Evolution of Cloud-to-Ground Lightning and Storm Structure in the Spencer, South Dakota, Tornadic Supercell of 30 May 1998

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ABSTRACT

On 30 May 1998, a tornado devastated the town of Spencer, South Dakota. The Spencer tornado (rated F4 on the Fujita tornado intensity scale) was the third and most intense of five tornadoes produced by a single supercell storm during an approximate 1-h period. The supercell produced over 76% positive cloud-to-ground (CG) lightning and a peak positive CG flash rate of 18 flashes min$^{-1}$ (5-min average) during a 2-h period surrounding the tornado damage. Earlier studies have reported anomalous positive CG lightning activity in some supercell storms producing violent tornadoes. However, what makes the CG lightning activity in this tornadic storm unique is the magnitude and timing of the positive ground flashes relative to the F4 tornado. In previous studies, supercells dominated by positive CG lightning produced their most violent tornado after they attained their maximum positive ground flash rate, whenever the rate exceeded 1.5 flashes min$^{-1}$. Further, tornadogenesis often occurred during a lull in CG lightning activity and sometimes during a reversal from positive to negative polarity. Contrary to these findings, the positive CG lightning flash rate and percentage of positive CG lightning in the Spencer supercell increased dramatically while the storm was producing F4 damage on Spencer.

These results have important implications for the use of CG lightning in the nowcasting of tornadoes and for the understanding of cloud electrification in these unique storms. In order to further explore these issues, the authors present detailed analyses of storm evolution and structure using Sioux Falls, South Dakota (KFSD) Weather Surveillance Radar-1988 Doppler (WSR-88D) radar reflectivity and Doppler velocity and National Lightning Detection Network (NLDN) CG lightning data. The analyses suggest that a merger between the Spencer supercell and a squall line on its rear flank may have provided the impetus for both the F4 tornadic damage and the dramatic increase in positive CG lightning during the tornado, possibly explaining the difference in timing compared to past studies.

1. Introduction

Most thunderstorms produce overwhelmingly (>90%) negative polarity cloud-to-ground lightning (NCGL) (e.g., MacGorman and Rust 1998; Orville and Huffines 2001). A large majority of tornadic storms also produce predominately NCGL (Knapp 1994; Carey et al. 2003). For example, Carey et al. (2003) found that about 84% of tornado reports in the contiguous United States during the warm season (April–September) are associated with a majority (>50%) of NCGL. Even storms that spawn violent tornadoes (F4 and F5) are typically dominated by NCGL (Perez et al. 1997). However, previous studies have reported anomalous$^1$ positive cloud-to-ground lightning (PCGL) activity in some supercell storms that produced tornadoes (e.g., Seimon 1993; Knapp 1994; MacGorman and Burgess 1994; Perez et al. 1997; Bluestein and MacGorman 1998; Carey and Rutledge 1998; Gilmore and Wicker 2002; Carey et al. 2003). Williams (2001) provides a recent review of these studies.


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positive CG lightning (PPCG; >50% positive polarity) occur primarily west of about 88°W longitude and are most frequent in the central and northern Plains (e.g., a southwest to northeast line stretching from eastern Kansas into western Nebraska–South Dakota to western North Dakota–eastern Minnesota). For example, 50% to 75% of tornado reports in western South Dakota are accompanied by PPCG lightning (Carey et al. 2003). The F4 tornado that killed six people and destroyed the town of Spencer, South Dakota, on 30 May 1998 was one such event. The supercell that spawned this deadly tornado produced over 76% PCGL and a peak PCGL flash rate of 17.6 min⁻¹ (5-min average) during a 2-h period surrounding the tornado damage.

What makes the CG lightning activity in the Spencer tornadic supercell especially unique and important to document is the magnitude and timing of the positive ground flash rate relative to radar-inferred storm structure and the F4 tornado. The peak PCGL rate is one of the highest published values associated with a supercell, even eclipsing the positive flash rate prior to the well-known Plainfield, Illinois, F5 tornado (Seimon 1993; MacGorman and Burgess 1994). Previous studies (e.g., MacGorman and Burgess 1994; Bluestein and MacGorman 1998) suggest that supercells dominated by PCGL produce their most violent tornadoes after attaining a maximum in PCGL flash rate, whenever this rate exceeds 1.5 flashes min⁻¹. Often, tornadogenesis occurs during a lull in CG lightning activity and sometimes during a reversal from positive to negative polarity CG lightning (e.g., Seimon 1993; MacGorman and Burgess 1994). Although Perez et al. (1997) note significant variability in the evolution of CG lightning behavior in supercells producing violent (F4 and F5) tornadoes, they found that CG lightning peaked before tornado genesis in a majority (4 out of 7) of positive CG lightning-dominated tornadic storms. Contrary to these findings, we will demonstrate that the PCGL flash rate and percentage of PCGL in the Spencer supercell began to increase dramatically while the storm was producing F4 damage on Spencer.

2. Data and analysis methods

a. Tornado data

The reported tornado times, track locations, and F-scale intensities for the Spencer supercell were obtained from the online Storm Data archive maintained by the National Climatic Data Center (NCDC 1998) of Asheville, North Carolina (available online at http://www4.ncdc.noaa.gov/cgi-win/wvweb.dll?wwEvent~Storms). These official tornado reports are well corroborated by a number of unofficial reports taken by several professionally trained tornado observers who were on the scene of the Spencer supercell. For details on these unofficial reports, other Spencer tornado observations, and a thorough description of the meteorological environment surrounding the Spencer tornado, one can access the Web page that is compiled and maintained by Dr. R. Edwards of the Storm Prediction Center (SPC, available online at http://www.spc.noaa.gov/misc/spencer/).

b. Lightning data

Cloud-to-ground lightning data analyzed in this study were collected by the National Lightning Detection Network (NLDN), which is owned and operated by Global Atmospherics, Inc. (GAI). The NLDN records the time, location, polarity, peak current of the first return stroke, and multiplicity (number of strokes per flash) of CG lightning flashes occurring over the contiguous United States and adjacent areas (Cummins et al. 1998).

Percentages of PCGL were tabulated for subjectively delineated areas representing the regional scale (synoptic to mesoscale: [100–1000 km]; entire domain of Fig. 1), the mesoscale ([100 km]; entire domain of Fig. 3), and the supercell scale (10–30 km; within analysis rings in Fig. 4) environment for the Spencer tornadic storm. Statistics (median, mean, standard deviation, maximum, minimum) of the positive and negative polarity peak current and multiplicity and 5-min average positive and negative polarity CG lightning flash rates were computed over the supercell scale. The supercell-scale analysis rings (see Fig. 4) were determined every 5 min via a subjective comparison of the KFSD Weather Surveillance Radar-1988 Doppler (WSR-88D) low-level radar reflectivity data and the NLDN ground stroke locations. For each radar volume, we subjectively placed the analysis ring centered on the low-level (2 km) echo centroid such that all reflectivities >30 dBZ associated with the supercell were included (cf. Figs. 4 and 7a–i.)

To avoid possible contamination of the ground flash sample by weak intracloud (IC) discharges, we eliminated all PCGL with peak currents < 10 kA from our PCGL flash rate and location analyses (e.g., Figs. 1, 2, 6, 8, 10a–c) as suggested by Cummins et al. (1998) and explained by Wacker and Orville (1999a,b). However, it is important to note that less than 1% of the NLDN-detected PCGL produced by the Spencer supercell had peak currents below this threshold. As a result, the implementation of a 10-kA threshold on positive peak current had little effect on our results. Interestingly, about 22% of NCGL on the supercell scale had [peak currents] < 10 kA. To emphasize these points and provide a meaningful comparison between the ground flash polarities, we have left all NLDN-detected CG lightning flashes in the sample for computation of flash statistics for each polarity (Tables 1, 2, and Fig. 5).
c. Radar reflectivity data

To provide a large-scale view of the precipitation system that spawned the Spencer tornadic supercell, we used a regional summary of WSR-88D radar reflectivity. This regional view was taken as a subset of a national composite of low-level WSR-88D radar reflectivity (dBZ) data at 8-km resolution that is produced by the Global Hydrology Resource Center (GHRC) at National Aeronautics and Space Administration (NASA) Marshall Space Flight Center (MSFC).

Storm structure analyses of the Spencer supercell were developed from the available Level-II Sioux Falls, South Dakota, (KFSD) WSR-88D radar data. The KFSD radar is located about 72 km to the southwest of Spencer, South Dakota, providing sufficient (~1 km) horizontal spatial resolution. During the storm's lifetime, the KFSD operated in Volume Coverage Pattern 11 (VCP-11), sweeping through 14 elevation angles in 5 min. Except for an unfortunate 17-min gap (~3 radar volumes) in the Level-II recording from 0111–0128 UTC, just prior to the beginning of F4 tornado damage at 0138 UTC, the Spencer supercell was well covered by KFSD both temporally and spatially (i.e., horizontally and vertically). The gap in archived Level-II data occurred when the NWS switched the power source at the WSR-88D from commercial to generator. During this gap, we linearly advected and expanded the lightning analysis circles shown (see Fig. 4) and used for computation of supercell CG lightning flash rates (see Fig. 6).

We used the radar reflectivity factor (or “reflectivity”) in dBZ. The data were first converted from Level-II format to UF (Universal Format; Barnes 1980). The UF data were carefully edited with the Research Data Support System (RDSS) software developed at the National Center for Atmospheric Research (NCAR; Oye and Carbone 1981). RDSS was used to remove the extra Doppler scans at the two lowest elevation angles and spurious reflectivity data (e.g., 2nd trip echoes, sidelobe contamination) at all elevation angles.

The UF data were then interpolated onto a Cartesian grid using the NCAR REORDER software package (Mohr et al. 1986), centered on Spencer (97.59°W longitude and 43.72°N latitude). Grid resolution is 1 km in the horizontal and 0.5 km in the vertical. The radius of influence for the Cressman filter (Cressman 1959) employed in the interpolation process was 1 km in the horizontal and vertical. Horizontal and vertical cross sections of reflectivity were used to reveal supercell storm structure associated with the F4 tornado and anomalous CG lightning behavior. In addition, we employed time–height cross sections of volumetric reflectivity statistics (e.g., mean volumetric reflectivity, maximum volumetric reflectivity, and the total volume of reflectivity ≥40 and ≥55 dBZ) to investigate storm structure and evolution. The analysis cylinders for this volumetric reflectivity study were defined by the diameters of the lightning analysis circles shown in Fig. 4 and the height of the top Cartesian grid level (18 km AGL). As discussed earlier, we subjectively placed the analysis ring for each radar volume centered on the low-level (2 km) echo centroid such that all reflectivities > 30 dBZ associated with the supercell were included (cf. Figs. 4 and 7a–i).

For determination of storm rotation and mesocyclone strength, we used the National Severe Storm Laboratory (NSSL) Mesocyclone Detection Algorithm (MDA) as implemented in NSSL’s WSR-88D Algorithm Testing and Display System (WATADS, version 10.0). The MDA assigned a mesocyclone strength rank (MSR) to each mesocyclone for each volume scan (Stumpf et al. 1998). MSR represents a composite of the strength ranks of the two-dimensional shear segments from each plan position indicator (PPI) scan that compose the mesocyclone with height. MSR is a nondimensional number based on various strength parameters derived from Doppler velocity (e.g., rotational velocity, shear, maximum gate-to-gate velocity difference). Since strength rank is range-dependent (e.g., the farther a mesocyclone is from the radar, the lower the strength values needed to have the same strength rank), it can be used as an objective measure of rotation that extends throughout a significant storm depth (Stumpf et al. 1998).

The mesocyclone strength index (MSI) is a nondimensional number derived from vertical integration of the three strength parameters, which define the MSR for each 2D feature comprising a 3D detection (Stumpf et al. 1998). The vertical integration is divided by the depth of the vortex, such that strong shallow vortices are not misrepresented as being weaker than strong deep vortices. The integration is weighted by density so that measurements closer to the surface are given more weight. MSI values of 0–2300, 2300–3600, and >3600 indicate a weak, moderate, and strong mesocyclone (Stumpf et al. 1998). The strongest mesocyclones have values around 7500–8500. Since we found little difference in the temporal trend of the two parameters (i.e., MSR and MSI) for the Spencer mesocyclone, we chose to use MSI as an objective measure of the three-dimensional mesocyclone strength (i.e., storm rotation through a deep storm layer).

3. Results

a. Overview

Spencer is located in southeastern South Dakota about 72 km west-northwest of Sioux Falls, South Dakota (e.g., see Fig. 1). On 30 May 1998 (31 May UTC) at approximately 0200 central daylight time (CDT) (0138 UTC, UTC = CDT + 5 h, all times UTC henceforth), a tornadic supercell struck Spencer killing 6 people, injuring 150 persons, destroying nearly all of the homes and buildings and causing about $18 million of property and crop damage in the small northern plains community (NCDC 1998). The Spencer F4 tornado was the third
and most intense of five tornadoes (see Table 1), creating a nearly continuous 46.4-km-long damage track (e.g., see Figs. 3 and 4 for a depiction of the tornado tracks). All five tornadoes were produced by a single supercell storm during a 1 h and 5 min period (e.g., see timeline of tornado intensity in Fig. 6 and Table 1). Although the most devastating damage was limited to less than 1.6 km along the Spencer tornado track in the immediate vicinity of the town, significant property and crop damage (F1 to F3 intensity) was inflicted on several nearby farms along the full 22.4-km track.

The regional cloud-to-ground lightning activity surrounding the lifetime of the Spencer supercell (0000–0300 UTC) is depicted in Fig. 1. The Spencer supercell was associated with a large area of CG lightning that was oriented southwest to northeast from eastern South Dakota through southern Minnesota and into northern Wisconsin and Michigan. Overall, 57% of the CG lightning was of positive polarity. The southwestern two-thirds of this zone was characterized by predominately PCGL while the northeastern one-third was associated with mostly NCGL.

The corresponding horizontal radar structure at 0130 UTC is provided by an 8-km-resolution low-level WSR-88D reflectivity composite shown in Fig. 2. An intense squall line extended from eastern South Dakota into south-central Minnesota. A band of radar reflectivity echoes ≥50 dBZ embedded with the squall line extended nearly contiguously for 600 km from eastern South Dakota across the entire state of Minnesota. Interestingly, the area dominated by PCGL in Fig. 1

<table>
<thead>
<tr>
<th>Location</th>
<th>Max F-scale</th>
<th>Length (km)</th>
<th>Time (UTC)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Fulton, SD</td>
<td>F1</td>
<td>3.2</td>
<td>0108–0115</td>
</tr>
<tr>
<td>Fulton, SD</td>
<td>F2</td>
<td>9.6</td>
<td>0116–0128</td>
</tr>
<tr>
<td>Spencer, SD</td>
<td>F3</td>
<td>22.4</td>
<td>0126–0152</td>
</tr>
<tr>
<td>Salem, SD</td>
<td>F2</td>
<td>9.6</td>
<td>0150–0205*</td>
</tr>
<tr>
<td>Canistota, SD</td>
<td>F1</td>
<td>1.6</td>
<td>0207–0210</td>
</tr>
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</table>

* There is some uncertainty in this time range. Storm Data lists time of Salem tornado as 0156 UTC. The given time range was estimated from the NWS Event Summary and eyewitness accounts.
roughly corresponds to the most intense portion of the squall line in Fig. 2. In addition to the five tornadoes near Spencer, severe weather (tornadoes, large hail, and strong straight-line winds) occurred along much of this intense convective line that was dominated by positive CG lightning, especially in South Dakota (NCDC 1998). The squall line, positive CG lightning, and severe weather were associated with substantial CAPE ($\geq 2500$ J kg$^{-1}$), resulting from a low-level jet ($\geq 15$ m s$^{-1}$) axis feeding warm moist air from the south-southwest, an upper-level jet ($\geq 50$ m s$^{-1}$) axis approaching from the west-southwest, strong tropospheric shear in a veering flow, a capping inversion, and an approaching dryline marking the western edge of the unstable, moist air (not shown).

Note the enhanced reflectivity ($\geq 50$ dBZ) appendage in Fig. 2 and positive CG lightning cluster in Fig. 1 (boxed region) that are approximately orthogonal to the southeastern end of the convective squall line over the Spencer region in eastern South Dakota. This reflectivity appendage and positive CG cluster are representations of the tornadic supercell under study here (e.g., see Fig. 7e for a close-up of the KFSD radar reflectivity in the boxed region of Fig. 1).

A mesoscale ($120$ km $\times$ $120$ km) depiction (boxed region of Fig. 1) of the ground flash locations and polarities along with the tornado tracks from 0018:30 to 0236:30 UTC is provided in Fig. 3. About 67% of the CG lightning during this time was positive polarity. Note the dense cluster of positive-polarity CG lightning flashes directly over Spencer at (0 km, 0 km). This PCGL cluster is embedded in the middle of the F4 tornado track that runs directly through Spencer. PCGL is clustered in at least two other locations during this period (e.g., $x = -8$ km, $y = 24$ km and $x = -20$ km and $y = 57$ km). From Fig. 3, it appears that NCGL is distributed preferentially along the outskirts of these PCGL clusters. As will be shown in section 3d, each PCGL cluster was associated with a high reflectivity ($\geq 50$ dBZ) low-level (2 km) core and NCGL flashes were scattered along the periphery of the core and the associated PCGL cluster (e.g., see Fig. 8).

Figure 4 depicts the track of the Spencer supercell as indicated by the high radar reflectivity ($\geq 50$ dBZ) echo swath. The swath was constructed by overplotting the enhanced ($\geq 50$ dBZ) reflectivity cores from low altitude (2 km) for the period 0021–0234 UTC. As a result, this swath shows the translation of the high-reflectivity cores in relation to the tornado tracks. Note that the high-reflectivity storm track direction deviated strongly toward the right while coincident with the tornado tracks and positive CG lightning (Figs. 3 and 4). The overplotted circles are the subjectively determined analysis rings (or cylinders in 3D) used to determine the CG lightning and radar reflectivity sample associated with the Spencer supercell (e.g., Figs. 10a–d). In general, we placed the analysis ring centered on the low-level (2 km) echo centroid such that all reflectivities $\geq 30$ dBZ associated with the supercell were included. Early on,
the supercell was compact and reasonably isolated so that the determination of the analysis rings or cylinders that encompassed the Spencer supercell was straightforward (e.g., see Figs. 7a–e). Later in its life cycle (e.g., Figs. 7f–i), the supercell grew in areal extent and merged with a nearby line of cells that overtook it from behind at about the time of the F4 tornado. This made determination of analysis rings/cylinders for the supercell at these later times problematic. In placing the analysis cylinders after about 0130 UTC, we manually selected the merged echo feature characterized by moderate-to-high reflectivity (≈ about 30 dBZ) at low levels (2 km) that was best representative of the Spencer supercell in all four dimensions. This unavoidable procedure likely introduces some unknown bias in the radar reflectivity and lightning statistics at later times but the resulting bias is less than if we included the entire convective line as representative of the supercell, or if we focused only on the original high reflectivity core. Indeed, as demonstrated in section 3d, the merger of the supercell and convective line appears to be a critical process in the life cycle of the supercell storm structure, CG lightning behavior, and tornado intensity.

b. Cloud-to-ground lightning properties

The analysis rings depicted in Fig. 4 were used to isolate a Lagrangian CG lightning sample that is representative of the Spencer supercell (i.e., CG lightning within the analysis rings in Fig. 4, which track the 30-dBZ echo centroid of the supercell in time). From 0021 to 0234 UTC, the supercell produced 474 ground flashes for a mean supercell CG lightning flash rate of 3.6 flashes min$^{-1}$. Approximately 77% of the ground flashes produced by the supercell were of positive polarity (Table 2), yielding a storm-average positive (negative) CG flash rate of 2.7 flashes min$^{-1}$ (0.8 flashes min$^{-1}$). By
using the total area of the analysis rings (4092 km$^2$), we determined an approximate storm-average flash density. The supercell average total, positive and negative CG lightning flash densities were 0.052, 0.040, and 0.012 flashes km$^{-2}$ h$^{-1}$, respectively.

Cloud-to-ground lightning statistics for the positive and negative peak current (kA) and multiplicity associated with the Spencer supercell are summarized in Table 3. The mean (median) positive peak current is 59.7 (52.4) kA. By contrast, the absolute mean (median) value of negative peak current is only 13.5 kA (13.7 kA). These values of positive (negative) peak current are large (small) compared to long-term annual and warm season means over South Dakota (Orville and Hufnies 2001 and Carey et al. 2003, respectively) but are comparable to climatological values within severe storms over the region (Carey and Rutledge 2003). The maximum absolute magnitude for positive flashes was 173 kA and only 28.8 kA for negative flashes. Only three of 363 (<1%) PCGL flashes had peak currents less than 10 kA. On the other hand, 22% of the NCGL flashes had very low peak currents (<10 kA). The mean positive and negative CG multiplicities are very close at 1.2 and 1.1, respectively. The maximum positive (negative) multiplicity is 4 (3). Interestingly, the standard deviations of the NCGL peak current and multiplicity are significantly less (by a factor of 7) than the corresponding values for PCGL.

Inspection of the absolute magnitude histogram for positive and negative CG peak currents (kA) associated with the Spencer supercell (Fig. 5) highlights the dramatic differences between the peak currents of each polarity. The positive CG peak current distribution is broad, possessing a mode between 30 and 50 kA and is strongly and positively skewed (i.e., toward large peak

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3 One wonders if these low (<10 kA) peak current negative CG lightning flashes were actually misidentified intracloud (IC) discharges in an inverted dipole structure. Carey and Rutledge (2003) also found that median negative peak currents within severe storms over South Dakota are typically low (12–16 kA). Dr. K. Cummins (Vaisala-GAI Inc 2002, personal communication) suggested that these NLDN measurements were likely valid.
Table 2. The CG lightning flashes.*

<table>
<thead>
<tr>
<th>Positive polarity</th>
<th>Negative polarity</th>
</tr>
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<tbody>
<tr>
<td>363 (76.6%)</td>
<td>111 (23.4%)</td>
</tr>
</tbody>
</table>

* Ground flashes within the analysis rings depicted in Fig. 4.

c. Cloud-to-ground lightning flash rate evolution relative to tornadic activity

A time series of PCGL and NCGL flash rates (5-min average) and associated percentage of positive CG lightning produced by the Spencer supercell is presented in Fig. 6 relative to the timing and intensity of tornadic activity (see also Table 1).

The percentage of PCGL was anomalously high (≥25%) throughout the entire 2.5-h life cycle of the supercell and nearly always dominated the NCGL flash rate during the tornadic activity. The overall peak in the percentage of positive ground flashes was about 91% and occurred during the tail end of F4 tornado damage near Spencer. Note that the percentage of positive ground flashes increased dramatically from 0134 to 0149 UTC, during the transition of the Spencer supercell from F3 to F4 tornado damage at 0138 UTC (NWS Service Assessment Team 1998). It then decreased rapidly as the Spencer tornado dissipated around 0150 UTC and the weaker Salem F2 tornado formed at 0152 UTC.

The NCGL flash rate exhibited significantly less variation compared to the PCGL flash rate [i.e., about a factor of 2 (20) variability in the NCGL (PCGL) flash rate]. In general, the NCGL flash rate increased gradually from about 0–1 flash min⁻¹ prior to the first tornado touching down (0020–0100 UTC) to about 5 flash min⁻¹ by tornadogenesis of the first Fulton F1 tornado (between 0105 and 0108 UTC according to eyewitness accounts). During the five tornadoes associated with the Spencer supercell, the NCGL flash rate oscillated between 0.5 and 2.0 flashes min⁻¹. One of these fluctuations occurred while the F4 tornado struck Spencer from 0138 to 0152 UTC. The NCGL flash rate increased steadily from a relative minimum of 0.6 flashes min⁻¹ at 0129 UTC to a relative maximum of 2.0 flashes min⁻¹ at 0144 UTC. As the F4 tornado dissipated, the NCGL flash rate also decreased (to 0.8 flashes min⁻¹ by 0159 UTC). The NCGL flash rate associated with the supercell was generally higher after the merger between the

Fig. 5. Histogram of the absolute magnitude of the positive and negative CG lightning peak current (kA) associated with the Spencer supercell (i.e., within the analysis rings shown in Fig. 4) from 0021–0234 UTC. Each bin label represents the maximum value in that bin.
supercell and convective line (during and after the tornadic activity) than during the development and intensification phase of the isolated supercell prior to tornadogenesis.

The PCGL flash rate was small (0–1.6 flashes min\(^{-1}\)) and went through a couple of peak–lull cycles prior to tornadogenesis of the first of five tornadoes (the Fulton F1 tornado) within the Spencer supercell at about 0108 UTC. During and after the tornadic activity, the PCGL flash rate remained at or well above 1 flash min\(^{-1}\). The most dramatic transition in the PCGL flash rate brackets the F4 tornado damage. Just prior to F4 tornado intensity at 0134 UTC, the PCGL flash rate was only 1.4 flashes min\(^{-1}\). During the onset of F4 tornado damage at 0138 UTC, the PCGL flash rate began to rapidly increase. By most eyewitness accounts, F4 tornado damage occurred within the city limits of Spencer until about 0144 UTC. During this period, the positive CG lightning flash rate increased to 6.4 flashes min\(^{-1}\). As the tornado exited a devastated Spencer, the 5-min average PCGL flash rate continued to increase to a maximum of 17.6 flashes min\(^{-1}\) centered on 0149 UTC. As the Spencer tornado dissipated and the weaker F2 Salem tornado formed in its place, the PCGL flash rate decreased just as rapidly to pre-F4 tornado values. By 0209 UTC, the positive ground flash rate was only 1.8 flashes min\(^{-1}\). After the tornadic activity ceased after 0210 UTC, the PCGL flash rate remained high (2–4 flashes min\(^{-1}\)) relative to the early, development phase of the supercell.

d. Radar reflectivity inferred storm structure and evolution

The Spencer supercell was within about 20–120 km of the KFSD WSR-88D radar throughout much of its life cycle, allowing for a detailed perspective of the severe storm. An overview of the low-level (2 km) KFSD horizontal reflectivity structure and evolution of the Spencer supercell from 0021 to 0229 UTC is presented in Figs. 7a–i.

Early on (0021 UTC, Fig. 7a), the Spencer supercell was the dominant cell of several cells at the southern end of the 600-km-long squall line (cf. Fig. 2). From 0021 to 0036 UTC, the area of intense reflectivity (≥55 dBZ) within the supercell expanded (Fig. 7b). The expansion and intensification of the supercell reflectivity structure at low levels (2 km) was associated with a local maximum in the PCGL flash rate (Fig. 6). By 0051 UTC (Fig. 7c), the supercell became more distinct from the rest of the cells, exhibiting a broad hook echo and inflow notch, associated with the mesocyclone and updraft, respectively. From 0051 to 0106 UTC, the storm rapidly intensified and expanded in size (Fig. 7d). Even in the smoothed Cartesian data (grid spacing 1 km), the influence of the strong mesocyclone on the reflectivity structure is obvious. A distinct hook echo and inflow notch are evident on the western side of the supercell (Fig. 7d). The first F1 tornado began to form beneath the supercell at about this time (NCDC 1998) and the storm track began to deviate strongly toward the southeast of its earlier eastward movement (Fig. 4). During
A three-volume gap in the recording of Level-II KFSD radar data occurred from 0111 to 0128 UTC. Base reflectivity data from KFSD (Level III, not shown) during this period reveal rapid development of the squall line along the left rear flank of the Spencer supercell. By 0129 UTC (Fig. 7e), the squall line was fully formed and yet still distinct at low levels to the rear of the supercell, exhibiting a large area (>50 km²) of intense reflectivity (>55 dBZ). According to NCDC (1998), the supercell produced three separate tornadoes from 0106 to 0129 UTC. Each successive tornado was more intense according to the maximum recorded F-scale damage rating (see Table 1). During this tornadic phase, the supercell was producing anomalously high PCGL (43%–71%, Fig. 6.). As shown in Fig. 6, the positive ground flash rate from the supercell was relatively steady at about 1–1.6 flashes min$^{-1}$, despite the increasingly more violent tornadic activity.

From 0129 to 0144 UTC, the low-level reflectivity associated with the squall line completely merged with the supercell (Fig. 7f). By 0144 UTC, the squall line possessed a solid line of robust convection (Z > 45 dBZ). The Spencer supercell became a large, intense east–west appendage near the southern side of the line. This merger process was coincident with the onset of F4 tornadic damage in the city of Spencer (Fig. 6). The Spencer tornado, which began west-northwest of Spencer at 0126 UTC, passed through Spencer producing F4 damage from about 0138 to 0144 UTC and continued eastward of Spencer until about 0152 UTC. The merger
FIG. 8. Horizontal cross section of KFSD reflectivity (dBZ, shaded as shown) at 2-km height for 0149 UTC. Positive/negative polarity lightning ground strike locations (×) for a 5-min period (0146:30–0151:30 UTC) are overlain. The lines at y = 0 km and x = 2 km highlight the planes of the vertical cross sections in Figs. 9a and 9b, respectively. The star indicates the center of the mesocyclone at x = 7 km and y = −2 km at this height and time. Although not shown here, a tornado vortex signature (TVS) was embedded within the mesocyclone.

process and F4 tornadic activity were also accompanied by a striking increase in the flash rate and percentage of PCGL (Fig. 6). From 0134 to 0149 UTC, the (5-min average) PCGL flash rate (percentage) increased dramatically from 1.4 flashes min⁻¹ (50%) to 17.6 flashes min⁻¹ (91%).

In Fig. 8, the ground flash locations and polarity are placed in the context of the low-level (2 km) reflectivity structure during the time of the maximum PCGL flash rate (0146:30–0151:30 UTC) and of the F4 tornado damage (0144–0152 UTC). The general horizontal structure is that of a northeast-to-southwest-oriented squall line with an east-to-west-oriented appendage near the southern end of the line that resulted from the merger of the original supercell and the rapidly developing squall line that overtook it from the rear. The portion of the squall line that merged with the supercell was still compact in horizontal extent at this time. The areal coverage of the merged feature was about 3500 km². The vertical structure of the Spencer storm is presented in Figs. 9a,b. Although some of the anvil structure was likely not scanned by the KFSD radar due to the limitations of the VCP-11 scan mode at high elevation angles (e.g., Fig. 9a for X > 20 KM), much of the vertical structure was captured. Echo tops were at 18 km and the 40 (50) dBZ echo surface extended to 15 (12) km above ground level (AGL). While merged at low-to-midlevels (0–8 km), the east-to-west (Fig. 9a) reflectivity structure of the original supercell and squall line are still distinguishable at all levels and have clearly separate echo cores at upper levels (>8 km).

During the period of peak positive ground flash rate and F4 tornadic activity, most of the PCGL flashes were tightly clustered in the vicinity of high (>50 dBZ) reflectivity cores (Figs. 8 and 9a,b) and were located just to the northwest of the mesocyclone center (Fig. 8) and tornado vortex center (not shown). As a result, the positive ground flashes were also clustered closely around the town of Spencer (i.e., X = 0 and Y = 0). The positive ground flash density beneath the merged supercell and
The squall line feature was approximately 0.3 km$^{-2}$ h$^{-1}$. Positive (negative) ground strike locations were generally associated with high, or $\geq 45$ dBZ, (low-to-moderate, or $< 45$ dBZ) reflectivity at the center (periphery) of echo cores. PCGL flashes were clustered along the leading edge of a high-reflectivity threshold at the interface between the merged supercell and squall line feature. The positive CG lightning cluster with the highest flash density was centered almost directly over Spencer and was collocated in time and space with the center of the F4 tornado track (cf. Figs. 3, 4, 6, and 8).

Interestingly, nearly all of the negative ground flashes at this time were located along the periphery of the original supercell and the portion of the squall line that had merged with the supercell. Close inspection of Figs. 8 and 9a–b reveals that about 60% of these NCGL flashes came to ground beneath moderate reflectivity in the forward flank (i.e., eastern, downdraft region of the original Spencer supercell convection while the remaining NCGL flashes were located on the very edge of the merged reflectivity feature on the right (i.e., southern) and rear (i.e., western) flanks.

By 0159 UTC, the merged supercell and squall line precipitation system was the dominant reflectivity feature at low levels in the analysis domain (Fig. 7g), the F4 tornado had dissipated and a new F2 tornado had formed (Figs. 4 and 6). At the same time, the PCGL flash rate rapidly dropped to pre-F4 tornado levels (i.e., 1–4 flashes min$^{-1}$). From 0214 to 0229 UTC (Figs. 4 and 7h,i), the system moved toward the east again (i.e.,
no longer a right mover), took on a more classic squall line structure along its southern end and all tornadoic activity ceased. The PCGL flash rate and percentage remained anomalously high but still well below the peak activity during the F4 tornado (Fig. 6).

e. Radar reflectivity time–height cross sections

In order to explore the evolution of vertical storm structure, time–height cross sections of the Spencer tornadic storm mean radar reflectivity ($Z_{\text{mean}}$, dBZ), maximum reflectivity ($Z_{\text{max}}$, dBZ), the echo volume ($V_{40}$, km$^3$) characterized by $Z > 55$ dBZ and the echo volume ($V_{45}$, km$^3$) characterized by $Z > 40$ dBZ are presented in Figs. 10a–d respectively. Three major pulses in the vertical development of the Spencer storm are evident in Figs. 10a–c, centered on 0036, 0101, and 0149 UTC. Each pulse is associated with an increase in the heights of the mean reflectivity surfaces aloft (Fig. 10a). All three phases of development of the Spencer storm are associated with relative maxima in the PCGL flash rate. The second pulse in vertical development was by far the most intense from a radar reflectivity standpoint, characterized by the highest $Z_{\text{mean}}$ and $Z_{\text{max}}$ and largest $V_{45}$ throughout the depth of the mixed-phase zone. The third pulse, which was also associated with the F4 tornado over Spencer, generated significantly more CG lightning despite exhibiting lower mean $Z$, $Z_{\text{max}}$, and $V_{45}$ in the mixed-phase zone (i.e., $-40^\circ C < T < 0^\circ C$ or $4.3$ km $< H < 9.7$ km) than the other two pulses. On the other hand, the third pulse was characterized by an impressive maximum in $V_{40}$ and a rapid increase in 40-dBZ echo heights, suggesting an associated increase in updraft strength. The maximum in $V_{40}$ and a dramatic increase in 40-dBZ echo heights (and hence updraft strength) led the peak in PCGL at 0149 UTC. The maximum in $V_{40}$ was the consequence of the merger between the original Spencer supercell and a developing squall line on its rear flank and the subsequent rapid growth and vertical development of the combined storm.

Coincident with the development of mean storm reflectivity $>45$ dBZ in the mixed-phase zone of the first pulse, the Spencer storm began to produce positive CG lightning (0021 to 0026 UTC in Fig. 10a). Vertical development of the first pulse was very rapid. Mean (maximum) reflectivity ranged from 49 to 53 dBZ (56 to 60 dBZ) in the mixed-phase zone (Figs. 10a,b). The positive CG lightning peaked at the same time as radar reflectivity aloft. Despite maximum reflectivity in excess of 62 dBZ near the surface, no large hail was reported at this time.

A brief lull in PCGL activity from 0041 to 0046 UTC was coincident with a decrease in $Z_{\text{mean}}$, $Z_{\text{max}}$, and $V_{45}$ at midlevels in the storm (Figs. 10a–c). After 0046 UTC, the Spencer supercell began to reinvigorate rapidly. The beginning of the second reflectivity pulse in the mixed-phase zone was concurrent with the reappearance of PCGL beneath the storm. The PCGL peaked during the rapid increase in $Z_{\text{mean}}$, $Z_{\text{max}}$, and $V_{45}$ and again as the reflectivity centroid began to descend towards the ground at 0106 UTC. Despite $Z_{\text{max}}$ aloft and near the surface in excess of 62 dBZ and $V_{45}$ $\approx 100$ km$^3$ descending toward the surface at 0106 UTC, no large hail (2.75 inches or 1.91 cm) was reported by the public beneath the Spencer supercell (NCDC 1998). The Spencer supercell was well observed by trained storm spotters so the lack of large hail reports in the official record appears to be justified. Unfortunately, a gap in the recording of Level-II KFSD WSR-88D data prevents us from discussing the reflectivity evolution from 0106 to 0129 UTC. As this large mass of small hail and heavy rain descended toward the surface at 0106 UTC, the onset of the tornadic phase of the Spencer supercell began (Figs. 10a–c). During the gap in Level-II KFSD radar data, three separate tornadoes occurred while the PCGL flash rate was nearly constant at about 1 flash min$^{-1}$.

The reflectivity echo heights were dramatically increasing again by (and likely prior to) 0129 UTC (e.g., Fig. 10a) when the recording of Level-II radar data recommenced, suggesting a reinvigoration of the updraft. This third pulse in the reflectivity structure was coincident in time and space with the supercell–squall line merger process, the onset of violent tornadic damage and the production of an intense PCGL cluster (Figs. 7–10). This merger process was also coincident with tornadogenesis of the Spencer supercell (0126 UTC) and later F4 tornado damage in and near Spencer (0138 UTC).

The merger process was associated with a gradual increase (0129–0139 UTC) and then a pulse (0139–0159 UTC) in $V_{40}$. The gradual (rapid) increase in $V_{40}$ and 40-dBZ echo height (and hence updraft strength) were coincident with or possibly preceded (i.e., during data gap) tornadogenesis (onset of F4 tornadic damage) and a steady (instantaneous) increase in the PCGL flash rate. The mean and maximum reflectivity isosurfaces at mid- to upper levels (i.e., 7–14 km) experienced an upward pulse from 0134 to 0149 UTC (e.g., see 40 $< Z_{\text{mean}} < 49$ dBZ and 50 $< Z_{\text{max}} < 58$ dBZ isosurfaces in Figs. 10a,b). At the same time, the mean low-level echo centroid began to descend from 5 to 6 km (i.e., $T \approx -10^\circ C$) to the surface. This pulse in the reflectivity structure, the descent of the reflectivity centroid at low levels and hence the unloading of precipitation mass were coincident with both the onset of F4 tornadoic damage and rapid increase in the PCGL flash rate from 0138 to 0149 UTC.

\footnote{Of course, the reporting of large hail in tornadic storms is historically very poor. But according to Edwards (1998); the Spencer tornadic storm was “the most intensely observed and analyzed” in South Dakota history. Edwards (1998) contains multiple eyewitness accounts from trained storm spotters confirming that precipitation near the surface was primarily heavy rain and some small hail.}
The third pulse in vertical reflectivity structure as seen in $Z_{\text{mean}}$, $Z_{\text{max}}$, and $V_{55}$ was broad (0134–0209 UTC) and significantly weaker than the earlier two pulses (Figs. 10a–c). Mean and maximum reflectivity throughout low- to midlevels (1–10 km AGL) in the Spencer storm were 2–4 dBZ lower in the third pulse compared to the second. Despite increasing horizontal extent of the Spencer storm from 0151 to 0214 UTC (Figs. 7c–h)
(and hence elevated $V_{40}$ at all levels) and rapidly increasing echo tops (and hence increasing updraft strength), $V_{55}$ was significantly lower in the third pulse compared to the second. The lower $Z_{\text{mean}}$ and $Z_{\text{max}}$ and significantly smaller $V_{55}$ at low- to midlevels were consistent with the absence of large hail reports and unofficial storm-spouter observations of heavy rain and pea-sized hail beneath the Spencer storm during the third pulse. As noted earlier, observations of large hail during tornadic activity are historically unreliable.

f. Evolution of mesocyclone strength

Since earlier studies have demonstrated important relationships between supercell development, mesocyclone evolution, tornado touchdown, and lightning (e.g., MacGorman et al. 1989; MacGorman and Nielsen 1991; Williams et al. 1999), we present the temporal evolution of the mesocyclone strength index and CG lightning flash rates associated with the Spencer supercell in Fig. 11.

During the first pulse in convective development
identified in section 3e earlier (e.g., Figs. 10a–b; 0020–0041 UTC), the mesocyclone and associated storm rotation increased rapidly in strength (e.g., MSI went from 1261 to 4702 as seen in Fig. 11). As discussed earlier, there was a relative maximum in the PCGL flash rate at 0036 UTC. The MSI remained at mostly strong values (>3600) during the second pulse in convective activity (e.g., Figs. 10a–b; 0046–0106 UTC) that led to tornadogenesis of the first Fulton F1 tornado at 0108 UTC. During this period, there were two relative maximum (1.6 min⁻¹) in the PCGL flash rate and the NCGL flash rate steadily increased from 0 to 1 min⁻¹. During the WSR-88D Level-II data gap from 0112 to 0129 UTC, the MSI increased dramatically by nearly a factor of 2 (from 3805 to 7291). Recall that the strongest mesocyclones have values approaching 7500. Of course, the higher-frequency behavior of the mesocyclone strength during the data gap is unknown. The PCGL (NCGL) flash rate remained in a range between 1 and 1.6 min⁻¹ (0.5 and 1.3 min⁻¹). During this same period, two distinct tornadoes formed, including the F2 Fulton tornado at 0116 UTC and the F4 Spencer tornado around 0126 UTC (Table 1). Clearly and as expected, the impressive intensification of the parent mesocyclone was a key factor in tornadogenesis for both of these tornadoes.

Strong midlevel rotation acts to lower pressure at midlevels on the flank of a supercell storm. The corresponding vertical gradient of dynamic pressure perturbation then encourages updraft growth on the right flank of the storm (e.g., Klemp 1987). The rapid increase in storm rotation during the gap (0112–0129 UTC) likely resulted in a stronger dynamically induced updraft on the right flank. As a result, the Spencer updraft likely also exhibited significant intensification during the data gap.

From 0129 to 0149 UTC, the MSI remained remarkably steady at very strong values (7000) and the positive CG flash rate increased spectacularly from 1.4 to 17.6 min⁻¹. While the Spencer tornado was on the ground, the PCGL flashes tended to cluster to the northwest of the mesocyclone center in a region of elevated (>50 dBZ) radar reflectivity (Fig. 8). The NCGL flash rate also climbed steadily from 0.6 to 1.8 min⁻¹ and NCGL was typically scattered along the periphery of the supercell (Fig. 8). It was during this period that the Spencer tornado increased in F-scale damage rating from F1 to F4 as it entered the town of Spencer around 0138 UTC. Although not shown here, the KFSD WSR-88D identified a tornado vortex signature (TVS) embedded within the parent mesocyclone during this entire period.

The very strong low- to midlevel rotation associated with the parent mesocyclone was likely also directly involved in the formation and subsequent intensification

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5 A detailed map of the track and associated F-scale damage was accomplished by B. Smith (NWS Forecast Office at Valley, Nebraska) and is available in the NWS Event Summary for the Spencer tornado. The Spencer tornado began around 0126 UTC as an F1 tornado in farm property about 2 mi northwest of Farmer, South Dakota, and increased in damage rating to F4 as it moved east-southeastward and finally entered the town of Spencer at about 0138 UTC.
of the Spencer tornado. Recall that the storm developed rapidly in the vertical during this period (Figs. 10a–d). For example, the 40-dBZ echo top heights rapidly increased from 13 to 15.5 km from 0129 to 0149 UTC (Fig. 10d). The height of all $V_{40}$ isopleths increased significantly during this time. If the height of the 40-dBZ echo can be used as a proxy for vertical development and updraft strength (e.g., Williams et al. 1999; Gilmore and Wicker 2002), then the updraft clearly intensified from 0129 to 0149 UTC. The stretching of low-to midlevel rotation within the parent mesocyclone by the strengthening updraft may have contributed to tornadogenesis and tornado intensification (e.g., Williams et al. 1999).

Increased $V_{40}$ and intensifying updraft strength (as indicated by increased 40-dBZ echo heights) likely also played an important role in cloud electrification and lightning production. For comparison purposes, we plotted the total vertically integrated $V_{40}$ (or total $V_{40}$) along with the MSI and the CG lightning flash rates in Fig. 11. Note that the total $V_{40}$ rapidly increased from 0129 to 0144 UTC and peaked 5 min prior to the PCGL flash rate. The decrease in total $V_{40}$ after 0144 UTC in Fig. 11 also preceded the decrease in the PCGL flash rate after 0149 UTC. In the mixed-phase zone from 0°C to −40°C (Fig. 10d), the coincident presence of large precipitation ice volume, intense updraft strength, and likely high supercooled liquid water contents may have resulted in the positive charging of graupel and hail via the so-called “charge reversal” process associated with noninductive charging (e.g., Takahashi 1978; Saunders et al. 1991). If all the ingredients were present (e.g., graupel/hail, ice crystals, and supercooled water), then the charge reversal process would have been most likely at warmer temperatures because the switch over from negative to positive charging of the graupel/hail occurs at lower values of cloud water content (e.g., Saunders et al. 1991). The differential sedimentation of the positively charged graupel and hail from the negatively charged ice crystals could have resulted in the formation of an enhanced low-level positive charge center and hence clusters of PCGL beneath the reflectivity core as observed (MacGorman and Nielsen 1991; Williams et al. 1999).

4. Discussion

It is appealing to speculate on the impact of these findings and others on our understanding of storm electrification and cloud-to-ground lightning. In particular, can we identify patterns of behavior common among PCGL-dominant severe storms? Interestingly, the reflectivity echo of the Spencer supercell began to merge at low- to midlevels with a rapidly developing squall line on the rear flank of the supercell about 10 min prior to the onset of F4 tornadic damage and the coincident dramatic increase in the PCGL flash rate and percentage. The timing of this merger process just prior to the intensification of the tornado and the production of a spatially and temporally collocated PCGL cluster is not likely a coincidence. We speculate that this merger process significantly altered the dynamics of the Spencer supercell and hence the nature and timing of microphysics, cloud electrification, and lightning production.

The merger process was coincident with and likely caused a dramatic increase in precipitation echo ($V_{40}$) aloft. This peak in $V_{40}$ just slightly led the peak PCGL flash rate. This result is consistent with Lang and Rutledge (2002) who found that high PCGL flash rates were associated with storms possessing much larger volumes of significant (i.e., $\geq 10$ m s$^{-1}$) updraft. Interestingly, the Edmond supercell presented by MacGorman and Nielsen (1991) formed 30 km ahead of a storm complex and produced its first damaging tornado (F3) just as the storm complex began to overtake it from the west. As in the Spencer supercell, both the positive and negative CG lightning flash rates increased following the storm merger and while tornadoes were on the ground. In Carey and Rutledge (1998), the peak PCGL flash rate (i.e., 2.7 flashes min$^{-1}$) and weak tornadic activity (F0–F1) also occurred just after the merger of two previously isolated supercells. As in the Spencer supercell discussed here, the PCGL flash rate peak and tornado activity were preceded by rapid vertical development of the storm and were coincident with unloading of precipitation at low- to midlevels (i.e., rain and hail descending from −10°C level to the surface) following a merger process (see also Williams et al. 1999).

Another common conclusion between this study and Carey and Rutledge (1998) is that large hail does not appear to play a direct role in the anomalous electrification of PCGL storms. In Carey and Rutledge (1998), large hail at the surface preceded the peak PCGL by tens of minutes. In the Spencer supercell, there was little radar and no in situ evidence for the presence of significant quantities of large hail during the peak PCGL phase. Williams (2001) also argues against a direct role for large hailstones in the production of positive CG lightning because of their low number concentration and associated low surface area available for the noninductive charging process (i.e., little charge-carrying capacity per unit volume of cloud). Even so, there was measurable $V_{55}$ and maximum reflectivity reached 58–60 dBZ aloft in the Spencer supercell during the peak PCGL flash rate. As a result, an indirect role for large hail aloft cannot be ruled out.

Several other studies (e.g., MacGorman and Nielsen 1991; Seimon 1993; Stolzenburg 1994; MacGorman and

$^4$ Since the depth of the warm layer ($T > 0$°C) was large (4 km), it is possible that some large hail was produced aloft but melted before reaching the surface, particularly during the earlier two pulses in storm development when maximum reflectivity exceeded 60 dBZ. However, there was little radar evidence for considerable echo volume of large hail (e.g., $V_{40}$ in Fig. 10c) during the peak in positive CG lightning at 0149 UTC.
Burgess 1994; Carey et al. 1996; Gauthier 1999; Gilmore and Wicker 2002) have found the sudden vertical development aloft, followed by a collapse of a low-level reflectivity centroid and onset or enhancement of tornadic intensity and increase in positive CG lightning activity. For evidence of this process in the Spencer supercell, see the reflectivity slump around 0106 UTC in Figs. 10a–d that was coincident with the onset of first Fulton F1 tornado. See also the centroid descent from 0138 to 0150 UTC in Figs. 10a–d that occurred during the intensification of the Spencer tornado at 0138 UTC and the genesis of the weaker Salem F2 tornado around 0150 UTC. Finally, see also centroid descent from 0204 to 0209 UTC in Figs. 10a–d during onset of the F1 Canistota tornado at 0207 UTC.

The F3 tornadic supercell documented in Gilmore and Wicker (2002) experienced this chain of events when it crossed a mesoscale outflow boundary from earlier precipitation. In Smith et al. (2000), tornadic supercells passing directly or obliquely through the gradient region of a surface $\theta_e$ ridge toward the $\theta_e$ maximum also went through the scenario described earlier. It is possible that the boundary crossing in Gilmore and Wicker (2002) and the passage through a surface $\theta_v$ gradient have a similar dynamical, microphysical, and electrical impact on supercell convection as the merger process did in this study and Carey and Rutledge (1998).

The details of the merger process and associated dynamical, microphysical, and electrical impacts on the Spencer supercell storm are beyond the reach of the available observations and the scope of this study. However, we suggest that the merger process somehow caused a pulse in the storm updraft size and strength, reflectivity structure, tornado intensity, and positive CG lightning prior to the merger process. The cumulus thunderstorms discussed previously is only one of several possibilities that we have not discussed here (e.g., Williams 2001). As a result, the theory discussed previously is only one of several possibilities that could be invoked to explain our observations. Nonetheless, the WSR-88D and NLDN observations do support our hypothesis.

The Spencer supercell was already producing positive CG lightning prior to the merger process. The cumulus merger process (e.g., Simpson and Woodley 1971; Westcott 1984) has been proposed to increase negative CG lightning flash rates in the upscale development of tropical convection (Carey and Rutledge 2000) by increasing the volume of cloud suitable for charge separation or by seeding cells characterized by intensifying updrafts with ice hydrometeors from surrounding, mature convection. In this case, a dynamical merger process may have increased the volume of coincident strong updraft (e.g., Lang and Rutledge 2000), cloud water and precipitation and/or the squall line may have seeded the intensifying updraft within the Spencer supercell with additional ice hydrometeors. Both hypotheses are consistent with increasing $V_w$ and CG lightning flash rates (e.g., Fig. 10d). Hence, the positive charging zone that was already operative in the Spencer supercell may have been dynamically or microphysically enhanced, subsequently increasing production of PCGL.
Negative CG lightning in typical thunderstorms usually peaks following an increase in precipitation echo volume and the subsequent descent of the echo core (e.g., Carey and Rutledge 1996, 1998). Therefore, the merger process likely enhanced the physical process (i.e., either NIC or some other mechanism) that was already causing anomalous positive charging and hence PCGL in the Spencer storm.

The collision of a supercell with another storm as in this study, MacGorman and Nielsen (1991), and Carey and Rutledge (1998), or an outflow boundary as in Gilmore and Wicker (2002) are more random in nature than the systematic passage of a supercell through a mesoscale-α environment such as a θe ridge (e.g., MacGorman and Burgess 1994; Smith et al. 2000). In other words, the merger of two cells or the crossing of an outflow boundary is more serendipitous compared to the advection of a supercell through a typical mesoscale-α environment. All of these events can explain the rapid intensification of the low-level updraft, production of hail, the generation of a low-level positive-charge center via the NIC theory, dominant PCGL behavior, and subsequent tornadogenesis associated with echo descent. However, the chance nature of cell mergers may explain the difference in timing between PCGL and tornado activity in the Spencer supercell and those studied by Seimon (1993), MacGorman and Burgess (1994), Perez et al. (1997), Bluestein and MacGorman (1998), and Smith et al. (2000).

Although no causal link was established, Lyons et al. (1998) suggest that smoke from forest fires in southern Mexico that was advected into the central United States from April to June 1998 may have been ingested into some storms, causing them to produce anomalously large numbers and percentages of PCGL. Although we cannot prove a negative, we strongly believe that the smoke from the Mexican fires played little or no role in the behavior of the CG lightning in the Spencer supercell. Climatological analyses of CG lightning and severe storm reports by Carey et al. (2003) clearly demonstrate that this region (eastern South Dakota) routinely experiences severe storms associated with positive CG lightning. From 1989 to 1998, about 50% of all severe storm reports over this area were associated with >50% PCGL. Certainly there were no major smoke outbreaks from Mexican fires during all of these warm seasons. PCGL-dominant severe storms are fairly typical for the region so no special circumstances such as smoke from Mexican fires need be invoked. However, we did investigate the aerosol (i.e., smoke/dust) index as seen by the TOMS (Total Ozone Mapping Spectrometer) Earth Probe for the Spencer case day (30 May 1998). Very little if any evidence of a smoke plume intrusion into the Spencer, South Dakota, region is evident on 30 May 1998 (not shown).

5. Conclusions
The Spencer supercell produced over 76% positive cloud-to-ground (CG) lightning and a peak positive CG flash rate in excess of 17 flashes min^{-1} (5-min average) during a 2-h period surrounding F4 tornadic damage. This PCGL flash rate is very large and is comparable to the rate beneath the Plainfield, Illinois, F5 tornadic supercell of 28 August 1990, which produced a peak PCGL flash rate of 14–15 min^{-1} (e.g., Seimon 1993; MacGorman and Burgess 1994).

Contrary to the limited number of observations of MacGorman and Burgess (1994) and Bluestein and MacGorman (1998), we have shown that PCGL does not always peak prior to the onset of the most damaging tornado in supercells whose CG lightning activity is dominated by a significant number (≥1.5 min^{-1}) of PCGL during the lifetime of the storm. The flash rate and percentage of PCGL in the Spencer supercell began to increase dramatically after tornadogenesis and during the onset of F4 tornadic damage. The actual peak in PCGL flash rate and polarity occurred during and just after the F4 tornadic damage. Just minutes prior to F4 tornadic damage in Spencer, the 5-min average PCGL flash rate was only 1.4 flashes min^{-1}. Within 15 min, the positive ground flash rate had increased by more than a factor of 12. The overall trend in the PCGL flash rate and polarity actually slightly lagged the window of F4 damage.

Knapp (1994), Williams (2001), and Carey et al. (2003) demonstrate that PCGL is not universally associated with violent tornadoes or large hail in the contiguous United States. The relationship between severe local storms and CG lightning polarity and flash density is apparently dictated by regional storm morphology and environmental factors. PCGL-dominant storms rarely occur in the eastern, southeastern, or Gulf of Mexico regions of the United States, despite experiencing violent tornadoes and large hail. In the central and especially northern plains of the midwestern United States, a stronger correlation exists between PCGL and severe weather. Even in these favorable regions, the correlation is not universal and as much as 50% or more of severe storm reports are associated with mostly NCGL (Carey et al. 2003). As MacGorman and Burgess (1994) point out, although not all severe storms are positive polarity dominant, most dominant PCGL storms are severe. As a result, CG lightning polarity and flash rate could still be a useful supplementary nowcasting tool for tornadoes and large hail.

For CG lightning to be useful however, the PCGL signal must consistently lead the severe weather by approximately 10 min or more. Many case studies have demonstrated that the PCGL signal can lead large hail and tornadoes (e.g., Seimon 1993; MacGorman and Burgess 1994; Bluestein and MacGorman 1998; Perez et al. 1997). Carey and Rutledge (1998) show an example of a PCGL-dominant severe hailstorm in which the PCGL lagged large hail over the high plains of Colorado. The Spencer supercell is another classic counterexample in which an extreme PCGL cluster was coincident and slightly lagged the most damaging tornado.
If PCGL does not necessarily lead severe weather in supercell storms with dominant PCGL activity, then CG lightning polarity may not be a useful tool in nowcasting tornadoes or large hail, even along the central and northern plains. However, it would be premature at this point to discount the idea that severe local storm nowcasting could be aided by CG lightning polarity. More integrated case studies of storm morphology, CG lightning behavior, and meteorological environment of severe local storms are required in a variety of geographic and seasonal conditions before this issue can be resolved.

Williams et al. (1999) and Williams (2001) have demonstrated that lightning jumps, or abrupt increases in the total lightning flash rate in advance of the maximum rate for the storm, are typically precursors (i.e., by tens of minutes) to severe weather (wind, hail, tornadoes) and are likely associated with the rapid development of the updraft that generate the conditions aloft for severe weather at the surface and simultaneously aid the ice production process that drives total lightning activity. As a result, total lightning has a more promising and perhaps a less-ambiguous role in the nowcasting of severe local weather than cloud-to-ground lightning. Because of the lack of total lightning measurements, we unfortunately could not investigate the relationship between total lightning and severe weather in the Spencer supercell.

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