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VULNERABILITY DUE TO NOCTURNAL TORNADOES

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1. INTRODUCTION

Nocturnal tornadoes appear to be particularly hazardous to humans as evidenced by recent killer tornadoes and tornado outbreaks. Nocturnal events are thought to 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. In addition, the public has a tendency to be in more vulnerable housing and building structures during the night in comparison to safer locations during the day. 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.

Previous studies (Simmons and Sutter 2005, 2008) have investigated the issue of nighttime tornadoes and human vulnerability; however, these studies have employed arbitrary time range delineations for what constitutes "day" versus "night." Ignoring geographic and seasonal variation in sunset and sunrise times and length of the local nocturnal period can lead to inaccurate analyses. For example, the length of the nocturnal period over the course of the year can change 4.5 hours in Tupelo and nearly 6 hours 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, whilst 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, 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 what extent these events contribute to the tornado vulnerability of the U.S. population.

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2. DATA AND METHODOLOGY

This study utilized several unique resources to acquire historical tornado event and fatality data, including: *Storm Data*, NCDC's Storm Event Database, a long-term study of U.S. tornadoes by Grazulis (1993, 1997), and the historical archives of event and fatality data provided by the SPC.

All times in the constructed databases were converted to LST in order to remove 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 (1999). Since visibility drops dramatically 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. Twilight was not used in 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, the simple "day" versus "night" demarcation for tornado events in this study was based solely on the above solar calculations of sunset and sunrise.

3. RESULTS

3.1 *Temporal analysis*

From 1880-2007, there were a total of 18,864 recorded tornado fatalities and 3,650 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 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 1950-2005, was employed for the latter period of record to illustrate differences between all tornado cases and those specific events that killed persons.

From 1950-2005, a *recorded* 48,165 tornadoes occurred throughout the U.S.; 143 of these events are subsequently removed from the analysis because they contained no location information or were in U.S.

territories and states (Alaska and Hawaii) outside of the scope of this analysis. During this period, only 27.3% of tornado events were nocturnal. It is hypothesized that the reporting efficiency for nocturnal tornadoes may be lower than daytime events, which would lead to larger undercounts for the nocturnal period. However, the author has no competing dataset to provide the evidence necessary to support the hypothesis. In comparison to the nocturnal tornado event percentage, 39.3% of tornado fatalities and 42.1% of killer tornadoes from 1950-2005 took place during the night. Results from a Two-sample Difference of Proportion Test (99% CI) 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 (2005), 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 1950-2005 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% CI. Thus, tornadoes at night are almost twice as likely to kill as those during the daytime.

Simmons and Sutter (2005) used three time of day delineations, including "day," "evening," and "overnight", in their investigations of tornado vulnerabilities. This study examines the vulnerability of similar time periods, while also employing specific sunset-sunrise information in all calculations rather than arbitrary temporal designations. Thus, the three time delineations in this study 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). To what degree the public uses the All Hazards Weather Radio in their place of residence for nocturnal warnings is unknown; but the author feels prudent with the assumption that it is more than likely less than 5% of the covered population.

Overall, only 9.3% (12.7%) of fatalities (killer events) occurred during the overnight period from 1950-2005, 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 (Figure 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 daytime 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 1950-2005 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.

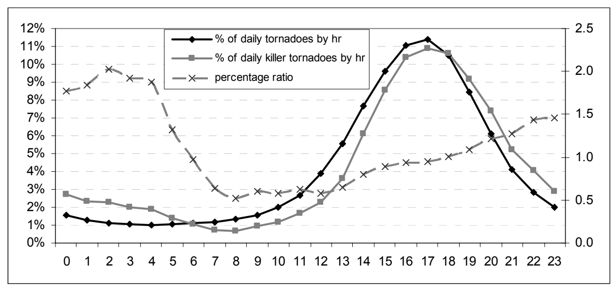

Figure 1. Three-hour running mean of the percent of tornadoes by hourly distribution (LST) of occurrence for a) all tornadoes (black; diamonds) and b) killer tornadoes (gray; squares) by hour. Percentages are based on the total number of events or killer events over a day for the period 1950-2005. The 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.

Brooks and Doswell (2002) have illustrated the substantial decrease in the rate of tornado deaths per million persons (DPM) in the U.S. since 1925. They revealed that death rates prior to 1925 hovered near 1.7 DPM. Since that time, 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 (not shown) has not benefited from the same rate of decrease as all tornado fatalities.

The percentage of nocturnal fatalities and killer events per decade has increased since the 1925 era and, in fact, has increased greatly since 1960 (Figure 2). 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 2000-07.

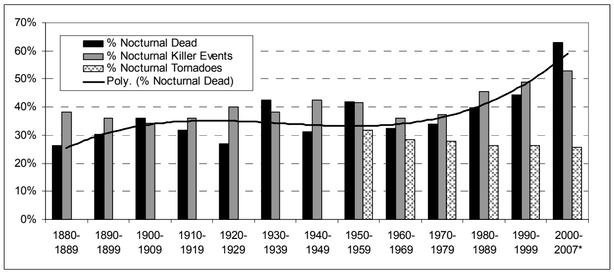

Figure 2. Average decadal values of percent nocturnal tornado fatalities, percent nocturnal killer tornadoes, and the percent nocturnal tornadoes. Asterisk indicates eight year analysis for fatalities and killer events, and only five years of analysis for the percent of nocturnal tornadoes. Third-order polynomial trend line is fit to the percent dead at night data.

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 U.S., especially since the mid part of 20th 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 U.S. during the 21st Century. In fact, this increase is likely taking place at present considering the fatality total during the most recent ten years on record – 1998-2007 – is 11.1% higher than the 1978-1987 tally and 48.0% higher than the 1988-1997 sum.

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-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.

This research suggests that the seasonality factor maybe entwined with the nocturnal tornado issue. For example, the cold- and spring-transitions season months of November-April have the highest nocturnal fatality rates (Figure 3), despite having relatively few tornado events in comparison to the warm-season and tornado climatological peak months of May and June. Climatologically, tornadoes during this November-April period occur throughout the southern-tier of the U.S., from Texas, eastward through the Deep South and Florida (Brooks et al. 2003). 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.

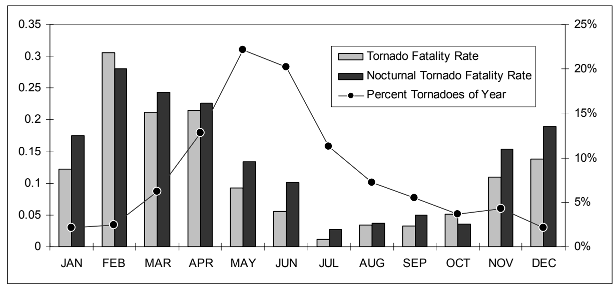

Figure 3. Monthly percent of tornadoes during the year (line with circles), tornado fatality rate (light gray), and nocturnal tornado fatality rate (dark gray) based on 1950-2005 data. The fatality rates are the number of fatalities for the period of interest divided by the number of tornadoes that occurred during that period. Left y-axis scale indicates fatality rates, while right y-axis scale indicates monthly percentage of tornadoes for the year.

3.2 *Spatial analysis*

Most of the top 15 states ranked by percentage of killer nocturnal tornado events (not shown) 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 (Figure 4). 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 (Figure 4.a), nocturnal fatalities (Figure 5.a), and number of nocturnal killer events (Figure 5.c) in comparison to all other regions of the U.S. This area also has the highest concentration of percent killer events at night from 1880-2007 (Figure 5.d), 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 U.S., despite the greater risk for tornadoes (including significant events) in the southern and central 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, three separate areas represented by the rectangles placed across the

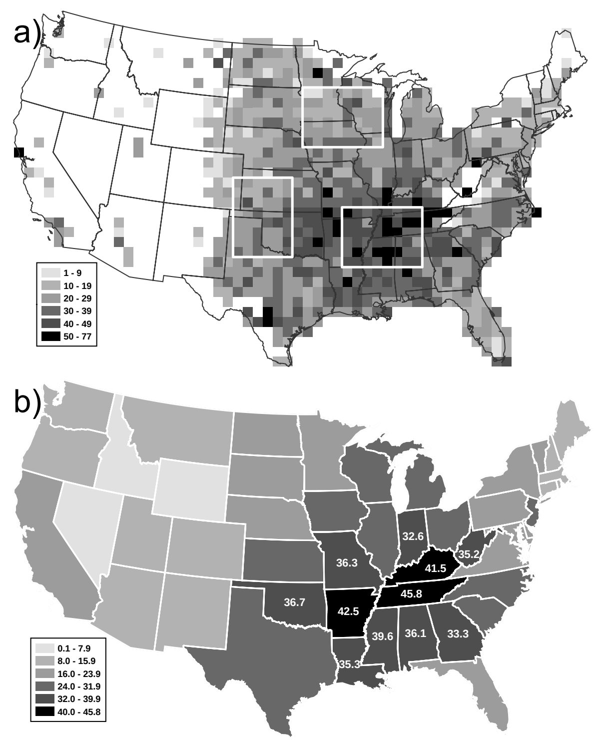

Figure 4. a) Percent of total tornadoes in 80 km x 80km grid cell from 1950-2005 that are nocturnal. Data are only displayed for grid cells with a minimum of 10 events occurring from 1950-2005. The panel includes three region-specific rectangles, each covering 48 grid cells. See text for explanation. b) Percent of tornadoes that are nocturnal events by state. Only those states with greater ≥ 32% are labeled.

existing 80 km x 80 km grid illustrated in Figure 4.a were examined. Individually, these rectangles encompass 48 (or, 6 x 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 U.S. Specifically, these three rectangular subregions epitomize: 1) the American South, an area with the highest frequency of fatalities and killer tornado events; 2) south-central Plains, an area that is theoretically the center of Tornado Alley and contains the highest supercellular tornado frequencies in the U.S. and, arguably, in the world; 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 1. Notice that 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 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.

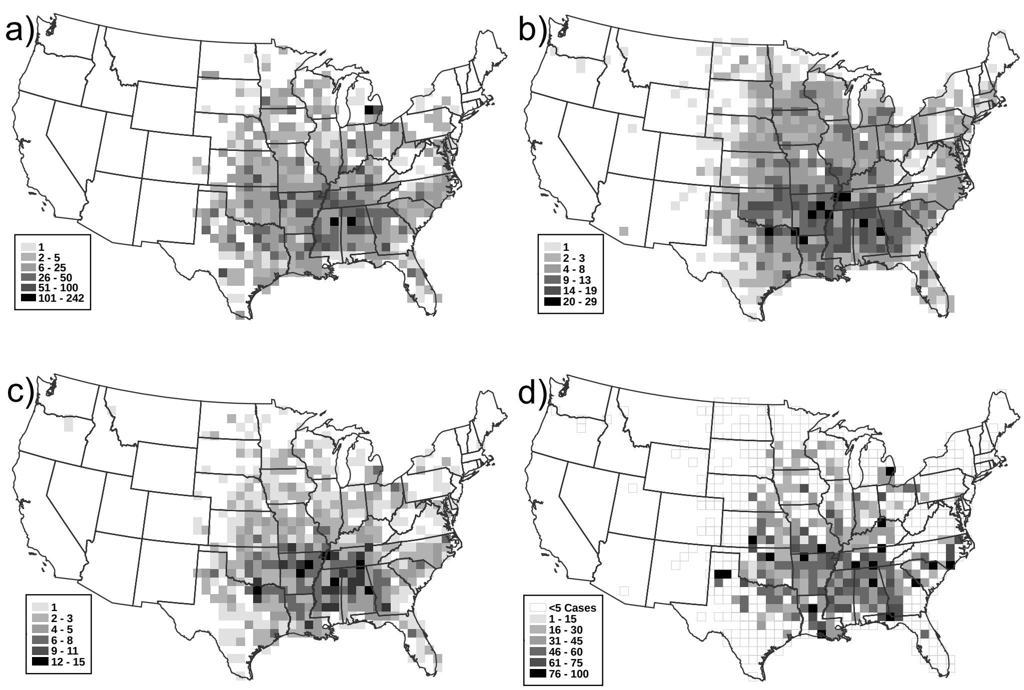

Figure 5. Number of a) nocturnal fatalities, b) killer events, c) nocturnal killer events, and d) percent nocturnal killer events (in grid cell with greater than or equal 10 fatalities during the period; hollow cell indicates a grid cell that contained less than 5 killer events) from 1880-2007.

Table 1. Descriptive statistics of percent nocturnal tornadoes, by subregion. See text and Figure 4 for regional illustrations.

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

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 (Figure 6). 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.

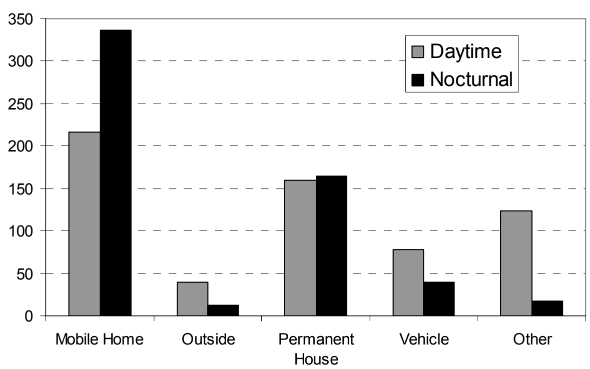

Figure 6. Tornado fatalities by location of where the fatality occurred, subdivided by daytime or nocturnal incidence, for 1985-2005.

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. A multitude of factors discussed elsewhere (Doswell et al. 1999, Brooks and Doswell 2002, Simmons and Sutter 2005) has led to a decrease in the tornado fatality rate in the U.S. since the 1920s. However, results from this research 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. This analysis confirms this vulnerability, as nocturnal (overnight) tornadoes are two (two and a half) 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 U.S. 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. 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 are required to afford a window into the public's mind during these hazardous situations. For example, just how many people own an All Hazards 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 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 the author 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 U.S. This enhancement is hypothesized to manifest itself in an escalating annual death toll from tornadoes. An analysis of the most recent 30 years 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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