The Relationship Between the Electric Field and Radar Reflectivity of Thunderstorms Producing Positive Cloud-to-ground Lightning in STEPS

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ABSTRACT

The Severe Thunderstorm Electrification and Precipitation Study (STEPS) was held between May 22-July 16, 2000 in Goodland, Kansas. One of the goals was to get a better understanding of predominantly positive cloud-to-ground flashes in thunderstorms on the High Plains. This paper discusses the relationships of the electric field and radar reflectivity of three different soundings taken during the project. All showed electric fields different from those found in storms with predominately −CG lightning. An extra upper positive layer was seen in the anvil flight and all +CG lightning was located between the anvil and core during the dissipating stage of the storm. A core flight showed an inverted polarity and all benchmark regions were in the updraft portion of the storm. The second core showed that no apparent negative electric field charge layer was present and all +CG lightning was clustered in regions of highest reflectivity. This cell had produced a tornado just 30 minutes prior to the sounding.
INTRODUCTION

For eight weeks in the summer of 2000, scientists from the National Center for Atmospheric Research (NCAR), National Severe Storms Laboratory (NSSL), Colorado State University (CSU), New Mexico Institute of Mining and Technology (NMIMT), South Dakota School of Mines and Technology (SDSMT), National Weather Service (NWS), and other research organizations came together to participate in the Severe Thunderstorm Electrification and Precipitation Study (STEPS). One of the goals of the field project was to better understand the behavior of the unusual lightning characteristics of thunderstorms in eastern Colorado and western Kansas. Of particular interest were cloud-to-ground lightning flashes that lower positive charge to ground (+CG) instead of the usual negative charges (-CG) (STEPS, 2000).

Lightning strikes can occur between clouds (inter-cloud lightning) or when electrical discharge travels between the cloud and the earth's surface (cloud-to-ground lightning). Cloud-to-ground lightning accounts for twenty percent of all lightning, and the majority of these cloud-to-ground strikes transport negative charge to the ground, less than ten percent are ground flashes that lower positive charge (MacGorman, 1998). The polarity of the lightning flash is the same as that of the sign of the charge region from which it originated. Charge regions are positive (negative) where the electric field increases (decreases) with height. The electric field structure of a storm producing predominately -CG lightning has been found recently to be much more complex than the long-believed vertical dipole, a positive charge above negative charge, or a tripole, a lower positive charge region added below the dipole. Stolzenburg et al. (1998c) concluded from nearly 50 electric field soundings that charge structures differed according to the type of storm (mesoscale convective systems, isolated supercells, and isolated thunderstorms), and that the electric field structure was much more complex than originally thought.

The question then is: Is the electric field of a storm producing predominately +CG lightning the same as that of a storm producing predominately -CG lightning? Within the past decade, there has been an explosive effort to investigate the electric field structure of these unique storms producing +CG lightning. Because +CG lightning has been found among severe thunderstorms and are closely linked to the occurrence of tornadoes, a better understanding of the electric field of these storms could lead to the improvement of severe weather forecasting (MacGorman, 1998). However, until STEPS, neither the technology nor the sounding data was available to gather a complete and understandable view of thunderstorms producing +CG lightning.

The hypothesis is that storms that produce +CG lightning tend to have an inverted polarity, meaning at mid-levels a positive charge region exists where normally a negative charge layer is found in a storm producing -CG lightning (STEPS, 2000). Balloon soundings were able to be taken in both anvils, a flat-topped upper portion of cloud that is more horizontal extensive, and cores, the most intense region of a thunderstorm, of +CG lightning storms. By locating where each +CG lightning flash occurred relative to the radar reflectivity (an indirect measure of the intensity of the
thunderstorm) a better understanding of the electric field of these unique storms may be obtained.

This paper presents the findings from soundings through an anvil and two cores. It will discuss instrumentation and data analysis, storm descriptions, and observations and interpretations of the relationship between the electric field and radar reflectivity of thunderstorms with +CG lightning in the STEPS domain.

INSTRUMENTATION AND DATA ANALYSIS

Primary instrumentation in STEPS included two S-band polarimetric research radars, an operational Doppler radar, the armored T-28 aircraft for storm penetrations, two mobile sounding systems to characterize the storm environment, six mobile mesonets for the observation of weather beneath storms, a lightning mapping array (LMA) to map the three-dimensional distribution of lightning, and the NSSL mobile balloon unit for electric field and state variable soundings within storms.

For the purposes of this paper only balloon soundings, the National Lightning Detection Network, and radar images were used to make cloud-to-ground lightning polarity and electric field observations. Below is a brief description of each.

Balloon Instruments

Data was analyzed from soundings made with balloon-borne electric field meters (EFM) and radiosondes as seen below in Figure 1. Once a storm is targeted, a polysynthetic balloon is filled with helium and taken onto the launch site. The paper parachute, radiosonde, and the EFM are then attached to the balloon with a nylon line. This strengthens the connection between the balloon and the EFM. The EFM is made with aluminum spheres attached to a fiberglass tube. One of the spheres is an electronic sensor while the other contains a battery pack. A small motor inside one end of the fiberglass tube spins the tube and the two spheres about the horizontal axis. Above the EFM is a swivel that allows the meter to rotate about the vertical axis without twisting the rigging line. As soon as the instruments are connected, the train is released into the storm. Once in the air, the let-down reel allows about 15 m of monofilament line to extend downward so that there is a 20 m distance between the balloon and EFM. This distance is to limit possible charge buildup on the balloon (Stolzenburg et al, 1998b). When the balloon bursts, the parachute brings the instruments safely to the ground.
Figure 1: EFM and Balloon instrument train (Stolzenburg et al, 1998b)

Balloon Sounding

Each sounding relays back the vertical electric field ($E_z$), horizontal electric field ($E_h$), temperature, dew point, relative humidity, latitude, longitude, altitude, time, wind direction, and wind speed. By plotting temperature, dew point, relative humidity, and $E_z$ against altitude, the vertical structure of the electric field can be interpreted as it is in the cloud.

Once the vertical structure of the electric field is graphed, one can tell several things. Lightning strikes can be determined when a rapid change in the electric field occurs within a charge layer. However, a rapid change near the top or bottom of the cloud, both boundaries determined when the temperature and dew point difference is less than five degrees, indicates a screening layer is present. A screening layer is a layer of charge formed at the clear air/cloud interface because of discontinuities in conductivity. At the upper boundary of electrified clouds, the screening layer should form because the electric field outside the cloud drives free ions to the cloud. The ions build up at the cloud boundary thus making a screen layer because they attach to cloud particles there (Marshall et al, 1995).

The vertical air motion along the balloon path is estimated by subtracting the still-air rise rate of the balloon from the observed ascent rate. The still-air rise rate is
5 m/s, while the observed balloon ascent rate is determined by plotting altitude versus time and finding the slope of the line. Vertical air motions reveal if the balloon went through an updraft or nonupdraft (because the distinction between a downdraft and precipitation loading of the balloon cannot be made, the term nonupdraft is used). If the rate is larger than 6 m/s, the balloon sounding is categorized as an updraft sounding (Stolzenburg et al, 1993a).

**National Lightning Detection Network (NLDN)**

The NLDN consists of over 100 remote, ground-based sensing stations that monitor CG lightning activity across the United States. Within seconds of a lightning strike, the NLDN detects both +CG and −CG lightning, locates where each flash strikes the ground, and estimates its peak current. Using precise waveform processing, Global Positioning System (GPS) time synchronization, high-speed signal processing, and wide-band peak gated magnetic direction finding techniques, its accuracy in terms of location and polarity is reliable (NLDN, 2000). The observation of the NLDN during operations was crucial since balloon team deployment depended on the location and dominant polarity of the CG flashes.

**Radar**

Two different radar images were used for this analysis. The NEXRAD Information Dissemination Services (NIDS) radar composite reflectivity was taken to overlap the NLDN data. The NIDS composite takes the maximum reflectivity in each vertical column from each NWS radar and displays all such maxima at the same time. This image gives a representation of horizontal reflectivity within regions larger than ones covered by each radar. In order to observe the vertical reflectivity, the Weather Surveillance Radar-1988 Doppler (WSR-88D) from Goodland, KS was used. The WSR-88D radar is designed to give a radar scan at several elevation angles. The balloon sounding was plotted in instantaneous time and space relative to the radar scans.

**STORM DESCRIPTIONS**

**Anvil Flight**

An anvil flight was launched into a high-based storm on June 1, 2000 at 00:27 UTC. The target was the leading edge of a large anvil from a thunderstorm north of Cheyenne Wells, CO. Figure 2 below shows NIDS radar images of the storm 30 minutes prior to the sounding, during the sounding, and 30 minutes after the sounding. Also shown is a zoomed in view of the targeted storm. As observed from the NLDN, the anvil was not producing any lightning but the region between the core, located to the southwest of the anvil, and the anvil was producing predominately +CG lightning. No surface hail was reported. The radar reflectivity data indicates the sounding made it into a max reflectivity of 20 dBZ. The core of the storm had a reflectivity of 55 dBZ at 00:30
UTC. Storm motion was northeastward. The ascent rate of the balloon was less than 6 m/s.

Figure 2: NLDN with NIDS radar for June 1, 2000

Thirty minutes prior to the sounding at 00:00 UTC, the core of the storm was 55 dBZ with +CG lightning located throughout the higher regions of reflectivity. When the sounding took place, the thunderstorm was at its peak in producing +CG lightning and all flashes were located near regions of high reflectivity. It is interesting, however, that neither +CG or −CG strikes were located near the core at any time prior, during or after the sounding. At 01:00 UTC the targeted storm was weakening with 50 dBZ and continued to dissipate. A few lightning strikes were observed but −CG lightning appeared to dominate. By 01:30 UTC only three −CG strikes appeared in the back of the storm in a core that later intensified to 60 dBZ but no more +CG lightning was observed.

Core Flight 1

On June 25, 2000 a core flight was made at 01:04 UTC between Haigler, Nebraska and Wray, Colorado. The cell was in the process of splitting and the balloon entered the northern core. The cell targeted was not a +CG lightning producer at that time, as seen in Figure 3 below. Hail up to ¾ inch was reported. The core had a max
radar reflectivity of 55 dBZ and was moving northeastward. The ascent rate of the balloon was less than 6 m/s, making it a nonupdraft sounding.

Figure 3: NLDN with NIDS radar on June 25, 2000

This supercell storm split at about 01:30 UTC. The northern cell continued to move northeast while the southern cell headed southeast. By 02:00 UTC, the southern cell had died while the northern cell joined a larger system just to the north. This larger system had previously produced −CG lightning, transformed to +CG lightning, and then a few −CG strikes were observed. Between 02:00 and 04:00 UTC, the cell began to produce intense +CG lightning.

Core Flight 2

At 00:04 UTC on June 30 a sounding was done in the core of a supercell right into a mesocyclone (a rotating cloud that can produce a tornado) near Brewster, Kansas. The balloon went in through the core that was producing an intense amount of +CG lightning in the highest reflectivity region as seen below in Figure 4. The core was moving east-southeast and was 65 dBZ at the time. Numerous reports of hail up to the size of golf balls were reported. Average ascent rate of the balloon was 37 m/s indicating the balloon was clearly in an updraft.
During sounding (00:00)

Figure 4: NLDN on NIDS on June 30, 2000

Thirty minutes prior to the sounding, the cell had produced a tornado near Wheeler, KS. Reflectivity in the core was 60 dBZ. Extreme amounts of +CG strikes were observed from 23:00 to well past 02:00 UTC and all were clustered in the core. At 01:00 UTC a max reflectivity of 70 dBZ was reached and +CG lightning was most intense.

OBSERVATIONS AND INTERPRETATIONS

Anvil Electric Field Structure

The sounding shown in Figure 5 shows the vertical electric field structure for the anvil flight. Beside it is a visual representation of the polarity of each charge layer. The upper region from 10-12 km where a negative then positive region exist are not shown in the bar graph to the side. The electric field data shows that there is a negative layer from 6-8 km. The electric field reversed polarity at 8 km and extended to 9.5 km and identified the net positive layer 1.5 km deep. A 0.3 km negative layer occurred from 9.5-9.8. A top positive layer then extended from 9.8-10 km. An upper negative region goes from 10-10.5 km and an upper positive region from 10.5 to cloud top at 12 km. The anvil was negative, positive, negative, positive structure. Peaks in the electric field reached up to 65 kV/m and 40 kV/m.
This sounding brings up some questions. The hypothesis was that storms producing +CG lightning may have an inverted electric field. The thunderstorm targeted here had +CG lightning but as seen in the electric field structure, an inverted electric field is not the case. Figure 6 from Stolzenburg et al (1998c) shows the electrical structure of a normal thunderstorm producing –CG lightning. The charge structure of the anvil is almost the same as that of a storm producing –CG lightning in which a positive layer is sandwiched between two negative screening layers (Marshall et al, 1989). However, in this sounding there is an additional upper positive layer.
Byrne (1995) found a similar case in which he proposed that the particles that had originally been charged as part of the upper negative screening layer had fallen slowly into the anvil interior. The cloud then rescreened itself on the top but this time with a positive charge. Eventually the electric field strength of the positive charge region decreases and the upper negative charge dominates. This would bring the negative, positive, negative structure as seen in many cases of −CG lightning producing storms. He hypothesized that one particular way for the upper negative charge region to dominate is to decrease the net positive charge in the interior of the anvil by cloud-to-ground lightning between the anvil and the core.

The NLDN data indicates that the anvil was not producing any CG lightning at the time of the sounding. However, just to the southwest of the anvil in reflectivity of 40-45 dBZ, many +CG strikes were observed. It appears that the positive anvil interior to the north could be interacting with the core of the storm to the south because all +CG strikes observed were located just between the core and the anvil as suggested by Byrne (1995). Wind data along with the LMA would have to be studied in this particular storm to truly say this was occurring.

The bottom negative layer in this sounding is also different. The normal depth for a screening layer is less than 1 km. In the case of this anvil sounding, there appears to be a top screening layer but no lower screening layer. The lower negative electric field layer was 2 km deep, different from the usual 1 km deep, and there was no rapid change in electric field. Marshall et al (1995) found a similar instance on two anvils but then found a 40 percent change in relative humidity as the balloon entered the cloud. In this case the relative humidity as the balloon entered did not make a rapid change. It went from about 87 to 89 percent then gradually decreased as it went through the anvil. The presence of the upper positive region may play a part in the lack of presence of the lower negative screening layer.

The WSR-88D radar images below show the vertical flight of the balloon in respect to the radar reflectivity. It should be noted at this time, however, that although the term vertical electric field is used, there is really no way one can get a straight vertical view due to the upper winds aloft that carry the balloon horizontally. The three radar images below in Figure 7 show the reflectivity when the balloon is launched (a), the middle of its ascent (b), and at the end of the flight (c). Red circles indicate the balloon’s position at each time.
Figure 7a: Radar reflectivity at cloud base angle, 0.5 degrees, at beginning of launch

Figure 7b: Radar reflectivity at 5.2 degrees elevation during at middle of launch
Figure 7c: Radar reflectivity at elevation angle of 7.5 degrees at the end of the balloon flight near 14.4 km

Figure 7a shows the balloon entered the anvil. Although no radar reflectivity is seen, this is because the scan is at base level, 0.5 degrees. Anvils are located at the upper portions of the thunderstorms along the leading edge, thus they would not be visible on the base scan of a thunderstorm. The launch site was downwind of the core where the max reflectivity was 55 dBZ. Between the beginning of the launch and the middle, Figure 7b, the balloon moves almost vertical. As observed, there is not much horizontal displacement.

The middle stage of the flight is shown at the elevation angle of 5.2 degrees and altitude of 8.3 km. During this time, the balloon entered a small region of reflectivity of 25 dBZ. A much larger region of 25 dBZ was to the northwest of the balloon. The electric field at this time was just entering the lower positive charge region.

Figure 7c shows the reflectivity at the end of the flight at an altitude of 14.4 km. The elevation angle is 7.5 degrees. The displacement from the middle to the end
shows a 20 km horizontal displacement versus a 6 km vertical displacement. The reason for the large horizontal displacement is due to the strong outflow at the top of the thunderstorm that causes the anvil to spread horizontally. The balloon was out of the cloud at the end of the flight. From the middle to the end of the flight, the balloon passed the upper negative and positive regions. The radar indicates they are near the top of the cloud.

Figure 8 below is a vertical profile of the balloon's path. The launch was located about 37 km from a reflectivity of 35 dBZ. The lower negative layer is found in a reflectivity of 20 dBZ. A region of 25 dBZ was a few km away extending eastward. At this time the balloon was shifted east. The lower negative layer does not appear to be a screening layer since it extended to the mid-portions of the cloud. The lower positive layer, middle negative layer, and small upper positive layer were all found in reflectivity region of 20 dBZ from 6 km to about 10 km. The upper negative region was in 15 dBZ and located in the upper portion of the cloud. The upper positive layer is in 5-0 dBZ and is clearly a screening layer. Some of the region is in the cloud while the rest is out of the cloud.

Figure 8: Vertical profile of the balloon path overlaid on radar reflectivity
Core Flight 1 Electric Field Structure

This core flight has a very complicated electric field structure as seen in Figure 9 below. Max positive peak was 80 kV/m at about 10.3 km. A lower positive peak of 70 kV/m was observed at about 6.8 km. Max negative peak of −45 kV/m at 9.4 km and a lower −40 kV/m at 6.6 km were observed. The total electric field structure is a negative layer from 6-7 km, positive layer from 7-7.5 km, negative layer from 7.5-7.8 km, positive layer from 7.8-8 km, negative layer from 8-9.3 km, positive layer from 9.3-10.2, negative layer from 10.2-10.5, and a zero E layer from 10.5 km to cloud top at 12 km. Thus the total structure is negative, positive, negative, positive, negative, positive, negative, zero.

Figure 9: Balloon sounding

This charge structure appears to have an inverted electric field structure. A normal supercell producing −CG lightning in a weak updraft sounding has this same structure only all charges are opposite, meaning there is a negative in place of a positive and positive in place of a negative as seen in Figure 6.

Also found in this sounding are 3 V-benchmark regions as indicated in the above sounding. A benchmark region is a substantial charge region of opposite polarity (negative above positive) (Marshall et al, 1995). Negative CG lightning producing storms can have several benchmark regions but they are normally located at lower heights. Also most electric field peak regions are lower than 5 km. This sounding indicates that they were higher than 6 km.
The WSR-88D shows the vertical radar reflectivity. Figure 10a, b, c again show the beginning, middle, and end of the balloon flight.

Figure 10a: Radar reflectivity with cloud base elevation of 0.5 degrees at the beginning of balloon flight
Figure 10b: Radar reflectivity at elevation of 4.3 degrees at middle of balloon flight near altitude of 6 km

Figure 10c: Radar reflectivity at elevation of 6.2 degrees at the end of balloon flight near altitude of 14 km
Figure 10a indicates the cloud base level reflectivity of the targeted storm was 60 dBZ. The launch site was located in between the northern splitting cell and the farther north larger storm. Horizontal displacement during the beginning and middle of the flight was about 10 km in a 6 km vertical displacement.

Figure 10b shows the middle of the flight entered the edge of the larger northern storm into a 35 dBZ reflectivity. A +CG lightning flash was observed just to the north of the balloon position in 35 dBZ. The elevation angle was 4.3 degrees with an altitude of about 6 km. Because there was missing data from about 4.5-6 km, the time of the radar was about 20 seconds less than the sounding when data again was recorded. The charge layer at this particular time is the lower negative region.

At the end of the flight, Figure 10c, the altitude of the balloon is 14.4 km where there is a zero electrical field. This is outside of the cloud but regions of 35 dBZ are still observed to the west of the balloon’s position. The northern cell has already joined the larger system. Horizontal displacement was 30 km versus an 8 km vertical displacement. This indicates that there were strong winds in the upper portions of the cloud. At this location is where all benchmark regions were observed. Three +CG lightning flashes were recorded in 20 and 30 dBZ.

**Core Flight 2 Electric Field Structure**

As seen from the sounding below in Figure 11, this core flight had a simple electric field charge structure. This sounding was taken through a strong updraft and as concluded by Stolzenburg et al (1998a), the electric field profile was simpler and had fewer charge regions. Max electric field was about 48 kV/m at 10.5 km. There appears to be no real negative layer. The electric field structure for the whole core is a positive layer from 3.2-4 km with a near zero electric field layer from 4-7.8 km and a positive layer from 7.8 km to cloud top at 10.5 km.
Figure 11: Balloon Sounding

There is a low magnitude electric field at the lower layers like that found in storms producing −CG lightning. The max electric field was located at higher heights than that for storms with predominantly −CG lightning in which the max electric field was located at lower heights. As seen from Figure 6, the electric field in this sounding differs from a storm producing predominately −CG in that this sounding shows no dominant negative layers. (Stolzenburg et al, 1998a)

All +CG strikes were located in the core of the supercell around 60 dBZ. At the time of the sounding the storm was still developing and not in its dissipating stage. The storm was intensifying and its lifecycle was more than three hours in which all +CG were concentrated near the core. Previous studies have shown that +CG is concentrated in the core when the storm is tornadic (MacGorman, 1998). This case further supports those findings. Negative regions in this sounding were almost nonexistent, thus positive charge layers dominated, producing the extensive amounts of +CG.

Figure 12a, b, and c show the radar reflectivity of the supercell at the beginning, middle, and end of the balloon flight. The balloon’s position is indicated by the black circle.

The launch site was to the north of the core that had a cloud-base scan reflectivity of 60 dBZ at the time. Two +CG lightning strikes where observed just to the east of the core in reflectivity regions of 50 dBZ as seen below in Figure 12a. The
Figure 12a: Radar reflectivity with cloud base elevation of 0.5 degrees at the beginning of balloon flight.

Figure 12b: Radar reflectivity at elevation of 10.0 degrees at middle of balloon flight near altitude of 12.3 km.
Figure 12a: Radar reflectivity with cloud base elevation of 0.5 degrees at the beginning of balloon flight

Figure 12b: Radar reflectivity at elevation of 10.0 degrees at middle of balloon flight near altitude of 12.3 km
Figure 12c: Radar reflectivity at elevation of 10.0 degrees at the end of balloon flight

Figure 12b shows the middle of the flight with an elevation angle of 10.0 degrees. At this time the balloon was at the top of the cloud near 12.3 km in a positive electric field charge region. As seen, the balloon was right in the core, as evidenced by a reflectivity of 60 dBZ.

Figure 12c shows the radar reflectivity at the end of the flight. The elevation angle is 10.0 degrees, and the balloon was on its way down. The radiosonde stopped measuring the altitude when the balloon reached 12.3 km, so the altitude at the end of the flight is not able to be determined. Positive CG lightning was observed in low regions of reflectivity near 40-25 dBZ and was located to the east of the core which was still at 60 dBZ.
SUMMARY OF RESULTS

Three different soundings were analyzed from thunderstorms producing predominately +CG lightning. Observations of the soundings along with radar reflectivity point to an electrical structure very different from storms producing −CG lightning.

The anvil sounding showed that an upper positive layer existed which could influence the production of +CG lightning between the core and the anvil. Positive CG lightning was located in moderate regions of reflectivity and during the dissipating stage of the thunderstorm. Radar reflectivity during the flight was 20 dBZ, indicating that the lower negative charge region was not a screening layer.

The core sounding in the nonupdraft showed that an inverted electric field polarity was present although at the time no +CG lightning was observed until an hour after the sounding, when the storm produced a large number of +CG lightning flashes. Radar reflectivity showed that all benchmark regions occurred near the end of the flight when the balloon was taken into an updraft. The lower negative region was located in 35 dBZ.

The core sounding in the updraft showed that no apparent negative electric field charge layer was present and all +CG lightning was clustered in regions of highest reflectivity, the core of the storm. This cell had produced a tornado just 30 minutes prior to the sounding. The storm was intensifying and its lifecycle was more than three hours in which all +CG flashes were concentrated near the core. Radar reflectivity showed the upper positive electric field charge region located in the core with a reflectivity of 60 dBZ.

Table 1 below gives a summary of the results of each of three soundings including both the radar reflectivity and the electric field. The observations in the +CG lightning column are those found in each of the flights discussed in this paper. The observation in the −CG lightning column are those reported from previous studies in the literature.
### Table 1: Summary of Results

<table>
<thead>
<tr>
<th>Positive Cloud-to-Ground (+CG)</th>
<th>Negative Cloud-to-Ground (-CG)</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Anvil</strong></td>
<td><strong>Anvil</strong></td>
</tr>
<tr>
<td>- Structure: -, +, -, + (-,+)</td>
<td>- Structure: -, +, -</td>
</tr>
<tr>
<td>- Extra positive region in upper portion of cloud could contribute to +CG formation</td>
<td>- Where negative regions are screening layers</td>
</tr>
<tr>
<td>- Absence of lower negative screening layer where radar reflectivity showed it in the mid-portions of the cloud</td>
<td></td>
</tr>
<tr>
<td>- No +CG in anvil but many strikes in regions of moderate reflectivity between core and anvil during dissipating stages of storm</td>
<td></td>
</tr>
<tr>
<td><strong>Core (nonupdraft)</strong></td>
<td><strong>Core (nonupdraft)</strong></td>
</tr>
<tr>
<td>- Inverted charge</td>
<td>- Structure: +, -, +, -, +, -</td>
</tr>
<tr>
<td>structure: -, +, -, +, -, +, -, 0</td>
<td>- 1 V-benchmark region near 6 km</td>
</tr>
<tr>
<td>- 3 V-benchmark regions in upper portions of the cloud</td>
<td>- E peaks lower than 5 km</td>
</tr>
<tr>
<td>- All E peaks higher than 6 km</td>
<td>- Densest near or inside contours of 20-30 dBZ</td>
</tr>
<tr>
<td>- Radar reflectivity showed benchmark regions when balloon was taken into updraft</td>
<td></td>
</tr>
<tr>
<td>- Lower negative region found in 35 dBZ</td>
<td></td>
</tr>
<tr>
<td><strong>Core (updraft)</strong></td>
<td><strong>Core (updraft)</strong></td>
</tr>
<tr>
<td>- Structure: +, 0, +</td>
<td>- Structure: +, -, +, -</td>
</tr>
<tr>
<td>- No real negative layer</td>
<td>- Large E associated with negative region bet. 6-10 km</td>
</tr>
<tr>
<td>- Large E located in positive layer</td>
<td></td>
</tr>
<tr>
<td>- +CG located in core throughout life cycle (produced a tornado)</td>
<td></td>
</tr>
<tr>
<td>- Upper positive region located in the core with 60 dBZ</td>
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More soundings of +CG lightning producing thunderstorms definitely need to be analyzed to see if findings are consistent. The NMIMT lightning mapping array (LMA) will also be beneficial in order to study the exact location of where the flashes originate. It allows one to see within storms to study the initiation and development of lightning.
flashes and determine the total CG lightning and intercloud flash rates for storms and individual cells much more accurately than has been possible previously (STEPS, 2000).

Time constraints prevented further investigation into the LMA and other soundings. During the field project several balloons were launched in both anvils and cores, sometimes within the same thunderstorm. As others analyze the vast amount of data in the following years collected from STEPS, a better picture of these unique storms will arise and hopefully lead to an improvement in the accuracy and reliability of severe weather forecasts.

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REFERENCES


