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REASSESSMENT OF LIGHTNING MORTALITY IN THE U.S.: ANALYSES OF CONTRASTING DATASETS, SPATIAL DISTRIBUTIONS, AND STORM MORPHOLOGIES

Walker S. Ashley*, Christopher W. Gilson, and David Keith
Meteorology Program, Department of Geography, Northern Illinois University, DeKalb, Illinois

1. INTRODUCTION

Lightning kills more people than tornadoes, hurricanes, and high winds on average each year in the U.S. (Holle and López 1998, Curran et al. 2000, Rakov and Uman 2003). Only floods trump lightning in terms of overall fatality numbers for thunderstorm-related phenomena on any given year (Curran et al. 2000, Rakov and Uman 2003, Ashley and Ashley 2008). 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 lightning mortality analyses to a single source of – likely incomplete – data, the dataset compiled and employed in this study includes information from several different resources. The method of combining data from a variety of sources illustrates how deficient current official weather-related casualty reporting procedures are in the U.S. and argues that existing methods of hazard data collection and dissemination (namely, *Storm Data*) are in need of a significant overhaul. 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 patterns in the U.S. Revealing these unique clusters will allow us to concentrate our mitigation efforts in areas that are most prone to lightning fatalities.

In addition, 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 to the average human than these other, more "severe," weather phenomenon. In order to begin to explain this disconnect in the perception of lightning as a hazard, warning data are compared with lightning fatality locations. This analysis provides evidence for the subsequent section of study, which suggests that lightning fatalities often occur in nonsevere, and therefore, unwarned storms. Finally, the study evaluates and classifies the storm morphology of killer lightning events during the latter part of the period of record.

2. DATA AND METHODOLOGY

One of the primary foci of this research is to examine the accuracy of fatality tallies often reported via various agencies. To this extent, we gathered lightning mortality data from a variety of resources. In constructing our dataset, we first employed the NCDC's "Lightning Archive", which contains a chronological listing of lightning hazard statistics, including fatalities from 1959-2003, compiled from *Storm Data*. Utilizing the system for online data access via NCDC, monthly *Storm Data* publications as well as the Storm Event Database 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 utilized during the latter period of record (1995-2006) to search (using a variety of keyword strings such as "lightning death") and, thereafter, catalog any unreported lightning-related fatalities not found in *Storm Data*. In addition, the CDC NCHS's electronic record of death identification was accessed to determine the completeness and supplement the information attained from *Storm Data* and *LexisNexis*. The CDC mortality data, which were examined for the period 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. Finally, we acquired a listing of recent (2005-2006) lightning-induced fatalities compiled by John Jensenius (2008, personal communication) and colleagues. This listing included a small number of fatalities that we did not identify through *Storm Data* or *LexisNexis*. We removed all fatalities that did not qualify as "struck-by-lightning" deaths – cases excluded include lightning-induced house fire asphyxiations, plane crashes, and vehicles driving into lightning-felled trees.

We focus on fatalities in this study since the classification of a death is unwavering (in comparison to injuries) and because damage tallies are almost exclusively based on estimates, which lead to large issues with data reliability. 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.

We gathered latitude and longitude information for nearly all fatalities in order to map the data at much greater resolution than previous research. Further, each case in the lightning fatality database from 1994-

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* *Corresponding author address:* Dr. Walker Ashley, #118 Davis Hall, Meteorology Program, Dept. of Geography, Northern Illinois University, DeKalb, IL 60115; e-mail: washley@niu.edu

2004 was compared with NWS tornado and severe thunderstorm warning data to determine whether there was a warning issued for that county at the time of death. Finally, an extensive set of archived Level III radar data were acquired from the NCDC's online "HDSS" access system for the period 1998-2006 in order to investigate the morphology and organization of parent thunderstorms associated with killer lightning events.

3. RESULTS AND DISCUSSION

3.1 *Conflicts with lightning mortality data*

A multitude of investigations have illustrated that *Storm Data* may have a number of shortcomings in its lightning fatality tallies due to possible undercounts (Mogil et al. 1977, López et al. 1993, López and Holle 1998, Cherington et al. 1999, Shearman and Ojala 1999, Curran et al. 2000, Adekoya and Nolte 2005). 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.'s weather-related casualty datasets by using lightning as a proxy for gauging this (in)accuracy.

Tallies obtained solely from *Storm Data* for the period 1959-2006 suggest that 3,645 struck-by-lightning deaths occurred, or 75.9 fatalities, on average, per year. If we combine the resources of *Storm Data*, CDC, and *Lexis Nexis*, there were 4,408 lightning fatalities reported from 1959-2006, an average of 91.8 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.

Restricting our analyses to 1977-2004 (Fig. 1) exemplifies the remarkable differences between the datasets and how the government's own "official" publication documenting storm casualties, *Storm Data*, continuously underreported fatalities. During this 28-yr period, *Storm Data* missed 752 of 2552 (29.5%) fatalities that were otherwise identified in the CDC mortality dataset or in *LexisNexis*. Somewhat surprisingly, the trend in underreporting did not decrease drastically during the 1990s and 2000s, a period after NWS "modernization" and when Internet-based resources, which could be used readily to identify and report casualties, became more ubiquitous.

3.2 *Spatial distribution of lightning fatalities*

Exploring the spatial distribution of lightning fatalities across the U.S. (Fig. 2) illustrates that elevated death counts concentrate in regional "hot spots" (e.g., Florida, Colorado 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 grid cell tallies revealing 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 U.S., with 45 fatalities during our temporal window. Two other Florida grid cells –

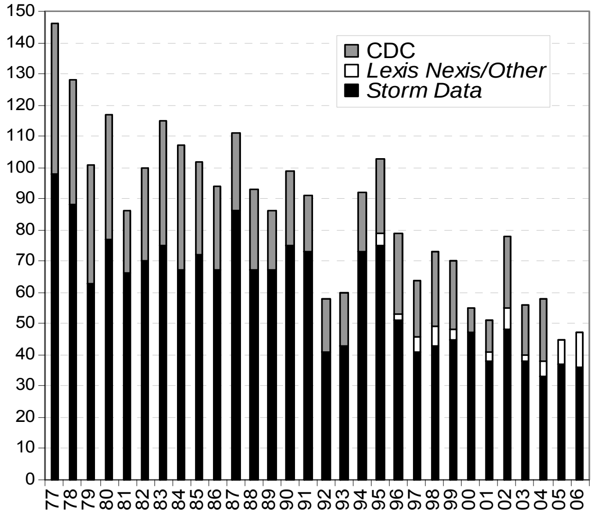

Figure 1. Number of fatalities per year, 1977-2006. Data are subdivided by their primary source to illustrate how *Storm Data* is not capturing all reported fatalities.

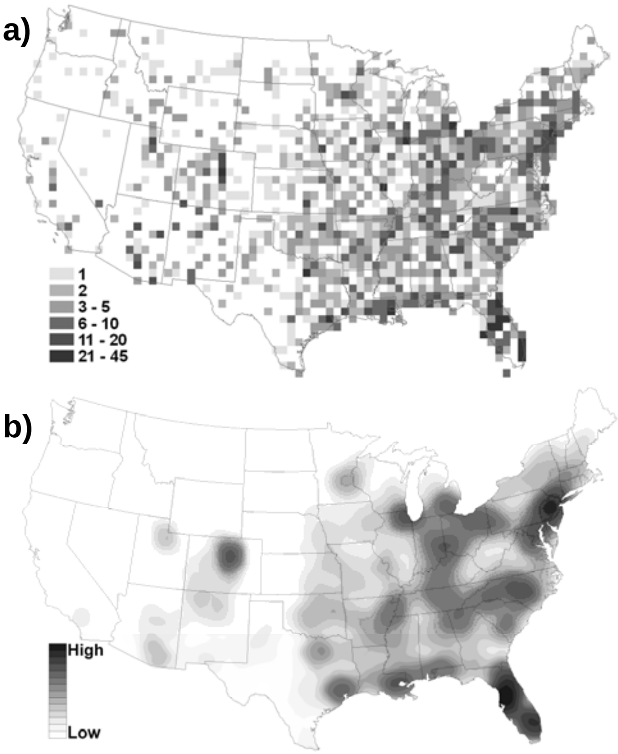

Figure 2. a) Number of fatalities in 60km x 60km grid, 1959-2006. Approximately 6.6% (or 290 of the 4,408) fatalities identified in our dataset do not contain county or municipality location and therefore cannot be mapped. b) As in panel (a), except data smoothed using a Gaussian (3x3) low-pass filter to illustrate the relative frequency of historical lightning fatalities.

centered on the cities of Tampa (43) and Ft. Lauderdale (34) – are in the top five highest grid cell tallies for the U.S.

Examining the distribution of lightning fatalities using greater spatial resolution reveals further the "urban" theme, with high fatality counts clustered along population centers and lower counts scattered across rural areas. Although the central and eastern Florida "hot spot" is somewhat expected due to the climatology of lightning revealed in prior research, the high-frequency corridor paralleling I-95 from D.C., Baltimore, Philadelphia, to New York City is unique considering the low-to-moderate mean annual lightning flash density common to this area. The contoured data revealed in Fig. 2.b provide additional evidence of this unique corridor – an area that appears to have the second highest regional fatality rates based on these historical data. 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 their may be more complacency toward lightning hazards in this corridor that may be inducing these bewildering death tallies. Future survey-based research should investigate these possible regional dichotomies in lightning hazard perceptions.

Examining fatality counts by metropolitan area (Table 1) 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 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 metro size, 10 of the top 25 (40%) cities are located in Florida.

Table 1. Ranking of the top 25 struck-by-lightning fatality counts by U.S. metropolitan areas. Metropolitan areas are defined using the Office of Management and Budget.

Rank	***Metropolitan Area***	***59-06 Deaths***
1	Miami-Fort Lauderdale-Miami Beach, FL	107
2	New York-N. 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)	Wash. D.C.-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

3.3 *Convective morphology of killer 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 though threatening and possibly lethal, does not typically produce extensive casualties or damage in its wake. For these reasons, our hypothesis suggests that lightning fatalities are often associated with unorganized, nonsevere, and thus unwarned thunderstorms, making mitigation activities troublesome.

To test our hypothesis, we first evaluated warning activities during these killer events. We assessed 11 years of warning data to determine if lightning fatalities were associated with either a severe thunderstorm or tornado warning. If there was a warning issued within +/–3 hours of the time of death then the 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-year period were associated with a severe- or tornado-warned storms, ranging from 12.8% to 34.6% annually (Table 2). 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 from 1998-2006.

Table 2. Percentage of fatalities that were associated with either tornado or severe thunderstorm warned storms. Only fatalities with known time of death were used in this analysis.

Year	*Assessed Fatalities**	*Svr. T-storm (Tornado) Warning*	*Warned Fatalities*	*Percent 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%**

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 – and counter to the previous statement – suggests that lightning-related fatalities are most often produced by unorganized, pulse-style thunderstorms. 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 is after Parker and Johnson (2000), who suggest an MCS is a convective phenomenon, as identified in base reflectivity, with a life timescale of ≥3 hr and a minimum spatial scale in one dimension of 100 km. In our classification, a supercell must contain: 1) NEXRAD Level III reflectivity features common to supercells (e.g., inflow notch, hook echo, tight-reflectivity gradient, V-notch, storm splits), 2) a persistent (≥6 radar scans; ~30 minutes) mesocyclone as identified by the NEXRAD’s Mesocyclone Detection Algorithm, and 3) a persistent mesocyclone as confirmed by examining multiple elevation slices of storm-relative velocity data. Unorganized, pulse-style convection are storms that do not fit the above MCS or supercell definitions and subjectively appear to lack any spatial or temporal organization in reflectivity data. 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 killer lightning events over the nine-year period. The next common convective type was MCSs, with 12.5% of total killer storms. Though supercells likely produce nearly all tornado fatalities, 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 are likely to 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. Furthermore, human vulnerability is enhanced during the warm-season because people tend to perform more outdoors activities and for longer periods of time (i.e., longer daylength) in comparison to other seasons.

4. SUMMARY AND CONCLUSIONS

Despite the tens of thousands of thunderstorms and tens of millions of cloud-to-ground lightning flashes that occur across the U.S. each year (Orville et al. 2002), only a small segment of the population is directly impacted or worse, killed, by the awe-inspiring spectacle of lightning. As shown in prior research (López and Holle 1996, 1998), the number of fatalities has decreased dramatically over the past century and is a testament to medical advances, technology improvements, NOAA’s mitigation activities, and strong lightning research “group” led by a number of private and government personnel interested in reducing the hazard’s impact. Yet, is it possible we have reached a minimum in the number of annual fatalities today with 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 thunderstorm approaches, persistence of outdoor work during thunderstorm, etc.,) and, therefore, mitigating all fatalities and injuries may not be possible. However, we must continue with the goal to eradicate all casualties. In doing so, we should concentrate mitigation efforts on areas and activities that appear to have a greater likelihood of hazard impact.

Our research supplements the existing knowledge of lightning mortality by providing a reassessment of the risks and vulnerabilities that produce killer 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 "hot spots" appear near large population centers throughout the U.S.

Analyses of radar morphologies of killer lightning-producing convection found that unorganized thunderstorms are the most likely convective type to kill. We argue that the fatality distribution found across the convective spectrum is at least in part due 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.

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 the inadequacies of our current U.S. hazard loss cataloging procedures. There is no doubt that the compilation of casualty and damage data is an extremely complex and difficult process, but it appears that our current post-event data gathering methods are functioning on "autopilot" and fail to gather the requisite information to assess accurately hazard effects. Some of the lack of detailed data gathering is likely due to budget constraints at our federal agencies; for example, NWS forecast offices are expected to create and disseminate more and more products, yet staffing levels remain, at best, constant. This managerial approach, which focuses more on "products" and provides little time for assessment, facilitates a reporting strategy that focuses solely on warning validation, which could mean that unwarned events that do produce damage or casualties may go undocumented while 19 mm hail reports that produce no impact are incessantly sought after to prop up abstract indices measuring forecast skill.

Since *Storm Data* is the primary source of information for assessing weather-related casualties and damage in the U.S., there should be greater emphasis on improving the methodological foundation of this database. Open discussion and assessment of the existing reporting procedures should induce 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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