Observed electric fields associated with lightning initiation

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[1] In situ electric field (E) measurements and inferred lightning initiation locations of three cloud-to-ground flashes are used to identify a thunderstorm region in which the preflash E exceeded the threshold for runaway breakdown. The maximum measured E in the region was 186 kV m^{-1} at 5.77 km altitude, which for runaway electrons is equivalent to 370 kV m^{-1} at sea level; this E value is ~130% of the estimated threshold for an avalanche of runaway electrons. In addition, the volume where E exceeded the runaway threshold was estimated to be 1–4 km^3, with a vertical depth of about 1000 m. At least within part of this volume the characteristic scale height for exponential growth of runaway electrons was 100 m or less. Thus for these three flashes the electric field conditions necessary for runaway breakdown existed, and runaway breakdown could have initiated the flashes.
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1. Introduction

[2] *Wilson* [1925] suggested that an energetic electron in a strong thunderstorm electric field would gain more energy from the field than it loses in collisions; such electrons are now called "runaway" electrons. *Gurevich et al.* [1992] suggested that an avalanche of runaway electrons, called runaway breakdown (RB), might initiate a lightning flash. The mean energy of runaway electrons is 7 MeV [*Babich et al.*, 2004].

[3] To look for evidence of runaway breakdown inside thunderstorms, *Marshall et al.* [1995a] compared vertical profiles of electric field, E, to the breakeven threshold field. In the breakeven field, E_{be}, an energetic electron gains as much energy from E as it loses in collisions. Marshall et al. estimated E_{be} as follows:

$$E_{be} = E_{th} \exp(-z/8.4) \quad (1)$$

where E_{be} is measured in kV m^{-1}, z is the altitude in km above sea level, and E_{th} is the threshold breakeven value at sea level (or 1 atm pressure). *Marshall et al.* [1995a] used 202 kV m^{-1} for E_{th}. Comparing 24 in situ E profiles, they found that E was close to E_{be} for a portion of most soundings, but it rarely exceeded E_{be}. When the measured E exceeded E_{be}, lightning occurred within a few seconds and reduced the local E to less than E_{be}. From this they hypothesized that runaway breakdown might be initiating some lightning flashes. In two soundings, the balloon instruments were struck by lightning and destroyed a few seconds after the local E exceeded E_{be}. Just before these two flashes the measured E values were 430 kV m^{-1} and 340 kV m^{-1} (both scaled to 1 atm), and the E: E_{be} ratios were ~210% and ~170%.

[4] The E_{th} calculated by *Gurevich and Zybin* [2001] was 216 kV m^{-1}, rather than 202 kV m^{-1} used by *Marshall et al.* [1995a], but this difference would not significantly change the results summarized above. Hereinafter we use 216 kV m^{-1} for E_{th}. The threshold for RB (i.e., for an avalanche of runaway electrons to occur) has been determined to be about 281 kV m^{-1} (i.e., 1.3 times E_{th}) [*Symbalisty et al.*, 1998] and about 284 kV m^{-1} [*Dwyer*, 2003]. We will use 281 kV m^{-1} as the RB threshold (RB_{th}) at 1 atm. One goal of this paper is to compare in situ E measurements with RB_{th}. As discussed below, RB requires a region in which E exceeds RB_{th} over a substantial vertical depth. Another goal of this paper is to estimate the vertical depth and volume in which E exceeds RB_{th}.

[5] Our comparisons to experimental data use one thunderstorm E profile in which the balloon instruments passed close to several flash initiation locations, as determined from a Lightning Mapping Array (LMA) [*Rison et al.*, 1999; *Maggio et al.*, 2005].

2. Instrumentation

[6] The data for this study were collected as part of the "Study of Electrical Evolution in Thunderstorms" or SEET experiment, conducted in 1999 at Langmuir Laboratory in central New Mexico to study mountain thunderstorms [*Coleman et al.*, 2003]. Series of balloons carrying electric field meters [*Marshall et al.*, 1995b], and Global Positioning System (GPS) radiosondes [*Coleman et al.*, 2003] were flown into thunderstorms occurring over the laboratory. Three-dimensional maps of individual lightning flashes were obtained with an LMA [*Rison et al.*, 1999; *Coleman et al.*, 2003].

[7] The balloon E meters measure magnitudes up to 220 kV m^{-1} with estimated error <10% [*Marshall et al.*, 1995b]. The horizontal balloon positions were determined from the GPS data, with errors <10 m. The vertical balloon positions were calculated from pressure, temperature, and humidity data from the radiosonde using the hypsometric

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equation, with errors <20 m (in the altitude range discussed in this paper).

[8] The LMA detected impulsive radiation at 63 MHz (bandwidth of 6 MHz) and located the strongest source (if any) above a threshold in successive 100 μs windows using a time-of-arrival technique [*Rison et al.*, 1999]. The lightning flashes discussed herein occurred near the center of the 10 LMA receiving stations, and the radiation sources of interest were located between 5 and 10 km altitude. For this situation, *Thomas et al.* [2004] showed that the rms errors in the location of individual radiation sources are 6–12 m in the horizontal and 20–30 m in the vertical.

[9] The balloon E meter measures E in a vertical plane at about 5 Hz and slowly rotates in azimuth, sweeping through 180° in about 2–4 s, thereby determining the magnitude of the total E vector at about 0.2–0.5 Hz [*Marshall et al.*, 1995b]. The E data in this paper show the maximum E measured in every 1 s interval of the sounding. The sign of the plotted E is the sign of the vertical component of E. For the E data of interest herein, the E vector was primarily vertical.

[10] By comparing LMA data with the occurrence of lightning field change measurements, *Maggio et al.* [2005] showed that the initial LMA radiation source from a lightning flash occurs at or near the flash initiation location: within 30 m in the best cases and within 400 m in the worst cases. This finding allows us to use the LMA to determine the initiation location of each flash. Furthermore, we assume that E at this location was large (large enough for flash initiation).

3. Theoretical Considerations

[11] As mentioned above, runaway breakdown should require a significant vertical depth in which $E > RB_{th}$. Since the large-scale structure inside thunderstorms is dominated by approximately horizontal layers of charge [e.g., *Stolzenburg et al.*, 1998], the E inside most of a thunderstorm has a vector orientation that is approximately vertical. To estimate the vertical depth of the volume necessary for RB, *Gurevich et al.* [1992] defined the characteristic length, λ, for an avalanche to develop as:

$$N_{re} = N_0 \exp(\Delta z/\lambda) \tag{2}$$

where N_{re} is the number of runaway electrons produced by N_0 ‘seed’ electrons, and Δz is the vertical distance from the start of the runaway avalanche. Unless there are many seed electrons, the volume of large E necessary for RB needs to have a Δz of 10λ or more for an avalanche to develop.

[12] *Dwyer* [2003] developed an empirical formula for λ from a Monte Carlo simulation of RB:

$$\lambda = 7200 \times (E - 275)^{-1} \tag{3}$$

with λ in meters and E in kV m^{-1}. Equation (3) is valid for E between 300 and 2500 kV m^{-1}, where E is scaled to sea level using the exponential factor of equation (1). The largest E observed by *Marshall et al.* [1995a] was 430 kV m^{-1}, which corresponds to a λ of 45 m, while the minimum E for which equation (3) is valid (300 kV m^{-1}) has a λ of about 290 m.

[13] Since the electrons that initiate RB have small mean free paths (of order meters), the horizontal extent, Δx, of the volume in which $E > RB_{th}$ can be as small as a few hundred meters. However, *Dwyer*'s [2003] model results indicate that RB will be enhanced if Δx is 400 m or more. We can only estimate a one-dimensional horizontal extent Δx from our data, so we will assume the volume is cylindrical with a radius or diameter of Δx. For RB leading to lightning initiation, having a volume with a substantial Δz is probably more important than having a substantial Δx.

[14] The energy of the cosmic ray that initiates runaway breakdown is also important because it produces the seed electrons (N_0 in equation (2)). More energetic cosmic rays produce more seed electrons. The flux of cosmic rays with energies sufficient to provide at least one energetic seed electron is of order 10^3 m^{-2} s^{-1} [*Gurevich and Zybin*, 2001]. However, lightning radio emission data suggest that cosmic rays with energy of 10^{16} eV may be needed for lightning initiation [*Gurevich et al.*, 2003]. Such high energy cosmic rays produce extensive showers of energetic electrons, but the flux of these cosmic rays is only 1 per km^2 every 50 s [*Gurevich et al.*, 2003].

4. Data and Analyses

[15] With respect to E_{be}, the majority of the SEET soundings were similar to those by *Marshall et al.* [1995a]. We will focus on one sounding on July 31, 1999, that passed through a region where lightning was initiating.

[16] Figure 1 shows 6 min of lightning data from the July 31 storm and the trajectory of the sounding balloon relative to the lightning. Ten intracloud (IC) flashes and four cloud-to-ground (CG) flashes occurred during the 6 min. The color-coded LMA observations indicate the inferred polarity of the storm charge regions involved in the lightning flashes [*Thomas et al.*, 2002]. The yellow/red colors indicate where negative polarity breakdown propagated through positive storm charge and the blue colors indicate where positive breakdown traveled through negative charge [*Coleman et al.*, 2003].

[17] The lightning data indicate that the storm had horizontally extensive upper positive and mid-level negative charges and localized lower positive charge in the southern part of the storm. The CG flashes (A–D) occurred in the southern part of the storm and were initiated either immediately above or within the inferred lower positive charge region. The IC flashes were bilevel discharges between the negative and upper positive charge regions. Eight of the ten IC flashes occurred in the northern part of the storm and made no significant change in E at the balloon. The other two (Flashes 3 and 5) occurred in the part of the storm traversed by the balloon and produced significant changes in E. However, their initiation altitudes were above the altitude of the balloon measurements, so they are not included in these analyses.

[18] Figure 2 shows an expanded view of the lightning data, the initiation locations of CG flashes A–D, and the balloon E profile. There is excellent agreement between the lightning-inferred charge regions and the charge regions inferred from the balloon data using a one-dimensional approximation to Gauss's Law. The sounding balloon was

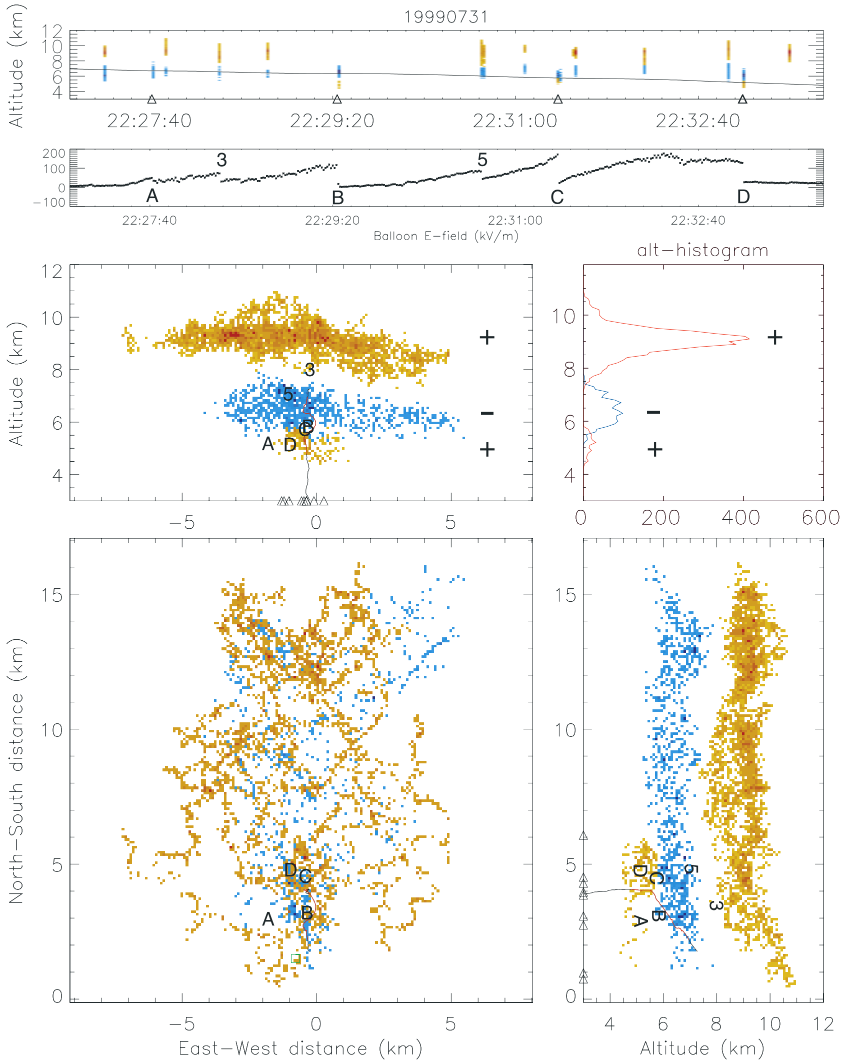

Figure 1. Lightning-inferred storm charge structure for a 6 min time interval of LMA data collected during the descent of the sounding balloon. Yellow/red regions indicate positive charge; the blue region indicates negative charge. The letters show the initiation points of the CG and IC flashes that occurred in the part of the storm observed by the balloon. The occurrence times of the flashes are shown in the upper panels, and the red part of the balloon trajectory corresponds to the time interval of the lightning data.

launched into the southern edge of the storm and rose to 7.26 km altitude, where it burst. The remnant balloon and instruments then descended by parachute along a northward path through the negative charge and then through the lower positive charge. Flash A occurred when the balloon was at 6.7 km altitude in a region of relatively small E. The flash initiated about 2 km below and west of the balloon and produced a change in E at the balloon of only -22 kV m^{-1} (from +55 to +33 kV m^{-1}). We focus on Flashes B–D, each of which initiated within 1.1 km of the balloon as it descended through a volume of very strong E.

[19] As the balloon descended through 6.35 km altitude, E rapidly increased, exceeded E_{th}, and approached RB_{th} before Flash B at 2229:22 UT (balloon altitude of 6.33 km) reduced E from 123 to 2 kV m^{-1} (a 98% reduction). The initiation point for Flash B, as determined from the first LMA source [*Maggio et al.*, 2005], was 600 m below the balloon (at 5.73 km) and only 200 m horizontally north of the balloon. The initial source of Flash B was located 40 m

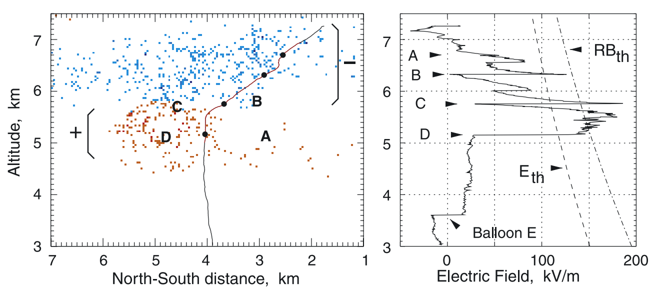

Figure 2. Expanded view of the balloon's descent trajectory (left, from Figure 1) and the measured E profile (right, solid line) of the sounding, initiation points of the CG flashes (letters), balloon location at the time of the flashes (black dots, descending with time) and times of the flashes during the sounding (arrows). The dashed curves are E_{th} (left) and RB_{th} (right).

below the altitude where the largest E in the sounding was observed when the balloon reached that altitude two minutes after Flash B. Further descent of the balloon (below 5.73 km) revealed that E values in excess of RB_{th} extended down to 5.28 km and that E_{th} was exceeded down to 5.16 km. Thus it is likely that the vertical depth of the volume in which the instantaneous E values equaled or exceeded RB_{th} at the time of Flash B was about 1000 m. The largest measured E in the region was 186 kV m^{-1} or 370 kV m^{-1} scaled to 1 atm. The corresponding λ for the largest E was only 75 m, so it is possible that there could have been numerous e-foldings of the seed electrons (equation (2)) to make a substantial runaway electron avalanche. Since the balloon location was 200 m from the flash initiation location, we infer that Δx was at least 200–400 m.

[20] As the balloon continued to descend after Flash B, E increased until IC Flash 5 occurred (see Figure 1) as the balloon passed through 6.0 km altitude. After that flash, E continued to increase rapidly until Flash C at 2231:23 UT reduced E from 172 kV m^{-1} to 29 kV m^{-1} (or by 83%) as the balloon descended through 5.76 km altitude. Two seconds before Flash C, the balloon measured the largest E of the flight (186 kV m^{-1}), which was 131% of RB_{th} (and 171% of E_{th}). The initiation point for Flash C, as determined from the first LMA source of the flash, was only 40 m below the balloon (at 5.72 km) and 1080 m horizontally NNW of the balloon. As for Flash B, it is likely that the vertical depth of the volume in which E equaled or exceeded RB_{th} was about 1000 m. Concerning the horizontal extent where $E \geq RB_{th}$, we assume that E at the initiation location was also large, with a magnitude similar to or greater than the 186 kV m^{-1} measured at the balloon. Thus, the horizontal extent, Δx, appears to have been at least 1080 m, and the volume of cloud in which $E \geq RB_{th}$ before Flash C was approximately 1–4 km^3. Such a large volume with a short λ (only 75 m for the largest measured E) makes a substantial runaway electron avalanche likely. Thus, it seems probable that Flash C was initiated by runaway breakdown.

[21] Since E at the balloon reached 131% of RB_{th}, it is somewhat surprising that Flash C did not initiate closer to the balloon. Perhaps the conditions for RB were simply better where Flash C initiated (bigger E, bigger Δz). Another possibility is that a substantially more energetic, and hence less common, cosmic ray was required for initiation of the flash, as suggested by *Gurevich et al.* [2003]. A third possibility is a combination of the previous two possibilities.

[22] As the balloon descended after Flash C, the measured E again increased rapidly. It took only 42 s for E to exceed E_{th} (at 5.62 km), and 63 s for E to reach a local maximum of 179 kV m^{-1} at an altitude of 5.50 km (E = 345 kV m^{-1} scaled to 1 atm, or 120% of RB_{th}). After E exceeded RB_{th}, no lightning flash occurred near the balloon for almost 40 s. At 2233:04 (101 s after Flash C), Flash D reduced E from 128 to 27 kV m^{-1} (or by 79%) as the balloon descended through 5.16 km altitude. The Flash D initiation location was 100 m below the balloon (at 5.06 km) and 1000 m horizontally NW of it. At the time of the flash, E scales to 235 kV m^{-1} at 1 atm, less than RB_{th} but more than E_{th}. Nonetheless, the probability that RB initiated Flash D is again fairly high.

[23] If RB was responsible for initiating Flash D, the relatively long delay (~40 s) with E > RB_{th} might have been due to an insufficient depth or volume of cloud with E > RB_{th}. Another possibility for the delay is that a more energetic cosmic ray might have been needed for the runaway breakdown, so the delay was caused by the lack of the appropriate cosmic ray [*Gurevich et al.*, 2003]. A third possibility is again a combination of the previous two.

5. Conclusions

[24] Overall, the inferences from the balloon E data coupled with the Lightning Mapping Array data are as follows. The balloon descended through a region of the cloud where lightning was initiating, as shown by the locations of the first LMA sources of Flashes A–D. In this region there appears to have been either substantial charge generation between Flashes B and D, or residual charge after Flashes B and C, or both, since the measured E increased rapidly between the flashes as the balloon descended. The measured E values along with the inferred flash initiation locations suggest that just before Flashes B, C, and D, there probably was a large volume (estimated to be 1–4 km^3) in which E exceeded the runaway breakdown threshold. This volume apparently had a vertical depth of about 1000 m. The maximum measured E magnitudes and the assumed large E magnitudes near the flash initiation locations suggest that within much of this volume the characteristic scale, λ for a runaway breakdown to develop was less than 100 m. Thus, just before Flashes B–D, the electric field conditions necessary for runaway breakdown apparently existed, so runaway breakdown avalanches could have initiated these lightning flashes.

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