A REASSESSMENT OF U.S. LIGHTNING MORTALITY

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Using a comprehensive lightning mortality dataset, this research provides a reassessment of the risks and vulnerabilities that produce fatal lightning events and further illustrates the deficiencies of current post–hazard event data-gathering methods.

The National Weather Service (NWS) issues specific watches and warnings for mitigating a variety of storm perils—except lightning. In fact, the NWS does not issue watches or warnings for lightning, no matter how intense the flash rate is within thunderstorms.[1] Yet, lightning kills more people than tornadoes, hurricanes, or high winds on average each year in the United States (Holle and López 1998; Curran et al. 2000; Rakov and Uman 2003). In comparison to all thunderstorm-related phenomena, only floods have more average annual fatalities than lightning (Curran et al. 2000; Rakov and Uman 2003; Ashley and Ashley 2008). Unique to the lightning hazard, deadly events are caused by a single lightning stroke, which may last only a few tens of microseconds—even a thunderstorm with little lightning can produce a fatality (e.g., Hodanish et al. 2004). This is different from the other phenomena, which are ▶

[1] We are not advocating the development of an official NWS warning specific to lightning. We also should state that the NWS does issue products related to the lightning threat, including nowcasts, Hazardous Weather Outlooks, and Public Information Statements.

Multiple cloud-to-ground and cloud-to-cloud lightning strokes observed during a night-time thunderstorm. [Photo: C. Clark, NOAA Photo Library, NOAA Central Library; OAR/ERL/National Severe Storms Laboratory (NSSL)]

considerably larger in time and space and therefore require more ingredients for their occurrence.

A number of studies have examined lightning as a hazard [see Rakov and Uman's (2003) chapter 19 for an overview], but these investigations have tended to aggregate data at the state or regional scale and/or have limited their analyses to broad generalizations without specific regard to geography (e.g., López and Holle 1996, 1998; Curran et al. 2000; Holle et al. 2005). Other studies have focused on single killer lightning cases in an attempt to illustrate that some deadly events can occur in improbable meteorological settings (e.g., Cherington et al. 1997; Holle et al. 1997; Hodanish et al. 2004). Furthermore, the medical community over the past two decades has produced a number of epidemiological studies examining the distinctive and unfortunate effects of lightning on the body (e.g., Duclos and Sanderson 1990; Cooper et al. 2001).

We seek to reassess and update the findings from contemporary literature on lightning mortality by first investigating the strengths and deficiencies of existing fatality data sources that were employed by these prior studies. Unlike previous studies that have restricted their U.S. lightning mortality analyses to a single source of data, the dataset compiled and employed in this study includes information from three separate resources including the National Climate Data Center's (NCDC's) *Storm Data, LexisNexis,* and the Center for Disease Control and Prevention's (CDC's) National Center for Health Statistics (NCHS) Multiple Cause-of-Death Mortality Data from the National Vital Statistics System (hereafter called the CDC mortality dataset). The method of combining data from a variety of sources illustrates a deficiency in current official weather-related casualty reporting procedures in the United States. In addition, the compiled dataset is mapped at much greater resolution than previous investigations, which aids in discovering the true geographical distribution of lightning vulnerability[2] patterns in the United States Revealing these unique clusters will allow us to concentrate our mitigation efforts in areas that are most prone to lightning fatalities.

Next, we hypothesize that people do not perceive lightning as a killer threat in the same manner as events such as hurricanes and tornadoes because lightning is essentially an unwarned storm peril and is much more common and familiar to the average human than these other, more severe, weather phenomena. To begin to explain this disconnect in the perception of lightning as a hazard, NWS warning data are compared with lightning fatality locations for the 11-yr period of 1994–2004. This analysis provides evidence for the subsequent section of this study, which suggests that lightning fatalities often occur in nonsevere and therefore unwarned storms. To assess this hypothesis, the study evaluates and classifies the storm morphology of killer lightning events during the latter part of the period of record.

We do not seek to replicate previous studies that have provided thorough analyses of lightning casualties in the United States; instead, we plan to update the data by expanding the period of record and providing additional information sources, reassessing the distribution of lightning-induced fatalities using greater spatial precision, and beginning to uncover the link between storm morphology, existing severe storm warnings, and human vulnerability in lightning situations. Ultimately, the results will enable meteorologists and the hazards community to formulate a better understanding of lightning-related hazards. Equipped with this information, these groups can act to reduce thunderstorm hazards and their impacts in the United States.

DATA AND METHODOLOGY. One of the primary foci of this research is to examine the completeness of fatality tallies often reported via various agencies (e.g., NWS's hazstats; online at www.nws.noaa.gov/om/hazstats.shtml). To this extent, we gathered U.S. lightning mortality data from a variety of publications and resources. We limited our analyses to the conterminous United States since no documented fatalities occurred in Alaska or Hawaii. Our first source of data, as with a majority of previous lightning mortality studies, was *Storm Data*. Since 1959, *Storm Data* has been the chief source of information used by atmospheric and hazard scientists

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[2] Following the definitions espoused by Cutter et al. (2003), risk is the likelihood of a hazard occurring, whereas vulnerability is the potential for loss from that hazard.

for locating areas of storm damage and determining the number of casualties produced by hazardous weather events. A number of lightning casualty studies, especially those with long temporal periods of record (e.g., López et al. 1993; López and Holle 1996; Shearman and Ojala 1999; Curran et al. 2000), have based analyses of lightning morbidity and mortality on *Storm Data* (Table 1). Curran et al. (2000) have provided a thorough overview of this resource and how it may be used to assess lightning casualties and damage in the United States. In addition, López et al. (1993) have illustrated, in a case study of Colorado, how the "flow of casualty information" transpires during reporting procedures from the onset of the lightning hazard, to newspaper reports, to official cataloging in *Storm Data*.

In constructing our dataset, we first employed the NCDC's "Lightning Archive" (DSI-9617), which contains a chronological listing of lightning hazard statistics, including fatalities from 1959 to 2003, compiled from *Storm Data*. Utilizing the system for online data access via NCDC, monthly *Storm Data* publications (NCDC 1959–2006) as well as the Storm Event Database (available online at http://www4.ncdc.noaa.gov/cgi-win/wwcgi.dll?wwEvent~Storms) were assessed for lightning mortality data.

Next, we used the online services of *LexisNexis Academic,* which provides access to over 6,000 historical news sources including national and regional newspapers, wire services, and broadcast transcripts. This service was employed during the latter period of record (1995–2006) to search for (using a variety of keyword strings such as "lightning death") and then catalog any unreported lightning-related fatalities not found in *Storm Data*.

Subsequently, the CDC NCHS's electronic record of death identification was accessed (C. Rothwell 2007, personal communication) to determine its completeness and supplement the information attained from *Storm Data* and *LexisNexis*. Readers are asked to consult Dixon et al. (2005), who provided a thorough overview of the CDC mortality data and its comparison with *Storm Data*. The CDC mortality data, which were examined for the period of 1977–2004, contain a complete listing of all U.S. deaths categorized as to the "underlying" mortality cause based on the victim's death certificate and the International Classification of Disease (ICD). Shearman and Ojala (1999) discussed how the ICD coding system produces some ambiguities in mortality and morbidity causes, which may lead to an undercounting of lightning casualties in these data.

Finally, we acquired a listing of recent (2005/06) lightning-induced fatalities compiled by J. Jensenius (2008, personal communication). This listing included a small number of fatalities that we did not

Table 1. Contemporary research on U.S. lightning mortality.

Study	Period of record	Area of focus	Data sources
Zegel (1967)	1959–65	U.S.	*Storm Data*
Mogil et al. (1977)	1968–76	TX	*Storm Data*
Duclos et al. (1990)	1978–87	FL	FL Department of Vital Statistics (death certificates), medical examiners' reports, *Storm Data*
Ferrett and Ojala (1992)	1959–87	MI	*Storm Data*
López et al. (1993)	1980–91	CO	*Storm Data,* CO Health Department death certificates, and CO Hospital Association discharge records
Cherington and Mathys (1995)	1963–89	U.S.	National Transportation Safety Board
López et al. (1995)	1950–91	CO	*Storm Data*
López and Holle (1996)	1959–90	U.S.	*Storm Data*
López and Holle (1998)	1900–91	U.S.	Bureau of Census *Mortality Statistics* and *Vital Statistics of the United States*
Shearman and Ojala (1999)	1978–94	MI	*Storm Data* and MI Department of Public Health death certificates
Cherington et al. (1999)	1989–95	CO	Newspapers
Curran et al. (2000)	1959–94	U.S.	*Storm Data*
Adekoya and Nolte (2005)	1995–2002	U.S.	CDC mortality data and Census of Fatal Occupational Injuries
Richey et al. (2007)	1995–2004	FL	*Storm Data,* Florida Department of Health Office of Vital Statistics, struckbylightning.org

identify through *Storm Data* or *LexisNexis* (CDC data were not available for 2005/06 and therefore could not be used for comparison purposes during these latter years).

We restricted our analysis to cases in which lightning was the primary—or "underlying"[3] as stated by the CDC documentation—cause of the fatality and removed cases in which lightning was a possible secondary cause of mortality (i.e., so-called "nature of injury" in the CDC mortality data coding). This restriction may lead to some underestimation in tallies since there may be unique fatality cases that were instigated by lightning but were not the primary cause of death [e.g., a struck tree felled, landing on person; a motorcycle driver killed after driving into felled tree; or an elderly person could not escape a house fire started by lightning and died of smoke inhalation; see López et al. (1993) and Shearman and Ojala (1999) for additional examples]. We also removed from consideration a lightning-induced plane crash (a Pan-American Boeing 707) that killed 81 persons in Maryland in 1963. These exclusions produce an accurate basis for comparing datasets.

All of the aforementioned datasets were meticulously compared and cross correlated to compile a master list of the thousands of lightning-related fatalities that have occurred in the United States since 1959. Despite the detailed intercomparison and merging of data sources, it is probable that our dataset fails to include all cases of lightning-induced mortality in the United States. To create a truly complete dataset would require 1) the assumption that all fatalities primarily caused by lightning were coded correctly in the data resources used and 2) the laborious and likely unfeasible task of examining death certificates and other mortality data for all municipalities, counties, and states in the United States that maintain those records—something that is more manageable, albeit still difficult, on the state level (see López et al. 1993; Shearman and Ojala 1999; Richey et al. 2007).

We focus on fatalities in this study because the classification of a death is unwavering (in comparison to injuries) and because damage tallies are almost exclusively based on estimates, which leads to large issues with data reliability (e.g., Gall et al. 2009). It could be argued that if fatalities, likely the single most important number conveyed in a post–hazard event situation, are not accurately reported and recorded, then other hazard assessment vectors such as injuries and damage tallies should be assessed with even greater caution.

As in recent atmospheric hazard fatality research (e.g., Ashley 2007), we gathered explicit spatial (i.e., latitude and longitude) information of fatalities from the variety of lightning sources described above. In most cases, the datasets included a report of the municipality closest to where the death occurred; although there are some cases in which only a county (or parish) name was provided. If municipality data were not provided, the county seat for the death in question was used to obtain surrogate geographic coordinates of the fatality location. Unfortunately, fatalities from the CDC mortality data do not include municipality location information of where the fatality occurred and in some cases do not contain county (or parish) data due to privacy concerns. Therefore, fatalities found solely in the CDC datasets that do not include county information were not mapped in our results and are instead listed by state. An additional issue that may contaminate or lead to some spatial inaccuracy occurs when a place of death is improperly assigned (e.g., a person was struck by lightning in one county and was transported to a regional hospital in a nearby county where the death was cataloged in a medical examiner report as the admitting hospital's county). These data issues appear more likely to occur in the CDC dataset and are controlled for by examining the textual descriptions that accompany *Storm Data* and *LexisNexis* newspaper articles. Otherwise, if a backup data source was not used to confirm the fatality location, we employed the place of death as documented by the source.

County-level severe thunderstorm and tornado warning data have been acquired from the National Oceanic and Atmospheric Administration (NOAA; B. MacAloney 2007, personal communication); these data include the corresponding warning type, county, date, begin time, end time, and issuing weather forecast office. Each case in the lightning fatality database from 1994 to 2004 was compared with the warning data to determine whether there was a severe thunderstorm or tornado warning issued for that county at or near the time of death. Finally, an extensive set of archived radar data were acquired from the NCDC's online Hierarchical Data Storage System (HDSS) for the period of 1998–2006 (this period was chosen because of the lack of comprehensive archived radar data required for analysis prior to this time). These Weather

[3] According to the World Health Organization (www.who.int/healthinfo/statistics/mortdata/en), the underlying cause of death is "the disease or injury which initiated the train of morbid events leading directly to death, or the circumstances of the accident or violence which produced the fatal injury."

Surveillance Radar-1988 Doppler (WSR-88D) Next Generation Weather Radar (NEXRAD) level III data were examined in order to investigate the morphology and organization of parent thunderstorms associated with fatal lightning events.

RESULTS AND DISCUSSION. *Differences in lightning mortality data.* Several investigations (Table 1; see studies with multiple data sources) have illustrated that *Storm Data* may have a number of shortcomings in its lightning fatality tallies due to possible undercounts. Curran et al. (2000) summarized the possible reasons for underreporting in *Storm Data,* including factors such as the following: 1) the NWS's reliance on media and newspaper clipping services for reports, which may or may not include all events; 2) the media and clipping services application has not been standardized, leading to inequalities in its usage by NWS offices during the history of *Storm Data;* 3) lightning events typically involve an individual or a small number of persons, making them less likely to be reported in comparison to other high-impact hazard events such as tornadoes and hurricanes; and 4) medical examiners and doctors may sometimes list lightning as a secondary cause of death, rather than the primary cause.

Lightning is not the only atmospheric hazard that has been illustrated recently as having differences in mortality data tallies. Dixon et al. (2005) revealed significant discrepancies in excessive heat and cold exposure-related mortality data compiled in *Storm Data* versus the CDC's mortality datasets. The study found that the CDC's mortality database was, in general, a more robust database than *Storm Data* since it is more likely to include hazards that produce low numbers of fatalities—like lightning. As an example of a single issue when intercomparing datasets, CDC data have no narrative text and often exclude specific date, time, location, and detailed circumstance of injury information of fatalities, whereas *Storm Data* often provides these types of data in addition to summary descriptions of a hazard event.

Consequently, before we begin reassessing lightning fatality distributions and vulnerabilities, we believe it is imperative to take a step back and look at the overall validity of the U.S. weather-related casualty datasets by using lightning as a proxy for gauging this (in)accuracy. That is, how accurate are lightning fatality data and have any of the documented deficiencies in *Storm Data* been removed since their acknowledgement in the aforementioned studies?

Annual fatality counts for the period of analysis, as well as their comparisons, are provided in Table 2. The variation in counts across the multitude of datasets and published works illustrates the unfortunate complexity required to obtain a best estimate of the number of lightning fatalities in the United States. Even with the various resources used in this study, it is unlikely that we can provide a perfect and accurate assessment. For example, tallies obtained from *Storm Data* for the period of 1959–2006 suggest that 3,645 lightning deaths occurred, or 75.9 fatalities, on average, per year. If we combine the resources of *Storm Data,* CDC, and *LexisNexis* for the period, there were 4,408 lightning fatalities reported from 1959 to 2006, an average of 91.8 deaths per year. However, we also assess the "best estimate" for the available data, which assumes the highest value from the aforementioned datasets and published manuscripts (see Table 2 for description). In this more likely case, there were 4,857 for the period, or an average of 101.2 deaths per year. Such discrepancies illustrate the difficulty in formulizing a tally for lightning-induced fatalities and calls into question the accuracy of all weather-related impact estimates reported by U.S. government agencies and the media.

Deaths from floods are the only thunderstorm-related hazard that ranks higher than lightning in terms of fatality tallies (Curran et al. 2000; Rakov and Uman 2003; Ashley and Ashley 2008). Ashley and Ashley (2008) illustrate that there were approximately 97.6 fatalities per year during 1959–2005, whereas, as illustrated above, our data indicate that lightning accounts for a few less fatalities per year. However, it is likely that a portion of flood fatalities were not directly related to convection and may have been caused by structural failures or long-term widespread river floods that are induced by above-normal rainfall and/or snowmelt. An analysis of updated data from Ashley (2007) indicates that tornadoes accounted for 70.9 fatalities per year during 1959–2007. It is unclear how many thunderstorm straight-line wind fatalities there were during the same period of analysis, but results from Ashley and Mote (2005) and Black and Ashley (2008) suggest that it may be much less than those associated with tornadoes, lightning, or floods. Thus, we surmise that lightning is likely the number-one *convectively induced* source of fatalities in the United States during 1959–2006. We cannot confirm this ranking since other weather-related hazards such as flash floods and damaging winds may include reporting deficiencies comparable to what we have found with lightning. We believe that the one mortality database that has been reported consistently since the 1950s is that of tornadoes (Grazulis 1993; Ashley 2007) and feel that those numbers are more robust

than other convective hazards, especially straight-line wind fatalities (Ashley and Black 2008) and flash flood fatalities (Ashley and Ashley 2008).

Restricting our analyses to 1977–2004 exemplifies the difference between the two primary datasets and how the official NWS publication documenting weather-related casualties, *Storm Data,* continuously underreported fatalities (Fig. 1). During this 28-yr period, *Storm Data* missed 752 of 2,552 fatalities that were otherwise identified in the CDC mortality dataset or in *LexisNexis.* That is, *Storm Data* underreported 29.47% of U.S. lightning-induced fatalities during this period. The trend in underreporting did not decrease drastically during the mid to late 1990s and 2000s, a period *after* NWS modernization (Friday 1994) and when Internet-based resources, which could be used readily to identify and report casualties, became more ubiquitous. Note that mortality datasets from the NWS (*Storm Data*) and CDC are unsuccessful at capturing all lightning strike fatalities, as illustrated by the addition of 43 fatalities gathered from *LexisNexis* for 1995–2006. Furthermore, this discrepancy between *LexisNexis* and the official numbers provided by the government indicate that the NWS's newspaper clipping service is imperfect since we were able to find a number of fatalities not reported via *LexisNexis* in comparison to *Storm Data.* In fact, an additional 11 fatalities in 2005/06

Table 2. Number of U.S. lightning fatalities based on a variety of resources, including *Storm Data* (from the monthly publication and NCDC's "Lightning Archive"), CDC mortality dataset, López and Holle's (1998) tallies based on CDC data, any *LexisNexis*-identified fatalities not found in *Storm Data* or CDC, and cases identified by John Jensenius not found via other sources. The "best estimate" summarizes the available data or assumes the highest value from the aforementioned datasets, except in cases where our CDC mortality tallies were different than López and Holle's (1998). In these cases, we sided with our CDC mortality values since it appears that some of the fatalities were counted twice by the CDC, leading to an overestimation of counts by López and Holle (1998).

Year	*Storm Data*	CDC total	López and Holle (1998)	Additional CDC cases not identified in *Storm Data*	LexisNexis cases not in *Storm Data* or CDC/additional events identified by Jensenius	"Best estimate" fatality total
1959	154	-	183	-	-	183
1960	96	-	129	-	-	129
1961	112	-	149	-	-	149
1962	120	-	153	-	-	153
1963	129	-	165	-	-	165
1964	108	-	129	-	-	129
1965	115	-	149	-	-	149
1966	76	-	110	-	-	110
1967	71	-	88	-	-	88
1968	103	-	129	-	-	129
1969	93	-	131	-	-	131
1970	108	-	122	-	-	122
1971	113	-	122	-	-	122
1972	91	-	94	-	-	94
1973	103	-	124	-	-	124
1974	92	-	112	-	-	112
1975	91	-	124	-	-	124
1976	70	-	81	-	-	81
1977	98	116	116	48	-	146
1978	88	98	98	40	-	128
1979	63	89	87	38	-	101
1980	77	95	94	40	-	117

were identified by the John Jensenius dataset that were not listed in *Storm Data* or *LexisNexis*.

As reported elsewhere (López and Holle 1996,

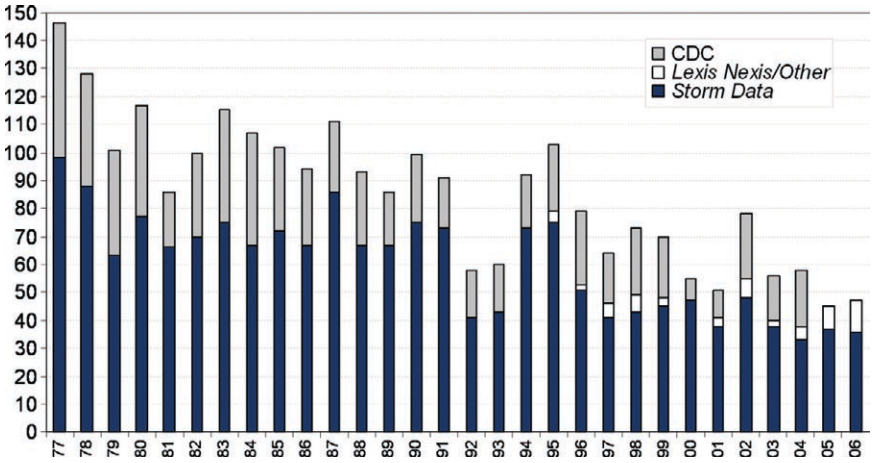

Fig. 1. Number of lightning fatalities per year, 1977–2006. Data are subdivided by their primary source to illustrate how *Storm Data* is not capturing all reported fatalities.

Table 2. Continued.

Year	*Storm Data*	CDC total	López and Holle (1998)	Additional CDC cases not identified in *Storm Data*	LexisNexis cases not in *Storm Data* or CDC/additional events identified by Jensenius	"Best estimate" fatality total
1981	66	75	87	20	-	86
1982	70	97	100	30	-	100
1983	75	95	93	40	-	115
1984	67	92	91	40	-	107
1984	72	85	85	30	-	102
1986	67	79	78	27	-	94
1987	86	99	99	25	-	111
1988	67	86	82	26	-	93
1989	67	76	75	19	-	86
1990	75	89	89	24	-	99
1991	73	75	75	18	-	91
1992	41	56	-	17	-	58
1993	43	57	-	17	-	60
1994	73	84	-	19	-	92
1995	75	78	-	24	4	103
1996	51	64	-	26	2	78
1997	41	59	-	18	5	64
1998	43	64	-	24	6	73
1999	45	65	-	22	3	70
2000	47	50	-	8	0	55
2001	38	44	-	10	3	51
2002	48	70	-	23	7	78
2003	38	47	-	16	2	56
2004	33	48	-	20	5	58
2005	37	-	-	-	3/5	45
2006	36	-	-	-	5/6	46
Total	**3645**					**4857**

1998), the number of lightning fatalities in the United States has decreased rather markedly in the last half century. For example, our "best estimate" data suggest that the 10-yr period in the 1960s witnessed 133.2 deaths per year whereas the latter 10 yr, 1997–2006, in our period of record suggest 59.6 deaths per year. Therefore, average annual fatality rates have decreased approximately 55.3% between the two decades. How much of the period counts are underreported is unknown. López and Holle (1996, 1998) surmise that the decreasing trend in the number of fatalities (and fatality rate) is due to a decreasing rural population (see López and Holle 1998, their Figs. 4 and 5), improvements in forecasts and warnings, mitigation efforts through public education of lightning hazards, and improvements in electrical systems and fire resistance of houses.

Spatial distribution of lightning fatalities. Previous research (Mogil et al. 1977; Curran et al. 2000) has illustrated the spatial distribution of lightning fatalities across the United States; however, these spatial analyses have been limited to the state or regional scale. Analyses using political boundaries are useful for ranking states in terms of their overall, population-weighted, or area-weighted risks, but they fail to capture the true and inherent variability in the hazard across the country or, for that matter, across a single state. For example, it is widely known that Florida leads in terms of raw counts of lightning casualties, deaths, and injuries (Curran et al. 2000), yet even in this "lightning capital" of the United States (Hodanish et al. 1997), there is much variation in vulnerability across the state as exemplified by historical fatality data (see Fig. 2 and other information in this section).

To reveal the spatial patterns of lightning fatality attributes, we counted the number of fatality occurrences on a set of grids, varying from 30 to 60 km resolution, on an Albers equal-area conic contiguous U.S. projection. Utilizing this technique affords a more comprehensive examination of fatalities across the United States but does not allow for ranking grid cells based on

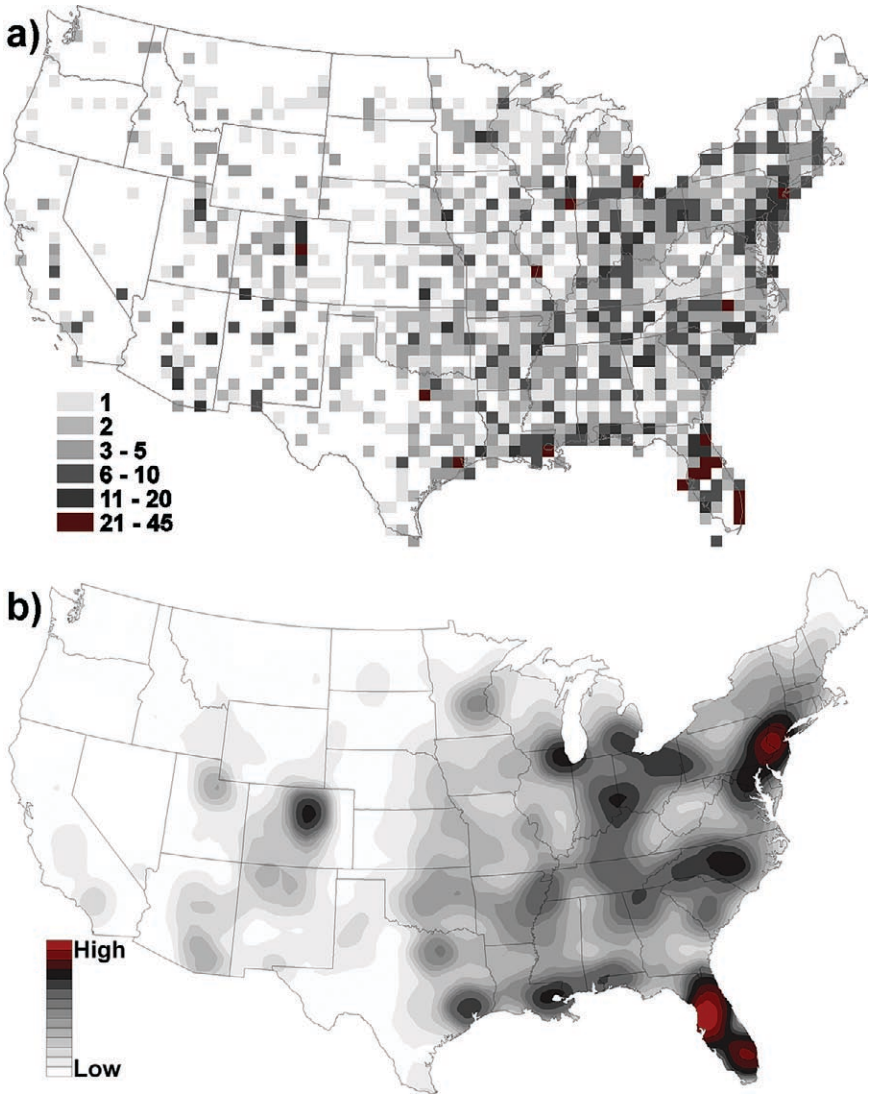

Fig. 2. (a) Number of lightning fatalities in a 60 km × 60 km grid across the conterminous United States, 1959–2006. Approximately 6.6% (or 290 of the 4,408) fatalities identified in our dataset do not contain county or municipality location and therefore cannot be mapped. These "missing" fatalities are listed in Table 3. (b) As in (a), but data are smoothed using a Gaussian (3 × 3) low-pass filter to illustrate the *relative* frequency of historical lightning fatalities. See Ashley (2007) for a discussion of caveats associated with these smoothed data.

population due to spatial incompatibilities in population and gridded lightning raster datasets. Further, the gridded data were smoothed using a Gaussian (3 × 3) low-pass filter to reveal the *broad* patterns in the data. As discussed in Ashley (2007), readers should use caution when evaluating these smoothed data due to a number of caveats associated with contouring methods; nevertheless, these contoured data are useful in distinguishing high-fatality corridors.

Exploring the spatial distribution of lightning fatalities across the United States (Fig. 2) illustrates that elevated death counts concentrate in specific regions (e.g., Florida, Colorado's Front Range, etc.) and/or near population centers (e.g., Chicago, Dallas–Ft. Worth, Houston, New Orleans, etc.). Central and eastern Florida has the greatest concentration of high gridcell tallies, indicating that this area, which contains the U.S. climatological maximum in lightning flash rates (exceeding 9 flashes km^2 yr^{-1}; Hodanish et al. 1997; Orville and Huffines 2001; Orville et al. 2002; Orville 2008), is the deadliest lightning region in the country. Indeed, the grid cell centered on Miami–Dade County contains the highest tally in the United States, with 45 fatalities during our temporal window. Two other Florida grid cells—centered near the cities of Tampa (43) and Ft. Lauderdale (34)—are in the top five highest gridcell tallies for the United States. Other top grid cells are centered near the cities of Chicago (42) and Houston (35).

As alluded to above and illustrated in the maps (Fig. 2a), population centers incur greater overall human vulnerability simply due to the larger amount of people that may be exposed to lightning hazards at any one time in comparison to more rural locales—that is the perhaps overly simplistic "more people equals greater hazard" argument (Stallins 2004). There is evidence (Rose et al. 2008) that the urban heat island (UHI) effect may modify or enhance lightning patterns in close proximity or immediately downwind of large urban areas. These local lightning climatology augmentations may be producing a human-induced enhancement of the lightning hazard in these areas (Stallins 2004). Further study will be required to find any correlations between UHI-enhanced convection and the lightning it engenders, population density/growth, land use, and lightning hazards.

Examining the distribution of lightning fatalities using greater spatial resolution reveals further the urban theme (Fig. 3), with high fatality counts clustered along population centers (noted primarily by interstate junctures) and lower counts scattered across rural areas. Although the central and eastern Florida high-frequency fatality region is somewhat

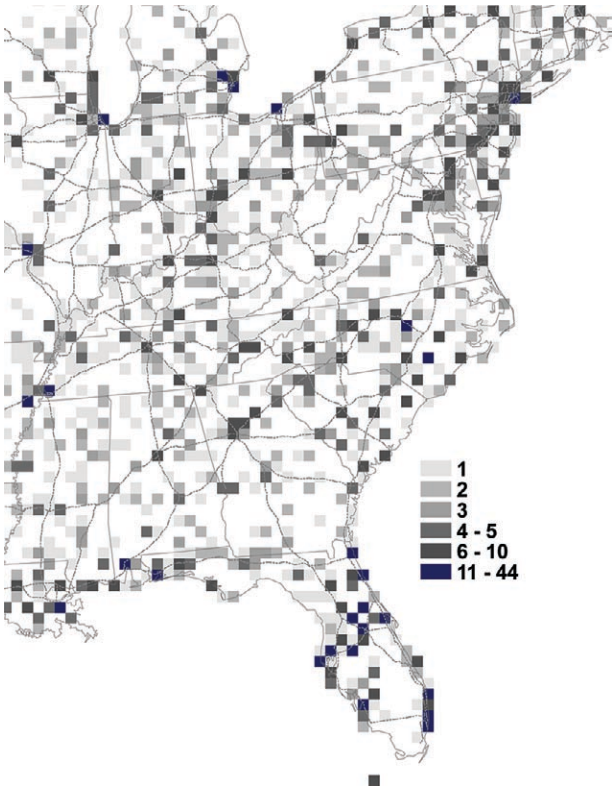

Fig. 3. As in Fig. 2a, except in 30 km × 30 km grid for the eastern United States. Interstates are illustrated by dotted–dashed lines.

expected due to the climatology of lightning revealed in prior research (Hodanish et al. 1997; Orville and Huffines 2001; Orville 2008), the high-frequency corridor paralleling I-95 from Washington, D.C., through Baltimore and Philadelphia to New York City is unique considering the low-to-moderate mean annual lightning flash density common to this area. The contoured data in Fig. 2b provide additional evidence of this unique high-frequency fatality region—an area that appears to have the second-highest regional fatality counts based on these historical data. However, the large number of fatalities in the Northeast, when weighted by population (i.e., the fatality rate; Table 3), are not as substantial as the raw fatality counts suggest. The modest risk found in the lightning flash climatology of this area is offset by the greater amount of human vulnerability produced by high population density found in the megalopolis, which ultimately leads to this belt of high fatalities. Since the population in this region does not have the same level of experience of thunderstorm hazards as areas in the Sun Belt, we hypothesize that there may be more complacency toward lightning hazards in this corridor that may be inducing these high fatality tallies. Future survey-based research should investi-

gate these possible regional dichotomies in lightning hazard perceptions.

As in Curran et al. (2000), we evaluated and ranked lightning fatalities by state (Table 3). The fatality rate (i.e., fatalities per million people per year) illustrates similar findings to that of Curran et al. (2000), with only slight rearranging in the top state rankings (we do not assess tourist populations and any biases those populations may create in our population-weighted analyses). The vulnerability picture is a bit different when fatality rankings are normalized by state size. When adjusted for area, four of the top five states normalized fatality rankings are in the Mid-Atlantic and Northeast. Once again, these data demonstrate further the enhanced and somewhat unique vulnerability found in this region. Only the state of Florida ranks in the top five in both normalized fatalities by state area and fatality rates. However, as described prior and illustrated in Figs. 2 and 3, ranking fatality rates by state boundaries may not be the most instructive way to identify concentrated areas where risk and human vulnerability juxtapose. Further, since fatality tallies appear to concentrate near population centers, mitigation measures may be better served by evaluating cities that appear to be the most vulnerable to lightning fatalities.

Examining fatality counts by metropolitan area (Table 4) confirms previous gridded data analysis the Miami–Ft. Lauderdale area has the highest fatality tallies in comparison to the 358 metropolitan areas identified by the Office of Management and Budget. Again, Florida cities are the most vulnerable, with 7 of Florida's 19 metropolitan areas represented in the top 25 fatality count list. New York City, centered within the I-95 Northeast lightning fatality corridor discussed above, is second on the list of absolute

Table 3. Population (average of decennial census values from 1960–2000), lightning fatality counts, number of fatalities not mapped in Figs. 2 and 3 (due to unknown municipality or county information), standardized fatalities (fatalities per square km × 10,000), and fatality rates (rate per million people per year of lightning fatalities) by state.

State	Average population	1959–2006 fatalities	Fatalities not mapped	Normalized fatalities		Fatality rate	
				Fatalities $(km^2)^{-1}$ × 10,000	Rank	Rate (per million per year)	Rank
Alabama	3,818,496	111	6	8.29	22	0.61	21
Arizona	2,917,427	116	26	3.94	33	0.83	8
Arkansas	2,204,025	124	4	9.05	19	1.17	3
California	24,593,982	46	3	1.13	43	0.04	48
Colorado	2,889,365	162	11	6.01	26	1.17	4
Connecticut	3,073,440	16	0	12.41	13	0.11	44
Delaware	607,700	18	3	33.83	3	0.62	20
Florida	10,081,526	514	15	35.56	2	1.06	5
Georgia	5,732,093	131	14	8.63	21	0.48	25
Idaho	924,879	29	1	1.34	40	0.65	18
Illinois	11,294,309	127	5	8.71	20	0.23	39
Indiana	5,394,207	109	8	11.56	15	0.42	28
Iowa	2,839,760	77	4	5.28	29	0.56	23
Kansas	2,390,972	68	5	3.19	36	0.59	22
Kentucky	3,528,941	112	9	10.73	16	0.66	17
Louisiana	3,958,635	152	4	12.80	11	0.80	9
Maine	1,117,765	24	1	2.88	37	0.45	26
Maryland and D.C.	4,931,155	57	4	22.44	5	0.24	38
Massachusetts	5,788,061	29	4	13.70	9	0.10	45
Michigan	9,038,819	118	6	7.87	23	0.27	36
Minnesota	4,117,877	73	7	3.33	34	0.37	31
Mississippi	2,466,713	115	7	9.32	18	0.97	6
Missouri	4,925,057	113	14	6.25	25	0.48	24

counts, with the Midwestern city of Chicago in third place. Both of these metropolitan areas are outside of the climatological high flash rate maximum found in the Southeast (Orville and Huffines 2001; Orville 2008), with mortality appearing to be augmented by population rates and other social factors such as complacency. When controlling for metropolitan size (Table 5), 12 of the top 25 (48%) cities are located in Florida.

Convective morphology of fatal lightning events. We propose that, in general, people do not prescribe the same threat perception, assessment, and/or mitigation behavior for lightning as they do for events like hurricanes, tornadoes, and even *severe* thunderstorms. First, lightning is much more common than tornadoes and hurricanes, with most lightning events lacking visual damage or casualties. Second, lightning is not a criterion for a formal NWS warning, which may lead to a psychological disconnect by the public between the actual hazard and its potential impacts. These two issues lead to a broad pattern of complacency among the public since most people associate lightning as a passive hazard (i.e., one that, although threatening and possibly lethal, does not typically produce extensive casualties or damage in its wake). In addition, research (Holle et al. 1993; Hodanish et al. 2004; Lengyel et al. 2005; Hodanish 2006) has illustrated that many lightning fatalities occur in thunderstorms that produce minimal or infrequent lightning, characteristics more common to unorganized, nonsevere convection (Goodman and MacGorman 1986; MacGorman and Morgenstern 1998; Carey and Rutledge 2003). For these reasons, our hypothesis suggests that lightning fatalities are often associated with unorganized, nonsevere, and

Table 3. Continued.

State	Average population	1959–2006 fatalities	Fatalities not mapped	Normalized fatalities		Fatality rate	
				Fatalities $(km^2)^{-1}$ × 10,000	Rank	Rate (per million per year)	Rank
Montana	771,425	29	2	0.76	44	0.78	10
Nevada	954,920	9	1	0.31	48	0.20	41
New Hampshire	922,050	13	2	5.42	28	0.29	34
New Jersey	7,348,861	77	1	39.60	1	0.22	40
New Mexico	1,320,806	102	3	3.23	35	1.61	2
New York	17,908,851	149	7	11.85	14	0.17	42
North Carolina	6,039,586	218	28	17.16	6	0.75	13
North Dakota	636,785	13	0	0.71	45	0.43	27
Ohio	10,671,260	168	11	15.75	7	0.33	33
Oklahoma	2,901,808	105	1	5.79	27	0.75	12
Oregon	2,551,379	10	4	0.40	47	0.08	46
Pennsylvania	11,827,973	148	12	12.60	12	0.26	37
Rhode Island	961,030	7	0	25.87	4	0.15	43
South Carolina	3,118,729	107	8	13.38	10	0.71	15
South Dakota	697,527	26	1	1.30	42	0.78	11
Tennessee	4,529,673	151	6	13.85	8	0.69	16
Texas	14,568,786	272	17	3.97	32	0.39	29
Utah	1,473,391	61	4	2.78	38	0.86	7
Vermont	503,450	18	1	7.24	24	0.74	14
Virginia	5,445,627	98	9	9.50	17	0.37	30
Washington	4,231,070	9	1	0.52	46	0.04	47
West Virginia	1,831,225	30	3	4.78	30	0.34	32
Wisconsin	4,666,144	65	1	4.47	31	0.29	35
Wyoming	415,882	34	6	1.34	41	1.70	1
United States	**227,842,537**	**4408**	**290**	**9.46**	**-**	**0.40**	**-**

Table 4. Ranking of the top 25 lightning fatality counts by U.S. metropolitan areas. Metropolitan areas are defined using the Office of Management and Budget's 2005 Core-Based Statistical Area delineations. Counts do not include the 290 fatalities that had no specific municipality location information highlighted in Table 3.

Rank	Metropolitan area (core-based statistical area)	1959–2006 fatalities
1	Miami–Fort Lauderdale–Miami Beach, FL	107
2	New York–Northern New Jersey–Long Island, NY–NJ–PA	89
3	Chicago–Naperville–Joliet, IL–IN–WI	70
4	Tampa–St. Petersburg–Clearwater, FL	69
5	Houston–Baytown–Sugar Land, TX	57
6	Denver–Aurora, CO	44
7 (t)	Orlando, FL	43
7 (t)	New Orleans–Metairie–Kenner, LA	43
9	Philadelphia–Camden–Wilmington, PA–NJ–DE–MD	42
10 (t)	Washington–Arlington–Alexandria, DC–VA–MD–WV	36
10 (t)	Dallas–Fort Worth–Arlington, TX	36
12	Jacksonville, FL	35
13 (t)	Detroit–Warren–Livonia, MI	33
13 (t)	Atlanta–Sandy Springs–Marietta, GA	33
15 (t)	Pittsburgh, PA	31
15 (t)	St. Louis, MO–IL	31
17	Cincinnati–Middletown, OH–KY–IN	29
18	Minneapolis–St. Paul–Bloomington, MN–WI	27
19 (t)	Palm Bay–Melbourne–Titusville, FL	26
19 (t)	Nashville–Davidson–Murfreesboro, TN	26
21 (t)	Lakeland, FL	25
21 (t)	Cleveland–Elyria-Mentor, OH	25
23 (t)	Raleigh–Cary, NC	21
23 (t)	Baltimore–Towson, MD	21
25 (t)	Pensacola–Ferry Pass–Brent, FL	20
25 (t)	Colorado Springs, CO	20
25 (t)	Columbus, OH	20

thus unwarned thunderstorms, making mitigation activities troublesome.

To test our hypothesis, we first evaluated warning activities during these fatal events. We assessed 11 yr of warning data to determine if lightning fatalities were associated with either a severe thunderstorm or tornado warning. If a warning was issued within ±3 h of the time of death, then the thunderstorm event was considered to be warned. Any fatality event that did not contain a county or time of death was removed from our analysis.

Results demonstrate that only 22.7% of fatalities over the 11-yr period were associated with severe or tornado-warned storms, ranging from 12.8% to 34.6% annually (Table 6). These results support our hypothesis that lightning fatalities most often occur with nonsevere convection. However, to confirm our suspicion, we further examined the morphology of storms associated with 530 lightning fatalities during 1998–2006.

Thunderstorms occur across a convective spectrum, from an unorganized cellular or pulse storm on one end to the supercell on the opposite end. This traditional spectrum view demarcates thunderstorms by their degree of organization, with more organized thunderstorms tending toward greater storm perils (e.g., tornado, hail, wind) and risk. However, our position—in contrast to the previous

Table 5. Same as Table 4, but ranked by metropolitan area fatality density. Only metropolitan areas with a minimum of 10 fatalities over the period of record are assessed.

Top 25 fatality densities by metropolitan area				
Rank	**Metropolitan area (core-based statistical area)**	**1959–2006 fatalities**	**km^2**	**Fatalities (km^2)$^{-1}$ × 1,000**
1	Tampa–St. Petersburg–Clearwater, FL	69	6784	10.17
2	Muncie, IN	10	1025	9.76
3	Palm Bay–Melbourne–Titusville, FL	26	2734	9.51
4	Cape Coral–Fort Myers, FL	19	2099	9.05
5	Miami–Fort Lauderdale–Miami Beach, FL	107	14051	7.62
6	Fort Walton Beach–Crestview-Destin, FL	13	2434	5.34
7	Boulder, CO	10	1918	5.21
8	New York–Northern New Jersey–Long Island, NY–NJ–PA	89	17911	4.97
9	Mobile, AL	16	3249	4.92
10	Lakeland, FL	25	5209	4.80
11	Cleveland–Elyria–Mentor, OH	25	5222	4.79
12	Pensacola–Ferry Pass–Brent, FL	20	4385	4.56
13	Deltona–Daytona Beach–Ormond Beach, FL	14	3131	4.47
14	Orlando, FL	43	10387	4.14
15	Sarasota–Bradenton–Venice, FL	14	3477	4.03
16	Jacksonville, FL	35	8827	3.97
17	Winston–Salem, NC	15	3815	3.93
18	New Orleans–Metairie–Kenner, LA	43	10966	3.92
19	Raleigh–Cary, NC	21	5561	3.78
20	Chicago–Naperville–Joliet, IL–IN–WI	70	18916	3.70
21	Philadelphia–Camden–Wilmington, PA–NJ–DE–MD	42	12323	3.41
22	Dayton, OH	15	4445	3.37
23	Gulfport–Biloxi, MS	13	3928	3.31
24	Gainesville, FL	11	3431	3.21
25	Detroit–Warren–Livonia, MI	33	10308	3.20

statement—suggests that lightning-related fatalities are most often produced by unorganized, pulse-style thunderstorms. This presents a unique problem for mitigating lightning casualties since unorganized convection is the least likely type of thunderstorm to produce mitigating activities by the public—even those driven by common sense. In our analysis, we are not interested in determining the initiating, forcing, or sustenance mechanisms of the convection; rather, we are trying to determine the overall organization of the killer thunderstorm as illustrated by radar morphology. To this extent, we limited our classification system to three options: 1) unorganized, pulse-style convection, 2) mesoscale convective system (MCS), or 3) supercell (either embedded in MCS or isolated).

Our MCS definition follows that of Parker and Johnson (2000), who suggest that an MCS is a convective phenomenon, as identified in base reflectivity, with a life time scale of ≥3 h and a minimum spatial scale in one dimension of 100 km. Determining a consistent supercell definition is much more problematic, as evidenced by the variety of definitions offered in the literature (see Doswell 2001 for discussion). In our classification, a supercell must contain 1) NEXRAD level III reflectivity features common to supercells [e.g., isolated cellular appearance or embedded cellular appearance when contained in an MCS (as illustrated in Miller and Johns 2000), inflow notch, hook echo, tight-reflectivity gradient, V-notch, and storm splits]; 2) a persistent (≥6 radar scans; ~30 min) mesocyclone as identified by NEXRAD's mesocyclone

Table 6. Percentage of lightning fatalities that were associated with either tornado or severe thunderstorm warned storms. Only fatalities with a known time of death were utilized in this analysis.

Year	Assessed fatalities	Severe T-storm (tornado) warning	Warned fatalities	% of fatalities warned
1994	73	13 (0)	13	17.8%
1995	78	19 (3)	21	26.9%
1996	51	10 (0)	10	19.6%
1997	41	11 (1)	12	29.3%
1998	47	13 (0)	13	27.7%
1999	49	9 (0)	9	18.4%
2000	47	6 (0)	6	12.8%
2001	40	10 (1)	11	27.5%
2002	52	18 (0)	18	34.6%
2003	38	3 (2)	5	13.2%
2004	35	7 (0)	7	20.0%
Total	**551**	**118 (7)**	**125**	**22.7%**

detection algorithm; and 3) a persistent mesocyclone as confirmed by examining multiple elevation slices of storm-relative velocity data. Unorganized, pulse-style convection includes storms that do not fit the above MCS or supercell definitions and subjectively appear to lack any spatial or temporal organization in reflectivity data. Unorganized convection exhibits cellular life times (0.5–1.5 h), with outflow, sea-breeze, orographic, or convective forcing appearing to be the predominant initiating mechanisms. Finally, we only classified events with detailed temporal and spatial information (i.e., known date, time, and municipality of fatality). We also removed from consideration events not sampled by radar, such as cases in higher terrain or those events that simply lacked available archived radar data.

Results illustrate that unorganized convection was responsible for 84.4% of fatal lightning events over the 9-yr period (Table 7). The next common convective type was MCSs, with 12.5% of total killer storms. Although supercells are usually prolific lightning producers (Steiger et al. 2007), they are responsible for only 3.1% of lightning fatalities during our period of record. Such relatively low lightning fatality counts for organized convection begs the question—Why? Are these low counts due to the greater likelihood that these more organized storm types will be warned, which could lead to less complacency and more successful mitigation activities by the public? Or perhaps the distribution of percentages is caused by the fact that these organized storm archetypes are less common climatologically than unorganized morphologies? Indeed, most lightning fatalities occur during June (20.8% of annual deaths), July (29.1%), and August (22.3%), when convection tends to be widespread, but largely unorganized due to low bulk shear (especially in July and August). Furthermore, human vulnerability is enhanced during the warm season because people tend to perform more outdoors activities for longer periods of time (i.e., longer day length) in comparison to other seasons. It is difficult to answer fully these questions since a climatological analysis of convective radar morphologies has yet to be completed and the issue of human vulnerability varies greatly from situation to situation. Nevertheless, we believe the results here demonstrate that just because a storm is not severe, does not mean that it cannot be deadly. While lightning casualty mitigation efforts should focus on all thunderstorms, attention should be given to unorganized convection since evidence confirms that it is this storm type that is the primary genitor of fatalities.

SUMMARY AND CONCLUSIONS. Despite the tens of thousands of thunderstorms and tens of millions of cloud-to-ground lightning flashes that occur across the United States each year (Orville et al. 2002), only a small segment of the population is directly impacted or worse, killed, by lightning. As shown in prior research (López and Holle 1996, 1998), the number of lightning fatalities has decreased dramatically over the past century and is a testament to medical advances (e.g., greater understanding of lightning impacts on the body, proliferation of portable defibrillators, etc.), technology improvements (e.g., Doppler radar, commercial lightning detection networks, communication), NOAA's mitigation activities (e.g., simple yet effective slogans such as "When thunder roars, go indoors"), and a strong lightning research group led by a number of private and government personnel interested in reducing the hazard's impact (see www.lightningsafety.noaa.gov). Yet, is it possible we have reached a minimum in the number of annual fatalities today given the future growth in hazard impact—both casualties and

damage—due to population increases and expansion? Undoubtedly, people will continue to take risks (e.g., playing outdoors as a thunderstorm approaches, persisting in outdoor work during a thunderstorm, etc.) and therefore mitigating all fatalities and injuries may not be possible. However, we must continue with the goal to minimize casualties. In doing so, we should concentrate mitigation efforts on areas and activities that appear to have a greater likelihood of hazard impact. Without a continuing educational and awareness effort, the number of lightning casualties will most likely increase.

Our research supplements the existing knowledge of lightning mortality by providing a reassessment of the risks and vulnerabilities that produce fatal events through a meteorological and spatial methodological approach. Our analyses illustrate a number of spatial corridors that have relatively high numbers of fatalities, including central and eastern Florida, the I-95 corridor in the Northeast U.S. megalopolis, and the Front Range of Colorado. Other more localized, high-frequency fatality locations appear near large population centers throughout the United States. The irregular spatial patterns in the fatality distribution appear to be due to varying combinations of both risk and human vulnerability, with places such as Florida and the Gulf Coast having high death totals due to enhanced thunderstorm risk and areas such as the I-95 corridor having larger fatality numbers due to human vulnerability factors rather than overall risk. Future research should examine these theorized explanations for regional differences in the fatality patterns by using a survey-based research approach. Such social-framework investigations could yield insight into the complex issue of complacency (e.g., why do people still play or work during thunderstorms?) and perplexing topics such as the dramatic gender discrepancy found between male and female lightning fatality victims (84.4% of victims during 1959–2006 with known gender were male).

Analyses of radar morphologies of fatal lightning-producing convection found that unorganized thunderstorms are the most likely convective type to cause a fatality. We argued that the fatality distribution found across the convective spectrum is due at least in part to the enhanced risk produced by more numerous unorganized storms and human vulnerability, which may be amplified in these cases since unorganized convection tends to be associated with less warning and mitigation activities. Future research should continue with the spatial analyses provided here by examining the correlation with lightning flash frequency, casualties, and damages. By combining the results from human subject surveys with our understanding of thunderstorm climatology and risk, we can work toward advancing mitigation activities and promoting public awareness of the hazards associated with lightning. However, before we can seek advancement of these aspects of the research, we need to reevaluate our current system for cataloging lightning—and for that matter, all—hazard impacts.

Of all the loss vectors we evaluate in post-event assessments, fatalities are probably the most sought-after appraisal of hazard effects. By solely focusing on a single hazard (lightning) and single measurement of this phenomenon's impact (fatalities), we have illustrated a shortcoming in our current hazard loss

Table 7. Number of lightning fatalities and deadly thunderstorms by year. Fatal storm events are subdivided by their radar morphological characteristics. Only "analyzed" storms (i.e., storms without issues related to mortality or radar data) were subdivided and used in the percentage calculation.

Year	Fatalities	Total killer storms	Analyzed killer storms	Supercell	MCS	Unorganized	Percent unorganized
1998	73	71	40	3	5	32	80.0%
1999	70	65	36	1	4	31	86.1%
2000	55	51	34	2	3	29	85.3%
2001	51	49	37	2	7	28	75.7%
2002	78	73	41	0	9	32	78.0%
2003	56	53	32	0	5	27	84.4%
2004	58	56	33	1	4	28	84.8%
2005	45	40	32	0	1	31	96.9%
2006	47	46	35	1	2	32	91.4%
Total	**530**	**507**	**320**	**10**	**40**	**270**	**84.4%**

cataloging procedures in the United States. Other recent research (Gall et al. 2009) has illustrated further the limitations of global and national databases that monitor hazard losses, especially damage tallies. There is no doubt that the compilation of casualty and damage data is an extremely complex and difficult process (Shearman and Ojala 1999), but it appears that our current post-event data gathering methods are insufficient and fail to gather the requisite information to assess accurately hazard effects.

Since *Storm Data* is the primary source of information for assessing weather-related casualties and damage in the United States, there should be greater emphasis on improving the methodological foundation of this database. Should the federal government's primary dataset for hazard impacts be populated with information gathered from media reports via newspaper clipping services? Is there not a more formal, efficient, and accurate way to collect the data necessary for hazard analysis? The data gathered have significant impacts on policy, mitigation, and resource allocation; thus, complete accuracy should be the ultimate goal. We argue that a more cohesive information pipeline for reporting weather-related impacts should be set up to streamline data gathering and transfer from county coroners, insurers, and state agencies, and to responsible federal parties such as NOAA and CDC. As suggested by López et al. (1993), NOAA should try to support a database relationship with state vital statistic departments and hospital associations. For example, we propose that coroners facilitate an accurate and expeditious method to assess weather-related casualty information and transmit these data to the CDC, who can in turn send the information to the NWS for inclusion in *Storm Data*. Such a data assessment and gathering pipeline would require cooperation across many agencies and various levels of government. Further, NOAA should investigate cataloging policies and tactics utilized by existing agencies and programs (e.g., the National Safety Council, the Insurance Institute for Highway Safety, the Federal Railroad Administration Office of Safety Analysis) that have experience in gathering other types of hazard assessment data. Open discussion and assessment of the existing reporting procedures should lead to a more effective program designed to catalog atmospheric hazard impacts, which in the future will lead to more informed policy decisions, improved mitigation efforts, and, most importantly, fewer casualties.

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