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Changes in U.S. Annual Lightning Fatalities from 1990-2015

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***Abstract*—Two updates are presented for the statistical model that predicts the expected number of lightning fatalities in the U.S. for any year and the number expected by any day within that year. The 95% confidence intervals for both are also updated. The update adds the most recent annual U.S. lightning fatalities for 2014 and 2015. Some older data that is no longer representative of the current U.S. lightning fatalities are also excluded. A new graphic display is presented that allows easy interpretation of the observed lightning fatalities as they accumulate throughout the year vs. predicted values. Two changes in the trend of U.S. annual lightning fatalities are identified: one beginning in 1994 and one beginning in 2008. The first model update is for 1994-2015 and the second is 2008-2015.**

***Keywords*—lightning safety, lightning fatalities**

I. Introduction

The annual lightning fatalities in the U.S. have been generally declining since the 1940s [Fig. 1] [Roeder, 2015; Roeder, 2014; Roeder, 2013; Roeder, 2012; Holle, 2012; Ashley and Gilson, 2009; Holle et al., 2005; Lopez and Holle, 1998]. This declining rate creates difficulties in estimating the current fatality rate. Traditionally, the National Weather Service uses a running 30-year mean for annual fatalities from various weather phenomena. While this is appropriate for weather fatality rates that have no overall trend in time, it can lead to misleading results for fatality rates that are changing over time. Since U.S. annual lightning fatality rates have been declining, the 30-year running mean overestimates the current rate. In such cases, the National Weather Service also uses a running 10-year mean. While a lag still exists, it yields a rate more representative of the current rate. However, a running 10-year mean is overly sensitive to extreme events. A better approach is to recognize the lightning annual fatality rates are varying over time and to model that trend. This results an estimate that has no lag, i.e. is representative of the current year, and is also consistent with all the previous years. A best-fit negative exponential curve has been previously used to model this trend and percentile regression used to model the error bars. In addition, logistic regression was used to model how the U.S. annual lightning fatalities accumulate throughout the year.

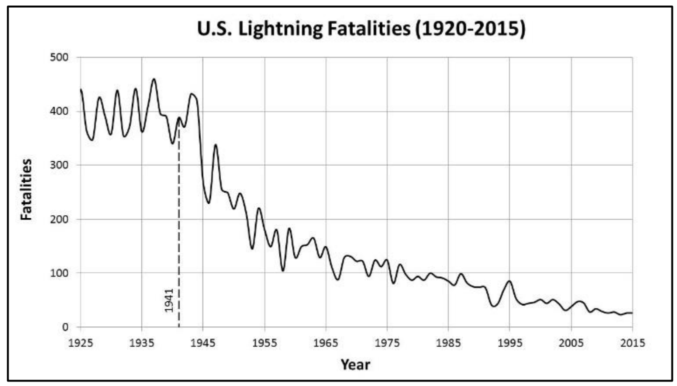

Fig. 1. U.S. annual lightning fatalities for 1940-2015. Lightning fatalities began a general decline around 1941 that has continued through 2015. Data from 1900-1991 are from Lopez and Holle [1998], 1992-2005 are from National Weather Service (2016a) and the 2006-2015 data are from National Weather Service [2016b].

This paper reports new results that add two more years (2014-2015) of U.S. lightning fatalities to the analysis. In addition, a sudden drop in the annual lightning fatalities and a decrease in annual variability beginning in 1994 was identified. The data prior to 1994 was excluded from the updated model since they were no longer representative of the current time. This resulted in a decrease in the estimated lightning fatalities and a decrease in the error bars.

Finally, the two new years of data (2014-2015) reinforce the previous evidence that another discontinuous drop in U.S. annual lightning fatalities and the annual variability began in 2008. A second version of the updated model is presented using only the data from 2008-2015. While more than an 8-year period would normally be desired to model annual rates, the data prior to 2008 appear to be no longer representative of the current time. This potential new sudden change in the pattern of lightning fatalities and new predictive model is discussed further in section-IV.

II. First Updated Model: 1994-2013

The original model of the U.S. annual lightning fatalities was developed by Roeder for the period 1941-2013 [Roeder, 2014; Roeder, 2013; Roeder, 2012]. Several updates have been added to the model. The first update added two more years (2014-2015) of U.S. lightning fatalities to the analysis [Roeder, 2015; Roeder, 2014]. As in the previous models, best-fit curves for various percentiles of annual U.S. lightning fatalities were also calculated ±10 years around each year in the analysis. In particular, the 2.5th percentile and the 97.5th percentile provide a 95% confidence interval around the median number of lightning fatalities. The previous percentiles covered 2006-2013 and now cover 2006-2015. The percentile period is less than the period for the number of annual lightning fatalities to allow for the ±10 year calculation period. The addition of the two more recent years to this part of the new model made only minor changes to the predicted number of annual lightning fatalities in the U.S. and its distribution.

The second update changed the period of annual U.S. lightning fatalities used in the analysis. Close examination of Fig. 1 indicated a discontinuous drop in the lightning fatalities beginning in 1994 and continuing thereafter. In addition, the variability of the fatalities year to year decreased at the same time, also indicating a change in the pattern of U.S. annual lightning fatalities began at that time. A close-up of this period makes the change easier to see [Fig. 2]. The cause of this change may be the unofficial nation lightning safety education started by a few individuals in the early 1990s [Cooper, 2012]. The analysis described in the previous paragraph was repeated for the new period 1994-2015. This resulted in a moderate increase in the expected median of U.S. annual lightning fatalities and a large reduction in the upper limit of the 95% confidence interval. More importantly, the expected number is now better centered in the confidence interval. For example, the previous model predicted a median of 22.5 lightning fatalities for 2015 with a 95% confidence interval of 19.6-60.9 deaths. The updated model predicted 33.1 and 16.4-54.9 fatalities for the same year. The observed number in 2015 was 26 deaths. The predictive equations of the updated model are in Table-I. Note that there is another possible upgrade for an even better model discussed in section-IV.

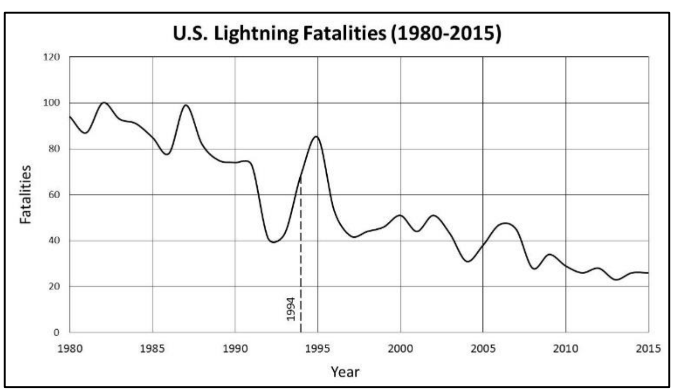

Fig. 2. U.S. annual lightning fatalities for 1980-2015. The pattern appears to have changed starting about 1994, dropping to a lower rate with less variability. Since there is a reasonable explanation for the change, the start of unoffical national lightning safety education in the early 1990s, a new model for U.S. annual lightning fatalities was developed using only data from 1994.

TABLE I. Updated Model for U.S. Annual Lightning Fatalities (1994-2015 (1985-2005, center year ± 10 years)). Use of the median for predicted value is recommended to minimize errors.

Parameter	Best-Fit Equation	r^2
2.5 Percentile	$y = 1{,}458.20e^{-(0.039(x-1900))}$	0.948
5.0 Percentile	$y = 2{,}857.80e^{-(0.045(x-1900))}$	0.921
10.0 Percentile	$y = 5{,}824.60e^{-(0.052(x-1900))}$	0.945
25.0 Percentile	$y = 2{,}799.80e^{-(0.043(x-1900))}$	0.842
Median	$y = 369.84e^{-(0.021(x-1900))}$	0.904
Mean	$y = 2{,}849.6e^{-(0.041(x-1900))}$	0.992
Expected Number	$y = 12{,}706.00e^{-(0.056(x-1900))}$	0.5859
75.0 Percentile	$y = 14{,}699.00e^{-(0.056(x-1900))}$	0.886
90.0 Percentile	$y = 14{,}352.00e^{-(0.054(x-1900))}$	0.8979
95.0 Percentile	$y = 3{,}094.90e^{-(0.037(x-1900))}$	0.851
97.5 Percentile	$y = 1{,}091.70e^{-(0.026(x-1900))}$	0.909

y = predicted value
x = year of interest

The predicted median and 95% confidence interval of the updated model for the next several years is in Fig. 3. Note that the distribution is well into the tail of the negative exponential curve so that the curves appear to be nearly linear. For 2016, the updated model predicts a median of 32.4 with a 95% confidence interval of 15.8 to 53.5 deaths.

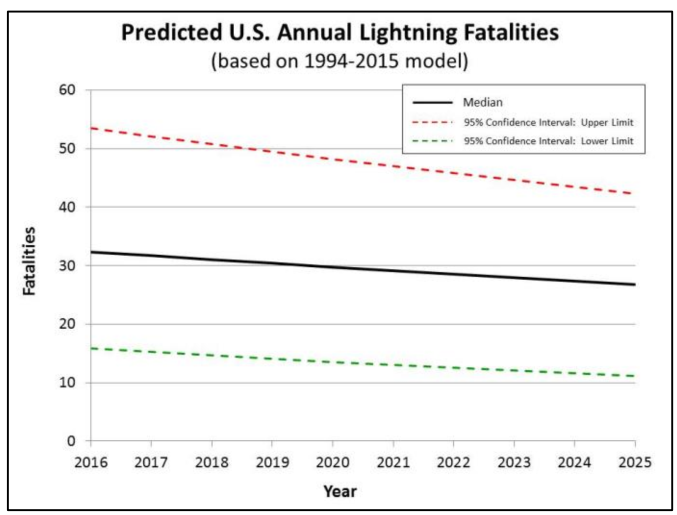

Fig. 3. Predicted median U.S. annual median lightning fatalities anfd the 95% confidence interval for 2016-2015. Note that another possible ugrade for an even better model is discussed in section-IV.

The third update added the data from 2014-2015 to the distribution of U.S. lightning fatalities during the year. The previous model used the dates of the lightning fatalities for 2006-2013. Earlier years were not used since only the total number of lightning fatalities for the year were available, not the dates of the individual deaths. As before, logistic regression was used to model the typical distribution of lightning fatalities throughout the year. The dates for various percentage of lightning fatalities for each year were calculated as listed in Table-II. Then the median date of each percentage for the 10 years (2006-2014) was calculated. The sample size for the lightning fatalities throughout the year appears to have become adequate since most of the median percentiles during the year changed from the previous model by only 2-days or less. Finally, the best-fit logistic equation was calculated for those average percentiles. A manual iteration method was used to minimize the RMSE of the differences between the curve and the desired percentiles. The best-fit logistic equation is in (1) and shown in Fig 4. The RMSE = 1.23%.

$$P = 100[1/\{1 + e^{-(0.0304 + 0.0425(D - 194.8325))}\}] \qquad (1)$$

where P = percentage of the U.S. lightning fatality season,
and
D = day of the year, e.g. 31 June = 182

As in the previous model, the expected number of lightning fatalities in any year, and the percentile of the total expected by any date of the year, are combined to provide the expected number of lightning fatalities by the desired date of that year. A spreadsheet was built to provide these results [Fig 5]. The user enters the desired date and the desired resultants are displayed, e.g. the median number of fatalities for that date, and the median U.S lightning fatalities expected for that year, and the 95% confidence interval for both.

The fourth and final update to the model is a new visualization of the predictions from the model to aid interpretation and application of the model. This new graphical display shows the observed number of lightning fatalities as they accumulated day by day up to the current day. In addition, the expected number of lightning fatalities and its 95% confidence interval as they accumulate day by day up to the current day. This allows an easy quick visual check if the current lightning season is above or below expectations and if the deviation is statistically significant at the 5% level. Two versions of the graphic are usually used, one through the current day and slightly beyond, and one showing the expectations though the end of the year. The former allows detailed examination of how the U.S. lightning fatality season is progressing. The latter shows how the U.S. lightning fatality season is expected to evolve through the rest of the year. An example of these two versions of the new graphic are shown in Fig 6.

TABLE II. MEDIAN DATE FOR VARIOUS PERCENTILES OF ACCUMULATED ANNUAL U.S. LIGHTNING FATALITIES (2006-2015)

Percentile	Day Of Year	Date
0th	1	1 Jan
2.5th	111	21 Apr
5th	122	2 May
10th	142	22 May
25th	166	15 Jun
50th	196	15 Jul
75th	220	8 Aug
90th	248	5 Sep
95th	254	11 Sep
97.5th	267	24 Sep
100th	365	31 Dec

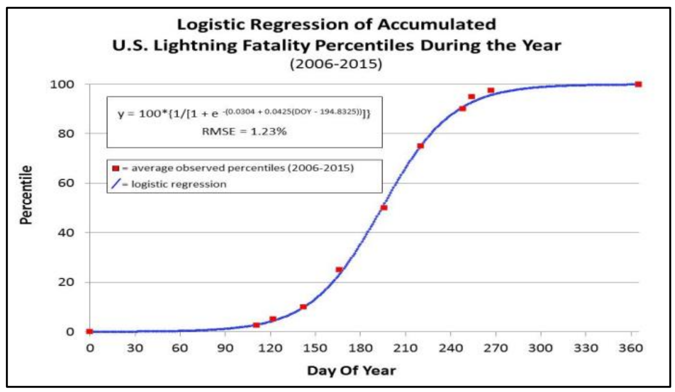

Fig. 4. The logistic regression for the distribution of U.S. lightning fatalities throughout the year.

Date		2.5th Percentile	5th Percentile	Median (50th Percentile)	95th Percentile	97.5th Percentile		
8-Jun-16		15.8	15.5	32.4	42.3	53.5		
		16.5		Mean	Number	21.1		
				23.3	24.3			
		For This Date (Annual Total: 1994-2015, Intra-Annual Percentiles: 2006-2015)						
		Day Of Year	Percentile of Annual Lightning Fataliies (logistic regression)	Expected Number of U.S. Lightning Fatalities by this Date				
		160	19.0	2.5th Percentile	5th Percentile	Median	95th Percentile	97.5th Percentile
				3.0	2.9	6.1	8.0	10.2
						Mean	Number	
						4.4	4.6	

Fig. 5. The spreadsheet that provides the expected number of U.S. lightning fatalities accumulated by a specified date. The user enters the desired date (yellow) and the spreadsheet returns the expected number of U.S. lightning fatalities by that date (green) and its 95% confidence interval. The total number expected for the entire year and its 95% confidence interval is also provided, along with other information.

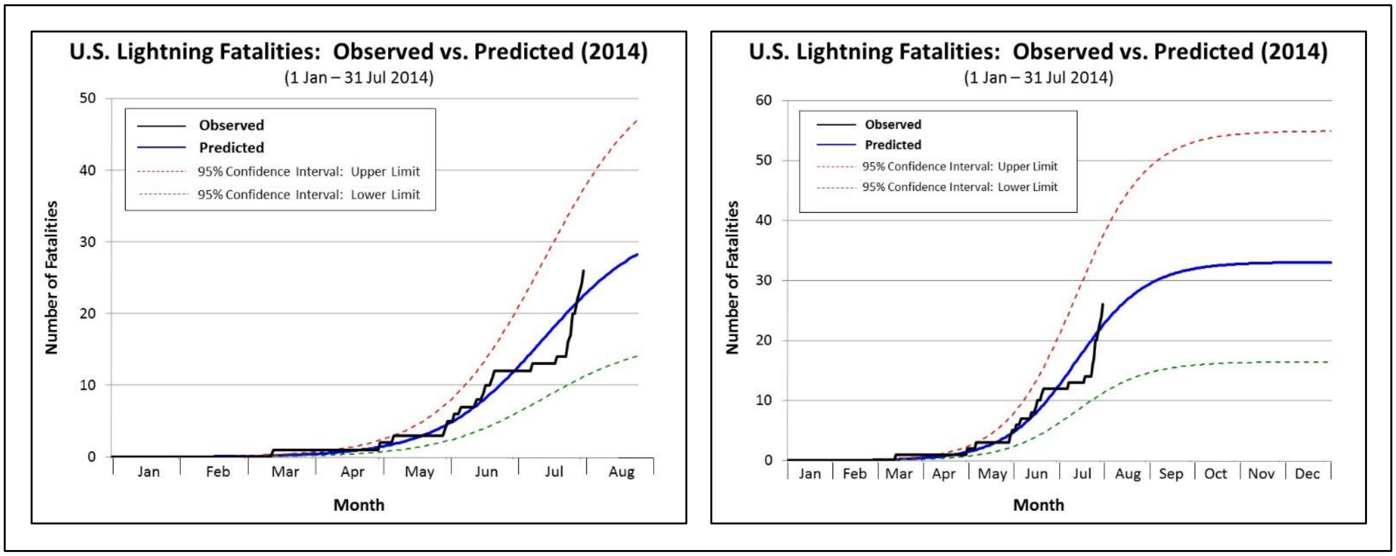

Fig. 6. The new graphics to visualize the observed U.S. lightning fatalities as they accumulate throughout the year and allow easy comparison to the model predictions. Two versions are used, one through the current date and about 4 weeks further to allow detailed examination (left), and one through the current date and through the end of year to show how the lightning fatalities are expected to evolve (right).

III. Applications

There are many applications for the updated equations and graphic for predicting the U.S. annual lightning fatalities and distribution throughout the year. Most importantly, the 95% confidence intervals allow easy identification if the observed lightning fatalities are statistically significantly different from the expected value at the 5% significance level. The other percentiles allow other significance levels. For example, 2011 had a then record low of 26 lightning fatalities in the U.S. This received considerable press coverage. However, the 95% confidence interval for the model at that time was 22.1 to 66.5 deaths. Therefore, even though that year had a record low, it was not statistically significantly different than the expected median of 27.0, though it was very close. Another new record low of 23 lightning deaths was set in 2013. This new record was also not statistically significant since the median and 95% confidence interval was 24.6 and 20.8 to 63.6 deaths.

A second application is identifying if the accumulating lightning fatalities during the year are statistically significantly different than expected. Usually one should wait until enough lightning deaths have occurred before identifying significant trends, typically in June. An example of the utility of tracking accumulating lightning fatalities occurred in 2015. The new graphic (discussed at the end of section-II) showed a sudden upward trend in U.S, lightning fatalities from 21-27 June [Fig 7 (top)]. Although not tested formally, the change in trend appears to be statistically significant; its slope is steeper than the slope of the upper bound of the 95% confidence interval for those dates. As a result, the National Weather Service (NWS) increased lightning safety education messaging at that time. The fatality rate quickly dropped thereafter [Fig. 7 (bottom)], although a causative effect cannot be scientifically proven. This reduction in lightning fatality appeared to be even more statistically significant than the initial increase. When the new graphic flagged the increase in lightning fatalities, Vaisala, Inc.

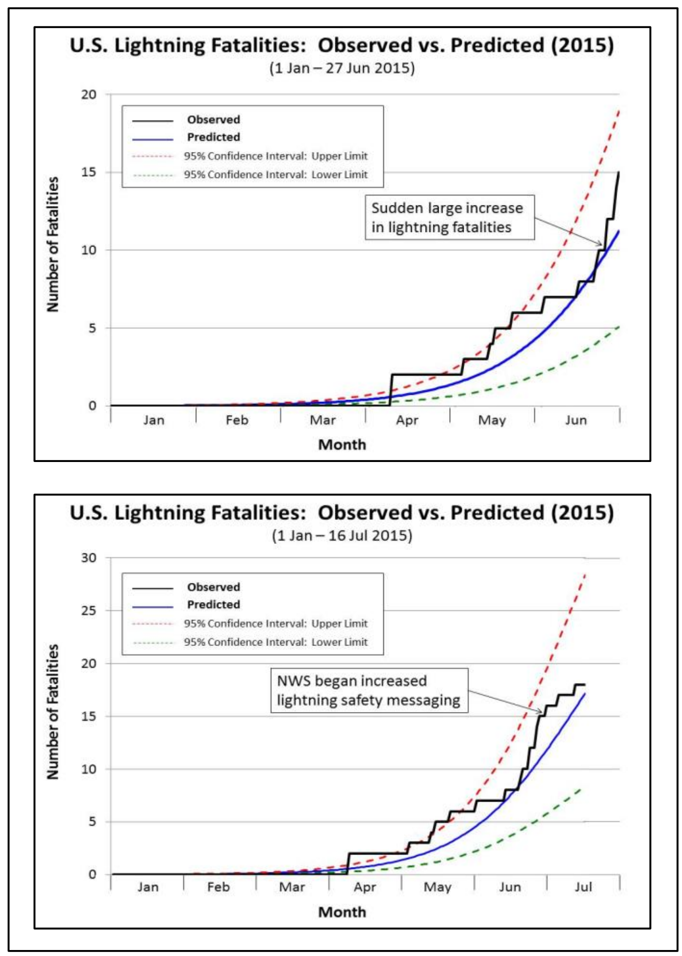

Fig. 7. The U.S. lightning fatalities began a sudden increase 21-27 June 2015 (top). The NWS increased lightning safety messaging around 27 June 2015 and the lightning fatality decreased soon thereafter (bottom), although a causitive effect cannot be scientifically proven.

investigated if the increase for those dates was due to a jump in lightning activity or in frequency of positive polarity high current lightning (Holle, 2015). Vaisala saw no change in U.S. lightning to explain the increase or subsequent decrease in lightning fatalities. This indirectly bolsters the supposition that the NWS messaging caused the decrease in lightning fatality rate. The three main causes of lightning fatality are lightning flash density, population density, and the lightning safety behavior of the population (Roeder et al., 2015). Vaisala indicated that a change in lightning flash density was not involved. Population shifts of this magnitude and timing are unreasonable. Therefore, the likely cause was a change in the lightning safety behavior of the population, presumably due to the NWS's increase in lightning safety messaging.

The third and final application discussed here is increasing interest in lightning safety education by providing timely input. If lightning fatalities are above expectations at the current date, then that can be used in lightning safety education to increase lightning safety awareness and motivate increased good lightning safety practices. Conversely, if the lightning fatalities are below expectations at the current date, that can be used to encourage continued good lightning safety practices.

IV. Second Updated Model: 2008-2015

This paper identified a discontinuous change in the U.S. annual lightning fatalities that began in 1994. Another discontinuous change appears to have occurred in 2008 [Fig. 8]. The number of annual fatalities dropped 5.4 deaths per year, as calculated from the prediction of the previous model and the new model for the mid-point of the transition to the new pattern (year = 2007.5). In addition, the variability of the year to year fatalities also appeared to decrease starting in 2008.

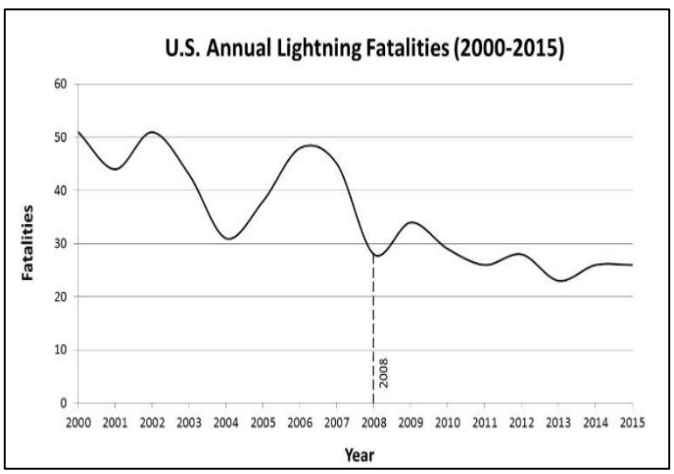

Fig. 8. The U.S. lightning fatalities U.S. annual lightning fatalities for 2000-2015. The pattern appears to have changed starting about 2008, dropping to a lower rate with less variability.

In the 8 years under the new pattern (2008-2015), none of the annual lightning fatalities were statistically significantly less than predicted by the previous model, even though three of those years being new record lows. However, all 8 of those years were less than predicted. If there was no change in the fatality rate, the chance of this occurring randomly is 0.39%. This strongly suggests that the change is real. A Student's t-test for the drop of 5.4 deaths being less than zero failed to reject ($p = 0.124$). A 1-tail test was used since we had a priori evidence that the lightning fatalities have been decreasing. The standard deviations were estimated from the 95% confidence intervals for both the previous and new model for the transition year (2007.5). Even though this change was not statistically significant for this one year, we have already seen that the overall change in the pattern over the past 8 years is statistically significnat. Although the variance appeared to decrease, a F-test for equal variances was not rejected (p-value = 0.067). This is likely due to the small sample size of only 8 years. If the current pattern persists, another 1-2 years will likely show the change in variance is statistically significant. Or if one can justify a priori that the variance is expected to decrease, then a 1-tail test would show that the reduction in variance is already statistically significant.

Given the new pattern of U.S. annual lightning fatalities that began in 2008, another new set of predictive equations based on this period are in Table-III. We start with the best-fit negative exponential equation for the expected number of U.S. annual lightning fatalities. Unfortunately, running ±10 year periods are not available for the 2008-2015 period, so the previous method to estimate percentile regressions is not possible. Instead, proportional scale factors from the previous percentiles were applied to the expected number of lightning fatalities from the new 2008-2015 regression. For example, the 1994-2015 model predicts 24.3 U.S. annual lightning fatalities in 2016 (see 'expected number' in Table-I). The 1994-2015 model also predictes a 97.5th percentile of 53.5 deaths for 2016. This gives a 97.5th percentile to expected number ratio of 2.20. This ratio is applied to the coefficient for the 2008-2015 expected number equation to infer the 97.5th percential equation, i.e the intermediate coefficient is 736.72 x 2.20 = 1,621.66. The exponential coefficient remains the same so that the error bars will follow the shape of the expected number equation. This accounts for the drop in the expected amounts of lightning fatalities, but not the decrease in variability. This second factor is accounted for by using the ratio of the standard deviation for the eight years under the new pattern (2008-2015) and the same period for the eight most recent years under the previous pattern (2000-2007). This same dual scaling factor approach is appled to the other percentile equations yielding the final predictive equations in Table-III. To predict the number of lightning daths for a specific date, assume the logistic distribution of the lightning fatalities during the year is unchanged.

This updated model accounts for the reduced number and reduced variability of U.S. annual lightning fatalities. As a result, for the same year the new model predicts a few less lightning deaths and much smaller co0nfidence intervals than the previous model. This can be easily seen in the predictions of both models for 2016 in Table IV. The predicted median U.S. annual lightning fatalities and their 95% coninfidence intervals for 2016-2025 are in Fig. 9. Note that this period is far into the tail of the negative exponential distribution so that the curves appear to be nearly linear. Since only 8 years were used for these equations, updates should continue to be made over the next several years, assuming the new pattern continues to verify.

TABLE III. SECOND UPDATED MODEL FOR U.S. ANNUAL LIGHTNING FATALITIES (2008-2015).

Parameter	Best-Fit Equation
2.5 Percentile	$y = 613.43e^{-(0.030(x-1900))}$
5.0 Percentile	$y = 618.81e^{-(0.030(x-1900))}$
Expected Number	$y = 736.72e^{-(0.030(x-1900))}$ $r^2 = 0.4091$
Median	$y = 853.89e^{-(0.030(x-1900))}$
95.0 Percentile	$y = 998.68e^{-(0.030(x-1900))}$
97.5 Percentile	$y = 1,160.81e^{-(0.030(x-1900))}$

y = predicted value
x = year of interest

TABLE IV. PREDICTED U.S. LIGHTNING FATALITIES FOR 2016 FROM THE TWO NEW MODELS. FOR COMPARISON, THE 30-YEAR RUNNING MEAN AND 10-YEAR RUNNING MEANS USED BY NWS ARE PROVIDED (NWS, 2016A).

MODEL	95% C. I. (lower)	EXPCTD NUM.	MEDIAN	95% C.I. (upper)
1994-2015	15.8	19.2	32.4	53.5
2008-2015	18.9	22.7	26.3	35.8
30-Yr Running Mean (1985-2014)	N/A	N/A	49	N/A
10-Yr Running Mean (2005-2014)	N/A	N/A	32	N/A

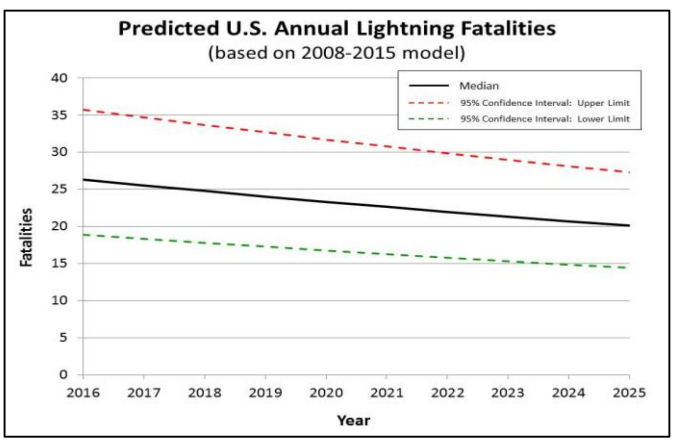

Fig. 9. The predicted median U.S. annual lightning fatalities and their 95% confidence interval for 2016-2025 based on the newest 2008-2015 model.

Given all the assumptions in developing the equations for the new model, a hindcast verification is in order for the 8 years of the new pattern (2008-2015) [Fig 10]. The expected number of lightning deaths closely matched the observed values. All of the 8 years of observed values were inside the 95% confidence interval, matching the expected number of 7.6 years.

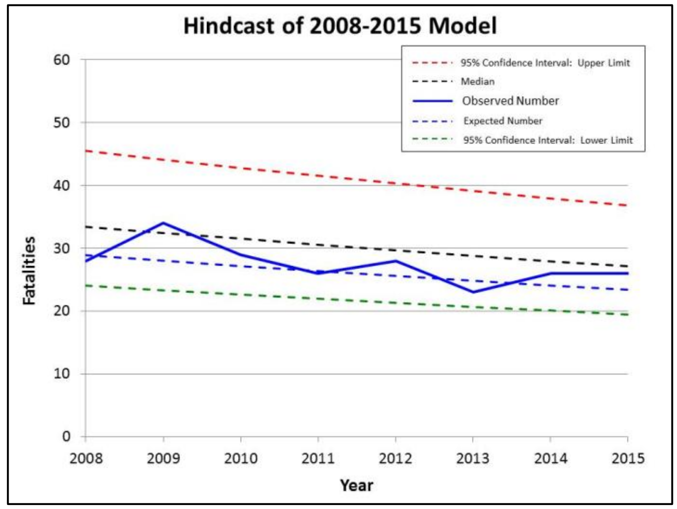

Fig. 10. Hindcast of the new model for the period from which it was created (2008-2015). Note that the observed number of U.S. annual lightning deaths matches the expected number well and all 8 of the events are within the 95% confidence interval, which is close to the expected number of 7.6.

V. FUTURE WORK

The new 2008-2015 model for U.S. annual lightning fatalities only covers 8 years. This model should continue to be updated as more data accumulates. In addition, although a new pattern strongly appears to have began in 2008, the U.S. annual lightning fatalities should continue to be monitored to ensure that the new pattern is persisting.

A statistical test should be developed for significant changes in the lightning fatality rate for any period during the year. As we saw in the second application in section-III, the new graphic for acumulating U.S. lightning fatalities can also be used for detecting changes in the rate of of those fatalities. A statistical test for significant changes in this rate is needed.

The large confidence intervals are due to the influence of large values from the mid-1980s to early-1990s. Over the next 4-7 years, those influences will decrease and completely dissappear. The model should be updated at the start of that period, and again at the end of that period to significantly improve the error estimates of the model.

A final issue is that U.S. annual lightning fatalities have entered the tail of their negative exponential distribution. As a result, the lightning fatalities are not declining as fast as previously and certainly not as fast as desired. This suggests a change in lightning safety education should be considered. If one conceedes that the lightning fatalities cannot be significantly decreased, then perhaps lightning safety education should be changed to a maintenance style of education—lightning safety awareness has been well established, so perhaps different education techniques would be better at maintaining that awareness, as opposed to the current methods used to build that increased awareness. Or perhaps new education methods are needed to significantly reduce the U.S. annual lightning fatalities further.

VI. Summary

Two updates to the previous model of U.S. annual lightning fatalities are presented. Both new models continue to use a best-fit negative exponential curve rather than 30-year or 10-year running means that are typically used by the NWS. The first new model restricts the analysis to 1994 onward since the pattern of U.S. lightning patterns changed starting in 1994 so the new model is more representative of the current time. The change was a sudden decrease in the number of fatalities and a decrease in the inter-annual variability. In addition, the two most recent years of observed fatalities were added to the analysis so that the period covers 1994-2015. The equations for predicting the distribution of U.S. annual lightning fatalities for this 1994-2015 model are in Table-I.

The logistic regression for the typical distribution of U.S. lightning fatalities during the year was also updated to include the two most recent years. The period now covers 2006-2015. The best-fit logistic regression for how lightning fatalities accumulate during a year is in (1) and shown in Fig-3.

The expected number of U.S. lightning fatalities for any date can be calculated by multiplying the number of lightning fatalities expected for that year by the percentage expected by that day of the year. In addition, various percentiles of the distribution can also be calculated, providing error bars for the predicted values. The 2.5th and 97.5th percentiles provide a 95% confidence interval, allowing hypothesis tests for whether the observed fatalities differs from the prediction at the 95% significance level. A new graph allows tracking how the U.S. lightning fatalities are accumulating during the year.

Evidence continues to accumulate that another discontinuous change in the pattern of U.S. annual lightning fatalities occurred in 2008 and continues through the present. The probability of this change occurring randomly is 0.39%. A second new model (2008-2015) for these fatalities was created (Table-III). Since the period is relatively small, only 8 years, frequent updates to this new model should be conducted as more data becomes available. The large error bars for both the 1994-2015 and 2008-2015 models will decrease significantly over the next 4-7 years as the influence of large values from the mid-1980s and early-1990s decreases and disappears. In addition, the pattern of annual U.S. lightning fatalities should continue to be monitored to ensure the new pattern is persisting.

Regardless of which model is used, the 1994-2015 or the 2006-2015 model, the U.S. annual lightning fatalities are in the tail of their negative exponential distributions. As a result, the lightning fatalities are no longer declining as fast as previously and certainly not as fast as desired. This suggests a different approach to lightning safety education be considered. If one concedes that the U.S. lightning fatalities are approaching an irreducible minimum, now that lightning safety awareness is well established, perhaps a different style of public education would be better at maintaining that awareness, rather than the previous approach used to increase lightning safety awareness. Or if a significant further reduction in the lightning fatalities is to be achieved, a new approach to lightning safety education may be needed.

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