P1.8

PRELIMINARY RESULTS FROM PHASE-1 OF THE STATISTICAL FORECASTING OF LIGHTNING CESSATION PROJECT

William P. Roeder
45th Weather Squadron
Patrick Air Force Base, FL

Jim E. Glover
Oral Roberts University
Tulsa, OK

1. INTRODUCTION

The 45th Weather Squadron (45 WS) provides comprehensive weather services to America's space program at Cape Canaveral Air Force Station (CCAFS) and NASA Kennedy Space Center (KSC) (Harms et al., 1999). One of the most important of these services is lightning advisories. The 45 WS lightning advisory requirements are among the most challenging in operational meteorology (Weems et al., 2002). Lightning advisories are the most frequent 45 WS product. The lighting advisories are issued for 13 points (figure 1) and include all types of lightning, including lightning aloft, not just cloud-to-ground lightning. The 45 WS uses the Lightning Detection And Ranging (LDAR) system that detects all lightning (Roeder et al., 2003). A Phase-1 lightning advisory is issued when lightning is expected with a desired lead-time of 30 min within 5 NM of the point(s). A Phase-2 advisory is issued when lightning is imminent or occurring in the circle(s). The advisories are cancelled when no longer required.

Some research has been done on forecasting the initiation of lightning, but has focused mostly on cloud-to-ground lightning, not 'all lightning', as required by 45 WS. Based on that research and on local experience, the 45 WS developed operational guidelines for forecasting the start of lightning. This lightning onset guidance uses mostly radar (thresholds, depth, and duration of reflectivity versus temperature levels for thunderstorms, anvil and debris clouds). For lightning in the local area, the onset prediction is supplemented with low altitude convergence calculated from 41 weather towers and 31 local surface electric field mills. The 45 WS techniques for forecasting the start of lightning are summarized in Roeder and Pinder (1988) and Roeder et al. (2002).

Unfortunately, very little research has been done on predicting the cessation of lightning (Hinson, 1997). As a result, the 45 WS operational guidance for canceling lightning advisories is not as well developed. The timing for the last lightning flash is especially problematic. The 45 WS techniques for terminating lightning advisories consist of waiting until the onset rules are no longer met, and waiting some variable time after the last observed lightning flash. The length of that time varies based on each storm, professional subjective judgment and experience. For decaying thunderstorms over the immediate area, the 31 surface electric field mills also supplement the decision to cancel the advisory. Both research and local experience indicate that predicting lightning cessation is exceedingly difficult.

Corresponding author: William Roeder, 45 WS/SYR, 1201 E. H. White II St., MS 7302, Patrick AFB, FL 32925; william.roeder@patrick.af.mil *(hot link)*, https://www.patrick.af.mil/45og/45ws/index.htm *(hot link)*

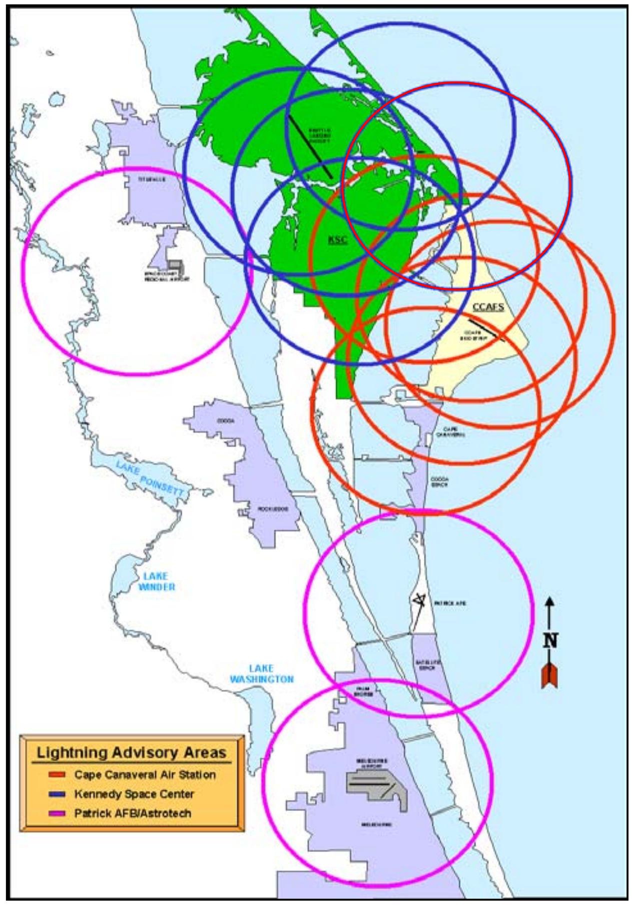

Figure 1. 45 WS Lightning Advisory Areas. Each of the thirteen circles represents a point for which 45 WS issues two-tiered advisories for lightning within 5 NM of the point.

The 45 WS lightning advisories must necessarily be terminated conservatively, erring on the side of safety, given the relative lack of objective techniques for forecasting the end of lightning, and since these advisories protect over 25,000 people. After-the-fact analysis confirms that 45 WS tends to leave their lightning advisories in effect longer than is optimal. While this is prudent, since personnel safety is the highest priority, it does cause extra financial costs and delays in preparing space launch vehicles and payloads. The development of objective reliable high-performance techniques to predict lightning cessation is the top operational research requirement and a strategic goal of 45 WS. Improved termination of lightning advisories is the activity most needing improvement in 45 WS operations.

2. THE STATISTICAL FORECASTING OF LIGHTNING CESSATION PROJECT

The 45 WS teamed with KSC to begin a new research project to improve forecasting of lightning cessation. The 'Statistical Forecasting Of Lightning Cessation' project was funded under the NASA Faculty Fellowship Program (www.nasa.gov/audience/foreducators/postsecondary/grants/NFFP.html *(hot link)*). This project brought Dr. Glover from the department of computer sciences and mathematics at Oral Roberts University to CCAFS/KSC for 9 weeks during the summer of 2004 to conduct this research.

The purpose of this project is to develop techniques that are highly focused on helping the operational forecaster. The forecaster can usually easily identify when thunderstorms are decaying based on radar and lightning flash rate. If several minutes have passed since the last flash, the forecaster is faced with the challenge to decide if that was actually the last flash and the advisory can be cancelled, or how likely is another lightning flash. This forecaster mindset inspired the statistical approach for this project and suggested two methodologies.

The first methodology is to develop climatology for the distribution of times between the last and second-last flash. Given some low operationally determined probability of acceptable risk, this distribution of times between last-2nd last lightning flashes could be integrated for guidance on how long to wait in general before canceling lightning advisories. After all, the first step in most forecast processes is climatology, but climatology for terminating lightning advisories did not exist. While far from a final solution, the low risk, speed of development, and initial utility made this a worthwhile goal of this project.

The second methodology is to determine if a specific family of curve can model the slowing lightning flash in decaying thunderstorms in general. Then find the best fit of that family of curves to the flash rate in an individual decaying thunderstorm. Finally, integrate that best fit curve to find the time when the probability of no more lightning drops below the operationally acceptable threshold. This second methodology was considered high-risk, given the extreme technical difficulty in forecasting the end of lightning and that the proposed approach is purely statistical with no explicit meteorological science. This second methodology was also considered potentially high-return, since it might deliver a large leap forward to 45 WS capability.

2.1 Phase-1 Design

The first phase of this project was considered a proof-of-concept to answer two main questions: 1) could a good curve be found for the distribution of times between last and 2nd last lightning flashes from many thunderstorms, and 2) did the concept of a decay curve to lightning flash rate in individual thunderstorms to predict the probability of another lightning flash have any validity. Because this phase of the project was considered proof-of-concept, and given the short time the summer visiting scientist was available (9 weeks), this preliminary research was restricted to only cloud-to-ground lightning. The lightning data were easily available from the Cloud-to-Ground Lightning Surveillance System (CGLSS) database (Roeder et al., 2005). The 'all lightning' data are also available from LDAR archive, but are very difficult to use quickly due to the shear volume of data (hundreds of step leaders per flash) and the tabular 4-D data format. Without a visualization tool, determining which step leader points go with which flash, and which flashes go with which thunderstorm, can not be determined quickly. The CGLSS is a local system, similar to the National Lightning Detection Network, but with better performance (Boyd et al., 2005). Because this phase of the project did not analyze 'all lightning', the results are not immediately useful for 45 WS lightning advisories.

The 45 WS is interested in research to convert the LDAR step leader archive into a lightning flash database. An optimized 'step leader to lightning flash' conversion algorithm is needed. A simple algorithm for this already exists, but there is considerable room for improvement (McNamara, 2002). A 'thunderstorm-ID assignment' algorithm is also required and would presumably be based on clustering the flash starting points in x-y location and time, with perhaps some weak cluster in z-location. Considering the time series of flash rate and morphology of flash might allow automatic identification of the lightning cloud classification: thunderstorm, anvil, or debris cloud lightning. These algorithms could be applied to the 10+ years of LDAR step leader observations to create a much easier to use lightning flash database. This LDAR flash database would facilitate many lightning research projects, including future phases of the 'statistical forecasting of lightning cessation' project.

Phase-1 analyzed 58 thunderstorms near CCAFS/KSC, which were sampled from five convective seasons during the summer convective season (May-Sep) as shown in Table-1 and Table-2. This was done to avoid any seasonal or monthly biases in the results. The timeline of flashes from one storm is shown in figure 2. Such timelines were part of the inspiration for this project, since anecdotally some sort of decay curve seemed to apply. Likely candidates for the decay curve included negative exponential, Poisson, log-linear, etc. The 58 storms were used to create a 59th composite "thunderstorm" that represents the average behavior of all the storms.

Table 1.
58 thunderstorms analyzed during Phase-1 of this project by season (May-Sep)

YEAR	NUMBER OF THUNDERSTORMS
1999	12 (May: 2, Jun: 2, Jul: 2, Aug: 4, Sep: 2)
2000	13 (May: 0, Jun: 4, Jul: 6, Aug: 1, Sep: 2)
2001	14 (May: 0, Jun: 5, Jul: 3, Aug: 5, Sep: 1)
2002	7 (May: 0, Jun: 1, Jul: 2, Aug: 4, Sep: 0)
2003	12 (May: 0, Jun: 2, Jul: 3, Aug: 7, Sep: 0)

Table 2.
58 thunderstorms analyzed during Phase-1 of this project by Month (May-Sep)

YEAR	NUMBER OF THUNDERSTORMS
May	2
Jun	14
Jul	16
Aug	21
Sep	5

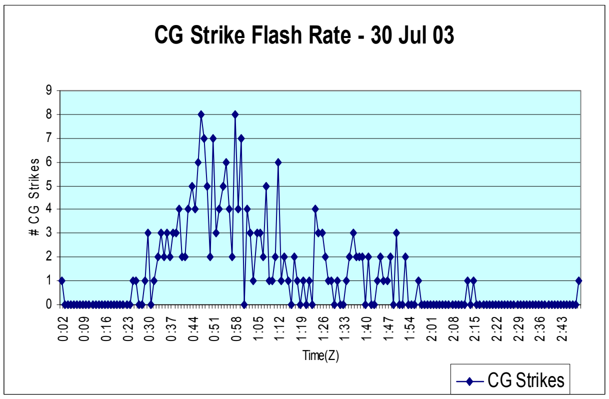

Figure 2. Timeline from one thunderstorm.

The 58 cases were actually all cloud-to-ground lightning observed in a ± 10 NM box centered on CCAFS/KSC. Therefore, flashes from more than one thunderstorm might have been included, although the person providing that cases tried to provide only isolated thunderstorms in the sample box, so this was not likely a significant problem. Likewise, flashes from thunderstorms moving into and out of the sample box could have contaminated the analysis, e.g. a storm of constant activity could appear to be decaying as it moves out of the sample box. However, again the person providing the cases tried to provide thunderstorms centered in box. Given that most of our thunderstorms are organized on relatively slow moving sea-breeze fronts, this centering of the data led this to not be considered a significant problem either. These compromises in sampling were required due to the short time the visiting scientist was available (9 weeks) and the lack of appropriate software for visualizing saved CGLSS lightning data at 45 WS. The thunderstorms sampled tended to be more active storms with above average lighting flash rates, though they were still mostly pulse thunderstorms on sea breeze fronts and other boundary interactions, as opposed to extremely lightning active squall lines. This was needed to provide enough flashes during the decaying part of the thunderstorm lifecycle to allow for effective curve fitting. This was a sample bias for which compensation could not be applied. However, the authors know of no reason why above average lightning storms should behave significantly different from other pulse more typical thunderstorms during their decay phases, so this may not be a significant problem either.

2.2 Phase-1 Results

Phase-1 of this project was a proof-of-concept effort to determine the promise of a statistical approach to forecasting lightning cessation. Phase-1 was successful and further development under future phases is justified.

2.2.1. Climatological distribution of times between last and 2nd to last lightning flashes:

The time differences between the last and 2nd last lightning flash were used to create a probability density function of the time differences (figure 3). Several standard statistical curves were fit to this probability density function. The best fit was a log-linear curve, with the following coefficients and constants, $P(\Delta t) = -0.0469 \, Ln(\Delta t) + 0.1493$, where Δt is the time difference between last and 2nd last flash and $P(\Delta t)$ is it's probability density function. This best fit curve yielded a correlation coefficient of 0.8665, so that 75% of the variation is explained by the log-linear curve ($r^2 = 0.7509$). Since the logarithmic function tends to produce a more linear result than the original curve, a Z-Score of $Ln(\Delta t)$ was used to check if the log-linear fit was appropriate. As shown in figure 4, the Z-Score is very linear, with a correlation coefficient of 0.9985, so that 99.7% of the variance is explained by the log-linear curve ($r^2 = 0.997$). Therefore, the log-linear fit is accepted as reasonable.

If a similar curve had been fit to for '<u>all</u> lightning', such as from the LDAR sensor, then a climatological tool for canceling 45 WS lightning advisories could be created. Integrating the probability density function from various times to infinity would produce a table of recommended times to wait after the last observed flash to achieve various probabilities of another flash occurring. A hypothetical example is shown in Table 3. Alternatively, if a specific probability of another flash is required for a specific operation, that time to wait after the last observed flash could also be calculated.

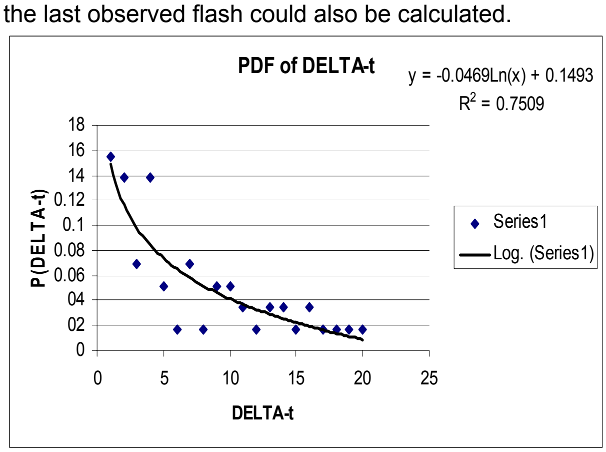

Figure 3. Probability density function of the times between last and 2nd last lightning flashes.

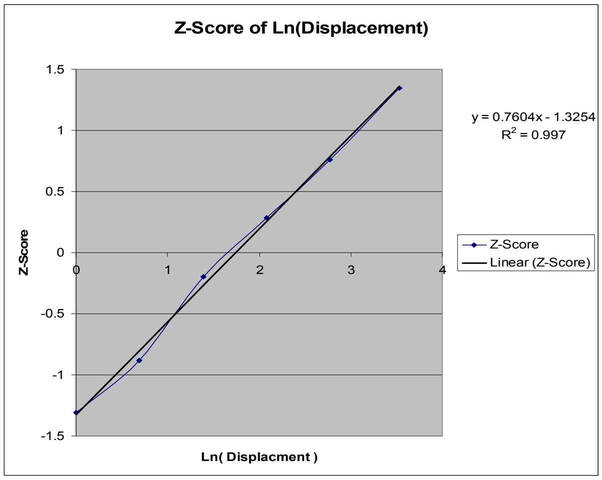

Figure 4. Z-Score of Ln(Δt), which helps confirm that the log-linear curve, is a reasonable fit.

Table 3.
Hypothetical example of climatological tool for canceling lightning advisories (not for operational use!)

% PROBABILITY OF ANOTHER FLASH	AVERAGE TIME
25%	10 min
10%	15 min
5%	20 min
1%	25 min
0.1%	50 min

2.2.2. Curve fitting of lightning flash rates in decaying thunderstorms:

Several standard statistical curves were fit to the decaying lighting rate in the composite thunderstorm, which represents the average behavior of the 58 individual thunderstorms in this analysis. The log-linear equation again provided the best fit curve with the following parameterization, P(t) = -0.2821 Ln(t) + 1.5115 (figure 5). The coefficient of regression was 0.8977, which explained 81% of the variation (r^2 = 0.8058). A linear fit with a slope of -0.0102 and intercept of 0.998 provided a better fit (r^2 = 0.9999), but the log-linear fit is preferred since this curve was one of the curves expected a priori, and agrees with the best fit curve to the entire composite thunderstorm lifecycle (P(t) = -0.3085 Ln(t) + 1.7599, r^2 = 0.8642). The linear fit having a higher correlation coefficient may be an artifact of identifying the start of the decay phase of the composite thunderstorm too late in the lifecycle. An example of a best-fit curve to the decaying flash rate from an individual thunderstorm is shown in figure 6. In this case, a negative exponential was the best-fit curve; P(flash rate) = $0.8551e^{-0.5876(t)}$. This equation yielded a correlation coefficient of r = 0.9839, which explains 97% of the variance (r^2 = 0.9681). This is consistent with the recent research on decaying flash rates of 'all lightning' in Dallas, TX (Holle and Murphy, 2003). If similar curves were fit to the decaying flash rate of 'all lightning' from a thunderstorm in real time, the integration of the equation could help predict the time when the probability of another flash would fall below some low operational threshold.

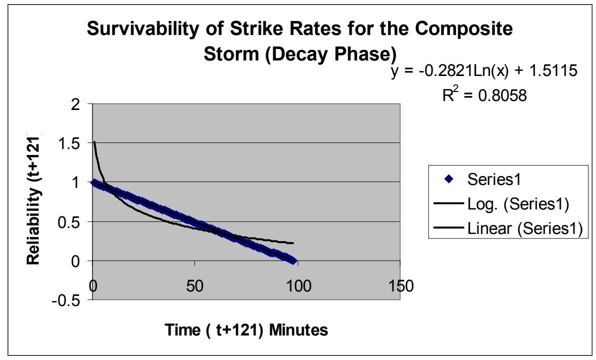

Figure 5. Probability density function of the times between last and 2nd last lightning flash from the 58 thunderstorms in this analysis and the best-fit curve.

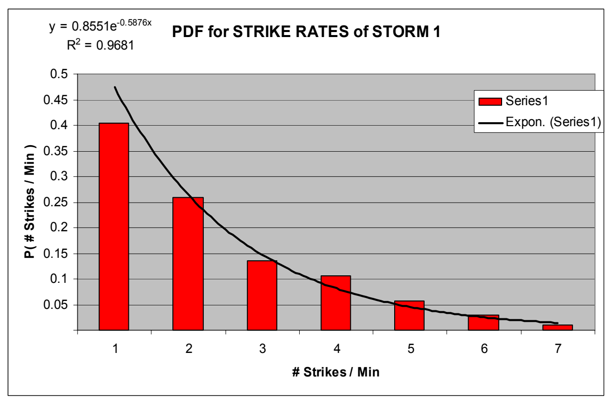

Figure 6. Probability density function and best-fit curve for an individual thunderstorm.

2.3 Future Phases

Phase-1 indicated that statistical forecasting of lightning cessation has promise and further development is justified. If funding is approved, Phase-2 and Phase-3 might be done during the summer of 2005 and the summer 2006, respectively.

2.3.1. Phase-2 Proposal:

Phase-2 would repeat the work of Phase-1 but using 'all lightning' from the LDAR sensor, rather than just cloud-to-ground lightning. Climatology for the distribution of time differences between last and 2nd last lightning flashes for 'all lightning' would be built. Since the climatology would be based on 'all lightning', matching 45 WS lightning advisory procedures, this climatology might be used immediately as guidance in ending lightning advisories operationally. Also, curve fitting to the 'all lightning' flash rate from decaying individual thunderstorms would be explored. The potential sampling shortfalls discussed previously would be explicitly avoided to ensure that all lightning would be recorded throughout the decaying lifecycle from only one thunderstorm. Verification against independent data would also be accomplished. Finally, estimation of the performance of the curve fitting approach in the real world would begin. Lightning flashes from individual decaying thunderstorms would be used to update the best-fit curve for each flash and integrated to estimate the timing for various probabilities of last flash, which would be verified against the actual last flashes. The average performance of the climatological and curve fitting methods would be compared against average performance of the 45 WS termination of advisories, especially as regards safely terminating the advisories sooner.

2.3.2. Phase-3 Proposal:

If justified by Phase-2 results, Phase-3 would enlarge the sample size of the climatology and curve fitting approach for 'all lightning'. In addition, the performance verification on independent data would be extended and completed. A performance comparison would be conducted between the climatological and curve fitting methods and 45 WS termination of lightning advisories on a sample of independent thunderstorms. Finally, a proposal for future research and preliminary design would be drafted to support the long-range goal of automated guidance for forecasting lightning cessation and terminating 45 WS lightning advisories.

3. LONG RANGE GOAL

The long-range goal is to create a system that would provide automated guidance on which thunderstorms are decaying, the expected time for the probability of another flash to drop below some low operational threshold, and flag storms that have already fallen below that operational threshold. Such an automated system would need an 'all lightning' detection system, such as LDAR. Special post-processing software would also be required. The first function of this post-processing software would be to assign each lightning flash to a specific thunderstorm, presumably via a statistical cluster algorithm operating on the x-y location, time, and to a lesser degree 'z' location of the starting point of the lightning flashes. The second function of the post-processing software would be to identify when thunderstorms start decaying, presumably through a simple analysis of a smoothed time-series of flash rate from individual thunderstorms. Finally, the post-processing software would calculate the best-fit coefficients for the appropriate family of curve for each thunderstorm and calculate when the integration of that best fit equation would suggest that the probability of another flash reaches a low operational threshold. As each flash occurs, the best fit coefficients of the curve and a new integration would be recalculated to update the timing guidance. Even more advanced systems could combine data from radar and electric field mills for even better lightning cessation guidance.

Automated guidance on lightning cessation will not be available for many years. In the meantime, interim techniques on how to cancel lightning advisories is required by 45 WS, such as climatology of the distribution of times between last and 2nd last flashes from all lightning.

4. SUMMARY

The 45 WS needs to terminate their lightning advisories sooner without compromising safety. Unfortunately, the lack of research on this topic makes improving the forecasting of lightning cessation very difficult. A preliminary examination of a new statistical approach was performed during summer 2004. Initial results were encouraging and further research on this statistical approach is justified.

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