Polarimetric and Electrical Characteristics of a Lightning Ring in a Supercell Storm

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ABSTRACT

On 30 May 2004, a supercell storm was sampled by a suite of instrumentation that had been deployed as part of the Thunderstorm Electrification and Lightning Experiment (TELEX). The instrumentation included the Oklahoma Lightning Mapping Array (OK-LMA), the National Severe Storms Laboratory S-band Weather Surveillance Radar-1988 Doppler (WSR-88D) polarimetric radar at Norman, Oklahoma, and two mobile C-band, Shared Mobile Atmospheric Research and Teaching Radars (SMART-R). Combined, datasets collected by these instruments provided a unique opportunity to investigate the possible relationships among the supercell’s kinematic, microphysical, and electrical characteristics. This study focuses on the evolution of a ring of lightning activity that formed near the main updraft at approximately 0012 UTC, matured near 0039 UTC, and collapsed near 0050 UTC. During this time period, an F2-intensity tornado occurred near the lightning-ring region. Lightning density contours computed over 1-km layers are overlaid on polarimetric and dual-Doppler data to assess the low- and midlevel kinematic and microphysical characteristics within the lightning-ring region. Results indicate that the lightning ring begins in the middle and upper levels of the precipitation-cascade region, which is characterized by inferred graupel. The second time period shows that the lightning source densities take on a horizontal u-shaped pattern that is collocated with midlevel differential reflectivity and correlation coefficient rings and with the strong cyclonic vertical vorticity noted in the dual-Doppler data. The final time period shows dissipation of the u-shaped pattern and the polarimetric signatures as well as an increase in the lightning activity at the lower levels associated with the development of the rear-flank downdraft (RFD) and the envelopment of the vertical vorticity maximum by the RFD.

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1. Introduction

Three-dimensional lightning mapping array observations of supercell thunderstorms over the past decade have occasionally revealed an intriguing lightning signature that consists of a region of low lightning density surrounded by a ring of high lightning density. This feature, which has come to be known as a lightning hole, was first observed by Krehbiel et al. (2000), who documented a lightning hole that was collocated with a very strong updraft. Since then, other studies have shown that lightning holes are typically horizontally collocated with, and defined best just above, bounded weak echo regions (BWER; e.g., Goodman et al. 2005; MacGorman et al. 2005; Wiens et al. 2005; MacGorman et al. 2008). The relation between lightning holes and tornado occurrence is more variable. Hamlin et al. (2003) and Buechler et al. (2004) examined storms where lightning holes developed several minutes prior to tornado formation, in one case by approximately 20 min. On the other hand, Steiger et al. (2007) presented an example of a tornadic storm that exhibited no lightning hole, as well as an example of a nontornadic supercell that produced a lightning hole. Murphy and Demetriades (2005) also presented an example of a nontornadic supercell that exhibited a lightning hole.

Though variable, the links between lightning holes and supercell storm features demonstrated by these previous studies clearly suggest that lightning holes are related to supercell kinematic and microphysical structures. It should be noted that all of the previously mentioned work focused on the hole in the lightning activity, not the origins of the dense lightning activity that surrounded the hole. Historically, studies of storm electrification have traditionally focused on the kinematic and microphysical structures that were conducive to electrification, not on the regions that were devoid of lightning activity. For this reason, and also because recent polarimetric radar observations of supercell storms have revealed ringlike microphysical signatures in the same region where this enhanced lightning activity is typically observed, we will hereafter refer to this feature as a lightning ring. The goal of this study is to investigate the links between a lightning ring and storm kinematic and microphysical structures in an Oklahoma supercell on 30 May 2004.

The precipitation and kinematic structures of supercell thunderstorms have been well documented. As summarized in Fig. 1, these features can be broadly characterized by a main updraft, a forward-flank downdraft (FFD), a rear-flank downdraft (RFD), a hook echo, and a BWER (e.g., Lemon and Doswell 1979; Lemon 1980). The electrical characteristics of supercells storms have also been examined. In addition to sometimes producing lightning rings, supercell storms also tend to have extraordinary flash rates. Furthermore, some types of supercell storms tend to produce cloud-to-ground (CG) flashes that lower positive charge to ground (+CG) flashes instead of the usual negative charge (−CG) flashes, and the dominant polarity of cloud-to-ground lightning can switch during a transition in supercell type (e.g., Curran and Rust 1992; Seimon 1993; MacGorman and Burgess 1994; Carey and Rutledge 1996; Gilmore and Wicker 2002; Goodman et al. 2005; Wiens et al. 2005; MacGorman et al. 2005). A major contributor to the charge that produces these lightning characteristics is thought to be charge exchange during a rebounding collision between graupel and cloud ice. The polarity and magnitude of charge gained by graupel during this transfer depends on a number of parameters, including the liquid water content, rime accretion rate, and temperature of the riming graupel and the size and impact velocity of the ice particle (e.g., Takahashi and Miyawaki 2002; Saunders and Peck 1998; Saunders et al. 2006). A thorough review of the thunderstorm electrification process is presented by Saunders et al. (2006).

Polarimetric radars can identify bulk microphysical characteristics, such as regions of graupel and cloud ice (e.g., Straka et al. 2000), which are of great relevance to the study of thunderstorm electrical properties. Furthermore, recent observations by polarimetric radars have documented features that appear to be relevant to the evolution of the lightning ring, including midlevel rings of increased differential reflectivity ($Z_{DR}$) and decreased...
correlation coefficient ($r_{HV}$) and columns of enhanced $Z_{DR}$. A detailed description of the polarimetric radar variables can be found in Doviak and Zrnic (1993), Zrnic and Ryzhkov (1999), Straka et al. (2000), and Bringi and Chandrasekar (2001).

The $Z_{DR}$ column is an elongated vertical column of large $Z_{DR}$ that is often observed to extend from the surface to temperatures colder than 0°C. The $Z_{DR}$ columns tend to be either collocated with updrafts or on the periphery of updrafts where hydrometeors are low in concentration but large in size. Caylor and Illingworth (1987) speculated that $Z_{DR}$ columns might be important for hail production, while later studies (Conway and Zrnic 1993; Höller et al. 1994; Brandes et al. 1995) concluded that $Z_{DR}$ columns near updrafts might indicate that melted graupel was circulating back into the updraft. Bringi et al. (1996) later proposed that the $Z_{DR}$ signature might be the result of the updraft lofting liquid drops to temperatures well above the environmental melting level. Loney et al. (2002) compared supercell $Z_{DR}$ signatures with in situ microphysical measurements and suggested that all of the aforementioned conclusions regarding the microphysics responsible for the $Z_{DR}$ columns were plausible.

Midlevel rings of high $Z_{DR}$ and low $r_{HV}$ in supercell storms were first documented by Kumjian and Ryzhkov (2008), who presented two hypotheses for these rings: 1) ice particles ingested into the periphery of the updraft (a warm perturbation with respect to its surrounding environment) at heights above and near the environmental melting level would become partially melted and exhibit polarimetric signatures analogous to that of a melting layer (high $Z_{DR}$ and low $r_{HV}$) and 2) the circular nature of the signatures may be partially related to the intense mesocyclonic circulation, which would cause size sorting of drops in that area.

The goal of this study is to present the observations of the evolution of a lightning ring during the mature phase of a supercell storm on 30 May 2004, during the Thunderstorm Electrification and Lightning Experiment (TELEX; MacGorman et al. 2008). No thorough investigation of the kinematic, microphysical, and electrical structure of a lightning ring has ever been reported in the literature. The large suite of instrumentation used to collect data on the 30 May supercell provides an opportunity to observe such features and investigate the relationship of the lightning ring to midlevel rings of $Z_{DR}$ and $r_{HV}$ [as observed by the polarimetric Weather Surveillance Radar-1988 Doppler (WSR-88D) at Norman, Oklahoma (KOUN)], as well as supercell vertical motion and vorticity structure [as derived from the Shared Mobile Atmospheric Research and Teaching Radars (SMART-R) dual-Doppler measurements].

2. Instrumentation, processing techniques, and data synthesis

The 30 May supercell initiated along a dryline in western Oklahoma, propagated in a generally eastward direction near Oklahoma City, and dissipated in northeastern Oklahoma. During its lifetime, it produced 18 F0–F3 tornadoes and hail as large as 12 cm in diameter. As it passed through the TELEX domain between 2330 UTC 29 May and 0400 UTC 30 May, it was sampled by the Oklahoma Lightning Mapping Array (OK-LMA), the KOUN polarimetric radar, and two mobile C-band radars (SMART-Rs). Soundings launched by a mobile ballooning crew provide vertical profiles of temperature and dewpoint. The locations of the KOUN polarimetric radar and OK-LMA sites, as well as a depiction of their typical range of data collection, are shown in Fig. 2. The instrumentation and data processing techniques, along with a description of how the data were synthesized are described below.

a. Instrumentation and processing techniques

1) Oklahoma Lightning Mapping Array

The OK-LMA consisted of 10 stations during TELEX, each of which collected very high frequency (VHF) radiation impulses from the lightning discharges within the supercell. Rison et al. (1999) and Thomas et al. (2004) describe this technology and its mapping accuracy in detail.

An individual lightning flash can emit thousands of VHF sources. In this study, these sources were grouped together to reconstruct individual flashes. The criteria for a group of sources to be considered a flash were that they must be within 150 ms of the previous source and within 3 km and 500 ms of any other source in the flash (MacGorman et al. 2008). The initiation location of each flash, which corresponds to its origination point in space and time, was also determined as described by Lund et al. (2009). The maximum duration of a flash allowed by the algorithm was 3 s.

It can also be useful to study the distribution of the sources within a storm. In this study, we summed the number of VHF signals in each horizontal grid box (0.5 km × 0.5 km) through 1-km depths, starting at 3 km and going through 8 km MSL, over the time period of a typical radar volume scan. We then divided that sum by the horizontal area of the grid box to get a density in units of number of sources per square kilometer per volume, where the time required to collect a radar volume was approximately 5 min. Murphy and Demetriades (2005) is the only prior study to examine layers of lightning densities in the vicinity of a lightning ring, though that study had only reflectivity for comparison, not polarimetric data or dual-Doppler wind fields.
2) KOUN POLARIMETRIC RADAR

The KOUN polarimetric radar is a WSR-88D (Crum and Alberty 1993) that was upgraded to include polarimetric capabilities in March 2002 (Doviak et al. 2000; Ryzhkov et al. 2005). In addition to the traditional moments of radar reflectivity ($Z$), velocity, and spectrum width, KOUN also measures the polarimetric variables $Z_{DR}$, $\rho_{HV}$, and differential phase.

The sensitivity of the polarimetric moments to statistical fluctuations required extensive processing and quality control to yield research quality data. The data underwent smoothing, noise correction, and attenuation correction as described in detail by Schuur et al. (2003) and Ryzhkov et al. (2005). The data were then interpolated to a three-dimensional Cartesian grid to generate constant altitude plan position indicator (CAPPI) plots of $Z$, $Z_{DR}$, and $\rho_{HV}$.

3) MOBILE DUAL-DOPPLER RADARS (SMART-Rs)

The two SMART-Rs are 5-cm wavelength mobile radars designed to obtain measurements of storm features with better spatial and temporal resolution than typical surveillance radars, such as the WSR-88D. Volume scans for this storm took approximately 3 min. A detailed description of these radars can be found in Biggerstaff et al. (2005).

Data from the two SMART-Rs were first corrected for noise and ground clutter. Velocity values were then manually dealiased and used to derive vertical vorticity and vertical velocity, which were computed using the following procedures (Kuhlman et al. 2009). First, the radar data were interpolated to a grid having 1-km horizontal spacing and 0.5-km vertical spacing by using a modified Barnes weighting scheme in the Reorder package (Oye et al. 1995) described in Trapp and Doswell (2000). The Custom Editing and Display of Reduced Information in Cartesian Space (CEDRIC) package (Miller and Fredrick 1998) was then used to complete the dual-Doppler wind synthesis to provide the vertical velocity $w$ and vertical vorticity fields at each level in the gridded data.

4) ATMOSPHERIC SOUNDINGS

The mobile ballooning crew launched two balloons into the supercell at 2347 UTC 29 May and 0012 UTC 30 May. Thermodynamic profiles of the storm itself were provided by dropsondes that used GPS tracking (Hock and Franklin 1999) and were modified with a simple baffle to redirect airflow over sensors to act as upsondes. The first sounding ascended through the supercell’s FFD while the second sounding, which was launched approximately 2 km south of the first, ascended into the main updraft. The elevation of the 2 balloon launch sites

Fig. 2. Map of coverage by the OK-LMA and the KOUN polarimetric radar used in TELEX. The black lines depict highways. The red shading having a radius of 100 km indicates the region in which lightning can be mapped well in three dimensions. The gold shading indicates the 200-km nominal range within which the lightning’s plan location can be mapped. The purple shading indicates the region within 60 km of the KOUN radar (from MacGorman et al. 2008).
were 460 and 452 m MSL, respectively. In this study, thermodynamic profiles from these soundings are used to help interpret the polarimetric radar data to determine microphysical signatures.

b. Data synthesis

The instrumentation and data described above were combined over the lightning-ring region, to examine how the lightning source density pattern was related to the kinematic and microphysical features of the supercell inferred by the dual-Doppler and polarimetric data. The first step in the synthesis process was to contour the lightning densities. The contour levels of 8 and 35 sources per kilometer squared per volume were chosen after extensive testing revealed that they combined to provide an optimal depiction of the evolution of the lightning ring. These lightning density contours, along with the lightning initiation points, were then overlaid onto the CAPPIs of the polarimetric and dual-Doppler data at 3, 5, and 7 km MSL. The thermodynamic sounding data provide temperature bounds for these altitudes and will be discussed in more detail in the next section.

3. Analysis

This section focuses on the main updraft and RFD region of the 30 May storm to examine possible relationships among the supercell’s kinematic, microphysical, and electrical structures. Analyses are shown at 3, 5, and 7 km at three separate times centered on the development and dissipation of the storm’s primary lightning ring and an F2 tornado. Figure 3 shows a timeline highlighting the analysis times and the evolution of important storm features. The first analysis time, at 0012 UTC, was 5 min before the tornado formed and approximately 20 min before the mature phase of the lightning ring. The second, at 0039 UTC, was the approximate time that the tornado achieved F2 intensity, as well as the time that the lightning ring and \(Z_{DR}\) and \(\rho_{HV}\) rings all reached maturity. The third, at 0050 UTC, was the time that the tornado, lightning ring, and \(Z_{DR}\) and \(\rho_{HV}\) rings all dissipated. Much care was taken to choose times when the KOUN and SMART-R data were heavily overlapped, though it was not possible to obtain perfect time correspondence. Given a storm motion of 12 m s\(^{-1}\), the maximum offset between features in the different observing platforms should be no more than 2–3 km in the east–west direction.

The thermodynamic profiles taken at 2347 UTC 29 May and 0012 UTC 30 May, plotted in Figs. 4 and 5, provide temperature references for the CAPPIs at 3, 5, and 7 km. An examination of Figs. 4 and 5 shows that the temperatures corresponding to the 3, 5, and 7 km CAPPIs are 10.5°C (FFD) and 11°C (updraft) at 3 km, −2.8°C (FFD) and 2°C (updraft) at 5 km, and −19.5°C (FFD) and −7.5°C (updraft) at 7 km, respectively. The melting level for both the soundings is also of note, since it was near 4.5 km in the FFD region and at 5.5 km inside the updraft.

a. 0012 UTC 30 May—Prior to tornado and lightning-ring formation

The 0012 UTC volume scans were collected approximately 5 min prior to the beginning of the first F2 tornado. At 3 km, Fig. 6 shows only sparse areas of the 8 sources per kilometer squared per volume density contour, centered at (−97, 56). The soundings show that the temperatures were much warmer than freezing inside the FFD (10.5°C) and in the updraft (11°C) at this level. These sparse areas of lightning density contours were located within a region of high \(Z\), low \(Z_{DR}\), and moderate downdraft, which was west-northwest of the main updraft at (−87, 51) (Fig. 6d) and its associated inflow notch and \(Z_{DR}\) column at (−90, 52) (Figs. 6a,b). This region of high \(Z\) corresponding with low \(Z_{DR}\) and moderate downdraft likely indicates graupel or small hail falling through the precipitation cascade on the rear side of the storm. The presence of lightning density sources in this region further suggests that the graupel or small hail is carrying charge, allowing lightning to propagate into this region. There were no lightning initiation points, however, at the 3-km level.

Figure 7 shows the lightning source densities at 5 km where temperatures were 2°C in the updraft and −2.8°C in the FFD regions. The lightning source density contours were generally located above those at 3 km but were broader in areal extent and larger in magnitude than those at 3 km. There were two distinct regions of 35
sources per kilometer squared per volume contours evident at \((-97,50)\) and \((-96,56)\). Both of these highly dense lightning source regions, along with the enveloping 8 sources per kilometer squared per volume contours, were still confined within a region of inferred charged graupel (high \(Z\) and low \(Z_{DR}\)) that was still located to the west of the main updraft and associated \(Z_{DR}\) column, along with a developing BWER at approximately \((-90,50)\) (Figs. 7a–d); however, contours of small charge density began to wrap around the southern side of the storm into the inflow notch, which suggests that some of the charged graupel was being ingested back into the updraft by the inflow. It is also interesting to note that there were two distinct downdrafts (Fig. 7d) in the precipitation cascade region, and much of the lightning was near the western boundary of these downdrafts. The offset between the lightning features (computed by summing lightning sources over the time period required to collect the KOUN volume) and the dual-Doppler features are most likely due to the difference in the KOUN and SMART-R analysis times. Large lightning source densities of \(>35\) sources per kilometer squared per volume were also found in or near downdrafts in the FFD region. In contrast to the absence of lightning initiation at the 3-km level, there were a few lightning initiation points at 5 km, located primarily within the 35 sources per kilometer squared per volume contours in the region of high \(Z\) and low \(Z_{DR}\) near the western edge of downdrafts (Figs. 7a,b,d).

At 7 km (Fig. 8), temperatures were near \(-7.5^\circ C\) in the updraft and \(-19.5^\circ C\) in the FFD. In the same horizontal region analyzed for the 3- and 5-km levels, the lightning source densities were connected to the activity in the FFD region and even broader in areal extent than at lower levels. Discussion of lightning source densities at this level, however, will focus only on the activity between approximately \(X = (-100, -90)\) and \(Y = (50, 60)\). Radar reflectivity (Fig. 8a) in this region shows an elongated southwest–northeast-oriented BWER structure in which two relative minima in \(Z\) appear to be collocated with the continuing \(Z_{DR}\) column and the main updraft. The majority of the lightning activity in the analysis region was concentrated mainly west and north of this BWER, with a narrow finger of source densities extending into a gap between the two BWER minima and smaller contours encircling south and east of the BWER minima. This region was characterized by low \(Z_{DR}\) (Fig. 8b) that was much more extensive than at 3 and 5 km, likely indicating

![Fig. 4. Skew T–log p plot of the sounding launched at 2347 UTC 29 May into the forward flank of the storm. The heavy black trace is the temperature data, and the thin black trace is the dewpoint data. The blue slanted line is the 0°C isotherm. The red horizontal lines denote the heights of the CAPPIs presented in this study.](image-url)
widespread graupel in the region surrounding the main updraft. The vertical velocity fields show that the main updraft was larger in areal extent than at 3 and 5 km (Fig. 8d). Even the precipitation cascade region, which was characterized by downdrafts at 3 and 5 km, was dominated by weak updrafts ($w < 10 \text{ m s}^{-1}$). The contoured lightning source densities were located above the downdrafts at lower levels. At 7 km, however, they were associated with weak updrafts that were located west and north of the main updraft. Note that they were outside the stronger updrafts ($w > 15 \text{ m s}^{-1}$). The number of lightning initiation points at 7 km was larger than the number at 5 km and a larger fraction of the initiation points extended out into the northern parts of the FFD region (Fig. 8a), suggesting that the electric field was even stronger at this level. Initiation points were no longer confined to regions of large $Z$, as at the 5-km level but were still in regions of relatively low $Z_{DR}$, west and north of the larger reflectivity values and within weak updrafts (0–10 m s$^{-1}$; Figs. 8a,b,d).

b. 0039 UTC 30 May—F2 tornado and mature lightning-ring formation

The storm produced its first F2 tornado toward the end of the 0012 UTC KOUN volume scan. Over the next 22 min, the $Z_{DR}$ and $\rho_{HV}$ rings gradually began to appear and were well defined by 0034 UTC. By 0039 UTC, the storm had developed a prominent lightning ring, as discussed in this section. According to the damage survey, the tornado began its low-end F2 damage at this time.

At 0039 UTC, the lightning source contours were quite sparse at the 3-km level, with only the 8 sources per kilometer squared per volume contours present, similar to the analysis at 0012 UTC (Fig. 9). By 0039 UTC, however, the sources had taken on a u-shaped pattern centered approximately at ($-76, 49$). These contours roughly followed the hook echo, as defined by the 55-dBZ reflectivity contour, into the inflow notch. The OK-LMA data showed the u-shaped feature in the lightning activity developing at the times of the previous three KOUN volumes (not shown). The most striking feature of the lightning source density contours at this time and height was that they wrapped around a well-defined circulation center, depicted by the vertical vorticity maximum located at ($-77, 49$) (Fig. 9e). The $Z_{DR}$ and $\rho_{HV}$ rings (Figs. 9b,c) were also centered on this vertical vorticity maximum supporting the hypothesis of Kumjian and Ryzhkov (2008) that these rings were related to the mesocyclonic circulations. Additionally, the collocation of the center of the polarimetric rings with the center of the u-shaped lightning source densities suggests the two features were related. On the northwest side of the $Z_{DR}$ ring, near
(−83, 52), a narrow band of high Z and low ZDR extended northward, similar to the high Z and low ZDR notch at the 3-km level at 0012 UTC. The lightning activity appeared to follow the 1.5–2-dB contours of the ZDR ring along the eastern, southern, and western sides connecting to the ZDR notch on the northwest side of the ring. We believe these signatures indicate that the charged graupel from the ZDR notch were being ingested into the inflow and circulated around the periphery of the main updraft by the intense vertical vorticity. As they circulated around

FIG. 6. CAPPI plots of the 3-km level at 0012 UTC for several parameters overlaid with lightning density contours: (a) reflectivity, (b) differential reflectivity, (c) correlation coefficient, (d) vertical velocity, and (e) vertical vorticity. The thick white contours are lightning source densities of 8 sources per kilometer squared per volume. There were no lightning initiations at this level and time.
the periphery of the main updraft, they followed a circular path and began to melt and develop a water torus that increased their $Z_{DR}$ and lowered their $\rho_{HV}$, thereby producing the rings. Because the particles were likely charged, lightning that occurred in this region followed along the same path producing the u-shaped signature in source densities. It is interesting to note, though that there was a small break in the lightning contours along the northern end of the $Z_{DR}$ ring where $Z_{DR} > 3$ dB. This portion of the $Z_{DR}$ ring was likely due to large drops that were not charged and had grown and been lofted as they rotated through the most intense portion of the

**FIG. 7.** As in Fig. 6, but for the 5-km level at 0012 UTC. Thin white contours are for lightning source densities of 35 sources per kilometer squared per volume, and the yellow dots are the initiation points.
horseshoe-shaped maximum in updraft. In the developing $p_{HV}$ ring, the source density contours followed values of 0.94–0.96 on the western and southern edges of the lightning ring, and approached values near 0.98 on the eastern side (Fig. 9c). In the vertical velocity, the source density contours closely followed a notch of weak updrafts at ($-77, 46$), on the west and south sides of the vorticity maximum, and entered a horseshoe-shaped region of stronger updrafts east of the vorticity maximum (Fig. 9d). The horseshoe-shaped nature of the main updraft with a notch of weaker updrafts to its west most likely indicates an occluding updraft with a developing

**Fig. 8.** As in Figs. 6 and 7, but for the 7-km level at 0012 UTC.
RFD (Lemon and Doswell 1979). As at 0012 UTC, no initiation points occurred at 3 km at 0039 UTC.

The patterns of lightning source densities at 5 km were similar to those at 3 km, but the contours were much broader and more continuous at the 5-km level, with several regions of 35 sources per kilometer squared per volume contours present (Fig. 10). Some of these regions of lightning were in the FFD region of the storm, but our focus is on the activity near the mesocyclone region centered at (−77, 47). Contours of lightning density in the
mesocyclone region were again u shaped and centered on the maximum in vertical vorticity at (−77, 49) (Fig. 10e) and followed the 55-dBZ contour through the hook echo region (Fig. 10a). The $Z_{DR}$ ring was still readily apparent at 5 km, but the relative maxima of $Z_{DR}$ were mostly less than at the 3-km level (3.5 dB at 3 km down to 2 dB at 5 km along the northern side of the ring and reduced to approximately 1 dB on the western side; Fig. 10b). The maximum in $Z_{DR}$ was again along the northern side of the $Z_{DR}$ ring and was associated with the maximum updraft...
velocity values in the horseshoe-shaped main updraft near (−73, 51). The lightning activity followed the eastern, southern, and western sides of the $Z_{\text{DR}}$ ring, as at the 3-km level but avoided the largest values of $Z_{\text{DR}}$, in the northern side of the ring. The largest lightning densities tended to be offset toward lower $Z_{\text{DR}}$ values in the interior of the ring, and the western branch of lightning density extended northward into a region of negative $Z_{\text{DR}}$ at (−83, 53). Only a few lightning initiation points were at the 5-km level. These were all in the western side of the $Z_{\text{DR}}$ ring (Fig. 10b), in regions with $Z_{\text{DR}} < 1.5$ dB and $Z > 50$ dBZ (Fig. 10a). This likely indicates that lightning was initiating in this region (a region of inferred graupel) and propagating around the main updraft approximately following the path of the polarimetric rings, thereby producing the u-shaped pattern.

The $\rho_{\text{HV}}$ ring of low $\rho_{\text{HV}}$ (Fig. 10c), centered at (−76, 48), was more prominent than at the 3-km level. Most of the lightning within the ring was in $\rho_{\text{HV}}$ values of 0.93–0.97, but the western branch of the lightning extended into regions having $\rho_{\text{HV}} \approx 0.98$. In the vertical velocity field (Fig. 10d), the eastern branch of lightning density extended along the larger updrafts in the horseshoe-shaped structure of strong updrafts. However, most of the areas of larger lightning density were in the region of weaker updrafts ($w = 0$–15 m s$^{-1}$) between the arms of the horseshoe, as were the lightning initiation points.

Figure 11 presents the lightning source densities at the 7-km level at 0039 UTC. As at 0012 UTC, the lightning activity in the mesocyclone region was connected with that in the forward-flank activity at this level, but our focus is on the activity in the mesocyclone region, between −85 and −70 km east, and 45–55 km north. Lightning source density contours in the mesocyclone region appeared more ringlike, rather than u shaped as at lower levels, as the lightning activity filled in across the north, similar to the filling in of the hook echo and BWER (Fig. 11a). At the 3- and 5-km levels, the larger lightning source densities wrapped around the vertical vorticity maximum at (−76, 49), but the center of the lightning ring was offset slightly north of the maximum vertical vorticity. The $Z_{\text{DR}}$ ring was almost completely absent at this level, suggesting that melting across the updraft periphery is important in the development of this ring, and the $Z_{\text{DR}}$ associated with the lightning activity was ≤0.5 dB (Fig. 11b). The $\rho_{\text{HV}}$ ring was still present (Fig. 11c), but the ringlike pattern in the lightning source densities was offset to the north-northwest of this ring by approximately 5 km. As at 0012 UTC, the number of initiation points was much larger at 7 km than at lower levels. The majority of the lightning initiation points in the lightning ring were along the southern and eastern sides of the reflectivity hook (Fig. 11a), and the $Z_{\text{DR}}$ values near the initiation points were mostly near 0.5 dB (Fig. 11b).

The main updraft was much broader than at the 3- and 5-km levels and was almost circular, with a notch of weaker updrafts extending from the center southward (Fig. 11d). The minimum in lightning density at the center of the lightning ring was over the larger updraft speeds [near (−75, 50)] along the north side of the circular region of updrafts, and most of the larger lightning densities on the west and north sides of the lightning ring were in updrafts <15 m s$^{-1}$. However, much of the eastern and southern parts of the lightning ring was associated with relative maxima in updraft velocity >15 m s$^{-1}$, which was likely due to charged graupel being ingested from the rear side of the storm. The lightning initiation points in the east part of the lightning ring were also in regions of strong updrafts, but those in the west part were in somewhat weaker updrafts ($w < 15$ m s$^{-1}$).

c. 0050 UTC 30 May—Tornado and lightning-ring dissipation

At 0050 UTC, the tornado was weakening and no longer producing F2 damage. At the 3-km level, the areal coverage and intensity of lightning VHF source density contours were greater than in the previous two time periods, though there still were no lightning initiation points at this level. Unlike those earlier periods, the 0050 UTC period had 35 sources per kilometer squared per volume contours [centered at (−70, 53) in Fig. 12]. The increase in lightning sources at this time was likely due to the development of the rear-flank downdraft carrying more charged graupel from above down to this level. The u-shaped pattern in the lightning density contours at 0039 UTC had become a complete ring northwest of the inflow notch in radar reflectivity by 0050 UTC. Whereas the source densities at 0039 UTC were centered around the vertical vorticity maximum, the central minimum in the lightning ring at 0050 UTC was just north of the vertical vorticity maximum, and the southern side of the ring was in the region of maximum vertical vorticity (Figs. 12a,c). The vertical vorticity maximum itself had a smaller peak value than before and was no longer within the main updraft, as it had been at the last two analysis times. Rather, a comparison of Figs. 12d,e shows that values of vorticity $>12.5 \times 10^{-3}$ s$^{-1}$ were mostly within the RFD or on the boundary between downdrafts and weak updrafts. The high-reflectivity hook was wrapped up and was mostly in a region of downdraft west of the updrafts, consistent with the former updraft pulse having become occluded. As at 0039 UTC, a fingerlike notch of low $Z_{\text{DR}}$ north and west of the inflow notch penetrated a region of higher $Z_{\text{DR}}$ in what remained of the $Z_{\text{DR}}$ ring (Fig. 12b). This notch was collocated with
the RFD. The region of $Z_{DR} > 3.0$ dB within the ring overlapped the region of updraft $>15$ m s$^{-1}$. The development of the RFD along with the translation of the vorticity maximum from the weakening main updraft (associated with the dissipation of the lightning ring and polarimetric rings) into the RFD, suggests that the location of the vorticity maximum relative to the main updraft plays a key role in the development of these features.

At the 5-km level, the lightning source density in the vicinity of the mesocyclone was not u shaped, as it had been at 0039 UTC, nor was it a ring, as at the 3-km level.

FIG. 11. As in Figs. 6 and 7, but for the 7-km level at 0039 UTC.
in the 0050 UTC volume scan. Rather, lightning density contours formed a roughly circular region, centered at approximately (−69, 50), in a region of reflectivity mostly greater than 55 dBZ northwest of the inflow notch (Figs. 13a). A $Z_{DR}$ ring was also no longer apparent at this level, and the majority of the lightning activity was located in regions of $Z_{DR} < 1.0$ dB (Fig. 13b). The $\rho_{HV}$ ring was also less well defined at this level, and the majority of lightning was within $\rho_{HV}$ of 0.9–0.97. The area and magnitude of downdrafts in the RFD was less at this level than at 3 km, and updraft magnitudes were slightly larger. The region of largest vertical vorticity...
values was still within the region of lightning activity in the mesocyclone but was shifted north of the lightning activity’s center. Furthermore, the magnitude of vertical vorticity was less than at the lower level or at previous times, and new maxima in vertical vorticity and updrafts appeared to be forming southeast of the old vorticity maximum (Figs. 13d,e). The few lightning initiation points at 5 km were mostly in regions of larger lightning densities and in regions of high $Z$ and low $Z_{DR}$ (Figs. 13a,b). In the dual-Doppler fields, the initiation points were

**Fig. 13.** As in Figs. 6 and 7, but for the 5-km level at 0050 UTC.
primarily in updrafts <15 m s\(^{-1}\) or near the border of downdrafts (Figs. 13a,c,e).

At the 7-km level, the lightning activity was connected to the FFD region. We will focus on the lightning activity between −75 and −60 km east and 45 and 55 km north, most of which was within reflectivity values >50 dBZ (Fig. 14a). The \(Z_{\text{DR}}\) ring was completely absent at 7 km as at previous times, and almost all of the regions of lightning activity were in regions of \(Z_{\text{DR}} < 0.5 \text{ dB}\) (Fig. 14b). The \(\rho_{\text{HV}}\) ring was also absent (Fig. 14c). A new BWER had formed in the region of new updrafts southeast of the old updraft and was adjacent to a large minimum in lightning source density (Figs. 14a,d). This minimum, centered at (−61, 48), was in the newer eastern portion of updrafts, mostly with speeds >20 m s\(^{-1}\). Larger lightning densities were south and west of the lightning minimum in regions that tended to have weaker updrafts than those found in the lightning minimum, though updrafts in some regions of intense lightning activity were still >15 m s\(^{-1}\).

Except near the new BWER, where there was a region of \(\rho_{\text{HV}} < 0.9\), \(\rho_{\text{HV}}\) was 0.98 or larger throughout most of the storm, including most regions of largest lightning source densities (Fig. 14c). Finally, the original vertical vorticity maximum, now at (−68, 53), had weakened substantially from previous times and was embedded in broader regions of intense lightning activity than before.

Lightning initiation points at the 7-km level were no longer clustered around the old vertical vorticity maximum, as at 0039 UTC but were west of it, similar in that respect to the pattern at 0012 UTC. As during all analyzed periods, most initiation points were along a reflectivity gradient, near the boundary of 50-dBZ contours; however, unlike the initiation points during earlier periods, most initiation points at 0050 UTC were near, but outside, the contours of larger lightning source densities (Fig. 14a). In the vicinity of most initiation points, \(Z_{\text{DR}}\) was <0.5 dB (Fig. 14b), and the vertical velocity values were <10 m s\(^{-1}\) (Fig. 14d). One initiation point occurred near the new vorticity maximum, in updrafts >15 m s\(^{-1}\) just east of the new BWER.

\(d\). **Time series observations**

Both CG and intracloud (IC) flash rates in tornadic thunderstorms have been investigated in previous studies. MacGorman et al. (1989) found that, during the mesocyclonic stage of a supercell, CG flash rates decreased but then dramatically increased when the mesocyclone dissipated. They related this to updraft pulsing, suggesting that during an updraft pulse, the lowest charge layer was lofted higher into the storm, thereby causing the altitude of the maximum electric field to be too high in the storm to initiate CG flashes. As the mesocyclone and updraft dissipate, this lowest charge region descends, so the possibility of initiating CG flashes increases. MacGorman and Rust (1998) also point out that a lower region of charge of the opposite polarity also can form as the updraft weakens, and this will further improve conditions for initiating CG flashes. MacGorman et al. (1989), Williams et al. (1999), McCaul et al. (2002), and Wiens et al. (2005) have shown that total flash rates (IC + CG) tend to be largest during the severe stage of the storm and suggested that this was due to increasing updraft mass flux or ice mass in the mixed phase region as storms increased their severe potential. Williams et al. (1999) and McCaul et al. (2002) also showed that total flash rates often increase substantially just prior to tornado genesis and severe hail.

Figure 15 shows a time series of lightning initiation points, computed by summing points over the entire horizontal extent of the storm, for 1-km layers from 3 to 7 km. It should be recalled that detection efficiency of lightning sources decreases with greater distance from the center of the network. Here, however, we primarily focus on trends in the source data that, unlike the raw number counts, should be unaffected by distance from the network. The time series spans the entire time during which the storm was in the KOUN and OK-LMA networks, and includes the time period investigated in the previous sections (0012–0050 UTC). Note that, at 0039 UTC, there is a sharp peak in the number of initiation points from 5 to 7 km, which coincides with the mature phase of the u-shape lightning activity and the \(Z_{\text{DR}}\) and \(\rho_{\text{HV}}\) rings at these levels. It also approximately coincides with the time during which the F2 tornado achieved maximum intensity (similar to the relationships with flash rates found by McCaul et al. 2002; Wiens et al. 2005). After this time, however, the rings quickly dissipated and the number of initiation points decreased at all levels until roughly the time at which the tornado dissipated.

An examination of the lightning initiation points at 0120 and 0200 UTC reveals a similar increase in the number of initiation points, which leads one to speculate that perhaps the polarimetric and lightning source density fields exhibit similar patterns at these times. An examination of the polarimetric and OK-LMA data (not shown), however, revealed that the u-shaped source density and \(Z_{\text{DR}}\) and \(\rho_{\text{HV}}\) rings were not discernible during the subsequent peaks in lightning initiations. While no dual-Doppler data has been processed at these times, it is possible that the vertical vorticity fields were not as strong as they were during the long-track F2 tornado. The lack of the u-shaped lightning activity and the \(Z_{\text{DR}}\) and \(\rho_{\text{HV}}\) rings in the lower to midevels at these later times suggests that vertical vorticity may play a key role in the evolution of the lightning ring at these levels, but this hypothesis needs to be evaluated with data from additional supercell storms.
4. Discussion and conclusions

The analysis presented in this study has examined how the evolution of kinematic and microphysical processes in the vicinity of the mesocyclone was related to the evolution of a lightning ring inside a supercell on 30 May 2004. Three time periods were analyzed: 0012 UTC, at the beginning stage of the lightning ring; 0039 UTC, during the mature stage of the lightning ring; and 0050 UTC, as the lightning, $Z_{DR}$, and $\rho_{HV}$ rings dissipated.

**Fig. 14.** As in Figs. 6 and 7, but for the 7-km level at 0050 UTC.
The beginning stage of the lightning ring (0012 UTC) was marked by lightning activity that was confined primarily to heights above 4 km in the high reflectivity corridor west of the main updraft region. This region also contained downdrafts and low values of $Z_{DR}$. These signatures indicate that this was likely the precipitation cascade, composed primarily of graupel and hail (Straka et al. 2000). Since the majority of charge inside thunderstorms is believed to be generated by rebounding collisions of graupel and ice (e.g., Takahashi 1978; Saunders et al. 2006), the inferred graupel was likely carrying charge acquired at higher levels (>6 km).

At 0039 UTC the lightning ring reached its mature stage, marked by the transition of the lightning activity from being located only in the precipitation cascade to extending around the southern sides of the main updraft and partially into the inflow side of the main updraft. This path traced out a u-shaped pattern of lightning activity that passed through the main updraft and was centered on the vertical vorticity maximum. The $Z_{DR}$ and $\rho_{HV}$ rings were also centered on this vertical vorticity maximum. The void in lightning activity on the north side of the u-shape source densities was associated with the maximum $Z_{DR}$ values in the ring, most likely caused by large drops developing in the main updraft and being carried rearward by the mesocyclonic circulation. The lack of lightning in this region suggests that these large drops had little charge. Lightning in the rest of the ring is thought to have propagated through charge carried by the graupel circulating around the mesocyclone and melting as it crossed the melting layer within the main updraft, a process that Kumjian and Ryzhkov (2008) speculated to be responsible for the rings in $Z_{DR}$ and $\rho_{HV}$.

The final time analyzed, 0050 UTC, presented the dissipating stage of the lightning ring. It was characterized by filling in what had been the u-shaped lightning activity. The most striking feature at this time was the broad expansion of the 8 sources per kilometer squared per volume contours and the appearance of the 35 sources per kilometer squared per volume contour at 3 km. This increase in lightning activity appeared to be associated with the complete wrapping up of the high reflectivity hook, the occlusion of the updraft, and the strengthening of the RFD. The vertical vorticity maximum appeared to be weakening, and was fully enveloped by the RFD. The $Z_{DR}$ and $\rho_{HV}$ rings were also dissipating at this time. While $Z_{DR}$ and $\rho_{HV}$ features were centered on the vertical vorticity maximum, as before, they no longer were full rings but were semicircular rings (high $Z_{DR}$ and low $\rho_{HV}$), located only along the curved portion of the now occluding updraft. This apparent spatial relationship between the $Z_{DR}$ and $\rho_{HV}$ rings, vertical vorticity maximum, and updraft/downdraft structure (mature rings when vertical vorticity maximum was in updraft, dissipating rings when vertical vorticity was in downdraft) suggests that the vertical vorticity maximum plays a role in circulating hydrometeors around the main updraft and that its location relative to the updraft influences how the $Z_{DR}$ and $\rho_{HV}$ rings develop, seemingly supporting the speculations of Kumjian and Ryzhkov (2008). Additionally, the development of the RFD, along with the appearance of broader lightning activity at the lower levels (e.g., 3 km), suggests that the RFD plays a role in transporting charge lower in the storm, thereby increasing the amount of lightning activity in the lower levels.

It was shown that the number of initiation points at each analyzed level increased dramatically in the entire storm as the lightning ring matured. While an increase in initiation points 40 min later suggested the possible formation of another lightning ring, an examination of the OK-LMA and polarimetric data did not reveal such signatures. One difference between those times and the times analyzed in this paper, however, was that the time period analyzed here was during a significant, long-track F2-intensity tornado. It may be that the vertical vorticity pattern or evolution during tornado occurrence plays a significant role in the formation of a lightning ring.

Overall, the evolution of the lightning ring is characterized by three stages:

1) **Developing stage**: Lightning activity is concentrated in the upper levels (>5 km), within the precipitation cascade, which is dominated by charged graupel.
2) **Mature stage**: Lightning activity takes on a u-shaped horizontal pattern as it wraps around the vertical vorticity maximum near the main updraft. The $Z_{DR}$
and $\rho_{HV}$ rings appear to be associated with this lightning-ring development.

3) **Dissipating stage:** The u-shape lightning activity fills in and increases in intensity at the lower heights. This occurs as the vertical vorticity maximum becomes enveloped by the RFD region and the $Z_{DR}$ and $\rho_{HV}$ rings dissipate.

This study provides some insight into the evolution of a lightning ring during the 30 May supercell during TELEX. An examination of the lightning ring by layers has shown that the lightning ring may actually consist of a stacked column of u-shaped activity in the middle layers (i.e., 3–7 km) and then fill in at the upper levels (>7 km), thereby giving the appearance of a ring when source densities are integrated through the entire depth of the storm. In an operational setting, lightning mapping and polarimetric data might be used to increase a forecaster’s confidence that a tornado is occurring when the u-shaped source densities or $Z_{DR}$ and $\rho_{HV}$ rings appear. In this study, these features appeared only when the strongest F2 tornado was present. All other tornadoes within range of the radar in this storm revealed no such signatures.

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