P1.13 ON THE NEED FOR ELECTRIC-FIELD METERS TO SUPPORT CRITICAL LIGHTNING HAZARD-WARNING DECISION PROCESSES

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1. INTRODUCTION

Lightning location systems use electromagnetic signals from lightning discharges to provide the location, time of occurrence and other parameters of cloud-to-ground lightning strikes in near-real time with good efficiency and accuracy. Government agencies and private-sector companies, such as the Los Alamos National Laboratory (LANL) and Weather Decision Technologies, Inc. (WDT), use lightning location data, often in combination with network radar data, to provide lightning-warning decision-support products such as the LANL LTRAX and the WDT Lightning Decision Support System (LDSS). These lightning data analysis products predict where lightning will occur within, say, the next 30 minutes, on the basis of where lightning has been occurring and storm motion up to the time of the projection. However, these predictions lack the rigor of objective local real-time measurement needed for many critical lightning hazard-warning decisions because they do not provide direct observations of the electric field at the location of the facility or personnel at risk. By "critical lightning hazard-warning decisions" we mean those decisions regarding lightning safety in which unacceptable loss of life or property might result from failure to provide timely warning.

Recent research reported in Lengyel (2004) showed that more than half of the lightning casualties studied occurred as a result of the first or one of the first few CG lightning flashes in a storm. Lengyel (2004) also found that among casualty cases for which there was sufficient warning, some appeared to be a result of a decision to resume outdoor activities too soon, as previously reported by Holle et al. (1993). In 1998, the Lightning Safety Group (LSG), comprising scientists, engineers and medical personnel, was convened to standardize recommendations for lightning safety precautions (American Meteorological Society, 2002). The LSG addressed the issue of lead time and recommended the “30-30 rule”, which says that “if the time delay between seeing the flash (lightning) and hearing the bang (thunder) is less than 30 seconds, the individual should be in, or seek, a safer location" (Holle et al. 1999). The LSG also specified what it considered to be safer locations. Since some lightning casualties occur after the threat has been perceived to have ended, the “30-30 rule” advocated by the LSG recommends waiting at least 30 minutes after the last sound of thunder to resume outdoor activities. Though generally the lightning threat diminishes with time after the last sound of thunder, the threat may persist for more than 30 minutes in some cases (Holle et al. 1999). The "30-30" rule is intended as advice for people who inadvertently find themselves in a thunderstorm. Though it can be argued that the "30-30" rule is much better than no rule at all, it was not intended to replace a rigorous program of lightning hazard warning decision support for high-value targets.

The threat of a last CG flash in a storm occurring at a specific location after a day of 30 minutes or more since the last previous flash is real, but not always realized. If the "30-30" rule or other conservative institutional guidelines based on averages is applied for lack of adequate information, both anecdotal experience and risk analysis (Bott et al., 2005, Paper 3.3, Eisenhawer et al., 2005, Paper P1.18, this conference) suggest that sometimes the result may be overly conservative, with concomitant loss of productivity. This may tempt people under economic or schedule pressures to take unwarranted risks. The risks would be unwarranted because without local electric-field measurements, decision makers do not have enough information to support overide of the "30-30" rule or other conservative institutional guidelines. Indeed, on occasion, local electric-field measurements might dictate an even longer waiting period. Furthermore, lightning ground-strike location data are not always useful for all-clear decisions, particularly for relatively slow-moving or stationary storms, because they cannot determine whether a particular storm or part of a storm is still sufficiently electrified to produce additional lightning flashes after long delays.

In order to know with confidence whether conditions are still such that the chance of another nearby CG lightning flash is greater than the acceptable level of

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risk dictates, it is necessary to know the electrical state of all storm clouds within striking distance. This task cannot be accomplished with lightning ground-strike location systems. It requires the deployment of ground-based electric-field meters in appropriate numbers at appropriate spacing covering the area of concern. This conclusion is not new, though it is not to be found readily in the reviewed literature. However, until recently, the cost of implementing a network of field meters has more often than not outweighed the perceived, less easily quantifiable potential benefits. Thus the only situations in which extended networks of field meters have been deployed are those such as exist at the NASA Kennedy Space Center, where the costs of a potential lightning-initiated catastrophe have been considered sufficiently high to warrant a sizeable investment in conventional field mills, with their requirement for frequent periodic maintenance. It is noteworthy that few if any of the tens of thousands of automated weather stations in use worldwide today can report electric-field hazards or the occurrence of a local thunderstorm, the very information needed to address the issues outlined above. The recently increased availability of reliable, low-cost electric-field meters makes it possible now to change that. It is now economically feasible to deploy field meters both independently and as integral parts of automated weather stations in sufficient numbers in many hazardous situations for which conventional field mills could not be justified on economic grounds. Such deployments can reduce risks and increase efficiency by providing improved, more objective information.

2. LIGHTNING CASUALTY STUDY

In the study by Lengyel (2004) there were 107 casualty cases that had enough specific verifiable information recorded in a storm report to support reliable conclusions. The 107 cases comprised 230 total casualties including 35 deaths and 195 injuries. The distance from the point at which each casualty occurred to the ground-strike location of every CG flash within 20 km radius was plotted as a function of time for 35 minutes before and after each incident. Then the occurrence of flashes within 10 km distance during the time preceding the incident was examined carefully in order to determine whether there would have been sufficient time to act upon the “30-30" rule. Since intra-cloud lightning sometimes precedes and succeeds the occurrence of CG lightning, use of NLDN lightning ground-strike data constitutes a "worst-case" approach. In other words, victims may have had more warning than indicated by the occurrence of nearby CG lightning flashes alone. The cases were divided into two categories: those in which on the basis of CG lightning flash data, the victim appeared to have little or no warning of approaching lightning danger and those in which the victim may have exercised poor judgment by not seeking proper shelter when there was frequent CG lightning and the danger should have been apparent. In a few cases in the first category there were no CG flash within 20 km before or after the one that caused the casualty.

Other casualty cases classified in the “little or no warning” category were situations in which there were very few flashes within range or time that could have served as warnings. The small circles plotted in Figure 1 illustrate an example in this category. The small circle at t = 0 represents the flash that struck the victim. There were only 3 CG flashes within a period of less than two minutes before the flash that caused the casualty. Even if the victim had been well-informed and tried to take cover, the 3 flashes in this case probably did not allow enough time.

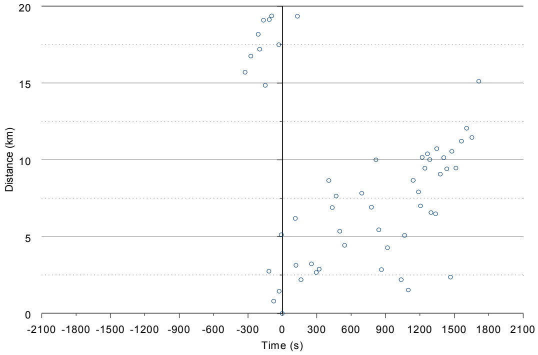

Figure 1. Casualty case (represented by ◦ at t = 0, D = 0) with little or no warning. This graph depicts all lightning flashes within a 20 km radius and ± 35 minute time period centered on the time of the ightning casualty at t = 0. There were only 3 flashes within 10 km before t = 0, and those occurred in a period of less than two minutes just before t = 0.

Lightning casualty cases classified in the “used poor judgment” category include those for which there were frequent CG flashes within 10 km for a sufficiently long period that an informed victim should have known to seek shelter. An example of this category is shown in Figure 2.

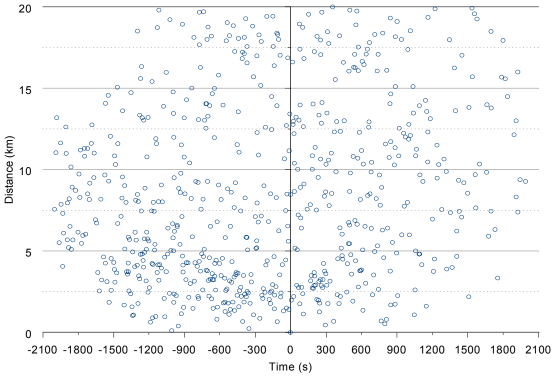

Figure 2. Casualty case (represented by ◦ at t = 0, D = 0) in which there was adequate warning.

The small circles show that there were more than 130 CG lightning flashes within 10 km for the period of 30 minutes leading up to the time of the casualty incident.

Other casualty cases that were classified in the “used poor judgment” category include those in which the victim apparently resumed outdoor activities too soon. An example of this category is provided in Figure 3. In this case, CG lightning was frequent nearby until about 7 minutes before the victim was struck. The rate of occurrence of flashes decreased rapidly, but clearly did not go to zero in that 7 minute period. In this case, it appears that the victim resumed outdoor activities too soon after what may have been perceived as the last lightning flash of the storm.

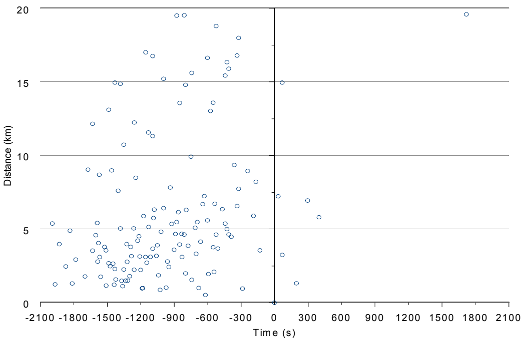

Figure 3. Casualty case (represented by ◦ at t = 0, D = 0) in which the victim may have resumed outdoor activity too soon.

Of the 107 lightning casualty cases studied, 54% were classified as victims who had little or no warning of the approaching threat of cloud-to-ground lightning. These cases included 131 casualties of which 19 were fatalities and 112 were injuries. The cases that were classified as having used poor judgment (ignoring warning signs of imminent CG lightning) totaled 42% of the high confidence cases. This included 90 casualties with 14 fatalities and 76 injuries. There were 7 cases (4%) that could not be classified into either category including 9 casualties with 2 fatalities and 7 injuries.

The period between 5 and 10 minutes before a victim is struck is a critical time in which the victim needs to realize the potential for lightning danger while still having time to take appropriate shelter. In 90% of the cases in the "used poor judgment" category there were at least 4 CG flashes during this five-minute interval. In all cases in the "little or no warning" category, there were fewer than 4 CG flashes during this five-minute interval, and in 90% of the cases there was only one flash or none.

It is arguable whether the period between 0 and 5 minutes before a lightning flash allows enough time for a victim to take shelter. It is nonetheless useful to note that in every case in the "used poor judgment" category, at least 1 CG flash occurred within 10 km in that time period and in 90% of the cases there were least 4 flashes. In contrast, in more than 90% of the cases in the "little or no warning" category, there were 4 or fewer CG flashes in the five-minute period before the casualty.

The work by Lengyel (2004) is, to the best of our knowledge, the first to address quantitatively the question of the extent to which the first or one of the first few CG lightning flashes in storms, i.e. those with little or no warning, are responsible for casualties. The study also demonstrates quantitatively the danger of returning to outdoor activities at the end of storms too soon after the last thunder heard, without benefit of local assessment of the potential for additional lightning flashes. Though there is considerable further work to be done to broaden and qualify the applicability of these first results, especially with regard to the possibility that intra-cloud lightning might provide additional warning, the implications of Lengyel (2004) for critical lightning hazard-warning decision support are clear: dependence on knowledge of the ongoing occurrence of lightning alone leaves personnel and facilities vulnerable to the possibility of a first or early strike from a storm approximately half the time. For critical lightning hazard-warning decision support, if risk is to be minimized to the greatest extent possible with state-of-the-art techniques, local measurement of electric field at the ground within striking distance of the point of concern is necessary to complement warnings based on ongoing occurrence of lightning.

MODEL STUDY

Though it is clear that elevated local electric field precedes a CG lightning flash, it is also true that there are cases in which elevated electric fields are not followed by a CG flash. It is not immediately obvious how to differentiate between those cases in which a CG flash is likely to occur and those in which a CG flash is not likely to occur. We took it as an article of faith that we ought to be able to elicit some useful patterns in the behavior of time series of electric field beneath storms as they become electrified in the period leading up to the first lightning flash and as they decay at the end of their lifetimes. In order to begin to grasp how the deployment of one or more electric-field meters might be used to predict the occurrence of first CG flashes within an area of interest, typically a few km^2, a few minutes in advance, we undertook a model study. The challenge is to determine the circumstances under which such predictions can be made reliably, in other words, to minimize the false-alarm rate. We used a thunderstorm model described in Mansell et al. (2000) to simulate the behavior of electric field at the ground beneath a thunderstorm. We postulated deployment of four electric-field meters in and around a point representing a high-value target and determined how the electric field at each of them would vary with time preceding a first lightning strike to the target and at the end of the period of vulnerability. We did this for two types of storm: a multi-cellular storm of the type often seen in the Great Plains, and a small storm in Florida. We present results of the former only in this paper. The layout of simulated field meters is shown in Figure 4. The triangles represent electric-field meters, with the red triangle at the location of the facility of concern and the other three symmetrically disposed around a circle of radius 4.5 km centered on central field meter.

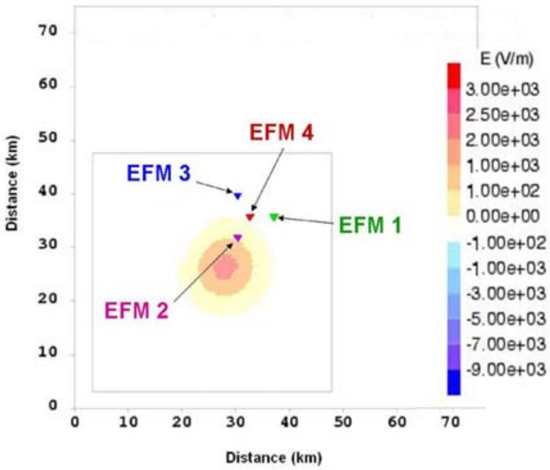

Figure 4. Layout of simulated field meters, showing field contours at t = 30 minutes.

The electric field at the ground is shown in Figure 5 at four times during the electrification and evolution of the thunderstorm.

From the data sets used to plot Figures 4 and 5, we then determined the electric field at each of the four simulated electric-field-meter sites as a function of time. The results are displayed in Figure 6.

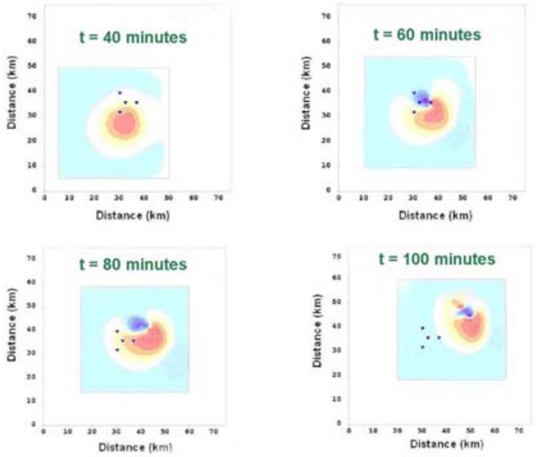

Figure 5. Patterns of simulated electric field at the ground beneath the model storm.

The first CG at the location of EFM 4 occurs at T = 56 minutes. If the only field meter deployed were EFM 4, using the reference warning criterion of ±2500 V/m, a warning would be issued at about 43 minutes, about 13 minutes before the first CG flash. With EFM 2 also present, a warning would be issued at about 33 minutes, about 23 minutes before the first CG flash. The steep negative slope of E at EFM 4 at about 50 minutes suggests the possibility of warning at a higher level of urgency at that time, 6 minutes before the CG flash. This is one of several issues to be explored in future algorithm development.

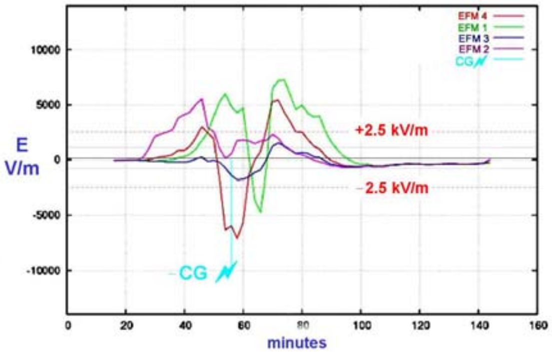

Figure 6. Electric field as a function of time at four field meter sites. Typical warning thresholds of ±2500 V/m are shown for reference.

First CG Flash

End-of-Storm-Considerations

If the CG at 56 minutes were the only flash, and if the only field meter were EFM 4, an "all-clear" might be issued at about 78 minutes using the ±2500 k/m criterion, 22 minutes after the flash. With EFM 1 present, an "all-clear" might be issued at about 89 minutes, 33 minutes after the flash. In this case the use of field meters would indicate a slightly more conservative "all-clear" time than the "30-30" rule. In other cases, the presence of field meters should allow for shortened waiting time for the "all clear".

DISCUSSION

The model study shows that at least under ideal conditions it ought to be possible to deploy field meters to provide objective determinations of the likelihood of a first CG lightning strike at a particular location about ten minutes in advance, and also to provide objective determination of diminished threat at the end of a storm. This is only a very preliminary study. More complex situations should be simulated and most importantly, real observations in real storms under a variety of conditions need to be made and analyzed, in order to address such issues as reliability and false alarm rate. The availability of low-cost, low-power field meters such as those described in Swenson et al. (2003) makes it possible to contemplate economically feasible field studies to address these issues.

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