Coordinated LMA, Balloon-borne Electric Field, and Polarimetric Radar Observations of a Triggered Lightning Flash at Camp Blanding

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ABSTRACT: In an 18-day period of July – August 2013, coordinated observations were attempted with a balloon-borne electric field meter, a balloon-borne particle imager, the 5-cm wavelength polarimetric Shared Mobile Atmospheric Research and Teaching Radar (SMART-R), a small-baseline VHF Lightning Mapping Array (LMA), and the extensive observing facilities for triggered lightning at the International Center for Lightning Research and Testing (ICLRT) at Camp Blanding, Florida. This experiment was the first to provide vertical profiles of the electric field, from which the vertical charge distribution could be inferred, relative to radar data in Florida storms. Furthermore, mapped three-dimensional lightning structure, surface measurements of lightning current, and multiple-station electric fields and electric field derivatives were provided by the ICLRT for triggered flashes. On 1 August, an electric field meter was flown during a period in which 3 flashes were triggered and confirmed the hypothesis that the turn to horizontal lightning structure just above the melting level occurred in a layer of negative charge.

INTRODUCTION

Based on previous studies that showed much of the horizontal structure of negative cloud-to-ground flashes tends to be within negative charge regions [e.g., MacGorman et al. 1981, 2001; Coleman et al. 2003], one suggestion was that the horizontal channels of Florida triggered lightning, which typically were just above the melting level of storms, were within negative charge [Hill et al. 2013, Pilkey et al. 2013]. (Note that the turn to from vertical to horizontal structure in the Florida cases occurred during initial stage (IS) propagation, which occurs before return strokes can occur.) However, microphysical effects on lightning propagation also were considered a possible explanation. One goal of the present effort to measure vertical profiles of the electric field at the International Center for Lightning Research and Testing (ICLRT) was to determine which hypothesis is correct.

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OBSERVATIONS

On 1 August, strong convection reaching up to 14 km MSL occurred over the ICLRT. Radar data showed that the storm was weakening as the balloon carrying an electric field meter was launched at 1912 UTC. Four attempts were made to trigger lightning in this storm during the balloon flight. A natural flash apparently interfered with the first trigger attempt, made approximately 2 minute after the balloon was launched. The last three attempts were successful and were mapped by the local 7-station lightning mapping array.

Only six stations were available on 1 August, but one station was very noisy, so most mapped sources were detected by only five stations, which makes the VHF source locations inherently noisier. Furthermore, the system detected fewer noise pulses for the third flash, so it was more difficult to use continuity to discriminate lightning signals from noise.

The gross structure of the first two triggered flashes turned from vertical to horizontal at an altitude of 4–5 km MSL (Fig. 1). The larger reflectivities at roughly 4 km MSL were caused by the increase in reflectivity as ice particles aggregated and melted. Thus, as noted in previous cases, the horizontal channels occurred at or just above the melting level of the storm.

The first triggered flash, at 1919 UTC, produced a relatively long (571 ms) IS discharge followed by a single leader/return stroke and 6 ms of continuing current. The second triggered flash, at 1925 UTC, produced a 532 ms IS discharge followed by 5 leader/return strokes, consistent with the somewhat greater horizontal extent of its channels (the difference in extent was even greater in the plane perpendicular to Fig. 1). Continuing current ranging from 10 ms to >40 ms followed return strokes 1, 4 and 5.

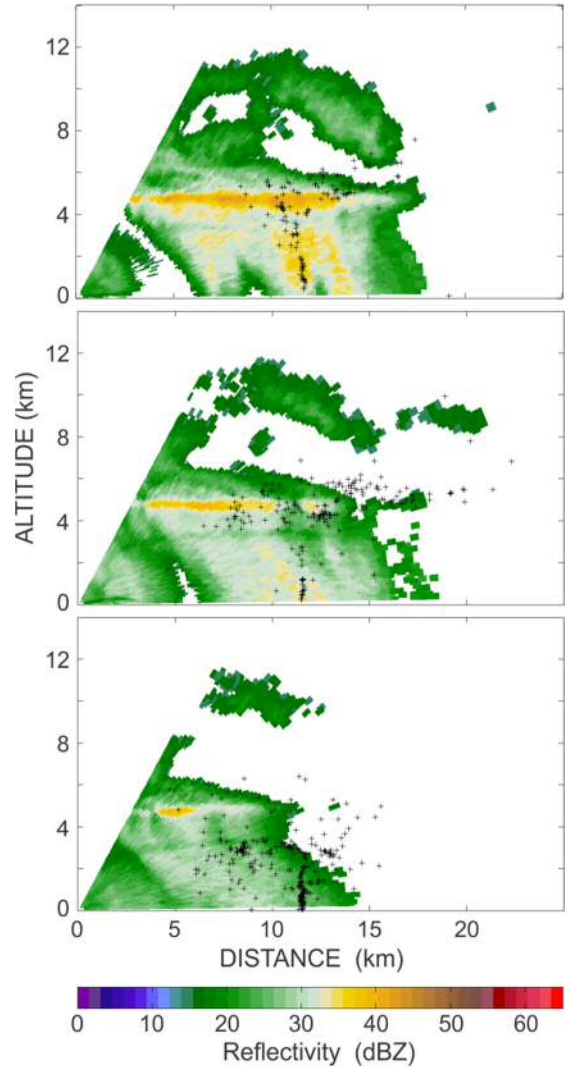


Figure 1. VHF source points for the three triggered flashes on 1 August 2013 relative to reflectivity from the 5-cm wavelength SMART-R radar [Biggerstaff et al. 2005]. The vertical projection is along the 9.6° azimuth from the radar through the flash. Note the bright band (yellow shading) near 4 km MSL, which indicates melting particles. Values of ρ_{hv} (not shown) indicate mixed-phase particles consistent with melting in roughly the same region. Triggered flash at (top) 1919 UTC, (middle) 1925 UTC, and (bottom) 1934 UTC. Data were available from six stations, but noise caused most mapped VHF sources to use data from only five,

The third triggered flash, which occurred when the electric field meter was near the melting level, produced a relatively short IS (205 ms) and no subsequent return strokes. While the plot of lightning

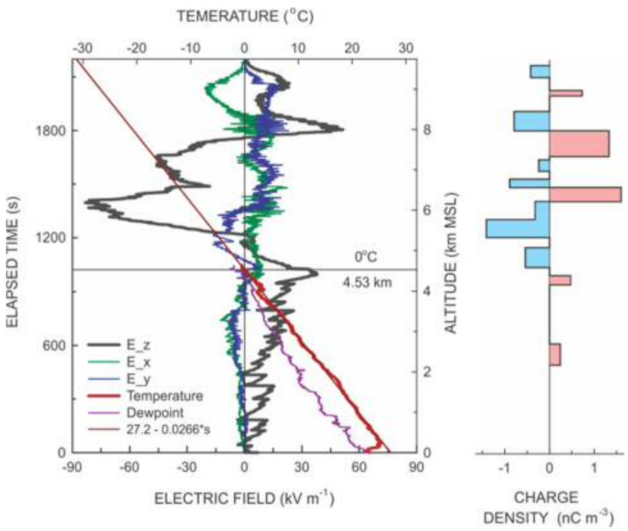


Figure 2. Electric field as a function of height and elapsed time from launch at approximately 1912 UTC. Radiosonde data were lost a short distance above the 0°C isotherm, but the electric field meter continued operating. Heights and temperatures at later times were extrapolated by assuming the rate of change with height was the same as a linear fit to the change at lower altitudes.

structure is noisier, it appears that extensive horizontal channels formed at roughly 2.5 km MSL, approximately half as high as for the two previous flashes. This is consistent with the shorter duration of the IS.

Electric field data from the balloon flight launched at approximately 1912 UTC is shown in Fig. 2. Just above the melting level, the vertical component of the *in situ* electric field had a large negative gradient with height spanning the mapped horizontal channel structure of the first and second triggered flashes. The 1-dimensional approximation of Gauss's Law, consistent with the relatively stratified structure of the weakening storm, indicates that the large negative gradient in the vertical component of the electric field was caused by a region of negative charge just above the melting layer. Thus, it appears that the horizontal structure of the first two triggered flashes did propagate through a negative charge layer at and just above the melting layer, as hypothesized by previous studies.

What caused the horizontal structure of the third triggered flash to be lower, around 2.5 km MSL, is less clear. To consider various hypotheses, it is helpful to look more closely at the reflectivity structure relative to the balloon and triggered flashes. Figure 3 shows the position of the balloon and the ICLRT before launch and near the time of each triggered flash relative to the base scan reflectivity from the Jacksonville, Florida WSR-88D. Note that the position of the balloon relative to the storm's structure is similar for the three launch times, although the storm overall is moving northeastward and is weakening. This implies the upward balloon track is roughly vertical in the reference frame moving with the storm, so the electric field sounding is approximately a vertical sounding through that part of the storm and reflects the vertical distribution of charge there. The balloon was just north of the ICLRT at the time of the first triggered flash, so the relatively small amounts of charge below the melting level and the prominent negative charge immediately above the melting level probably is at least qualitatively the configuration of charge experienced by the first flash, and the similar structure of the second flash suggests it experienced a similar charge configuration.

We suggest three hypotheses for the shorter vertical extent of the third flash:

(1) The region of negative charge experienced by the first two flashes descended to an altitude of 2-3 km by the time of the third flash. Although charge regions have been observed to descend in other storms, the region over the ICLRT at the time of the third flash in Fig. 3 had a region weak precipitation move overhead and there is no evidence of a precipitation core having descending there. Furthermore,

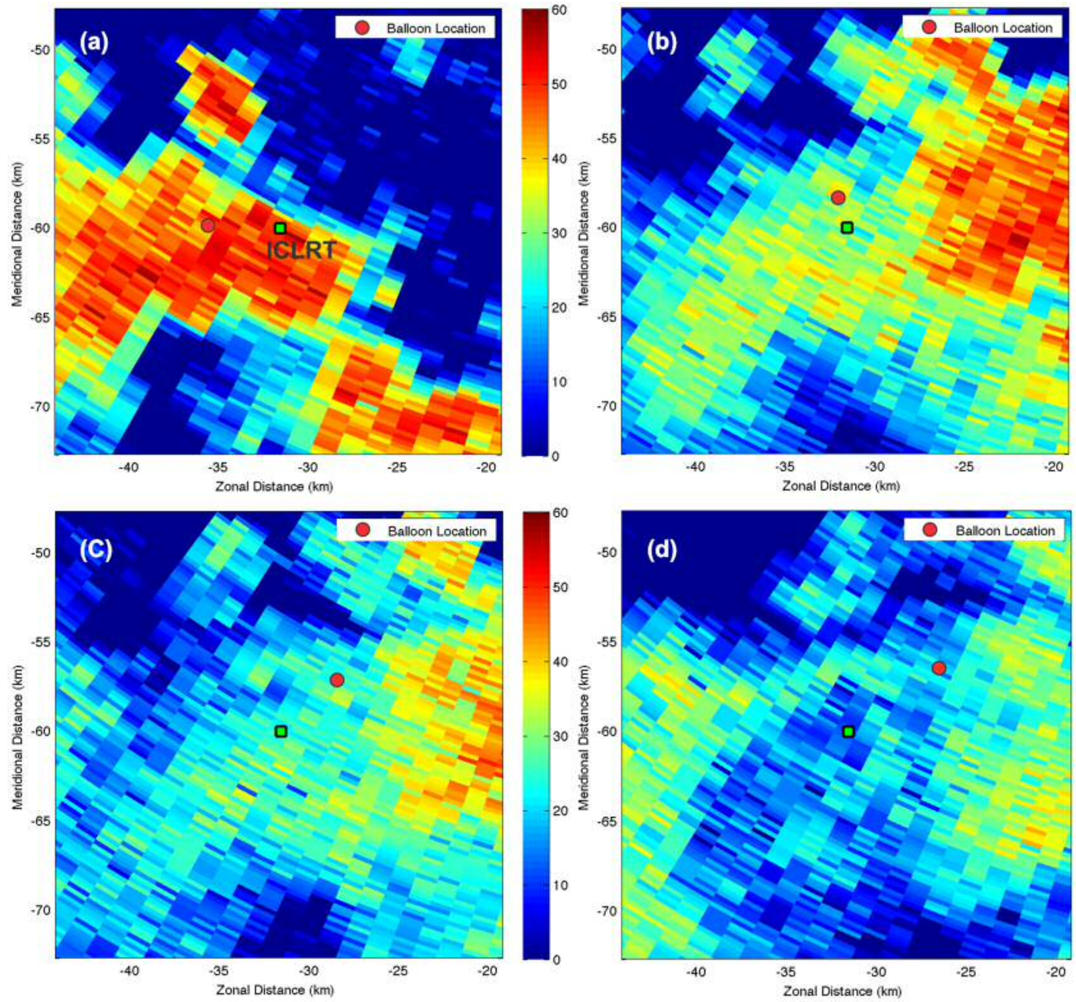


Figure 3. The location of the balloon and ICLRT relative to base scan reflectivity from the S-band WSR-88D radar at Jacksonville, Florida for (a) 185212 UTC, near the time when it was decided to begin preparing to launch a balloon at the site marked as the balloon location, (b) 191555 UTC, before the first triggered flash at 191923 UTC, (c) 192523 UTC, 8 s before the launch producing the second flash, and (d) 193450 UTC, 36 s after the launch producing the third flash.

while the horizontal structure of the second triggered flash may extend slightly lower than the first, the rate of change in altitude was less than needed to reach 3 km by the time of the third flash. Thus, while this is a reasonable hypothesis, the observational evidence gives little support for it.

(2) Our first analysis of the vertical electric field profile had indicated a region of relatively small positive charge density just below the negative layer and another region of even smaller positive charge density at roughly 2.5 km MSL (Fig. 2). We consider evidence for this lowest positive charge region to be weak. The electric field at the ground at the time of launch still met the operational threshold for launch intending to trigger a negative cloud-to-ground flash, so either the spatial extent or the amount of lower positive charge was relatively small. However, it is possible that positive charge in a small region reduced the local electric field magnitude enough to inhibit further upward propagation as the third triggered flash approached the charge. If so, the flash did not reach the negative charge region and could

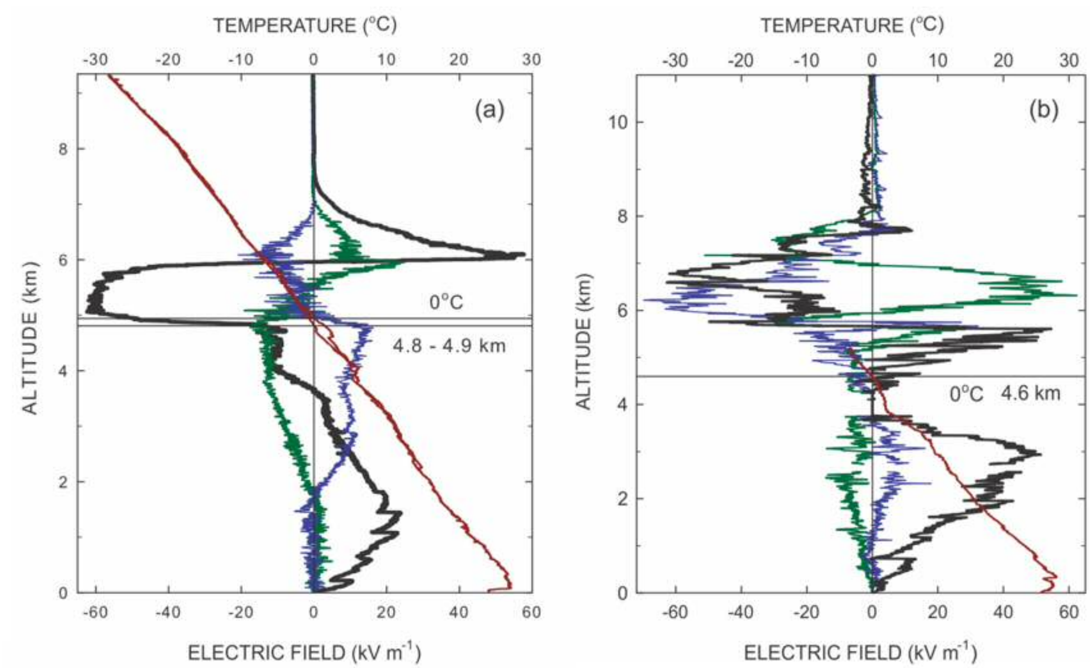
produce no return strokes. The effect would be similar to the tendency of sparks to propagate around regions of charge deficit in the doped blocks of plastic treated by Williams et al. [1985]. While this may explain the behavior of the third triggered flash, there is not enough evidence of a localized region of positive charge to give much confidence in it.

(3) The propagation path is influenced by the geometry of the storm's upper boundary of 15 dBZ reflectivity. The transition from vertical to horizontal structure for the third flash occurs as the flash reaches the upper 15 dBZ boundary (Fig. 1). Although weaker reflectivity extends beyond this region, this region is marked by a reflectivity gradient. As discussed by MacGorman and Rust [1998] (pp. 200–209), several studies have noted the tendency for lightning structure to grossly parallel reflectivity contours and to remain within regions of low to moderate reflectivity [e.g., MacGorman 1978, MacGorman et al. 1983; Proctor 1983; Taylor et al. 1984; Shao and Krehbiel 1996]. This tendency has traditionally been attributed to both precipitation and charge being transported similarly (an influence similar to that in the first hypothesis above), but it is also possible that the detailed microphysics of spark development in the presence of precipitation noted by Pišler and Atkinson [1971] enables precipitation to influence the discharge path directly.

The four vertical soundings of the electric field from August 2013 are the first that have been acquired for Florida storms, which occur in a much different climatology than that of the Great Plains or western mountains in which most previous soundings in the United States were acquired. Storms tended to be either small isolated storms or part of a line of storms resulting from interactions with the sea breeze. All storms we observed were relatively short lived, forming and dissipating in less than 1 h.

In three of the four cases (Figs. 2, 4a,c), the vertical structure of the inferred charge consisted of a vertical stack of alternating charge polarities, with the lowest region of large charge density ($|\rho| \geq 0.5$ nC m^{-3}) being a negative layer near or just above the melting layer. As in the 1 August case shown here, these three soundings were launched as the storms were dissipating (as was the storm in Hill et al. 2013). These soundings appear similar to those from the stratiform precipitation region of mesoscale convective systems (MCSs) in having a layer of charge near the melting layer, but in stratiform regions the charge near the melting level can be of either polarity and is often positive [Stolzenburg et al. 1998a; MacGorman et al. 2008], while all three of these Florida cases had negative charge. As has been suggested for MCSs, it appears that melting processes may well produce a charge layer, but what controls the polarity of that charging is uncertain. Shepherd et al. [1996] suggested that charge could be produced during melting by inductive processes, in which case the polarity would be controlled by the pre-existing electric field, or by noninductive processes, in which case microphysical properties of melting itself would be responsible.

The fourth sounding (Fig. 4b) was launched as the storm was still growing, having formed over the launch site and moved a few kilometers east of the site by the time of launch, so that the balloon ascended a short distance west of the storm's reflectivity core. The vertical profile of E_z is much more complex than those for the other three cases, with considerable charge below the 0°C isotherm and significant positive charge, rather than negative charge, just above it. Above the freezing level, the charge distribution is similar to that seen by Stolzenburg et al. [1998b] near, but outside, strong updrafts in isolated storms: the charge distribution above the freezing level could be grossly characterized as a tripolar distribution made more complex in part by lightning activity, but additional charge regions of alternating polarity were below the freezing level.



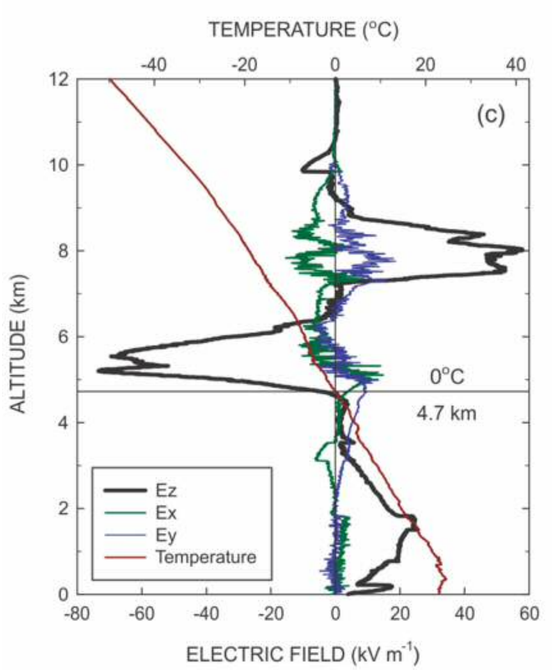


Figure 4. Electric field soundings on (a) 10 August, (b) 12 August, and (c) 15 August in 2013. Altitude is relative to mean sea level. The sounding on 12 August had some data gaps. On 10 August, the temperature profile shows both the ascending and descending soundings. The 4.9 km altitude of 0°C is from the ascent. Note that E_z in both (a) and (c) has a large negative slope just above the 0°C isotherm due to the balloon passing through a layer of substantial negative charge density. E_z at lower altitudes has smaller slopes and smaller maximum magnitudes indicating less charge there. The vertical profile of E_z in (b) is much different, with larger changes at altitude below the 0°C isotherm and a substantial region of positive charge, instead of negative charge, just above the melting layer.

In July–August 2014, we plan to acquire additional soundings in Florida to evaluate how broadly the electric field profiles shown here are characteristic of storms there, as well as to relate the microphysics seen by our particle imager to the storm's electrical structure and to polarimetric radar signatures.

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