes and permanent homes lead fatality location totals with 44.8% and 26.2% of all deaths occurring in these structures, respectively. Whereas fatalities occurring within permanent housing stock or other locations have similar, or even lower, percentages of nocturnal counts, more than 60.8% of mobile home fatalities occur at night. This division in the nocturnal vulnerability between fatality locations reveals further the heightened threat to persons in mobile homes during tornadoes. Furthermore, 55.2% of nocturnal mobile home fatalities during this period occurred in just the five southern states of Arkansas, Mississippi, Alabama, Georgia, and Florida.

4. Discussion and conclusions

This study investigated a single physical risk—nocturnal tornadoes—in order to improve our understanding of the human vulnerability to nature's most intense windstorm. Of the nearly 19 000 tornado fatalities that have occurred since 1880, approximately 34% of those fatalities took place between sunset and sunrise. However, the proportion of nocturnal fatalities and killer tornado events has increased during the last half century. Nocturnal tornadoes appear to be a principal reason for enhancing human vulnerability to this particular atmospheric hazard since these nocturnal events are difficult to spot and are more likely to impact weak building structure types that tend to be occupied at night. Furthermore, a breakdown in warning dissemination appears to coincide with the overnight hours as most people are asleep during this period and fail to receive critical warning information (Paul et al. 2003; Simmons and Sutter 2007). A multitude of factors discussed elsewhere (Doswell et al. 1999; Brooks and Doswell 2002; Simmons and Sutter 2005a) has led to a decrease in the tornado fatality rate in the United States since the 1920s. However, our results indicate that this rate of decline is not as substantial as it could have been due to a continued and growing vulnerability attributable, at least in part, to nocturnal events. Our analysis confirms this vulnerability, as nocturnal (overnight) tornadoes are 2 (2.5) times as likely to kill as those events occurring during the daytime. Unfortunately, this nocturnal fatality rate appears to be a major factor for the stalled decline in national tornado fatality tallies during the past few decades.

In addition, nocturnal tornado vulnerability is not distributed uniformly across the United States. Instead, the American South is at a much greater risk to nocturnal events and therefore receives an enhanced vulnerability that may be leading to the significant fatality totals found in this region (see Ashley 2007). Conversely, tornadoes in the Upper Midwest and Tornado Alley have a greater propensity to occur during the warm season when daylength is at a maximum. These areas tend to have more events occurring during the daytime in comparison to the South, which allows for more successful—as illustrated by lower fatalities tallies, despite higher risk—warning activities used to mitigate against events in these regions.

This analysis has supplied a single piece to the complex puzzle required to successfully unmask and mitigate human tornado vulnerability. Beyond further investigations into the physical risks of these types of events, additional social science–oriented studies employing qualitative analysis techniques [e.g., survey-based research such as Hayden et al. (2007), which examined sources of flood warning information in Austin, Texas, and Denver, Colorado, and Zhang et al. (2007), which examined perceptions and responses to Hurricane Rita forecasts] are required to afford a window into the public's mind during these hazardous situations. For example, just how many people own a NOAA All Hazards Weather Radio and utilize this system as a primary deterrent for nocturnal tornado events? If awoken during a severe storm situation, where do people most often go for immediate weather information and what sort of action do people take once they hear warning information (e.g., take shelter or run outside)? Do people expect existing siren systems to awaken them while they are asleep in their homes during short-fuse tornado warning situations? Such questions could not only provide a foundation for a benefit–cost analysis of existing warning systems such as the All Hazards Weather Radio program, but could also impart a strategy for implementing new and improved warning dissemination and mitigation systems. After all, what good are monetary investments in new technologies and research investments into new dynamical and physical understandings of severe storms if the methods used to deliver the life-saving knowledge garnered from such technologies and research are broken? This is obviously a serious, complex, and—no doubt—contentious policy question that cannot be solely answered by us or the meteorological community [see Doswell and Brooks (1998) for a similar and somewhat parallel discussion on the lack of a true understanding of the value of NWS products and services]. However, we must begin to stare down these questions and not sidestep them with the assumption that "technology" will deliver complete and successful mitigation against these events in the future.

In conclusion, nocturnal tornadoes, in addition to other variables such as increasing mobile home stock, expanding populations, and a growing elderly population, appear to be culminating to produce an overall enhancement in tornado vulnerability in the United States. This enhancement is hypothesized to manifest itself in an escalating annual death toll from tornadoes. An analysis of the most recent 30 yr of the period of record indicates that despite the rapid growth in our knowledge and detection technologies, the decreasing annual fatality toll may have bottomed out and is likely increasing. Fortunately, with the aforementioned improvements in forecasting techniques and detection technologies, we have kept the tallies from rising rapidly. How long this improved technology and increase in knowledge will outweigh the negative impacts of population growth and dispersion as well as a continued breakdown of some warning dissemination methods is up for debate.

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