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EMPIRICAL FORECASTING OF LIGHTNING CESSATION AT THE KENNEDY SPACE CENTER

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1. INTRODUCTION

The annual effects of lightning are a major concern across the United States. Economically, lightning has been estimated to cost 5 billion dollars annually. These costs are incurred through physical damage to outdoor equipment, such as communication and power lines, and the loss of manpower hours. Furthermore, lightning is a major public safety hazard. According to Curran et al. (1997), cloud-to-ground lightning is the second leading source of storm deaths, killing more than tornadoes and hurricanes in the United States each year. These impacts suggest that improved forecasts of the timing and location of lightning activity will be beneficial.

Studying thunderstorms across Central Florida, Holle et al. (1992) found that the majority of lightning casualties occurred either during the initiation or cessation of the thunderstorm. Between these times, when the threat of lightning is obvious, casualties are less. This is an important finding that impacts lightning advisories issued for the Kennedy Space Center (KSC), Cape Canaveral Air Force Station (CCAFS), and other nearby locations, by the United States Air Force 45th Weather Squadron (45WS) as they issue advisories for any lightning within 5 NM of their advisory points (Roeder and Pinder 1998; Weems 2001) (Figure 1). The advisories for lightning initiation perform reasonably well. However, analysis indicates that the advisories are left in effect for too long due to safety concerns.

Currently, the 45 WS doesn't have sufficient guidelines for forecasting when lightning activity has ceased. The current rule of thumb is to cancel a lightning advisory some time after the lightning initiation criteria are no longer met. The problem is the length of time a forecaster should wait before canceling an advisory once these lightning initiation criteria are no longer met. Therefore, to ensure personnel safety, 45WS tends to leave the lightning advisories in effect a conservatively long time. Improved guidance for lightning cessation could provide an estimated millions of dollars worth of savings each year (Roeder and Glover 2005).

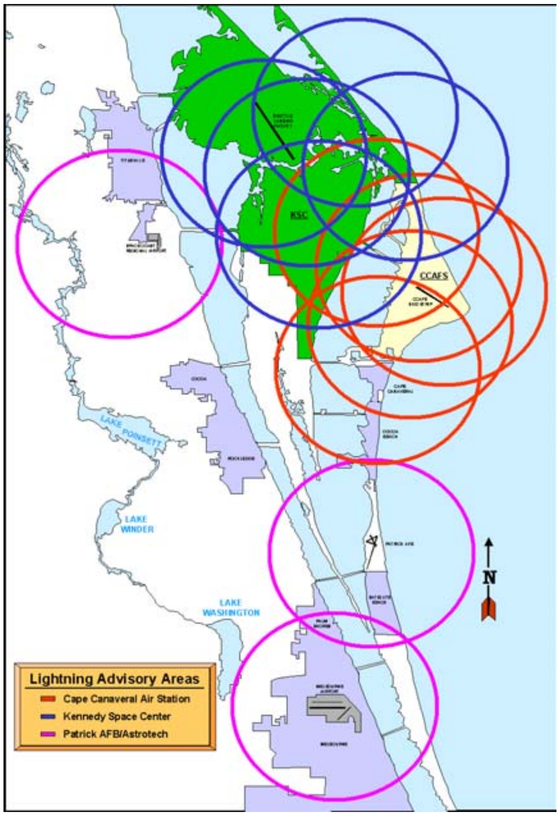


Figure 1. The 45th Weather Squadron's lightning advisory locations and the 5 NM (9.62 km) advisory areas around each location. (After Weems et al. 2001).

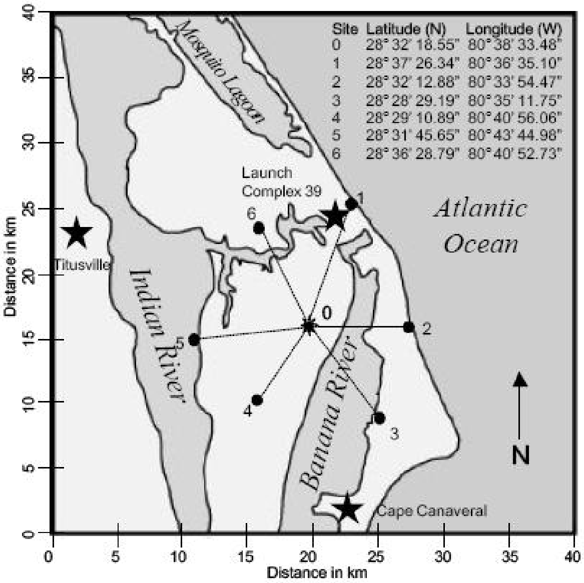
Despite the importance of this endeavor, forecasting lightning cessation is extremely challenging and only three improvement projects have been undertaken (Hinson 1997; Holmes 2000; Roeder and Glover 2005). These studies have highlighted the difficulty in attempting to study lightning cessation. An important limitation of these studies was their sole use of cloud-to-ground (CG) lightning data, whereas the 45WS issues advisories based on all types of lightning, both CG and intracloud (IC) flashes. This research utilizes a larger dataset and includes IC flashes to develop an empirical forecasting guide for lightning cessation.

2. DATA

Unlike previous cessation studies, this research focuses on total lightning cessation (i.e., cloud-to-ground and intracloud activity). This will be accomplished using the Lightning Detection and Ranging (LDAR) Network (Poehler and Lennon 1979; Maier et al. 1995; Britt et al. 1998; Boccippio et al. 2001). LDAR data in this study covers the years 1997-2005.

The LDAR network is a short-baseline system utilizing a Time of Arrival (TOA) detection scheme. Originally designed by NASA and located at KSC/CCAFS (Britt et al. 1998), the network consists of seven sensors (Figure 2) in a hexagonal pattern. Each sensor is located 6-10 km away from the controlling central receiving sensor in the middle of the network. LDAR is a passive observing system (Maier et al. 1995) that operates at 66 MHz and a bandwidth of 6 MHz, sensing the VHF electromagnetic pulses generated by each step leading in a developing lightning flash.

According to the Applied Meteorology Unit (AMU) (1996) at KSC, LDAR's step leader detection efficiency is approximately 97%, increasing to 99% for events within 25 km of the central LDAR receiver (sensor 0, Fig. 2). These values have been confirmed by Maier et al. (1995) and Murphy et al. (2000). LDAR has a typical detection range of 100 km (Boccippio et al. 2001). Since there are typically hundreds of step leaders per lightning flash, LDAR detects virtually 100% of the flashes.



Site	Latitude (N)	Longitude (W)
0	28° 32' 18.55"	80° 38' 33.48"
1	28° 37' 26.34"	80° 36' 35.10"
2	28° 32' 12.88"	80° 33' 54.47"
3	28° 28' 29.19"	80° 35' 11.75"
4	28° 29' 10.89"	80° 40' 56.06"
5	28° 31' 45.65"	80° 43' 44.98"
6	28° 36' 28.79"	80° 40' 52.73"

Figure 2. The LDAR network located at the Kennedy Space Center. Sensor 0 is the central LDAR receiver. (After Poehler and Lennon 1979 and Vollmer 2002).

Supporting the LDAR observations are data from the KSC's Cloud-to-Ground Lightning Surveillance System (CGLSS) (Roeder et al. 2000; Boyd et al. 2005). CGLSS is a local high-performance CG lightning detector consisting of six Improved Accuracy via Combined Technology sensors (Cummins et al. 1998), similar to the National Lightning Detection Network (NLDN). Figure 3 shows the location of the CGLSS network. CGLSS has greater detection efficiency and location accuracy than the National Lightning Detection Network (NLDN) due to its greater density of sensors in the region (Boyd et al. 2005). The CGLSS network is preferred over NLDN for this research because CGLSS has a 98% detection efficiency and 250 m location accuracy over the area of interest (Roeder et al. 2000).

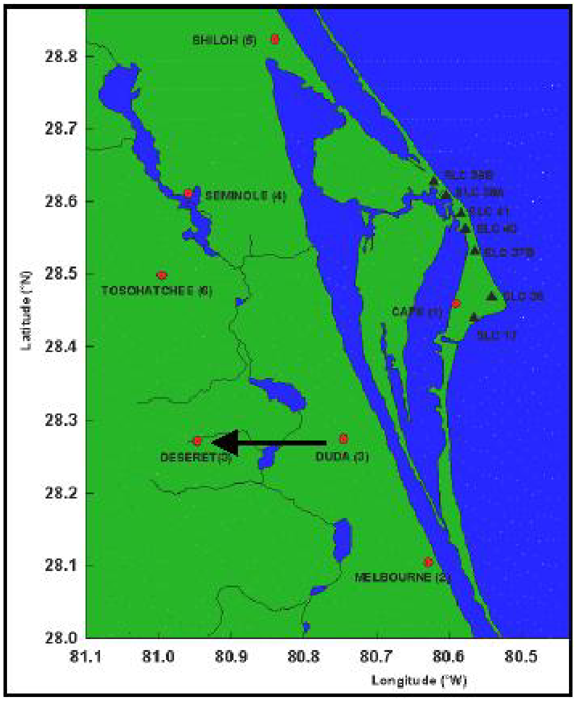


Figure 3. Locations of the Cloud-to-Ground Lightning Surveillance network (after Boyd et al. 2005).

3. METHODOLOGY

The first step is to quality control the two datasets. The CGLSS data are treated like NLDN data and follow suggestions by Cummins et al. (1998) for quality control. One step is to remove weak positive strikes (< 10 kA) which are considered to be IC flashes, falsely detected as weak positive ground strokes. In addition, when multiple CG strikes occur within 1 s and 10 km, only the first is kept in order to remove duplicate strikes from the dataset. The multiplicity of these strikes is retained.

The LDAR data include calibration information embedded with the raw dataset. To prevent the calibration data from being included in a flash, all observations within a region around the calibration transmitter are removed. Specifically, all data within a 200 m radius and 900 m above the calibration transmitter are deleted. The transmitter is located 1,318 m south and 1,609 m west of the central LDAR receiver (sensor 0, Fig. 2). This procedure removes valid data; however, the impact is minimal since the volume of this region compared to the volume of the LDAR observation range is quite small (McNamara 2002).

A major and ongoing effort of this research is to create a flash climatology. The raw LDAR data are simply the locations and occurrence times of individual stepped leaders. The climatology requires an algorithm to combine these components into flashes. With the LDAR data assembled into flashes, individual CG strikes from the CGLSS data are merged with the most likely LDAR flash, including its start and end points. These inferred flashes will then be organized into a database by date and time, and assigned to a storm-ID based on a cluster analysis of the flash start points.

The creation of LDAR flashes is achieved by using a flash grouping algorithm derived by Nelson (2002) from the NASA code first developed by Murphy et al. (2000). A brief description is summarized by McNamara (2002) and illustrated in Fig. 4. First, for a data point to be included in a flash, it must have occurred within 3 s of the first allowed data point (P1). Furthermore, each data point in a flash must be within 0.5 s of the previous point comprising the flash. Along with these temporal constraints, the distances between data points being considered must be analyzed. LDAR location errors that increase with range must be considered in this process. Therefore, an ellipse is computed based on the range of the data point from the LDAR network. Its major axis is determined by the range error associated with LDAR, equaling 5000 m plus a factor that is a function of the range error of the network. A similar calculation is used for the minor axis of the ellipse. It is based on the range error associated with the azimuthal error and equaling 5000 m plus the angle error times the distance from the LDAR network. The major and minor axes increase as the data point's distance from the LDAR network increases. As the size of the ellipse increases, the allowable distance between data points comprising a flash increases. The computed ellipse is centered over the current data point (P2) being considered for inclusion into the flash. If the previous data point (P1) lies within the ellipse, the current data point (P2) is considered to be part of the current flash. Some data points cannot be grouped into any flash.

These are given a flash number of -1 and are removed from the flash dataset.

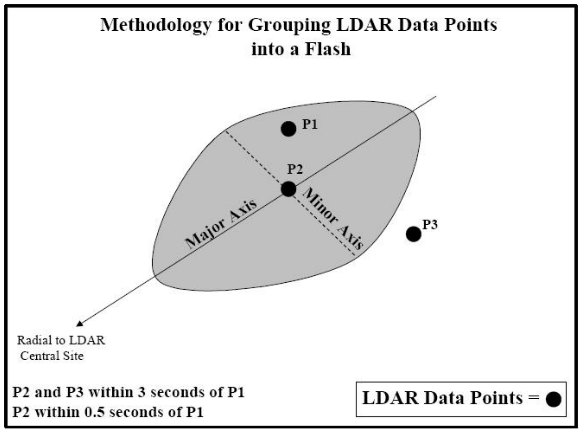


Figure 4. Flash grouping methodology for combining individual LDAR data events into lightning flashes. The point P1 is the previous data point included in the flash, while P2 fits the temporal and spatial constraints and is included within the current lightning flash (after McNamara 2002).

With the LDAR data combined into flashes, the CGLSS cloud-to-ground strikes must be matched to these flashes. Previous research matching CG strikes to LDAR flashes has utilized the NLDN. The current research is the first time that CGLSS is being matched to LDAR observed flashes. The procedure is illustrated in Fig. 5. The process to determine matches selects all LDAR data points within 1 s and 50 km of the ground flash. The first flash (triangles), while satisfying the temporal constraint, is too far away from the ground flash to be considered. Flashes 2 (circles) and 3 (squares) are both valid because they have data points within 1 s and 50 km of the CG strike. With two potentially valid flashes, each point comprising Flashes 2 and 3 is analyzed to compare the distance between the LDAR point and the ground flash. Since flash 3 is determined to have the closest data point to the CG flash, it is selected as the flash which created the cloud-to-ground strike. The matching algorithm combines between 70 – 90% of all CG strikes with an LDAR flash, depending on the month being studied. At this time, any CG strike not associated with an LDAR flash is deleted. Analysis of the unmatched CG strikes in the current dataset indicates that this deletion will not significantly affect the results. Only 1% of all unmatched flashes are within 20 km of the central LDAR sensor. This value increases to ~17% within 60 km. These are good results for the local area around the LDAR network, which is the preferred region to sample isolated thunderstorms.

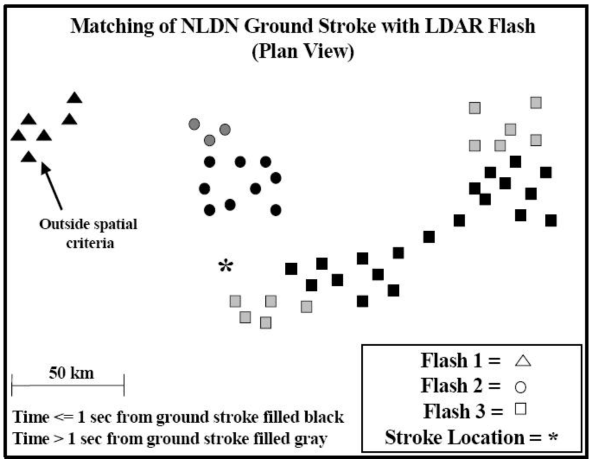


Figure 5. Illustration of matching cloud-to-ground strikes with LDAR flashes. In this example, Flash 3 meets all of the temporal and spatial constraints in addition to having the closest data point to the CG strike. As a result, Flash 3 is selected as the flash resulting in the CG strike. (After McNamara 2002).

These two steps provide a very useful dataset that the authors believe is unique. However, the goals of this research require these data to be divided into individual thunderstorms. To facilitate the process, the newly created flash climatology is processed into “storm clusters”, i.e., periods of lightning activity with no time gaps between separate flashes exceeding 90 minutes. At this stage, no attempt has been made to separate the data spatially.

From these storm clusters, the data will be separated into isolated thunderstorms. To determine these isolated storms, the starting point of each flash is utilized. As suggested by the 45WS, the initiation point of a lightning flash should be the parameter most correlated with the particular thunderstorm with which the flash is associated with. As of this writing, the exact spatial and temporal constraints for separating the data into isolated thunderstorms are being determined.

Once the flash climatology has been divided into isolated thunderstorms, we will calculate a large array of lightning cessation characteristics. For example, we will determine whether the last flash in a thunderstorm is a CG or IC flash. Furthermore, the inter-flash time periods between the last ten flashes, for example, can be calculated and analyzed for any correlation to the timing of lightning cessation. The distribution of times between the last and second-to-last flash should provide climatological guidance to the 45WS on ending lightning advisories. A best fit curve to that time distribution, and integration under that curve, will provide the expected time to wait after a candidate last flash to meet operational criteria for no more flashes. For example, waiting 15 min since the last flash might give a 20% chance of more flashes, while waiting 30 min might drop that probability to 5%. If we want an operationally acceptable threshold of 0.1% chance of more flashes, then we might need to typically wait 47 min after the last observed flash before canceling advisories. Other correlations can be made utilizing data specific to the LDAR observations. These include the horizontal and vertical lengths of lightning flashes at the end of a thunderstorm and the average starting height of a flash as a storm decays. Correlations also will be made between total thunderstorm lightning activity and cessation, the power of associated CG strikes, and the distance from the origin of a lightning flash to the CG strike point. With each of these calculations, we will attempt to fit a curve to the data. A determination will be made as to whether a single curve or a family of curves fits these lightning cessation characteristics.

The ultimate goal of this research is to develop an empirical forecasting technique for lightning cessation that will reduce the uncertainty in ending lightning warnings, while maintaining the utmost levels of safety. Our study of the lightning cessation characteristics will lead to this technique. We plan to test if curve fitting the slowing total lightning flash rate from decaying storms can reliably predict the probability of more lightning for various times in the future. Essentially, this will extend the work of Roeder and Glover (2005) but apply their techniques to total lightning, using a much larger sample size, and overcome the sampling restrictions in their small proof of concept study. The technique will be tested. In particular, a cross validation technique will be used (Chambers and Hastie 1992, Venables and Ripley 1997). Here, a random sample of isolated thunderstorms, for example 25%, will be set aside and not used in the development of the empirical technique. Once developed, the lightning cessation guidelines will be applied to the thunderstorms set aside. This will provide a thorough analysis of the capabilities of the forecast technique's abilities on an independent dataset.

4. CONCLUSIONS

At the time of this writing the flash climatology is still being analyzed. However, initial results show that the flashes from LDAR data are similar to those of previous studies that have used the algorithm (McNamara 2002; Nelson 2002; Vollmer 2002). The vast majority of unmatched LDAR data points are located at ranges greater than 100 km from the central LDAR sensor. According to Boccippio et al. (2001), the effective range of LDAR is 100 km. Therefore, the data points not included and consequently not used in the flash climatology are safe to remove. The matching algorithm has produced results on par or slightly better than the previous studies, which utilized NLDN data instead of CGLSS. The majority of unmatched CG strikes occur at ranges greater than 60 km from the central LDAR sensor.

Initial analysis of the sample flash climatology currently available has found that the constructed flashes are consistent with observations from other related lightning mapping array observations. Several flashes have lengths of tens of kilometers. Some of the events in the sample dataset also have very active lightning activity. LDAR flashes with CG strikes have averaged between 1 to 3 associated CG strikes. As of this writing, data analysis is still underway and more detailed results will be presented at the conference.

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