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Mapping Lightning Fatality Risk

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***Abstract*—A new method to calculate lightning fatality risk is presented. This new method uses GIS software to multiply lightning flash density and population density on a grid and display the results on a map. The method is verified against observed lightning fatalities in the United States and appears to work well. These lightning fatality risk maps may be useful in helping plan lightning safety initiatives in developing countries.**

Keywords—lightning; fatality, death; GIS; safety; education

I. BACKGROUND

Lightning is the third leading source of storm deaths in the U.S., with tornadoes having recently replaced its longstanding #2 rank (Roeder, 2012). Lightning is also a significant source of storm deaths worldwide with an estimated average number of fatalities of up to 24,000 per year (Cardoso et al., 2011; Holle, 2008; Holle and Lopez, 2003). The geographical distribution of lightning fatalities in the U.S. is well known. The distribution by state has been extensively studied (Roeder and Jensenius, 2012; Holle, 2012a; Holle, 2011; Holle, 2009; Curran et al., 2000) as well on a 60 x 60 km raster map (Ashley and Gilson, 2009). Such information is very useful in lightning safety education since tuning lightning safety to the local population is important (Roeder et al., 2012; Roeder et al., 2011). Unfortunately, the geographical distribution of lightning in developing countries may not be as well known. Therefore, a method to estimate this distribution may be useful in guiding lightning safety initiatives in developing countries more effectively and at lower cost. This work was inspired by GIS applications of lightning data by Gijben (2012).

II. INTRODUCTION

A new method to estimate the risk of annual lightning fatalities was developed. This new method uses Geographical Information System (GIS) software to multiply annual cloud-to-ground (CG) lightning flash density by population density and display on a map for easy visualization. This new method was used to create a lightning fatality risk map for the contiguous U.S (CONUS). This multiplication is assumed to be a first approximation for the risk of lightning fatalities. For example, if there is a high population density but little lightning, there should be few lightning fatalities, e.g. Los Angeles, CA. Likewise, if there is a high lightning flash density but few people, there should also be few lightning fatalities, e.g. the Everglades in Florida. For a high risk of lightning fatality, both a high population density and a high lightning flash density are required, e.g. Tampa and Orlando, FL, Atlanta, GA, and Dallas and Houston, TX.

Other factors impacting the risk of lightning fatality not included in this first approximation include the relative amount of time spent outdoors and other at-risk behaviors by the local population, and changes in the population such as from tourism. In addition, the diurnal and seasonal distribution of CG lightning are not considered, i.e. this is an annual analysis only.

A comparison to the known lightning fatality data will be provided to test the assumption that this approach can be used to indicate the relative risk of lightning fatalities. If the approach is verified, similar maps for developing countries, where lightning fatality reports may not be reliable, may be useful as an aid to determine where to allocate scarce resources for lightning safety initiatives.

III. LIGHTNING FATALITY RISK MAP

The lightning fatality risk map for the CONUS was created by multiplying the CG lightning flash density by the population density. The lightning flash density for the CONUS is shown in Figure-1 and the population density is shown in Figure-2. The CG lightning flashes are from the National Lightning Detection Network (Cummins and Murphy, 2009; Cummins et al., 2006). The population density is from the 2000 National Historical Geographic Information System (https://www.nhgis.org). Some of the details of this map was created are listed in Table-1.

The resulting lightning fatality risk map is shown in Figure-3. For comparison purposes, the observed lightning fatality pattern is in Figure-4. Close-up maps for selected areas are provided to ease viewing of finer detail. These close-up maps are listed in Table-2 and are shown in section-4 where they are part of the verification of the lightning fatality risk method.

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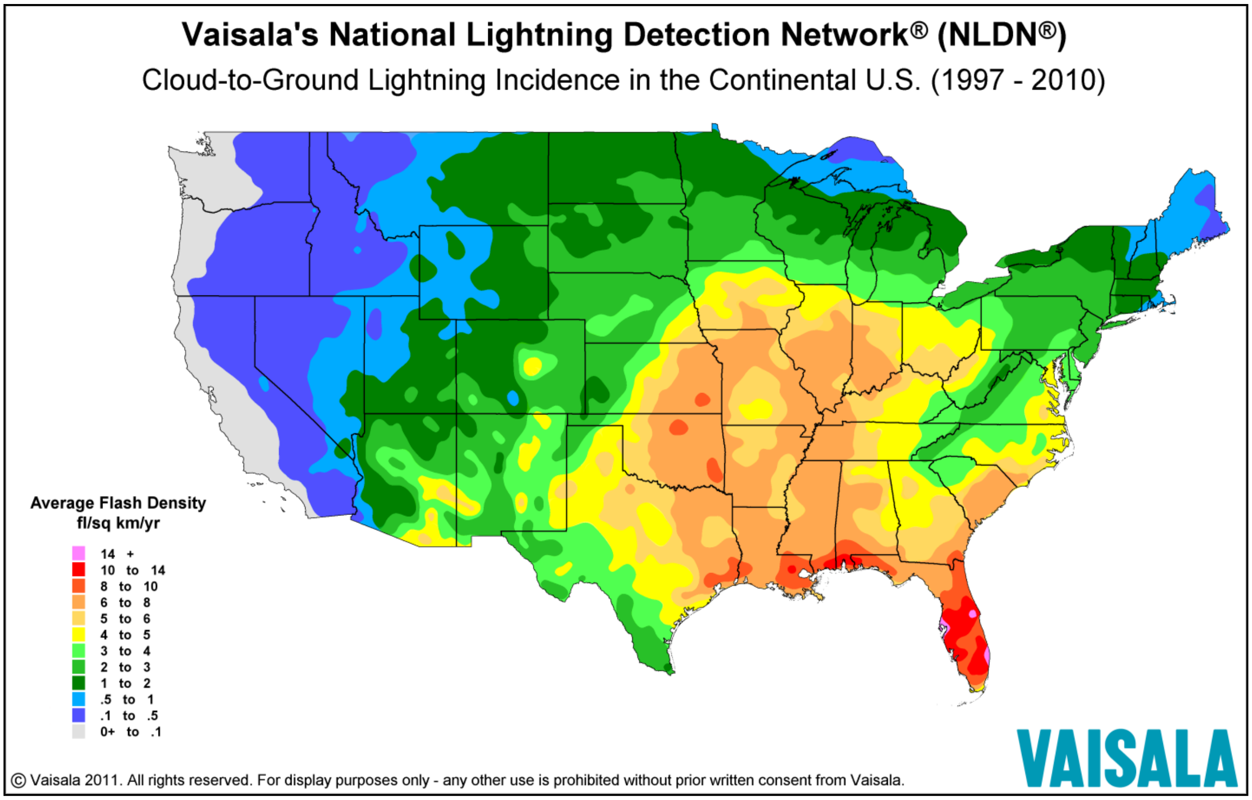


Figure-1. CG lightning flash density (1997-2010) for the U.S. from the National Lightning Detection Network (Cummins and Murphy, 2009; Cummins et al., 2006). The NLDN is owned and operated by Vaisala, Inc.

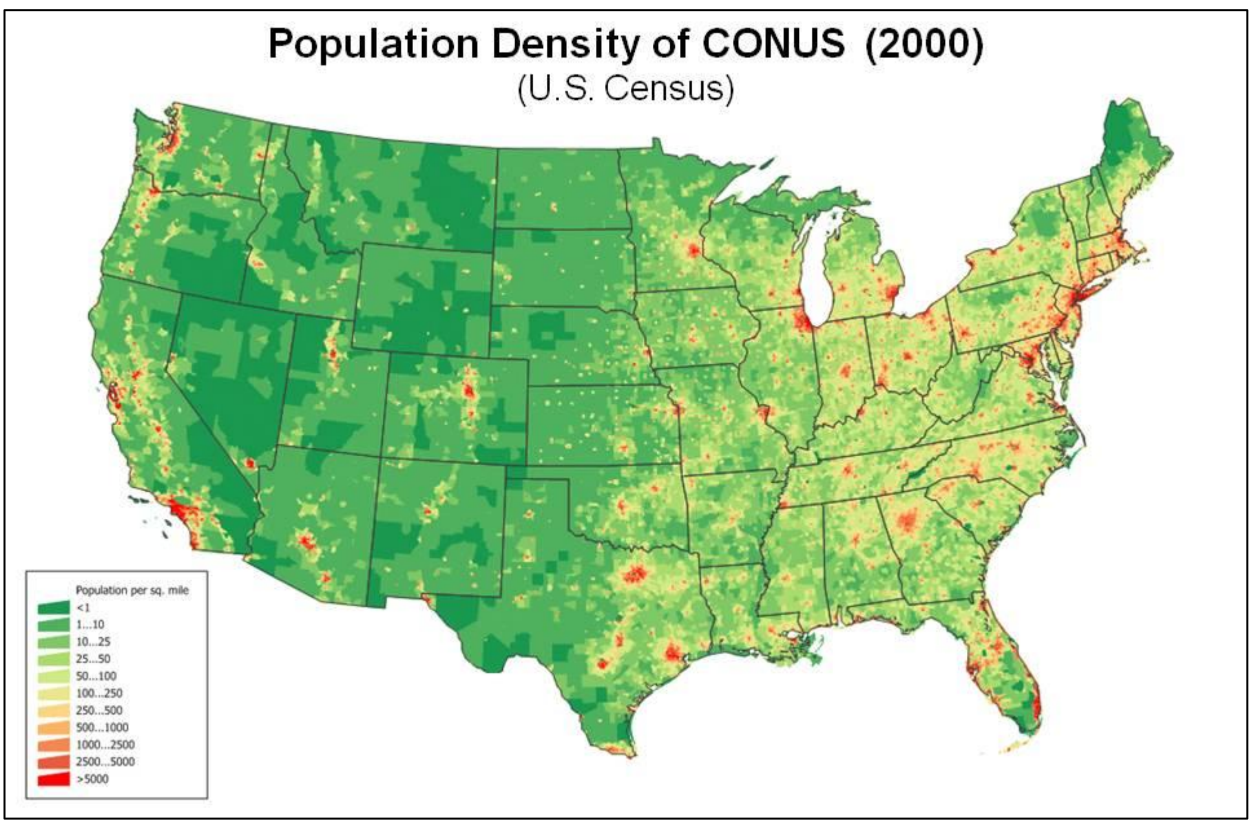


Figure-2. 2000 Population density for the U.S. from the U.S. Census (2013).

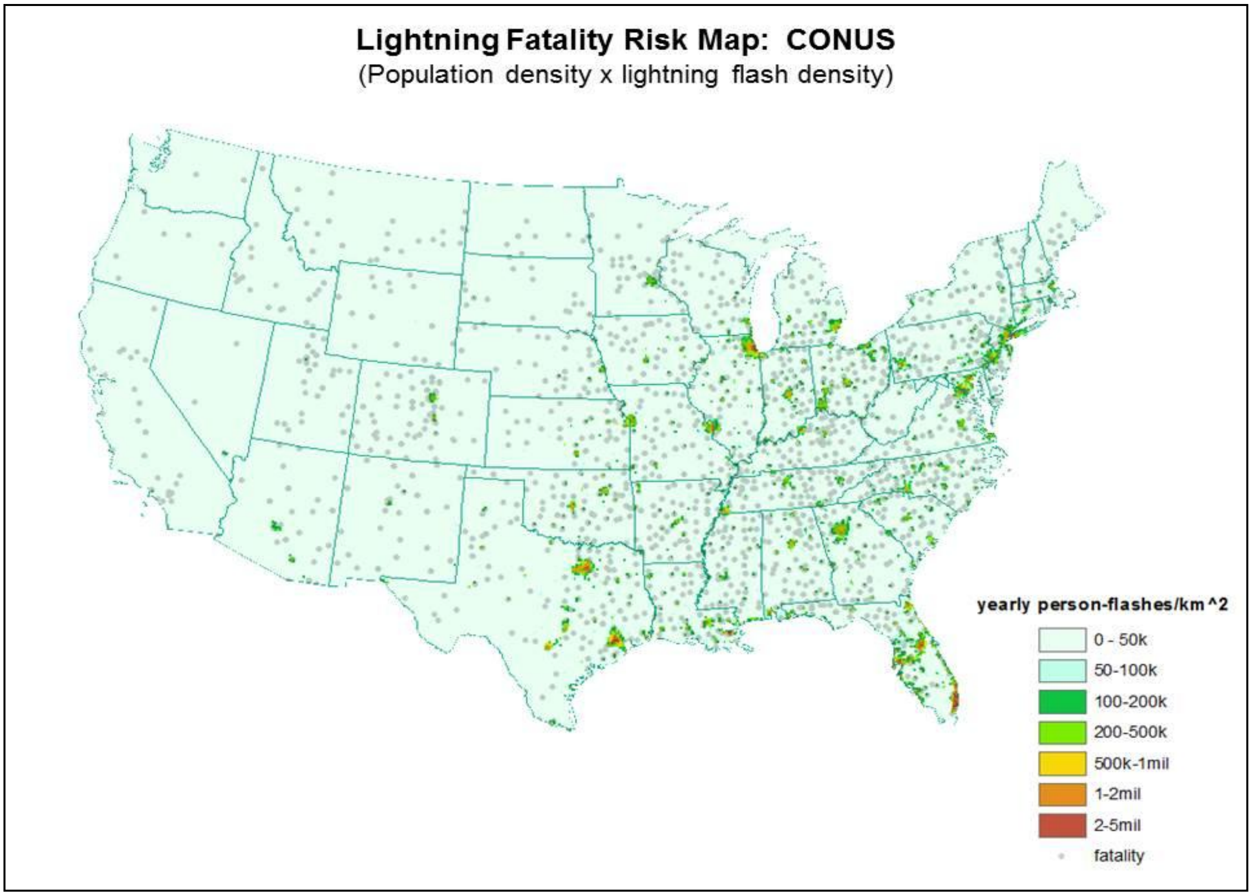


Figure-3. Lightning fatality risk for the CONUS. Lightning fatality risk is the product of CG lightning flash density (2003-2012) and population density (2000). Details of the map are in Table-1. The gray dots are the individual lightning fatalities, which are included for visualizing spatial correlation.

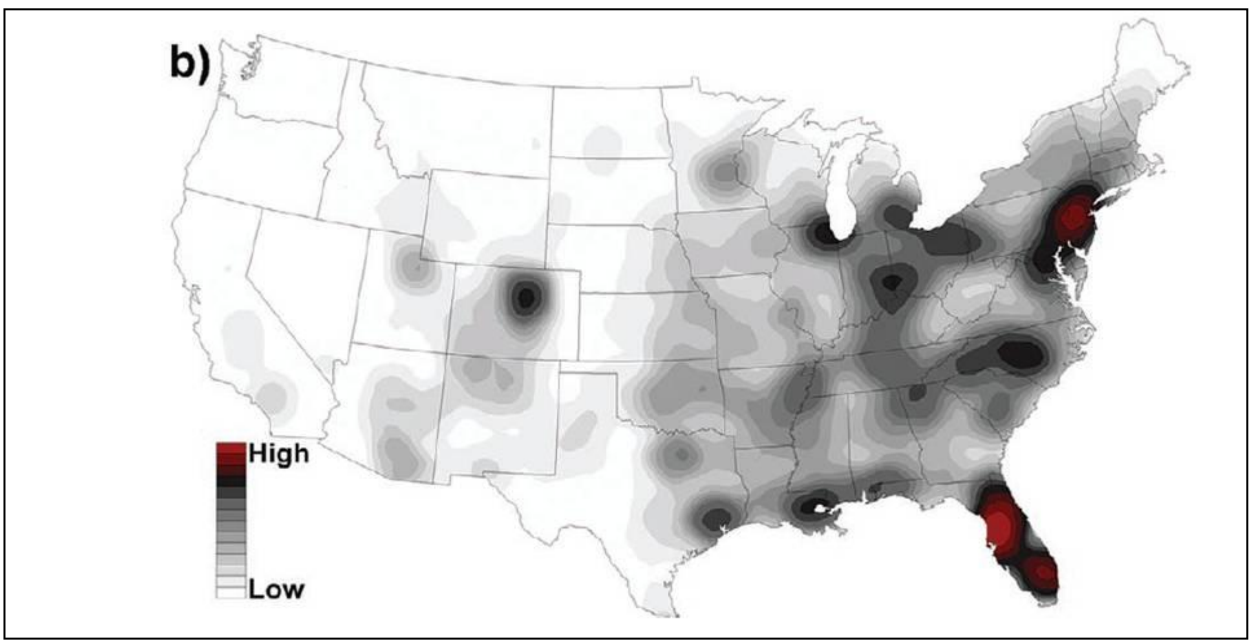


Figure-4. Number of observed lightning fatalities in the U.S (1959-2006) smoothed on a 60 x 60 km grid (from Ashley and Gilson, 2009). This is the ground truth for verification of the new lightning fatality risk maps presented here. Details of the map are in Table-3

Table-1. Technical details of the CONUS lightning fatality risk map (Figure-3).

GIS Software	ArcMap v10.0
Grid Spacing	0.1° x 0.1° lat/lon (~10 x 8 km)
Population Data	U.S. Census (2000) [1]
Lightning Flash Data	NLDN [2] (2003-2012)
Map Projection	Albers Equal Area Conic
Smoothing	None
Number of Lightning Fatalities (1959-2006)	4,408 (291 not plotted due to no location provided)
Fatalities with inexact locations	714 (15.5% of total)
Fatalities with no locations	291 *(not plotted)* (6.3 % of total)

1 from Socioeconomic Data and Applications Center, Columbia University (http://sedac.ciesin.org)

2 Cummins and Murphy, 2009; Cummins et al., 2006

Table-2. Lightning fatality risk close-up maps.

Region	Reason for interest	Figure
Florida	Highest lightning flash density and most fatalities	5*
Southeast	Region with many lightning fatalities	7*
Gulf States	Region with many lightning fatalities	8
Northeast	Moderate lightning fatalities	9
Colorado	Very localized high lightning fatality density	10
Midwest	Lower highly-localized lightning fatalities	12

∗ Figure-6 is a map of Florida mean lightning flash density.

IV. VERIFICATION

While the concept of the lightning fatality risk map seems reasonable, it is a new approach and verification is required. Fortunately, verification data of observed lightning fatalities are available (Ashley and Gilson, 2009). Some details of this observed lightning fatality map are in Table-3 and shown previously in Figure-4. The differences in the period of record between the lighting fatality risk map and the lightning fatality map are assumed not to be significant. However, as will be discussed later, this assumption may not be entirely true. It should be noted that 6.6% of the lightning fatalities had no location and were not plotted. In addition, 15.5% had uncertain locations, e.g. being recorded at the county seat even though the fatality may have occurred anywhere in the county, and introduce a small amount of variability into the map, which affects verification of the lightning risk map.

The verification will include both subjective and objective components. The subjective verification will be a visual comparison of the lightning fatality risk maps with the known lightning flash density and population density across the U.S. This does not verify that the map represents lightning fatality risk, but rather that the lightning fatality risk was calculated properly, and provides a basis for developing explanations for areas of disagreement between computed risk and observed fatalities. The objective verification will quantify the degree to which the lightning risk corresponds to lightning fatalities.

Table-3. Technical details of the CONUS lightning fatality map (Figure-4) (Ashley and Gilson, 2009).

GIS Software	ArcGIS 9.3
Grid Spacing	60 x 60 km
Period of Record	1959-2006
Number of Fatalities (1959-2006)	4,408 (290 not plotted due to no location provided)
Map Projection	Albers equal-area conic projection
Smoothing	3 x 3 low pass Gaussian filter
Lightning fatalities with inexact locations	714 (15.5 % of total)
Lightning fatalities with no locations	290 *(not plotted)* (6.6% of total)

A. Subjective Verification

The subjective verification has three parts: 1) visual inspection of the CONUS map, 2) visual inspection of close-up maps, and 3) more rigorous comparison of CONUS details. The CONUS lightning flash densities are shown in Figure-1 and the population densities are shown in Figure-2.

1) Visual Inspection of the CONUS Map

A visual inspection of the CONUS lightning fatality risk map (Figure-3) was done focusing on each of four combinations of high and low population density and high and low lightning flash density. This verification only examines if the patterns of population density and lightning flash density appear to be correct. However, it does not compare the lightning fatality risk to the observed lightning fatalities (gray dots in Figure-3), which is done in the subjective verification of the close-up maps and in the section on objective verification. Overall, the CONUS map for lightning fatality risk shows good correspondence between the overlap of population and lightning flash densities.

The calculated lightning fatality risk appears to be correct in areas of high lightning flash density and high population density. The highest lightning flash densities in the U.S. are in Florida, the Southeast U.S., Gulf States, the Mississippi and Ohio River Valleys, and the Front Range of the Rocky Mountains and some other mountains in the Desert Southwest. The high population densities in the high lightning areas are readily apparent in the lightning fatality risk maps, e.g. Miami, Orlando, Atlanta, Dallas, Houston, St. Louis, Chicago, Denver, etc.

Just as important for the verification of calculated lightning fatality risk are high population densities in areas of low lightning activity. For example, the Pacific Coast and Colorado Plateau have relatively low lightning activity (Figure-1) and, as expected, large cities in these areas are not seen in the risk map, e.g. San Diego, Los Angeles, San Francisco, Salt Lake City, Portland, Seattle, and others.

The calculated lightning fatality risk also appears correct in areas of low population density in areas of high lightning flash density. This is most easily seen in the eastern half of the CONUS. There are no major centers of calculated lightning fatality risk outside the major cities in this area.

Finally, the calculated lightning fatality risk show good correspondence to lightning fatality risk in areas of low population density and low lightning flash density. This can be seen in the rural areas of the Pacific Northwest and the Colorado Plateau. There are no major centers of calculated lightning fatality risk in those areas.

2) Visual inspection of close-up maps

A visual inspection of the close-up maps is even more instructive. It not only confirms proper calculation at finer horizontal scales than can be seen with the CONUS map, but the overlay of the observed lightning fatalities (black dots) allows a visual inspection of the spatial correspondence between calculated lightning fatality risk and actual fatalities.

There is one persistent pattern where the lightning fatality risk map does not verify well. There are many rural areas that have widely dispersed observed lightning fatalities without an apparently corresponding level of calculated lightning fatality risk. It may that the color scale used on the lightning fatality risk map does not have sufficient resolution at the lower risk levels. Another possibility is the difference in the period of records between the observed lightning fatalities (1959-2006) and calculated risk (2003-2012). The authors initially assumed the difference in periods would not be important. However, on further reflection, this may help explain the problem with rural areas. The frequency of lightning fatalities in the U.S. has been decreasing since the 1940s (Roeder, 2012; Holle, 2012a; Holle et al., 2005a; Ashley and Gilson, 2009; Lopez and Holle, 1998). In addition, the lightning fatalities in the U.S. have been shifting from rural occupations such as farming and ranching (Holle, 2012a.; Holle et al., 2005a; Lopez and Holle, 1998). Although these studies did not specifically analyze the trend since 1959, it is reasonable to assume the trend is representative of that period. Therefore, the observed lightning fatalities shown here likely contain somewhat more rural fatalities in earlier years than is represented in the calculation of lightning fatality risk.

a) <u>Florida Map</u>: The Florida map (Figure-5) is useful for verifying the lightning fatality risk technique since that state has the highest lightning fatality rate in the U.S., the highest lightning flash density, and some of the sharpest gradients of population density. The highest flash rates in the U.S. are in 'Lightning Alley' across central Florida (Figure-6).

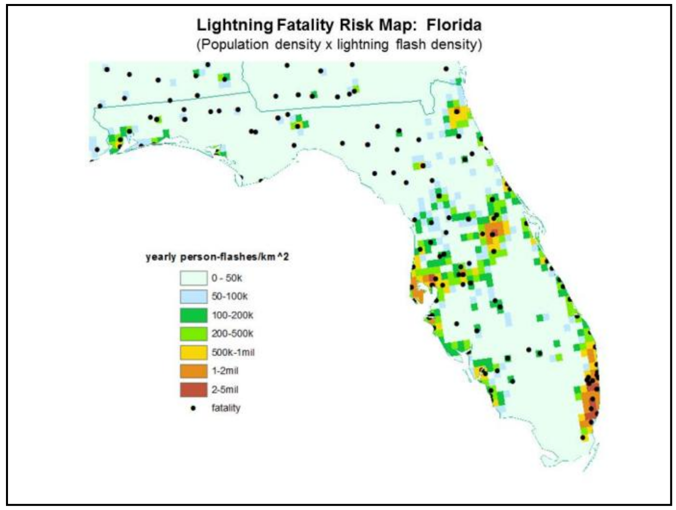


Figure-5. Lightning fatality risk map for Florida.

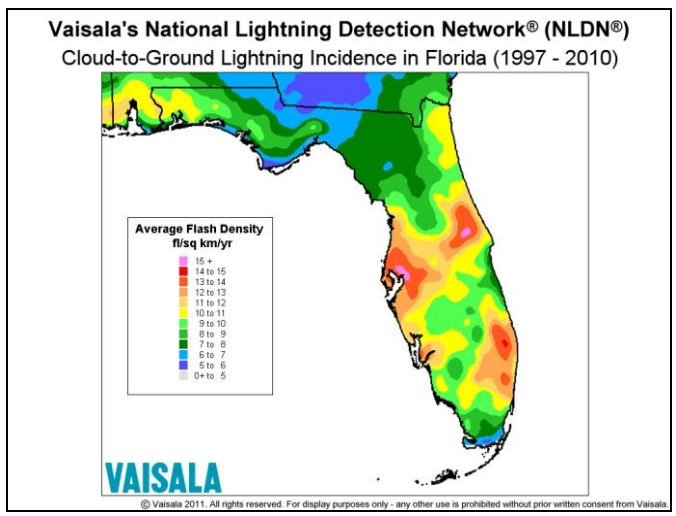


Figure-6. Lightning flash density for Florida. Note that the flash density color scale is different than for the CONUS in Figure-1.

Population centers in 'Lightning Alley' are clearly visible in the Florida lightning risk map, e.g. Tampa/St. Petersburg and Orlando, both with more than 1M yearly person-flashes/km^2. Likewise the high population density of the Miami area is evident, even though that area has less lightning activity than central Florida. The city of Jacksonville is also evident, even though it lies in an area of relatively lower lightning activity. Even Port Charlotte, in southwest Florida, can be seen in the lightning fatality risk map as a region with more than 500k person flashes/km^2. All of these areas show one or more spatially-proximate fatalities.

The areas of low lightning fatality risk in Florida are very encouraging. For example, there is a rapid decrease of population density southeast of Orlando due to rural areas and swamps. Even though the lightning flash rate remains high in that area, the drop of lightning fatality risk due to the much lower population density is shown in the lightning fatality risk map. Likewise, the extremely rapid decrease in population west of Miami/Ft. Lauderdale is also indicated by the lightning fatality risk map. These strongly indicate that the lightning fatality risk technique was implemented properly. It is also encouraging that these two areas have no reported fatalities.

Central and southern Florida exhibit excellent spatial coherence between the new risk map and fatalities, whereas northwest Florida, including the panhandle, exhibits less spatial coherence. This difference between northwest Florida and the rest of the state may be due to differences in behavior between the people in those regions. Perhaps the people in northwest Florida spend more time outside far away from their residences where their population is counted, either in outdoor recreation or employment, as compared to the rest of the state. Outdoor activities increase lightning risk. Or, as noted previously, the difference may be due to the difference in periods of the observed lightning fatalities and calculated lightning fatality risk.

b) <u>Southeast U.S. Map</u>: The Southeast U.S. map (Figure-7) is useful since that region has some of the higher lightning and lightning fatality rates in the U.S. As expected, Atlanta, GA is a prominent maximum of lightning fatality risk. The population density more than compensates for this city being near an area of decreasing lightning activity over the Appalachian Mountains (see Figure-1). Note the dense clustering of observed fatalities directory over this high-risk area.

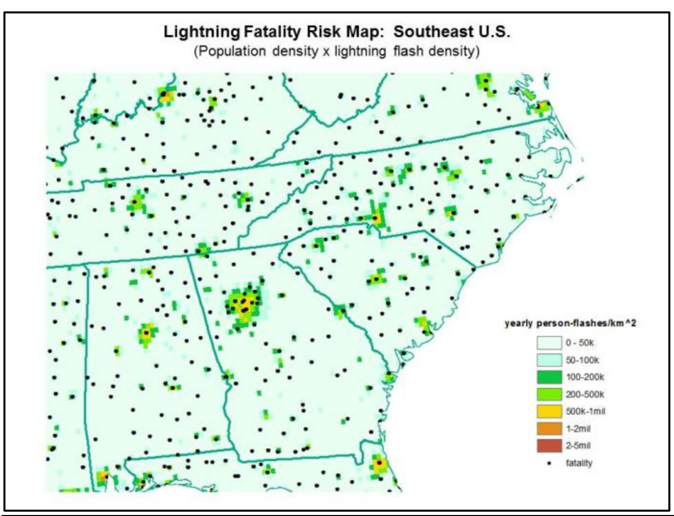


Figure-7. Lightning fatality risk map for the Southeast U.S.

c) <u>Gulf States Map</u>: The Gulf States map (Figure-8) is useful since that region also has some of the higher lightning and lightning fatality rates in the U.S. There are two strong maxima of lightning fatality risk over Dallas and Houston, TX. The area between these cities has a fairly constant lightning flash density so the population densities in these cities produce higher lightning fatality risk.

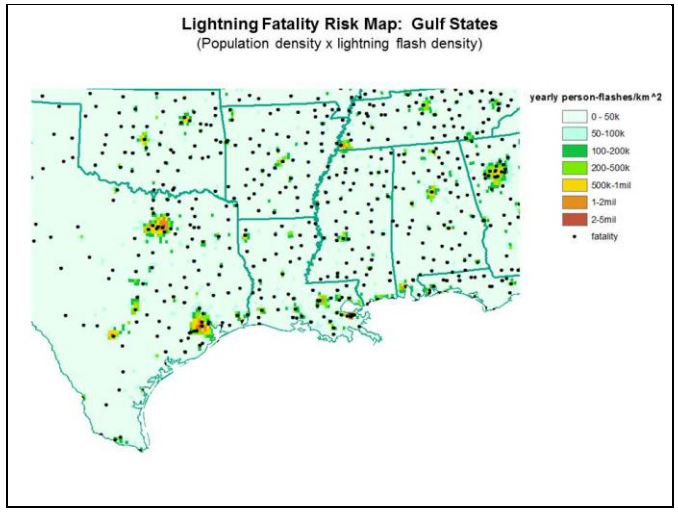


Figure-8. Lightning fatality risk map for the Gulf States of the U.S.

The spatial coherence in the Southeast U.S. shows a mixture of good correspondence in the population centers and poor correspondence outside the population centers. There is a concentration of lightning fatalities, the black dots, in major cities such as Atlanta, GA, and Dallas and Houston, TX. However, there appears to be a fairly high and fairly uniform distribution of lightning fatalities across the region outside the major cities. As with northwest Florida, this may be related to the amount of time people spend outside away from their residences, either in recreation or employment. Or as noted previously, the difference may be due to the difference in data periods of the observed lightning fatalities and calculated lightning fatality risk.

d) <u>Northeast U.S. Map</u>: The Northeast U.S. map (Figure-9) is useful since that region has some of the highest population densities in the U.S. but only moderate lightning activity.

It is encouraging that the lightning fatality risk map indicated several small but intense maxima at New York City, Philadelphia, and Washington D.C. Even nearby large cities can be resolved, e.g. Baltimore, MD. This matches the strong lightning fatality in this area recently revealed by the gridded lightning fatality map by Ashley and Gilson (2009) (Figure-4). This feature was not obvious in previous geographical analysis of lightning fatalities in the U.S. that stratified the data by states. While a weak maximum in the state maps was seen in New Jersey, it was not obvious since the lightning fatalities in and around New York City were counted in New York State and New Jersey, those in and around Philadelphia were counted in Pennsylvania and New Jersey, those in and around Baltimore were counted in Maryland, and those in and around Washington D.C. were counted in Maryland or Virginia.

The spatial coherence in the Northeast U.S. shows very good correspondence in the population centers, especially between New York City and Washington D.C. There is a moderate amount of lightning fatalities outside the population centers, but the density is not as high as in Northwest Florida and the Southeast U.S. Again, this may be related to the amount of time people spend outside away from their residences, either in recreation or employment. Or, as noted previously, the dissimilarity may be due to the difference in periods of the observed lightning fatalities and calculated lightning fatality risk.

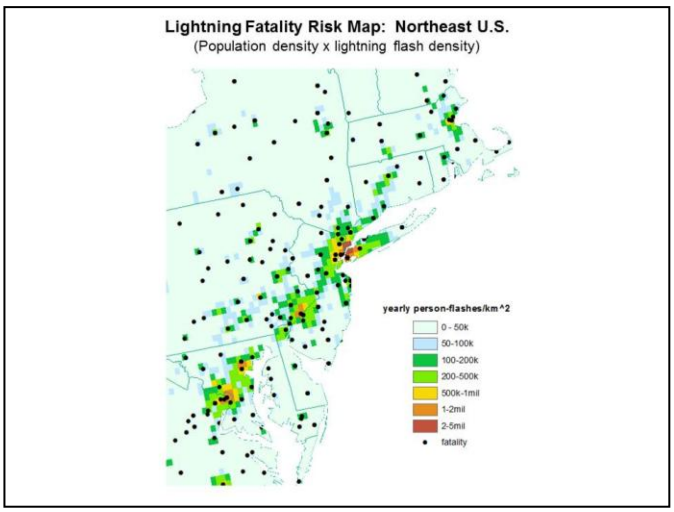


Figure-9. Lightning fatality risk map for the Northeast U.S.

e) *Colorado Map:* The Colorado map (Figure-10) is useful since that region has some very localized lightning fatalities. Colorado has a strong maximum of lightning along the Front Range of the Rocky Mountains, especially along the Palmer Divide (Figure-11). Combined with the concentration of cities near these features, this leads to two strong maxima of lightning fatality risk in this area of Colorado.

The spatial coherence between lightning fatality risk and observed fatalities shows very good correspondence in the population centers of Colorado, especially in the Denver and Colorado Springs areas. Note that both the maxima of lightning fatality risk and the observed lightning fatalities are coincident and displaced eastward from the maxima of lightning flash density. While the lightning is concentrated over the mountains, the population is concentrated in the plains and foothills just east of the mountains. In this case, the lightning fatality risk method worked very well, catching these localized details.

There is a wide scatter of low density observed lightning fatalities across the mountains in the western two-thirds of the state. Colorado has a reputation for relatively high frequency of lightning fatalities due to wilderness recreation. However, the local maxima of observed lightning fatalities in Figure-10 are fairly concentrated in the major cities. On the other hand, the density of the observed fatalities in the mountains is higher than in the mountainous regions in the surrounding states of Wyoming and New Mexico, suggesting that Colorado's reputation for more lightning fatalities in the wilderness may be at least partially deserved. As noted previously, the difference in periods of the observed lightning fatalities and calculated lightning fatality risk may be a factor.

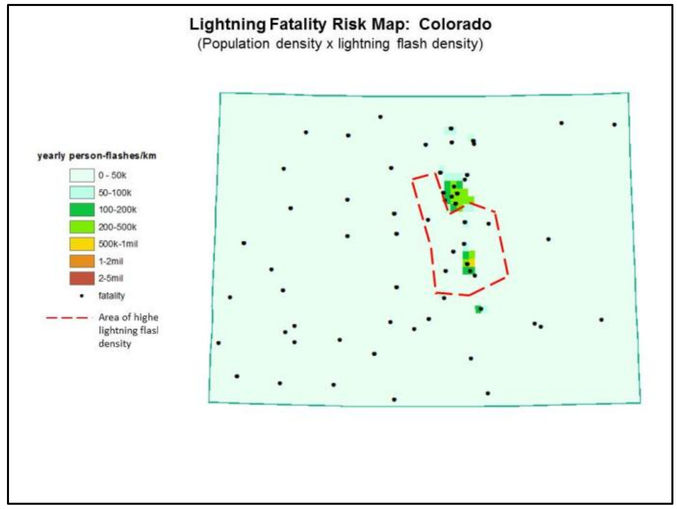


Figure-10. Lightning fatality risk map for Colorado. The red dashed line outlines the area of highest lightning flash density in the state, taken from Figure-11.

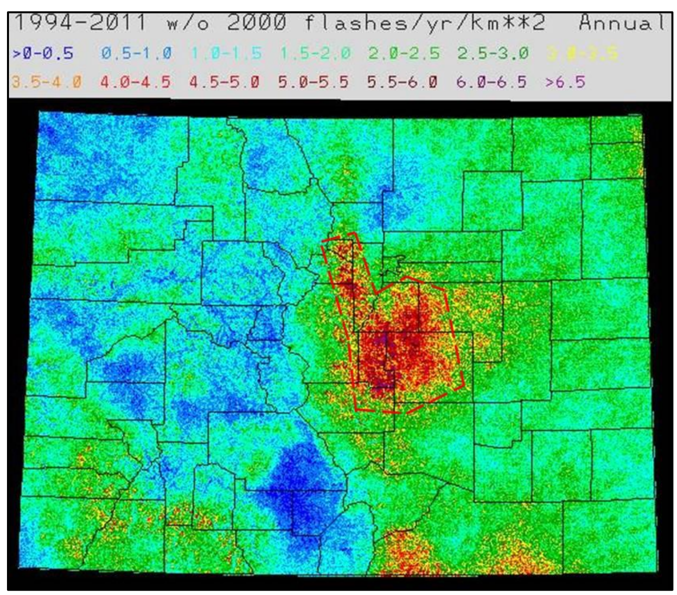


Figure-11. Annual lightning flash density climatology for Colorado (1994-1999, 2001-2011) (Hodanish and Wolyn, 2012). The red dashed line outlines the highest lightning flash density, which is also shown in Figure-10.

f) <u>Midwest Map</u>: The spatial coherence between lightning fatality risk and lightning fatalities shows good correspondence in some of the Midwest population centers: Chicago, IL, St. Louis, MO, Indianapolis, IN, and others. However, there are high concentrations of observed lightning fatalities in rural areas. As before, this may be due to the amount of time that people spend in outdoor activities away from their residences.

The upper Midwest has a moderate lightning flash rate that tends to decrease northward (Figure-1). However, there are some large cities in this region that lead to strong lightning fatality risk maxima despite the decreasing flash rates, especially Chicago, IL (Figure-12).

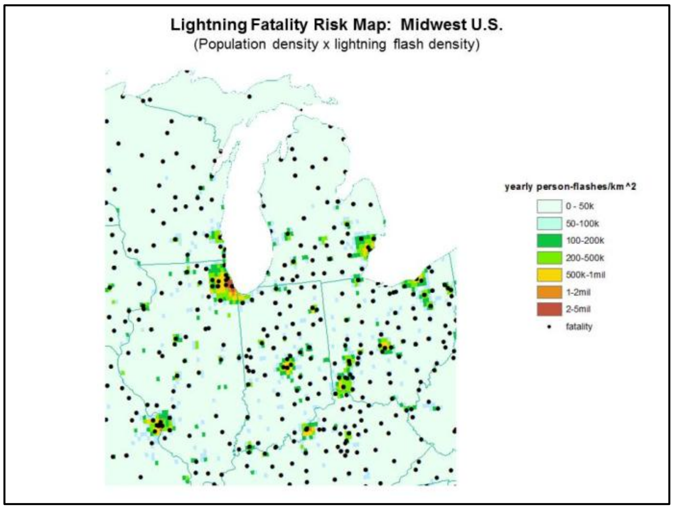


Figure-12. Lightning fatality risk map for the Midwest.

3) More Rigorous Comparison of CONUS

A semi-quantitate assessment of the CONUS lightning fatality risk map (Figure-1) was conducted. The relative magnitudes of 46 local maxima were visually estimated from the lightning fatality risk map (Figure-3) and then compared with the observed lightning fatalities (Figure-4) for the same locations. The results are listed in Table-4.

There was 97.8% agreement between the locations of local maxima in the lightning fatality risk map and the observed fatalities. The only disagreement was Reno, NV, which may be due to this location's relatively small population that may have been lost in the smoothing of the lightning fatality map.

There was only 69.6% agreement when comparing the intensities of lightning fatality risk with observed lightning fatality. If one allows for a difference in one category of intensity to the account for this smoothing, then agreement on intensity becomes 95.7% Only two of the disagreements were by two categories of intensity and none disagreed by three or more categories. Other contributions to the disagreements could be the inherent subjectivity of the process and the difference in the period of records. In addition, there were large shifts in the population density in the U.S. during the time period of observed lightning fatality map (1959-2006), especially a shift towards the 'Sun Belt', which complicates the comparison with the time period of the lightning fatality risk map (2003-2012). Unlike the previous verifications does indicate if the lightning risk technique correctly captures lightning fatality.

B. Objective Verification

The objective verification is a comparison of the lightning fatality risks with the actual lightning fatalities across the CONUS. As discussed previously, the lightning fatalities are taken from the database in Ashley and Gilson (2009). The difference in period of records was initially assumed to not be significant: 2003-2012 for the lightning fatality risk vs. 1959-2006 for the lightning fatalities. However, as will be discussed later, this assumption mat not be entirely true. Since the map of the lightning fatalities shown in Figure-4 had extensive smoothing, this objective verification was done using Ashely and Gilson's original data set of lightning fatalities. The lightning fatality risk (population density x CG lightning flash density) and lightning fatality were analyzed on the same grid spacing with the same smoothing. A linear regression of observed lightning fatality on calculated lightning fatality risk was then performed on the data pairs.

Linear regressions were performed on eight variations of the data: two grid spacings, each with four different amounts of smoothing (Table-5). A Gaussian smoothing function was used with the scale factor based on various number of grid spaces. The best linear regression was the 1.0° lat/lon grid with the Gaussian smoothing of 1.5 grid spaces and is shown in (1).

$$y = (3.27 \times 10^{-8})x - 0.84 \qquad (1)$$

$$r^2 = 0.820$$

where y = lightning fatalities
(fatalities/degree^2)

x = lightning fatality risk
(annual person-flashes/km^2)

Even though this linear regression has the best correlation coefficient, a different linear regression using the 0.5° lat/lon grid and 1.5 grid space Gaussian smoothing is shown in Figure-13. This linear regression was chosen because the associated maps for this grid spacing and smoothing appear to show the overall pattern while preserving the most fine-scale detail (Figure-14). This preferred (though lower r^2) regression is shown in (2).

$$y = (1.13 \times 10^{-7})x + 0.25 \qquad (2)$$

$$r^2 = 0.773$$

where y and x are as in (1)

Table-4. Subjective verification of the lightning fatality risk map vs. actual lightning fatalities.

	Lightning Fatalities (Ashley and Gilson, 2009)			**Lightning Fatality Risk Map**	
No.	**Location**	**Relative Intensity**		**Location**	**Relative Intensity**
1	Central Florida	Extreme		Yes (Tampa, Orlando)	Extreme
2	NYC to DC	Extreme		Yes (New York City, Phila., D.C.)	Extreme
3	Southwest Florida	Extreme		Yes	Extreme
4	Denver	Major		Yes	Minor
5	Houston	Major		Yes	Extreme
6	New Orleans	Major		Yes	Major
7	North Carolina	Major		Yes (Greensboro, Raleigh, Matthews, Fayetteville)	Major
8	Chicago	Major		Yes	Extreme
9	Indianapolis	Major		Yes	Major
10	Detroit to Pittsburg	Major		Yes (Detroit, Cleveland, Pittsburgh)	Major
11	Atlanta	Minor		Yes	Major
12	Salt Lake City	Minor		Yes	Slight
13	Phoenix to Tucson	Minor		Yes (Phoenix, Tucson)	Minor
14	Minneapolis	Minor		Yes	Major
15	Memphis	Minor		Yes	Major
16	South Carolina	Minor		Yes (Columbia, SC)	Minor
17	East Oklahoma	Minor		Yes (Oklahoma City, Tulsa)	Major
18	Mobile	Minor		Yes	Major
19	St. Louis	Slight		Yes	Major
20	Los Angeles	Slight		Yes	Slight
21	El Paso	Slight		Yes	Slight
22	Flagstaff	Slight		Yes	Slight
23	Albuquerque/Santa Fe	Slight		Yes	Slight
24	Omaha	Slight		Yes	Slight
25	Boston	Slight		Yes	Slight (lobe)
26	Seattle	Null		Yes	Null
27	Tacoma	Null		Yes	Null
28	Boise	Null		Yes	Null
29	Portland, OR	Null		Yes	Null
30	Las Vegas	Null		Yes	Null
31	Reno	Null		No	Slight (barely)
32	San Francisco	Null		Yes	Null
33	San Diego	Null		Yes	Null
34	Cheyenne	Null		Yes	Null
35	Bismarck	Null		Yes	Null
36	Rural SW of Orlando	Null		Yes	Null
37	Everglades	Null		Yes	Null
38	West Virginia	Null		Yes	Null
39	Maine	Null		Yes	Null
40	Southern NM	Null		Yes	Null
41	Southwest TX	Null		Yes	Null
42	San Antonio-Austin	Major		Yes	Slight (lobe)
43	Kansas City, MO	Major		Yes	Slight
44	Des Moines	Minor		Yes	Slight (lobe)
45	Albany, NY	Slight		Yes	Slight (lobe)
46	Hartford, CT	Slight		Yes	Slight (lobe)

Table-5. Results of the linear regression of observed lightning fatality on calculated lightning fatality risk.

VARIATION EXPLAINED (r^2)

	Grid Spacing (° lat/lon) <# of data pairs>	
Smoothing (Gaussian Scale factor)	**0.5°** <6,136>	**1.0°** <1.534>
None	0.541	0.654
0.5 grid	0.626	0.724
1.0 grid	0.744	0.810
1.5 grids	0.773	0.820

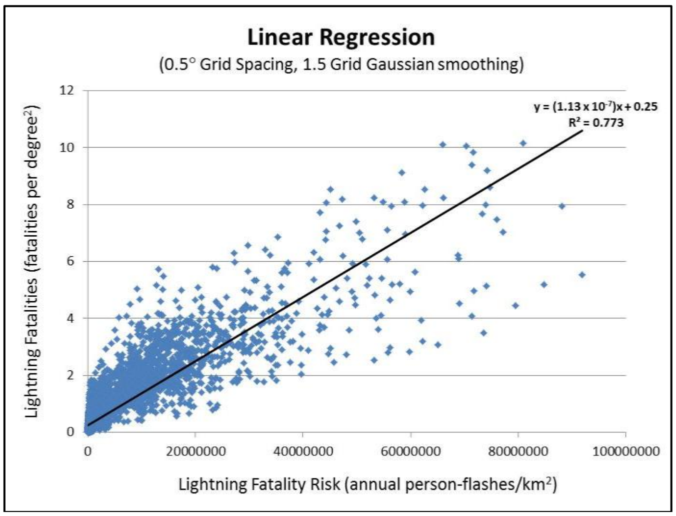
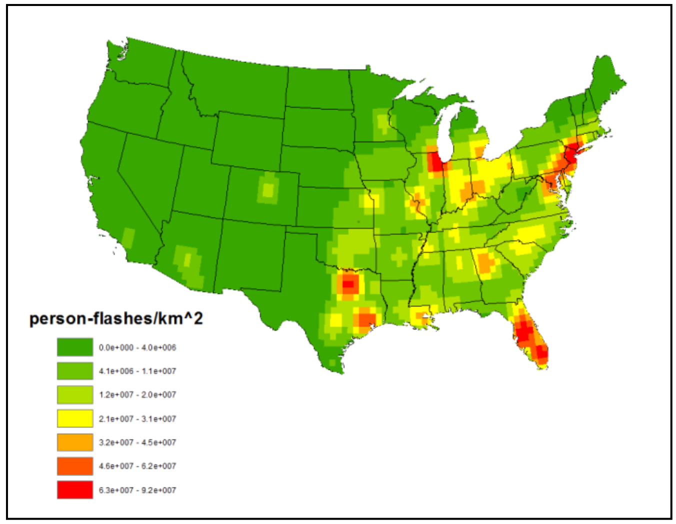


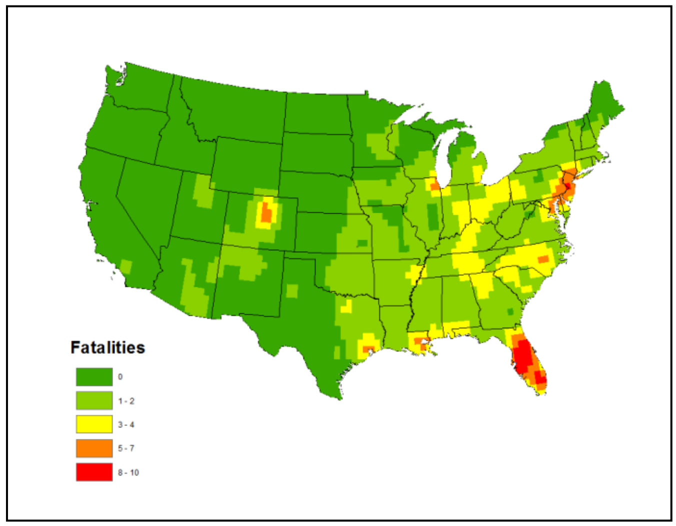
Figure-13. The linear regression is shown for the 0.5° grid spacing with 1.5 grid smoothing. While other regressions had higher r^2, the corresponding map appeared to show the overall pattern while preserving the most fine-scale detail.

Linear regression through the origin was considered but not used. While one might assume that zero lightning flash density or zero population density would lead to zero lightning fatalities, that assumption does not consider people traveling to outdoor areas, which would not be assessed in the population density which is counted where people live. Since the assumption of intersection at the origin cannot be made *a priori*, regression through the origin is not justified.

The linear regression in Figure-13 (grid spacing of 0.5°, 1.5 grid Gaussian smoothing) appears to have a systematic bias. At lower lightning fatality risk, the fatalities appear to trend toward being above the linear regression. At higher risk, the fatalities may be trending toward larger deviations below the regression, even though there may be about equal numbers



a) Calculated lightning fatality risk



b) Observed lightning fatalities.

Figure-14. Map of (a) calculated lightning fatality risk and (b) observed lightning fatalities for the 0.5° grid spacing with 1.5 grid smoothing.

above and below the regression. This suggests a nonlinear regression may give better results, perhaps a best-fit log-linear or quadratic polynomial. The log-linear regression was dominated by the large number of lower risk values and so yielded a poor r^2 of only 0.311, much lower than the linear regression. Of course, risk values of zero had to be excluded to allow the log-linear regression, reducing the number of data pairs to 1204, as compared to 1534 in the full data set. The quadratic regression yielded an r^2 of 0.786, slightly better than the linear regression (r^2 of 0.773) for this grid spacing and smoothing. More importantly, the quadratic regression did not have the systematic bias of the linear regression. Given these two factors, the quadratic regression is preferred. However, care must be taken in extrapolating the quadratic regression to higher values of lightning fatality risk. At risk values higher than about 7.5×10^7 annual person-flashes/km^2, the predicted lightning fatalities will decrease at higher risk, which is contrary to expectation. Care must also be taken with the linear regression since it tends to underestimate the lightning fatalities at lower risk and significantly overestimate the fatalities at higher risks. The quadratic regression is given by (3) and shown in Figure-15.

$$y = -1x10^{-15}x^2 + 2x10^{-7}x + 0.167 \quad (3)$$

$$r^2 = 0.817$$

where y = lightning fatalities (fatalities/degree^2)

x = lightning fatality risk (annual person-flashes/km^2)

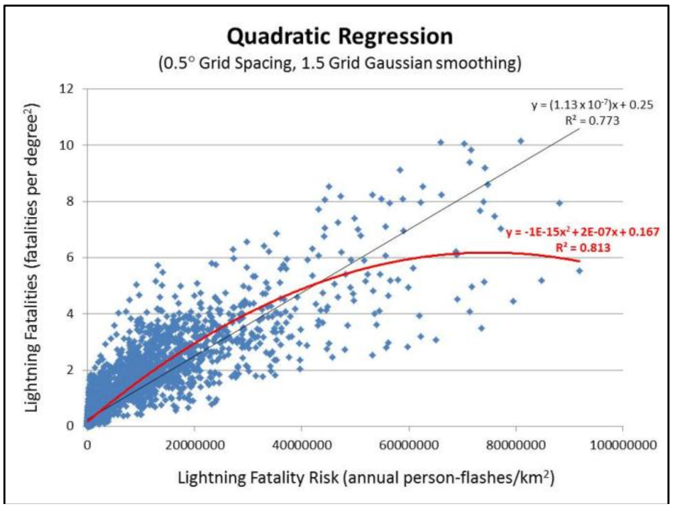


Figure-15. The quadratic regression is shown for the 0.5° grid spacing and 1.5 grid smoothing. This quadratic regression had a slightly higher r^2 than the linear regression, but more importantly did not have the systematic bias of the linear regression.

A quadratic regression was also marginally better than the linear regression for the grid spacing and smoothing with the best performance (1.0° lat/lon, 1.5 grid point smoothing), $r^2 = 0.857$ vs. 0.820, respectively. This quadratic regression is given by $y = -5x10^{-17}x^2 + 5x10^{-8}x + 0.563$, where y and x are as defined previously.

A visual comparison of Figure-14 suggests that the lightning fatality risk map shows sharper structure than the lightning fatality map, even though they are plotted with the same grid spacing and smoothing. There are four possible explanations. The first possibility is it could be an artifact of the color scales and the sharper structure is not real. This might be eliminated as a cause if color scales had been chosen to represent the range of each data set and using the same number of colors. The second possibility is it could also indicate that people's lightning safety behavior changes from cities to rural with higher risk in the rural areas. For example, rural people might spend more time outside and/or not going to safety as quickly when lightning threatens. The latter might be from action being intentionally delayed and/or safe locations simply being farther away. The third possibility is it could also indicate that outside activity away from residences, where population is counted, may be important. For example, travel to outdoor recreation or employment or tourism. The fourth possibility is that cities may be inherently safer from lightning than rural areas, regardless of the amount of time people spend outside or speed seeking safety. For example, lightning may be more likely to strike buildings and be dissipated through the grounding system.

V. FUTURE WORK

The lightning fatality risk map presented here was a preliminary attempt to establish and verify the new method. There is considerable room for improvement. Since the method is verifying well, the most important work is to extend the method to other countries besides the U.S. This would first be done preferably in countries where the pattern of lightning fatality are already known for additional verification before applying it in developing countries where the lightning fatalities may not be reported well. This is especially important since the main motivation for this work was to help guide lightning safety efforts in developing countries. If the lightning fatality risk method continues to verify well, then lightning fatality risk maps could be constructed for the entire Earth, perhaps built and distributed by the World Meteorological Organization to help guide lightning safety initiatives globally.

Some areas of the calculated lightning fatality risk maps showed poor correspondence with the observed lightning fatalities, especially in some rural areas. This may be due to differences in the amount of time people in different areas spend outside at-risk from lightning away from their residences where their population is counted, e.g. from outdoor recreation and/or employment. If the appropriate data were available, the lightning fatality risk calculation could be modified to take into account these factors. Unfortunately, the authors do not know if such metrics for time spent outside and distance from residence are available. Another possible reason may be that the color scale used for the lightning fatality risk map may have insufficient resolution at lower values. Alternate color scales should be explored to see if this resolves the issue.

Another possible explanation for poor correspondence in some rural areas may be the older period of the lightning fatalities. As discussed earlier, the declining lightning fatality rate in the U.S. and shift of lightning fatalities away from rural occupations may over-represent rural lightning fatalities compared with the calculated lightning fatality risk. Redoing the maps with the observed lightning fatalities from the same period as the calculated lightning fatality risk should be done to see if this helps resolve the issue.

The lightning fatality risk map developed here was for the annual lightning risk. It would be useful to apply the same method but for monthly or seasonal maps. Likewise, diurnal patterns of lightning fatality risk may be useful. For example, other lightning studies have noted a relatively high frequency of lightning after local midnight from Oklahoma to Iowa (Holle, 2012b). This is not critically important to lightning safety since most people in those states are inside buildings with wiring and plumbing that provide significant lightning safety. However, other countries may not have such lightning safe buildings and the local populations would be exposed to risk even if inside at night.

The response of observed lightning fatalities to calculated lightning fatality risk may not be linear. A residual plot of the linear regression might make the nonlinear patterns easier to detect. Some nonlinear regressions were briefly considered and this topic should be explored further. For example, a nonlinear regression on the residual plot might be useful with the resultant nonlinear regression to be added to the linear regression for the final regression.

The CG lightning flash rate was used in constructing the lightning fatality risk map. However, the rate of ground contact points would be more appropriate. This is not the same as the stroke rate, since in flashes with multiple strokes, the subsequent strokes often strike the same point and represent little additional risk of lightning fatality (the first stroke will usually be enough to kill a person). However, the subsequent strokes also often contact the ground elsewhere (Valine and Krider, 2002), often a few km away, and so represent significant additional risk. Unfortunately, the number of ground strike points is not reported by most lightning detection systems. However, it could be inferred from stroke detection systems, as demonstrated by Cummins (2012).

Another important factor in lightning fatalities is behavior of the local population. Groups that spend more time outside, especially during lightning activity, or cannot or will not seek safety when lightning threatens have a larger likelihood of lightning fatality. If the data were available or inferable, variations in behavior could be included as another multiplicative factor in the construction of lighting fatality maps, perhaps as a percent of time spent at risk. However, in areas without lightning safe locations such as some parts of the developing world, the variations in behavior would not be important.

The lightning fatality risk map presented here assumed that the population density was always at the reported grid point. However, there are areas with significant population change throughout the year, e.g. due to tourism. In addition, local populations may move out of the immediate area during lightning season, e.g. recreation. In some developing countries, migration may also be an important factor.

The verification would be best done with lightning fatality data sets that match the same period of time, grid spacing, and smoothing. As mentioned previously, the observed lightning fatality map covered 1959-2006, while the lightning fatality risk map covered 2003-2012 for its lightning data and 2000 for its population data. During the time of the observed lightning fatalities, there has been considerable change in the population pattern in the U.S., especially a shift towards the 'sun belt'. In addition, the verification may allow the construction of a predictive model to convert lightning fatality risk into expected lightning fatality. The regression analysis in the objective verification is a first step in creating such a predictive model.

The lightning fatality risk map indicates a strong concentration of lightning risk in major cities. This could refine how lightning safety education is performed in the U.S., placing more emphasis on education tuned to specific cities rather than just states or regions. However, there is some question if this would be true since recent years have seen a shift of lightning fatalities in the U.S. toward outdoor sports and recreation (Holle, 2012a; Holle, 2005b; Holle, 2005c), so the lightning fatalities may be in parks and outdoor recreation areas near the cities, but not necessarily in the cities themselves. Even so, tuning the lightning safety messages to the individual cities might still be beneficial. However, the lightning fatality reports may not allow such a precise analysis.

Finally, as discussed in a previous section, the linear regression of lightning fatalities on lightning fatality risk may have some systematic bias. A residual plot would help confirm that bias. If the systematic bias is true, a non-linear regression may provide a better correlation coefficient.

VI. SUMMARY

A new method to estimate the risk of lightning fatality was developed. This method uses a GIS to combine lightning flash density and population density to map the spatial distribution of lightning fatality risk. This method was applied to the contiguous U.S. and verified against the observed lightning fatalities. The method verifies well with the best quadratic regression having an $r^2 = 0.857$ and the best linear regression having an $r^2 = 0.820$ for the 1.0° lat/lon grid with 1.5 grid point Gaussian smoothing. Further refinements are possible.

The main motivation for developing the lightning fatality risk method is to potentially help guide lightning safety efforts in developing countries. Since the method risk works well for the U.S., it may be useful in some developing countries where the geographical distribution of actual lightning fatalities may not be well documented. Given that the distribution of CG lightning can be reasonably well determined from the various global lightning detection networks, or other sources if available, and if the distribution of population density is also known, then GIS software can be used to create lightning fatality risk maps for those countries. These maps could then be used to guide lightning safety efforts in those countries to be more cost-efficient and perhaps more effective by spending funds on areas where it is most needed and by tailoring the efforts to the people living in that area, respectively. While a map of lightning fatality risk is not needed for the U.S., since the geographical distribution of lightning fatalities there is well known, the method still may help refine lightning safety education in the U.S. by suggesting the opportunity focus on population centers in addition to states or regions.

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