Relationships between Lightning Location and Polarimetric Radar Signatures in a Small Mesoscale Convective System

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ABSTRACT

On 19 June 2004, the Thunderstorm Electrification and Lightning Experiment observed electrical, microphysical, and kinematic properties of a small mesoscale convective system (MCS). The primary observing systems were the Oklahoma Lightning Mapping Array, the KOUN S-band polarimetric radar, two mobile C-band Doppler radars, and balloonborne electric field meters. During its mature phase, this MCS had a normal tripolar charge structure (lightning involved a midlevel negative charge between an upper and a lower positive charge), and flash rates fluctuated between 80 and 100 flashes per minute. Most lightning was initiated within one of two altitude ranges (3–6 or 7–10 km MSL) and within the 35–50 dBZ contours of convective cells embedded within the convective line. The properties of two such cells were investigated in detail, with the first lasting approximately 40 min and producing only 12 flashes and the second lasting over an hour and producing 105 flashes. In both, lightning was initiated in or near regions containing graupel. The upper lightning initiation region (7–10 km MSL) was near 35–47.5 dBZ contours, with graupel inferred below and ice crystals inferred above. The lower lightning initiation region (3–6 km MSL) was in the upper part of melting or freezing layers, often near differential reflectivity columns extending above the 0°C isotherm, which is suggestive of graupel formation. Both lightning initiation regions are consistent with what is expected from the noninductive graupel–ice thunderstorm electrification mechanism, though inductive processes may also have contributed to initiations in the lower region.

1. Introduction

A mesoscale convective system (MCS) was observed on 19 June 2004 during the Thunderstorm Electrification and Lightning Experiment (TELEX; MacGorman et al. 2008). Five observational systems were used: the
Oklahoma Lightning Mapping Array (OK-LMA), the KOUN 11-cm polarimetric Doppler radar, two mobile 5-cm Doppler radars, balloonborne electric field meters, and radiosondes with GPS tracking. This study utilized all of the datasets available for the convective line to investigate the microphysical and electrical properties of regions in which lightning flashes were initiated.

Most studies of lightning in MCSs have analyzed only cloud-to-ground (CG) flashes (for a review, see MacGorman and Rust 1998, section 8.2). Goodman and MacGorman (1986), for example, found that CG flash rates in mesoscale convective complexes (MCCs; i.e., large persistent MCSs) tend to increase rapidly as isolated storms merge to form a MCC. Throughout the mature stage of an MCS, most CG flashes strike the ground in the convective line; however, as the stratiform precipitation region forms, some CG flashes strike the ground in the stratiform region (e.g., Rutledge and MacGorman 1988; Holle et al. 1994; MacGorman and Morgenstern 1998). Usually CG strikes in the stratiform region lower positive charge to ground (+CG flashes), instead of lowering negative charge (−CG flashes), as most CG flashes do.

With the increasing availability of data from systems that map all types of lightning, several more recent studies have analyzed all lightning relative to the reflectivity and wind field of MCSs, but they have focused on lightning propagating in the stratiform region (Lyons et al. 2003; Lang et al. 2004; Carey et al. 2005; Dotzek et al. 2005; MacGorman et al. 2008; Ely et al. 2008). Most flashes observed in the stratiform region have begun in the upper part of the convective line (roughly 8–12 km MSL) and descended downward with distance back into the stratiform region until they reached the radar bright band, near 0°C, after which further propagation was horizontal. Only a few flashes were initiated in the stratiform region itself (e.g., Lang et al. 2004). Ely et al. (2008) reported one MCS in which initial flashes in the stratiform region did not descend with distance from the convective line but propagated horizontally at approximately the height of flash initiation. They suggested that, during the earlier periods, the charge through which the lightning propagated was carried from the convective line by particles that were smaller and grew more slowly than the charged particles produced later and so fell much more slowly.

Recent studies analyzing lightning relative to storm microphysics have inferred the microphysics from polarimetric radar data (Carey and Rutledge 2000; Wiens et al. 2005; Fehr et al. 2005; Tessendorf et al. 2007a,b; Deierling et al. 2005; Bruning et al. 2007; MacGorman et al. 2008). Of these studies, only Fehr et al. (2005) and MacGorman et al. (2008) analyzed an MCS. Many of these studies have examined the relationships of lightning with graupel, cloud ice, or updrafts, which one would expect to observe if storms are electrified primarily by rebounding collisions between graupel and cloud ice in the mixed-phase region, as discussed by Saunders (1993) and MacGorman and Rust (1998). Bruning et al. (2007), for example, investigated a small multicell storm that produced only 30 flashes in 40 min. From polarimetric radar data, they inferred that lightning activity began shortly after graupel was first detected, and lightning flashes were usually initiated in or near regions of graupel. Wiens et al. (2005) found that lightning flash rates in a supercell storm were correlated with the volume of the storm containing graupel and with the volume having updraft speeds greater than 10 m s⁻¹. Note, however, that Fehr et al. (2005) found in an MCS that the correlation between flash rates and inferred graupel mass was poor, in contrast to the good correlation they found with graupel mass in two isolated storms. Fehr et al. (2005) attributed the lack of correlation with graupel in the MCS to its greater complexity and to electrical interactions between cells.

In this paper, we focus particularly 1) on the evolution of lightning initiation height and flash rates throughout the life cycle of the MCS that occurred on 19 June 2004 during TELEX and 2) on the microphysical and kinematic conditions in the regions of the convective line in which flashes were initiated. Electrical properties were inferred from the total lightning activity mapped by the LMA and from a balloon sounding of the electric field. Microphysical and kinematic properties were inferred from polarimetric and dual-Doppler radar data, respectively.

2. Instrumentation and data processing

a. Lightning mapping array

During the TELEX field program (MacGorman et al. 2008), the OK-LMA consisted of 11 sensors in central Oklahoma (Fig. 1). The sensors detect 60–66-MHz [in the very high frequency (VHF) band] impulsive radiation emitted by a lightning channel as it propagates. A central processor then determines the time, latitude, longitude, and altitude for the source of each VHF signal from the set of times at which the signal was received at each station in the array. Thomas et al. (2004) discuss the technique for computing the time and location of VHF sources and estimate the resulting errors. The nominal range of the Oklahoma network is 100 km for three-dimensional mapping and 200 km for mapping the plan location of flashes. Detailed analysis of the 19 June 2004 case was performed on data within 100 km of the
network center. The accuracy of sources in this region was approximately 10 m in the horizontal, 30 m in the vertical, and 40 ns in time. VHF sources that had an altitude greater than 20 km MSL, a reduced $\chi^2$ greater than 2, or fewer than seven contributing stations were not used in this study, because we considered their locations less reliable.

The mapped radiation sources were fed into an algorithm described by MacGorman et al. (2008) for grouping together sources belonging to the same flash by using criteria based on the distance and time between VHF sources. The location at which each flash was initiated was calculated for all flashes that contained more than 10 mapped points (the terms “points” and “sources” are used interchangeably in this paper). Flashes that had $\leq$10 points were not used in studying lightning initiations.

For the initiation location, our intent was to use the centroid of a compact cluster of initial points from which the influence of outliers had been removed. To begin the calculation, the average location of the first 10 points in the flash was computed:

$$\bar{\lambda} = \frac{\pi}{180} \frac{1}{n} \sum_{i=1}^{n} \lambda_i,$$

$$\bar{\phi} = \frac{\pi}{180} \frac{1}{n} \sum_{i=1}^{n} \phi_i,$$

$$\bar{z} = \frac{1}{n} \sum_{i=1}^{n} z_i,$$

where $n$ is the number of points; $\lambda$, $\phi$, and $z$ are the average latitude, longitude (in radians), and altitude, respectively; and $\lambda_i$, $\phi_i$, and $z_i$ are the latitude, longitude (in degrees), and altitude of point $i$. If the standard deviation $\sigma$ of the first 10 points—given by

$$\sigma = \sqrt{\frac{1}{n-1} \sum_{i=1}^{n} R_e^2 (\bar{\lambda} - \lambda_i)^2 \cos^2 \bar{\phi} + R_e^2 (\bar{\phi} - \phi_i)^2 + (\bar{z} - z_i)^2},$$

where $R_e$ is the radius of the earth—was $\leq$0.5 km, then the region was considered compact enough, and the average location was taken to be the location at which the flash was initiated. If the standard deviation was $>0.5$ km, then the average location and standard deviation were calculated for all 10 subsets that contained 9 of the original 10 points. The subset that yielded the smallest standard deviation replaced the original set. The iterative process of removing one point at a time from the previous subset was repeated until either the standard deviation dropped to $\leq$0.5 km or only 5 points remained. There is no physical basis for choosing these specific values of initial and final number of points and of standard deviation; other values could reasonably be used.

b. Radars

1) KOUN

The KOUN radar is the original prototype for the Weather Surveillance Radar-1988 Doppler (WSR-88D) and has been upgraded to include polarimetric capabilities (Doviak et al. 2000; Ryzhkov et al. 2005; Scharfenberg et al. 2005). This S-band radar simultaneously transmits horizontally and vertically polarized waves and measures horizontal reflectivity factor $Z$, differential reflectivity $Z_{\text{dr}}$, differential phase shift $\Phi_{\text{dp}}$, and correlation coefficient $\rho_{\text{HV}}$. Specific differential phase $K_{\text{dp}}$ was computed from $\Phi_{\text{dp}}$. Schuur et al. (2003) and Ryzhkov et al. (2005) describe the postcollection processing in detail. Further discussion of the theory of polarimetric
radar can be found in Zrnić and Ryzhkov (1999), Straka et al. (2000), and Bringi and Chandrasekar (2001).

KOUN was approximately 40 km east-southeast of the center of the LMA network (Fig. 1). Our polarimetric data analysis focused on MCS characteristics within 70 km of KOUN in the southwest quadrant of its coverage area, a region of high-quality data from both KOUN and the LMA. Each full volume scan for this case required 6–7 min.

In addition to analyzing constant-elevation-angle scans [i.e., plan position indicators (PPPs)], a single-pass, isotropic Barnes-type inverse exponential weighting scheme was used to interpolate the data to a Cartesian grid, so horizontal and vertical slices of the polarimetric variables could be examined (Koch et al. 1983; Trapp and Doswell 2000; Bruning et al. 2007). Wavelengths that were less than 2 times the maximum data spacing (the Nyquist wavelength) were filtered from the resulting gridded dataset. With independent radials separated by approximately $1^\circ$ in azimuth and elevation, the horizontal and vertical spacing between radials varied from 1 to 2.6 km over the grid used in this study. A nondimensional smoothing parameter $\kappa^*$ of 0.1 was used (Koch et al. 1983), because it retained the most detail for data input wavelengths near the Nyquist wavelength. The grid spacing of 0.5 km was more than sufficient to preserve the spatial resolution of the objective analysis, which is governed by $\kappa^*$.

2) SMART-R

The two horizontally polarized C-band Doppler Shared Mobile Atmospheric Research and Teaching Radars (SMART-Rs; Biggerstaff et al. 2005) were deployed south of KOUN along a 46-km baseline. Coordinated sector volume scans were obtained approximately every 3 min. Dual-Doppler wind retrievals were conducted following the procedure of Biggerstaff and Houze (1991), except that a range-dependent Cressman-type weighting scheme was used to perform the objective analysis from polar to Cartesian coordinates. Biermann et al. (2005) provides additional information regarding the dual-Doppler analysis procedure used for this storm system.

3. Observations

a. Storm environment and evolution

The MCS that occurred on 19 June 2004 was chosen for analysis, because most of the storm system occurred within range of the LMA and the KOUN radar for much of its life cycle. This system formed early in the morning (local time) in an environment characterized by small CAPE (200 J kg$^{-1}$) and very weak, low-level shear (Fig. 2). Figure 3 shows the overall evolution of this system in a 5-h series of radar images starting at 1041 UTC (the color scales for all radar figures are shown in Fig. 4). Initially, scattered storm cells formed in southwest Oklahoma, east of a dissipating squall line at 0900 UTC. By 1200 UTC, the cluster of storm cells had merged into a line. A fully formed, albeit weak, convective line and stratiform precipitation region formed 30 min later. The resulting MCS was a nonsevere, asymmetric MCS adding a simple baffle to redirect airflow past the temperature and relative humidity sensor. Electric field meters, described by Rust et al. (2005) and MacGorman et al. (2008), recorded the vector electric field. This study focused on the vertical component of the electric field to infer the charge distribution near the balloon by using the one-dimensional approximation of Gauss’s law (e.g., Rust et al. 2005; Bruning et al. 2007) for comparison with the charge distribution inferred from lightning.
After 1415 UTC, the whole system weakened. By 1540 UTC, the original line of storms in central Oklahoma had dissipated and was becoming absorbed into the stratiform precipitation region of a new line of storms that was forming east of the original line.

Our initial analysis of overall trends in the lightning activity focused on flashes that were initiated within a 300 km × 300 km square centered on the KOUN radar, the approximate area shown in Fig. 3. Flash rates, VHF source production rates, time–height densities of the locations at which lightning flashes were initiated, and time–height densities of VHF source locations were all analyzed for this region. Almost all flash rates (Fig. 5a) were 60–160 flashes per minute, relatively modest among MCSs observed by the OK-LMA for a system roughly the size of this one. The highest flash rates occurred before the convective line was fully formed and were produced mainly by a few cells that had among the largest reflectivity values observed during the study period. For the next 2 h (1230–1430 UTC, 114347

![Fig. 3. Hourly sequence of PPIs of radar reflectivity Z at an elevation angle of 0.5° observed by the KOUN radar from 1041:22 to 1540:36 UTC. Refer to Fig. 4 for the reflectivity color scale.](http://journals.ametsoc.org/mwr/article-pdf/137/12/4151/4249493/2009mwr2860_1.pdf)
during the MCS’s mature phase, which will be described later), flash rates fluctuated over a smaller range, between 80 and 110 flashes per minute. Unlike the relatively steady nature of the flash rates, the VHF source production rates increased with time from 1245 UTC until roughly 1400 UTC (Fig. 5b). VHF source rates then remained relatively steady until 1445 UTC, after which they suddenly decreased. Thus, the average number of VHF sources per flash tended to increase with time during 1245–1400 UTC.

Because of the large areal extent and the multicellular organization of MCSs, lightning can extend far beyond the confines of its originating cell, and flashes in the 19 June 2004 MCS typically spanned more than one cell or propagated into the stratiform precipitation and anvil regions. The majority of flashes were 10–20 km in horizontal extent; approximately 16% of the flashes were greater than 30 km. The increase in average number of VHF sources per flash, mentioned previously, is consistent with the observed tendency for the maximum length of lightning channels to increase as the MCS became larger and more organized.

A time–height density plot of the locations at which lightning flashes were initiated (Fig. 6a) shows the evolution of the vertical distribution of lightning within the MCS. Most lightning flashes were initiated in one of two altitude ranges: 3–6 or 7–10 km MSL. (The convective-line balloon sounding in Fig. 7 shows that the 0°C isotherm was at approximately 4.5 km MSL within the updraft.) During some periods (especially before 1230 UTC), lightning also was initiated higher, at 11–14 km MSL, probably because of charged hydrometeors being lofted to higher levels within cells that had stronger updraft pulses than most other cells had.

Early in the lifetime of the MCS, the 7–10-km MSL altitude range dominated lightning initiation; however, as time passed, the 3–6-km MSL altitude range became increasingly active, until it dominated lightning initiation after roughly 1400 UTC (Fig. 6a). The layering was not as pronounced in the density of VHF sources (Fig. 6b), as in the density of flash initiations. Until roughly 1330 UTC,
the maximum in VHF source density was located between 8 and 10 km MSL. After 1330 UTC, the vertical distribution of VHF source density became more bivel, with maxima at 4–6.5 and 7–9 km MSL. (Note that the number of lightning initiations and VHF sources decreased throughout most heights of the MCS from 1245 UTC to 1300 UTC in Figs. 6a,b, but the contrast of colors in the color scale emphasizes the minimum in source density across that period at 3–7 km MSL in Fig. 6b.) The evolution of the convective line dominated the evolution in lightning initiation heights and the vertical distribution of VHF sources, because almost all flashes were initiated in the convective line and most VHF sources were located there (not shown).

By combining results from the reflectivity structure and the lightning characteristics, the evolution of the MCS can be divided into three phases:

- In the organizing phase (1000–1230 UTC), the storm system evolved from scattered storms to an organized line of storms lacking a stratiform region. Flash rates
b. Evolution of embedded convective-line components

Besides having preferred altitudes, lightning flash initiations also tended to cluster horizontally in and near the reflectivity (Figs. 8a,b) and updraft (Figs. 8m,n) maxima of embedded cells. To further investigate the cellular nature of the lightning initiations within the MCS, two cells were chosen, because of their location with respect to the KOUN radar (within 70 km) and their lightning characteristics. These cells were identified and tracked by subjective visual identification of features in plots of radar reflectivity and lightning density. The chosen cells are identified in Figs. 8a,b by two squares. Each square encompassed the entire region of lightning initiation for the cell and was allowed to propagate with the cell’s motion throughout its lifetime. The northern cell (weak and short lived, shown early in its life cycle) produced only 12 flashes throughout its lifetime, whereas the southern cell (large and long lived, shown while it was dissipating) produced almost an order of magnitude more flashes during its lifetime.

Table I presents statistics concerning the flashes initiated within the focus cells. The majority (83%) of the flashes that were initiated within these two cells remained within the confines of the convective line. The rest of the flashes branched into either the anvil region (8.5%) or the stratiform region (8.5%) of the MCS. A major difference between the two cells was in the proportion of flashes that were CG flashes; 37% of the flashes initiated by the larger cell were CG, whereas only 17% of the flashes initiated by the smaller cell were CG. However, if one considers only the first 12 flashes initiated in the large cell (the same as the total number produced by the small cell), then the percentage of flashes that were CG was the same. Thus, having a greater fraction of CG flashes in the larger cell may have been related in some way to its longer lifetime. The greater size and duration of the larger cell probably meant it had larger updraft speeds or a broader updraft, and this may have been related to its having a larger volume of graupel and more complex precipitation structure (not shown). These would cause the cell to produce more lightning flashes, and the greater complexity of precipitation structure may have more readily provided the lower charge regions thought to be needed to produce cloud-to-ground lightning, as suggested by MacGorman et al. (2007).

Fig. 8. KOUN polarimetric data, SMART-R dual-Doppler data, and the locations at which lightning flashes were initiated (white dots) from the 1256 UTC volume scan. Each row shows one parameter of the polarimetric or dual-Doppler data. The altitude of each CAPPI is through the center of one of the two preferred altitude ranges for lightning initiation: (left) 4.6 and (middle) 8.6 km MSL. The 4.6-km MSL plane shows lightning initiations between 3 and 6 km MSL. The 8.6-km MSL plane shows lightning initiations between 6 and 10 km MSL. The location of the KOUN radar is the origin in the CAPPIs. The pink line in (a) and (b) indicates the location of the vertical cross section shown in the right column. The horizontal coordinate in the vertical cross section is the distance along the pink line, increasing toward the northwest. Lightning initiation locations shown in the right column were no more than 5 km from the plane of the vertical slice. The open squares in (a) and (b) delineate the focus cells. (a)–(c) Horizontal reflectivity Z, (d)–(f) differential reflectivity Zdr, (g)–(i) specific differential phase Kdp, (j)–(l) correlation coefficient ρHV, and (m)–(o) vertical velocity w. See Fig. 4 for the color scales.
The two cells focused on here were embedded within the greater MCS storm structure, so they were not isolated. As mentioned previously, channels of flashes that were initiated in other areas traversed the focus cells throughout their lifetime and beyond. The time–height plots of VHF source density and lightning initiations in Fig. 9 show that lightning propagated through each cell at least 10 min before any lightning was initiated within.
the cell and continued at least 10 min after lightning initiations ended. It became impossible to track a cell reliably for more than 10 min before and after it produced lightning initiations, because no corresponding feature of the cell could be visually identified in plots of the radar and lightning data at earlier and later times.

As in the whole MCS, the vertical distribution of VHF source density for the flashes initiated within each cell had vertically spaced maxima. The small, short-lived cell had two vertically spaced maxima in VHF source density during peak lightning production (at roughly 9 and 5 km MSL), whereas the large, long-lived cell had three (at roughly 10, 7, and 4 km MSL). The altitudes at which lightning was initiated tended to lie near the edge of maxima in VHF source density for the cells. Because the maxima indicate regions of positive charge, this observation is consistent with lightning being initiated between regions of opposite charge.

The most obvious difference between the two cells lies in the altitude trends of both the VHF source density maxima and the altitude ranges in which lightning flashes were initiated (cf. Figs. 8a,b). In the small, short-lived cell, the upper region of lightning initiations and VHF source density both had a downward trend from the time that flashes first were initiated in the cell. In the large, long-lived cell, however, the upper region of lightning initiations and mid-to-upper region of VHF source density had an upward trend until 1255 UTC, after which the altitude of VHF source density tended to decrease. How this trend related to trends in polarimetric radar variables and microphysics will be examined in a later section.

c. Inferred charge distribution

One of the five balloons launched on this day measured the vector electric field in the convective line outside, but

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**TABLE 1. Lightning flash count for each cell separately and combined. Numbers in parentheses are percent.**

<table>
<thead>
<tr>
<th>Flash type</th>
<th>IC (N)</th>
<th>CG (N)</th>
<th>Tot (N)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Small cell</td>
<td>1 (8.33)</td>
<td>0 (0)</td>
<td>1 (8.33)</td>
</tr>
<tr>
<td>Anvil region</td>
<td>9 (75)</td>
<td>1 (8.33)</td>
<td>10 (83.33)</td>
</tr>
<tr>
<td>Convective line</td>
<td>0 (0)</td>
<td>1 (8.33)</td>
<td>1 (8.33)</td>
</tr>
<tr>
<td>Stratiform region</td>
<td>10 (83.33)</td>
<td>2 (16.67)</td>
<td>12 (100)</td>
</tr>
<tr>
<td>All regions</td>
<td>10 (83.33)</td>
<td>2 (16.67)</td>
<td>12 (100)</td>
</tr>
<tr>
<td>Large cell</td>
<td>7 (6.67)</td>
<td>2 (1.9)</td>
<td>9 (8.57)</td>
</tr>
<tr>
<td>Anvil region</td>
<td>52 (49.52)</td>
<td>35* (33.33)</td>
<td>87 (82.85)</td>
</tr>
<tr>
<td>Convective line</td>
<td>7 (6.67)</td>
<td>2** (1.9)</td>
<td>9 (8.57)</td>
</tr>
<tr>
<td>Stratiform region</td>
<td>66 (62.86)</td>
<td>39 (37.14)</td>
<td>105 (100)</td>
</tr>
<tr>
<td>All regions</td>
<td>66 (62.86)</td>
<td>39 (37.14)</td>
<td>105 (100)</td>
</tr>
<tr>
<td>Both cells</td>
<td>8 (6.84)</td>
<td>2 (1.71)</td>
<td>10 (8.55)</td>
</tr>
<tr>
<td>Anvil region</td>
<td>61 (52.14)</td>
<td>36* (30.77)</td>
<td>97 (82.91)</td>
</tr>
<tr>
<td>Convective line</td>
<td>7 (5.98)</td>
<td>3** (2.56)</td>
<td>10 (8.55)</td>
</tr>
<tr>
<td>Stratiform region</td>
<td>76 (64.96)</td>
<td>41 (35.04)</td>
<td>117 (100)</td>
</tr>
</tbody>
</table>

* Two were positive CGs.
** One was a positive CG.

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Fig. 9. Time–height plot of VHF source density for all lightning within a 10 km $\times$ 10 km square centered on (a) the small, short-lived cell and (b) the large, long-lived cell. Densities were calculated by counting the number of sources that fell into each 2-min by 250-m altitude bin. The altitudes and times at which lightning flashes were initiated within each cell are indicated by maroon circles.

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near, the large, long-lived cell (the other four balloons were farther away in space and time and so will not be considered here). Figure 7 shows the vertical component of the electric field and the five altitude ranges in which charge was inferred from the electric field, as described by Rust et al.
The electric field analysis was compared with the charge inferred from the distribution of mapped LMA sources in the region surrounding the balloon and in both focus cells (Fig. 10). The method used to infer the charge associated with lightning is described by Bruning et al. (2007) and MacGorman et al. (2008). As noted by several investigators (Rison et al. 1999; MacGorman et al. 2008), lightning channels propagating in positively charged regions tend to radiate much stronger electromagnetic signals than radiated by channels propagating in negatively charged regions and so are detected more readily. Thus, both for the individual flashes analyzed to produce this figure and for the aggregate distribution, the VHF sources tend to be more numerous and to be distributed more densely in positive charge than in negative charge. One must keep this disparity in mind when interpreting the densities in the figure.

Unfortunately, neither the electric field sounding nor the LMA data can fully diagnose the storm’s four-dimensional charge structure. Charge can be inferred from the electric field sounding only along the path of the balloon and only for the time and specific location at which the balloon traversed a particular layer of the storm. The LMA charge analysis is limited to those charge layers that participated in lightning and tends to represent broad regions, rather than the specific set of locations sampled by the balloon. Therefore, the charge regions inferred from one instrument are likely to be somewhat different than the charge regions inferred from the other instrument, and individual charge regions may be missed by one or the other. Note, for example, that the lowest positive charge inferred from the balloon sounding is absent in the analysis of LMA data.

All three regions of the MCS shown in Fig. 10 were inferred from the LMA data to have an upper-level positive charge above a midlevel negative charge, which is in rough agreement with the upper two charge regions inferred from the electric field sounding. The LMA data near the balloon sounding (Fig. 10a) and in the large, long-lived cell areas (Fig. 10c) indicated an additional positive charge layer near 4 km MSL, which is also in agreement with the electric field sounding. Thus, this storm had a normal polarity charge structure similar to the MCS charge structures found by Stolzenburg et al. (1998).

Lightning flashes tend to be initiated in regions with the largest electric field magnitudes (needed to cause electric breakdown of air), typically near a boundary between positive and negative charge. One end of the flash then propagates toward and into positive charge, and the other end propagates toward and into negative charge (e.g., Kasemir 1960; Mazur 1989; MacGorman et al. 2001). Thus, lightning initiations overall (not shown in Fig. 10) tend to occur between the positive and negative charge regions inferred from the LMA. Because the largest densities tend to occur in positive charge, as previously noted, this is consistent with the previously noted tendency in Fig. 9 for lightning initiations to occur near the top or bottom edges of maxima in VHF source density.

FIG. 10. Charge analysis for (a) the region surrounding the convective-line balloon sounding from 1312 to 1330 UTC; (b) the small, short-lived cell from 1256 to 1316 UTC; and (c) the large, long-lived cell from 1223 to 1309 UTC. VHF sources inferred to be in positive charge are indicated by red dots; sources in negative charge are indicated by blue dots. The rising line in (a) indicates the balloon track in this projection, and the black line between plus signs was the part of the track during the period of lightning data, 1312–1330 UTC. The colored bar to the right depicts the charge polarity inferred from the convective-line balloon sounding in Fig. 7. Red bars indicate positive charge, and blue bars indicate negative charge.
d. Spatial relationships with lightning

1) FULL STORM

A major focus of this study was to improve understanding of the storm electrification mechanism by analyzing the microphysical properties of the regions in which lightning was being initiated. The noninductive electrification mechanism of charge exchange during rebounding collisions of cloud ice with actively riming graupel (for a review, see MacGorman and Rust 1998, chapter 3) tends to put one polarity of charge on graupel and the opposite polarity on cloud ice, and differential sedimentation subsequently separates these charges to create macroscopic regions of net charge. The polarity on each type of particle can vary as a function of riming rate and temperature, but the expected result in a storm would be that the net charge in regions in which graupel predominates is typically opposite to that of adjoining regions in which cloud ice predominates. If so, lightning should often be initiated between a region of graupel and a region of cloud ice. To test this, the locations at which lightning flashes were initiated were overlaid on
horizontal constant-altitude PPIs (CAPPs) and vertical slices of the radar data during two phases of the MCS life cycle.

Figures 8 and 11 depict the mature and weakening phases of the MCS, respectively. The vertical slice in the right panels was chosen along the convective line to try to capture as much detail as possible in the cellular structure associated with lightning initiations. The data shown in Fig. 8 at 1256 UTC were representative of the storm during the mature MCS phase. The convective line consisted of individual convective cells, each of which had a maximum reflectivity of roughly 50 dBZ embedded within a more widespread region of 35 dBZ (Fig. 8a). Each cell’s 35-dBZ contour extended to at least 8 km MSL and one cell extended to as high as 12 km MSL (Fig. 8c). Southwest of the convective line, the stratiform rain region at 4.6 km MSL had a maximum reflectivity of 40 dBZ (Fig. 8a).

The upper level of lightning initiations (shown on the 8.6-km MSL plane in Fig. 8) tended to cluster near and inside cores of larger updraft speeds (5–10 m s\(^{-1}\); Fig. 8m). Updraft speeds >5 m s\(^{-1}\) extended from roughly 4 km MSL to 10–12 km MSL in the vertical plane shown in Fig. 8o. Figures 8b,c show that the lightning initiations in the upper level (mostly 8–10 km MSL) tended to occur around or near the top of columns of 35–40-dBZ reflectivity.

The maximum height of the 35-dBZ reflectivity contour is likely near the maximum altitude at which graupel existed within each cell (Straka et al. 2000). Above this level, the reflectivity decreased significantly, despite the strong updraft signatures seen in a few of the cells. Therefore, it appears that the upper lightning initiations tended to be near the upper boundary of graupel. If, as we expect, charge in the upper part of the storm was being generated microphysically by rebounding collisions between graupel and cloud ice particles and then being separated macroscopically by differential sedimentation, then lightning in upper regions of the storm was being initiated near the boundary of the region of charge carried by graupel. Because these lightning flashes were of normal vertical polarity (discharging positive charge over negative charge), it appears that the graupel was carrying negative charge, which is consistent with laboratory experiments at these temperatures (Takahashi and Miyawaki 2002; Saunders et al. 2006).

Negative values of \(Z_{dr}\) at 8.6 km MSL (Fig. 8e), probably caused by ice particles being aligned vertically by large vertical electric field magnitudes, were in or near several clusters of lightning initiations (e.g., at north = −40 km and around north = −60 km). The pattern of minima in \(Z_{dr}\) extending radially from the radar behind the larger cells was probably caused by the depolarization that can occur when transmitting vertically and horizontally polarized signals simultaneously (as is done with KOUN) through electric fields oriented by the electric fields in the upper portions of convective cells (Ryzhkov and Zrnić 2007). Negative \(K_{dp}\) values (another hint of ice particles being aligned by electric fields but one weighted by number density instead of reflectivity) were also found directly above the strongest convective cells (Fig. 8h) near the upper level of lightning initiations. Large electric field magnitudes are required to initiate lightning, so having a signature of larger electric field magnitudes aloft near regions of flash initiation is consistent with what is known about lightning physics.

Though polarimetric data around the lower level of initiations are consistent with noninductive graupel–ice charging, as will be shown, it is possible that other processes also contributed to charge in this lower region. In the 4.6-km MSL horizontal plane (recall that the 0°C isotherm was at approximately 4.5 km MSL), all embedded cells with a reflectivity maximum greater than 50 dBZ had a corresponding area of enhanced \(K_{dp}\) (0.25°–0.75° km\(^{-1}\)), encompassing almost all lightning initiations at this level (Fig. 8g). All lightning initiations at this level were also in regions of positive \(Z_{dr}\) indicative of oblate hydrometeors (Fig. 8d), but most were outside regions of \(Z_{dr} > 1.25\) dB that were probably due to larger raindrops, as discussed by Doviak and Zrnić (1993). The areal coverage of \(Z_{dr} > 1.25\) dB was much smaller than the areas of enhanced \(K_{dp}\) but was similar in size and location to that of regions in which updraft speeds were greater than 5 m s\(^{-1}\) (Fig. 8m). These updraft speeds possibly indicate that raindrops were being lofted. Most lightning initiations at this level were within or near regions with updraft speeds >2 m s\(^{-1}\), but they were a little to the rear of the cores of updraft >5 m s\(^{-1}\), behind regions in which larger raindrops were inferred from \(Z_{dr}\). Because \(K_{dp}\) depends on number density, whereas \(Z_{dr}\) is independent of number density (Zrnić and Ryzhkov 1999, their Table 1), it is likely that most lightning initiations at this level were in areas characterized by a high number density of smaller raindrops, outside or near the boundary of areas with the largest raindrops.

Additional information about the microphysics associated with the lower level of lightning initiations is provided by the polarimetric radar parameters in the vertical slice along the convective line. All of the cells had a relative minimum in \(\rho_{HV}\), suggesting mixed-phase hydrometeors, somewhere between roughly 3 and 6 km MSL (Fig. 8l). Some of the greatest depressions in \(\rho_{HV}\) extended to the lowest part of this altitude range (e.g., near distance = −12 and 0 km) and were in downdrafts or very weak updrafts (<2 m s\(^{-1}\)), so they probably
were associated with melting. However, some of the minima (e.g., near distance = −60 and −40 km) were more elevated, stretching up almost to 6.5 km MSL, the altitude of the −10°C isotherm, and were within regions of updrafts of 5–10 m s\(^{-1}\). These elevated minima were probably associated with regions in which hydrometeors were freezing. Lofting of raindrops that were in the process of freezing is also consistent with the columns of \(Z_{dr} > 1\) dB stretching up to the −10°C isotherm (Fig. 8f). Previous research has shown that lofted raindrops, as evidenced by \(Z_{dr}\) columns, typically freeze between the 0° and −10°C levels, thereby forming graupel and hail embryos (Bringi et al. 1997; Carey and Rutledge 2000; Bruning et al. 2007). The process of freezing in this temperature range produces ice crystals through splintering (Hallett and Mossop 1974).

Lightning initiations at 3.5–5.5 km MSL tended to cluster near the edges of regions in which a mixture of hydrometeor phases is inferred from \(Z_{dr}\) and \(\rho_{HV}\). Having graupel and ice splinters in an updraft region containing supercooled liquid water is the classic situation for noninductive charge exchange between actively riming graupel and smaller ice particles, as observed in the laboratory by Takahashi and Miyawaki (2002) and Saunders et al. (2006). The laboratory results also suggest, however, that active charging by the noninductive graupel–ice mechanism would not occur in regions of melting graupel in older cells with weak updrafts or downdrafts. It is possible that precipitation particles in regions of melting still carried the charge gained by graupel previously, but it is also possible that other mechanisms contributed to charge in these older cells. Lightning, for example, can deposit charge on hydrometeors (Marshall et al. 1989; Helsdon et al. 1992; Ziegler and MacGorman 1994), and other inductive or noninductive mechanisms for microphysical charging may also contribute during melting (e.g., Shepherd et al. 1996).

Although the convective line was not fully formed during the MCS organizing phase (not shown), the lightning and microphysical patterns in the convective cells during the organizing phase were similar to those seen during the mature MCS phase. In both phases of the MCS, for example, lightning initiations in an upper layer (7.5–10 km MSL) tended to occur near and above 35–40-dBZ contours and near and inside cores of larger updrafts (>5 m s\(^{-1}\)). Initiations in a lower layer (3.5–5.5 km MSL) tended to occur to the side of strong updrafts and mixed-phase columns in which freezing was occurring. In both layers, lightning initiations tended to occur near the boundary of regions of graupel. The primary differences between the two phases were in the height of the convective cells and their average flash rates. As shown in Fig. 5, for example, some initial periods had flash rates of 120–160 min\(^{-1}\) versus 80–110 min\(^{-1}\) during the mature MCS stage. Almost all cells that had already joined the convective line in the organizing phase had 35-dBZ reflectivity cores extending up to 10–12 km MSL, but most cells in the convective line during the mature MCS phase had 35-dBZ cores extending up to only 8–10 km MSL (Fig. 8c). The organizing phase also had stronger \(Z_{dr}\) columns (maxima greater than 2.25 dB). Carey and Rutledge (1996) showed that intracloud (IC) flash rates were strongly correlated with the accumulated graupel suspended in the upper levels of storm updrafts. Their bulk hydrometeor classification scheme, applied visually to the radar displays for the MCS we are studying, indicates that the organizing stage would have had more graupel in the upper level than the mature MCS phase had, because of the taller reflectivity cores during the organizing phase. Therefore, the larger flash rates seen at times during the organizing phase of the MCS are consistent with their results.

The weakening MCS phase, depicted in Fig. 11 at 1514 UTC, was dynamically quite different from the earlier phases. At this time, the convective line was dissipating and forming a widespread stratiform precipitation region and radar bright band. Zrnić et al. (1993) and Giangrande et al. (2008) discuss the brightband region that forms around the level of the 0°C isotherm (approximately 4.5 km MSL on this day) in stratiform precipitation. If the updraft is too weak to suspend ice hydrometeors, then the bright band will form by the aggregation and melting of falling ice particles. The values of \(Z\) and \(Z_{dr}\) increase in the upper part of the bright band because of enhanced aggregation at freezing temperatures near 0°C and increase in the lower part because of an increase in the hydrometeors’ dielectric constant as the aggregates begin to melt and become water coated. Finally, \(\rho_{HV}\) decreases in the melting layer, because the sample volume contains a mixture of frozen and liquid hydrometeors. The most prominent polarimetric feature of the radar brightband during the weakening phase of the 19 June 2004 MCS was the expanded areal coverage of \(\rho_{HV}\) values less than 0.975 at the 4.6-km MSL level (Figs. 11j,l).

During the weakening phase, much of the relatively small remaining area of larger \(\rho_{HV}\) values was in the most vigorous of the remaining cells (maximum reflectivity of 50 dBZ, with 35-dBZ contours extending up to approximately 9 km), where the widespread fallout of precipitation needed to form a bright band had not yet occurred (Figs. 11b,c). Overall, however, cell heights had decreased (35-dBZ contours extended up only to approximately 6 km MSL in most cells), and the brightband signature in \(\rho_{HV}\) was widespread. As in the mature MCS phase, evidence for ice crystal alignment by large
electric field magnitudes can be seen in the radial patterns of negative $Z_{dr}$ values in Fig. 11e.

The locations at which lightning flashes were initiated during the weakening phase had one primary difference from those during the mature MCS phase; the bi-level nature of the height distribution in the mature phase became much less pronounced during the weakening phase (Fig. 11c). The most vigorous cells still had an upper group of lightning initiations at 8–10 km MSL, just within or above the upper 35-dBZ boundary, as during the mature MCS phase. However, the lower level of lightning initiation was more dispersed than before (it had broadened to 2.5–7 km MSL), and three flashes were initiated at 7–8 km MSL, between the two former levels, so there was no longer a 1-km-thick layer without lightning initiations anywhere between 3 and 10 km MSL. As during the mature MCS phase, lightning flashes were initiated mainly within or near the edges of regions of solid precipitation, often near the outer edges of $\rho_{HV}$ minima at 2.5–6 km MSL (Fig. 11f), which were associated with mixed-phase hydrometeors. However, most of these minima in $\rho_{HV}$ during the weakening phase appear to have been associated with melting, not freezing, because there were few $Z_{dr}$ towers extending higher than the freezing level. Although most lightning flashes were initiated in the tallest, most vigorous cells (near north = 20 and 30 km in Figs. 11a–c), a few lightning flashes were initiated in regions associated with dissipating convective cells (e.g., at approximately north = 10 and 45 km in Fig. 11c). As noted already in the discussion of the mature phase, it is possible that the infrequent lightning initiations in dissipating cells were caused by previous noninductive charging of graupel, but it is also possible that they were caused by charge from previous lightning flashes or from inductive or noninductive charging processes during melting.

2) EMBEDDED CONVECTIVE-LINE COMPONENTS

The locations at which lightning flashes were initiated were examined in more detail by superimposing the initiation locations on polarimetric radar data at two different stages in the life cycle of each of the two embedded cells on which we focused earlier. Dual-Doppler synthesis has been done only for a single time period during the lifetimes of the two cells, but this time period is during the beginning of lightning production in the small, short-lived cell. Figure 13 shows the end of lightning production in the large, long-lived cell. The locations at which lightning flashes were initiated were overlaid on PPIs and vertical slices. The vertical slices passed through the center of lightning initiation regions, which were also near the cell’s maximum reflectivity. Note that the change in altitude for the chosen PPI elevation angles was approximately 1 km across the PPIs at the lower elevation angle and approximately 2 km across the PPIs at the upper elevation angle. The chosen elevation angles cut through roughly the center altitude of the cell’s cluster of lightning initiations for each level (4–6 and 8–10 km MSL), so the lightning initiations were within roughly 1 km of the altitude of the PPI radar data shown in their vicinity in the figures.

During the beginning stage of lightning production, the lightning initiation regions were in weak updrafts near the boundary of stronger updrafts (>5 m s$^{-1}$; Figs. 12j–l; the maximum calculated updraft was 8 m s$^{-1}$ at 6 km MSL at this time). Updraft speeds >5 m s$^{-1}$ extended from below the altitude of the 0°C isotherm up to 8 km MSL (Figs. 12j,l). Lightning initiations occurred in both the upper and lower levels, but most initiations were in the upper level and were oriented along the upper edge of the high reflectivity region, mostly in regions of reflectivity >35 dBZ (Figs. 12h,c). This pattern relative to reflectivity continued in both cells as long as the cells initiated lightning in the upper region in Fig. 9. The dominant hydrometeor signal in the region of upper lightning initiations is best characterized as resulting from graupel, with $Z_H$ of 35–47.5 dBZ, $Z_{dr}$ of 0.1–0.5 dB, and $\rho_{HV}$ > 0.975 (Straka et al. 2000). Above this level, the reflectivity dropped off quickly to values below 35 dBZ, probably because of smaller ice particles in a dry environment. This result is essentially the same as the earlier result for the whole convective line; the upper region of lightning initiations was near the upper boundary of the region containing graupel and just below regions of cloud ice particles.

In the weakening stage of cell lightning production, lightning no longer was initiated in the upper level, though it continued to be initiated in the lower level, at 4–6 km MSL, throughout the period of lightning production in both cells. The updraft was elevated, reaching 5 m s$^{-1}$ only in upper levels of the storm and having been replaced mainly by downdrafts below 4 km MSL (Figs. 13j–l). This pattern of a deep updraft in a growing cell being replaced by an elevated updraft and low-level downdraft during cell dissipation is consistent with the well-established pattern of cell evolution first found by the Thunderstorm Project (Byers and Braham 1949).] During the weakening stage of the cell, lightning initiations were still near updraft boundaries, but only along
FIG. 12. KOUN polarimetric data, SMART-R dual-Doppler data, and the locations at which lightning flashes were initiated (white dots and squares) from the 1256 UTC volume scan for the small, short-lived cell. (left) The lower and (middle) upper elevation angles. At the range of the lightning, the altitude of the upper (lower) PPI is near the center of the upper (lower) level of lightning initiations. The pink line in (a) and (b) indicates the location of the vertical cross section shown in the right column. (a)–(c) Horizontal reflectivity $Z$, (d)–(f) differential reflectivity $Z_{dr}$, (g)–(i) correlation coefficient $\rho_{hv}$, and (j)–(l) vertical velocity $w$. The horizontal coordinate for the vertical cross section is the distance along the radial through KOUN, which is increasingly positive in a generally eastward direction. Refer to Fig. 4 for the color scales.
the lower boundary of updrafts, between 4 and 6 km MSL (Fig. 13).

Most measures of storm vigor in the vicinity of the low-level initiations declined in the weakening stage of the cells. For example, initiations were along the upper boundary of larger $Z_{dr}$ values throughout the lifetime of the MCS, but were in values of 0.75–1.625 dB during the first stage (Figs. 12d,f) and in values of 0.375–0.875 dB during the weakening stage (Figs. 13d,f). Similarly, they were in regions of 47.5–57.5-dBZ reflectivity and near boundaries of minima (0.97–0.98) in the correlation coefficient during the first stage (Figs. 12a,c,g,i), but they were in 37.5–47.5-dBZ reflectivity and in weaker gradients of correlation coefficient closer to 1.0 during the last stage (Figs. 13a,c,g,i).

In summary, during the initial stage of lightning activity in a cell, when updraft speeds greater than 5 m s$^{-1}$ were relatively deep, it appears that lightning was initiated

![Fig. 13. As in Fig. 12, but for the large, long-lived cell at 1256 UTC. The radial distance in the vertical cross section increases to the northeast.](http://journals.ametsoc.org/mwr/article-pdf/137/12/4151/4249493/2009mwr2860_1.pdf)
in regions of graupel at two levels, often just outside the strongest updrafts and near the boundary of regions having a mixture of hydrometeor phases, probably associated with freezing, rather than melting. In the weakening stage of the cell, when the updraft was elevated, lightning initiations occurred mainly in the lower level, near the boundary of regions that probably contained graupel at approximately the same height above the freezing level as before. However, most of the larger precipitation particles that had been in these regions had already fallen below the 0°C isotherm in the dissipating cell, and much of the mixed phase in the cell was due to graupel melting as it fell, rather than to rain freezing as it rose in updrafts.

4. Summary

High-quality lightning, electric field, and radar observations were available for much of the relatively weak 19 June 2004 MCS. As the MCS formed, lightning initiations clustered in three altitude ranges: 3–6, 7–10, and 11–13 km MSL. By the time the stratiform region formed, however, the distribution of lightning initiations had become bimodal, with the uppermost cluster having weakened as individual cells in the convective line tended to become less vigorous. The higher of the two remaining modes dominated lightning initiation at the beginning of the mature phase of the MCS. However, as the system matured further and dissipated, the fraction of flashes initiated in the lower mode increased until it was greater than the fraction in the upper mode.

A second aspect of lightning that evolved during the MCS life cycle was the average number of VHF sources per flash. Over a 1-h period during the mature MCS phase, flash rates were fairly steady at 80–110 flashes per minute, whereas the VHF source production rates roughly doubled. Such an increase in the average number of points per flash is consistent with the observed tendency for the maximum size of flashes, including flashes into the trailing-stratiform region and leading anvil, to increase as the MCS became larger and more organized.

Lightning initiations tended to cluster in and around individual cells in the convective line. To examine the temporal and spatial relationships of lightning initiation to the cells, we focused on two cells: a small, short-lived cell and a large, long-lived cell. The lightning in these two cells had more similarities than differences, and these similarities may be more generally characteristic of lightning in MCSs. The common properties exhibited by the cells were as follows:

- Each cell had two vertically separated maxima in the VHF source density and in the regions where lightning flashes were initiated. During the organizing phase of the MCS, some cells had three vertically separated maxima in flash initiations. Each maximum of source density appeared to be associated with a region of positive charge, as expected and found by others (Rison et al. 1999; Rust et al. 2005; MacGorman et al. 2008).
- The majority of lightning flashes in the cells involved an upper region of positive charge above a midlevel region of negative charge, which is in agreement with the top two layers of charge inferred from the electric field sounding through the convective line. Thus, the vertical polarity of these flashes and of the storm’s electrical structure was the polarity that is normally observed in storms.
- The charge structure inferred from lightning and electric field data agrees well with the conceptual model of MCS charge structure suggested by Stolzenburg et al. (1998). Their conceptual model separates the electrical structure of MCSs into four different regions: the convective-line updraft, regions of the convective line outside cores of strong updraft, the transition zone, and the stratiform region. In the stronger updrafts of the convective line, their model has four vertically separated charge regions: positive charge at roughly 4 km MSL, negative charge at roughly 6 km MSL, positive charge at roughly 9 km MSL, and negative charge at roughly 12 km MSL. In our study, the charge analysis of the balloon sounding and of the LMA data both pertained to the updraft region of the convective line and indicated that three charge regions in the 19 June 2004 MCS corresponded well with the three lowest layers of charge in the conceptual model. The highest negative charge in the conceptual model was not apparent in the lightning mapping data. The electric field profile could be interpreted as consistent with having negative charge at approximately 12 km MSL, as in the conceptual model, but the profile ended near 12 km MSL and the evidence is not conclusive, so the negative charge was not shown in Fig. 7.
- Each upper region of lightning initiation formed above a local reflectivity maximum, along the upper contours of 35–47.5-dBZ reflectivity. Each lower region of lightning initiation formed near the top of a $Z_{dr}$ column extending above the 0°C level and near relative minima in $\rho_{HV}$. The regions in which lightning was initiated were typically near the boundary between graupel and cloud ice, often within regions of graupel. This is similar to the observation by Bruning et al. (2007) that lightning initiation in a small multicell storm occurred near regions of graupel.
Both graupel and cloud ice are required by the non-inductive, graupel–ice electrification mechanism [studied by Saunders (1993) and discussed by MacGorman and Rust (1998)]. This mechanism also requires sufficient cloud liquid water to promote active riming, but the presence of cloud liquid particles is typically masked in polarimetric radar data by signals from graupel. One assumes, therefore, that the liquid water content is sufficient for electrification in strong updrafts having graupel at temperatures at which one expects mixed phase.

During the weakening stage of each cell, when lightning initiations were much less frequent but still present, graupel was probably falling and melting, not actively riming, so one would not expect the noninductive graupel–ice mechanism to contribute further charging. The charge causing these later flashes may have been produced earlier by the noninductive graupel–ice mechanism, but charge may also have been deposited by previous lightning flashes (Marshall and Winn 1982) or produced by inductive or noninductive processes during melting (Shepherd et al. 1996). During the beginning stage of cells, however, updrafts in the mixed-phase region were stronger, and microphysical conditions were favorable for the noninductive graupel–ice mechanism. The timing of the beginning of lightning initiation relative to the growth of reflectivity and to the inferred appearance of graupel in the mixed-phase region suggests that, although each embedded cell contained lightning activity at least 10 min before lightning was initiated within the cell, the cell needed to have substantial graupel and cloud ice within updrafts to initiate lightning.

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