Evolution of Cloud-to-Ground Lightning Characteristics and Storm Structure in the Spearman, Texas, Tornadic Supercells of 31 May 1990

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ABSTRACT

On 31 May 1990, four tornadic supercell storms formed sequentially near the intersection of a dryline and an outflow boundary in the northern Texas panhandle. “Staccato” lightning flashes, which have been hypothesized to be positive ground flashes, were observed beneath the anvil of one storm during the most violent tornado that the storm produced. Evidence was found from a lightning mapping system that at least some of the staccato flashes were negative ground flashes.

Although the four supercell storms on this day formed in approximately the same area, traveled over roughly the same region, and produced tornadoes and large hail, the relationship between the genesis and evolution of tornadoes and the polarity and flash rates of ground flashes varied widely, as in previous studies. The second of the supercell storms had low-precipitation supercell characteristics; the third and fourth did not. In previously studied storms, ground flash activity in low-precipitation supercell storms has always been dominated by positive ground flashes. However, all ground flashes detected in the second, low-precipitation storm were negative ground flashes.

Positive ground flashes dominated ground flash activity in the third and fourth supercell storms for roughly their first hour, after which the dominant polarity switched to negative. In the third storm, the maximum positive ground flash rate before this polarity reversal was 1 min⁻¹ and the most intense tornado produced by the storm occurred before the maximum positive ground flash rate. In the fourth storm, positive ground flash rates increased to 7.4 min⁻¹ over a period of 30 min early in the storm, followed by a rapid decrease to 0 min⁻¹ over the next 10 min; the most intense tornado produced by the fourth storm occurred during the lull in ground flash rates following the large maximum. These observations are consistent with a previously reported tendency for a storm dominated by positive ground flashes to produce its most violent tornado after it attains its maximum positive ground flash rate, whenever the rate is in excess of 1.5 min⁻¹.

1. Introduction

There have been a number of studies correlating both positive and negative cloud-to-ground (CG) lightning flashes detected by lightning-mapping systems with the occurrence of tornadoes (MacGorman and Nielsen 1991; Branick and Doswell 1992; Curran and Rust 1992; MacGorman and Burgess 1994; Stolzenburg 1994). [Positive (negative) CG flashes effectively lower positive (negative) charge to ground.] One purpose of such studies is to see if a signature in the lightning data can be used as a forecasting tool. Another purpose is to elucidate the mechanisms responsible for CG lightning in tornadic storms and to relate them to features in the wind field such as mesocyclones.

The results of some studies have suggested that at times the polarity of the CG flashes changes abruptly when a tornado touches down (Seimon 1993). Other studies have found that such a relationship is far from universal (MacGorman and Burgess 1994). There is, furthermore, folklore among storm chasers that rapidly repeating bright strikes to the same location, colloquially referred to as “staccato” flashes, are sometimes observed from the anvil to the ground east of mesocyclones, and that these flashes transport positive charge to the ground. The identification of staccato flashes is based on visual observations only; they could actually be different strokes in the same flash striking in different places, which give the impression of flickering, rather than different flashes in rapid succession. On 31 May 1990 a storm intercept team from the University of Oklahoma (OU) documented with still

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photography and video two of four tornadic supercells that travelled across the northern Texas panhandle. One of these supercells produced a large tornado, whose wind field was probed with a portable Doppler radar (Bluestein et al. 1993; Bluestein and Unruh 1993). Unlike the other studies of the 31 May 1990 events, which focused on one tornado, the main purpose of this paper is to correlate the evolution of all four supercells and their associated severe weather events (i.e., damaging straight-line winds, large hail, and tornadoes) with CG lightning data from a lightning-detection network. If there is a clear association among severe weather events, storm structure, and the polarity and/or frequency of CG lightning activity, then hypotheses may be formulated that relate the latter to the former two.

2. Storm environment

During the afternoon of 31 May 1990 an outflow boundary created by earlier convective activity stretched along a southeast-to-northwest oriented line from north-central Texas through extreme southwestern Oklahoma and into the northern Texas panhandle (Fig. 1). A dryline extended from west Texas northward into the northern Texas panhandle. The greatest surface convergence was evident in the northern Texas panhandle, where the wind veered from southeasterly to southwesterly from east to west across the region; the dryline and outflow boundary intersected near this area. Although the air mass behind the outflow boundary was very moist, with dewpoints at some observing stations well above 20°C, the temperature was relatively cool. The highest combination of surface temperatures and dewpoints was found in a band from near Dallas northwestward into southwestern Oklahoma. With a southeasterly wind, we can infer that a tongue of locally high equivalent potential temperature air was being advected into the northern Texas panhandle.

Since there were no soundings released in the northern Texas panhandle, we must infer environmental con-
ditions from the nearest soundings (Fig. 2) and the nearby surface observations (Fig. 1). The Dodge City, Kansas, sounding (Fig. 2a), which is typical of the environment of many severe weather events (Bluestein 1993), had a low-level moist layer whose depth exceeded 100 mb, which is relatively deep, surmounted by a dry column of air having a dry-adiabatic lapse rate. The low-level moist layer was being drawn from the southeast, behind the outflow boundary, while the dry air aloft was being drawn from the southwest. The Amarillo, Texas, sounding (Fig. 2b), on the other hand, was apparently released behind the dryline; the low-level nearly well mixed layer extended from the surface up to 550 mb. A composite sounding (not shown) having surface conditions warmer than those behind the outflow boundary, but cooler than those behind the dryline, had a CAPE (convective available potential energy) of approximately 2000 J kg\(^{-1}\). Hodographs from both Dodge City and Amarillo had vertical shear of approximately 20 m s\(^{-1}\) in the lowest 6 km (Fig. 3). This combination of vertical shear and CAPE is sufficient to produce supercells in numerical cloud simulations (Weisman and Klemp 1982).

3. Overview of storm history

Four supercells formed near the intersection of the dryline and an outflow boundary in the northern Texas panhandle. The second and third supercell were observed by the OU storm intercept team. The evolution of each supercell was examined by inspection of microfilm data recorded by the National Weather Service WSR-57 radar in Amarillo and obtained from the National Data Climatic Center. The evolution of the fourth storm cannot be discussed in detail because adequate radar data were not available.

Each supercell formed in approximately the same location (Fig. 4) near the dryline–outflow boundary intersection, produced one or more tornadoes and large hail (Table 1), and moved northeastward or east-northeastward from its place of birth. The first storm began around 1500 (all times given in CDT) and began tracking more to the right about 1.5 h later, when it produced a tornado and large hail. Two secondary cells formed to the north of the first cell: one formed at approximately 1600 and moved to the north-northeast; the second formed at approximately 1700 and moved along a track nearly parallel to the first supercell. Large hail and a tornado were reported at 1630, about when the first cell began to turn to the right.

The second storm began at 1800 as a line segment of three cells, oriented in a north-northeast to south-southwest direction and spaced about 10–20 km apart. Such a storm-initiation mode, the “line segment” mode, is characteristic of many supercells that begin near the dryline (Bluestein and Parker 1993). The middle member of the triplet turned to the right about 30 min after its first appearance and tracked to the east, well to the right of the winds aloft at both Amarillo and Dodge City (Fig. 3). During this time the most intense tornado and the largest hail of the day were observed (Bluestein et al. 1993). The satellite image in Fig. 5 shows the second storm and cumulus congeugus forming to its west. The cumulus congestus eventually developed into the third storm. The second storm dissipated around 2000 as it moved eastward farther behind the outflow boundary.

Based on its visual appearance, we categorize the second storm as an LP (low precipitation) supercell (Bluestein and Parks 1983). As in many LP storms, the region downshear from the main tower, where the most intense precipitation is usually found in typical supercells, was translucent (right side of Fig. 6). (We have no visual observations of the first storm.) Just after the tornado had dissipated, this region of the storm moved overhead; we observed widely spaced large hailstones falling, as noted in other LP storms (e.g., Bluestein and Woodall 1990). The radar reflectivity core was composed of hail, but little if any rain; visually, the storm looked like the skeleton of a typical supercell. It appeared to us as if the farther east the storm moved, the cooler the air being ingested into its updraft: Toward the east, no cumuliform clouds were observed growing in the boundary layer and the base of the wall cloud of the storm assumed a stable-looking, laminar appearance [see Bluestein and Unruh (1993)]. However, we have no direct meteorological measurements to confirm our interpretation.

The third storm, like the second storm, began around 2000 as a line segment of three cells, oriented in a north-northeast to south-southwest direction. However, the initial cells were more widely spaced and it was the southern member of the triplet that developed into a supercell. This supercell spawned a tornado that struck Spearman, Texas. This supercell and its tornado (not shown) looked nearly identical visually to the large one produced by the previous supercell. However, we observed a significant core of rain underneath the anvil, well to the east of the tornado; the storm was therefore not an LP storm, unlike the previous supercell. The third storm dissipated about 2200.

In summary, storms 1–3 each lasted about 2–3 h; the formation of each subsequent storm, which occurred in approximately the same location as the previous storm, also lagged the previous one by 2–3 h, the approximate lifetime of each.

4. Analysis of cloud-to-ground lightning flash data

Detailed discussions of the lightning mapping networks used in this study are found in MacGorman and Nielsen (1991) and Orville et al. (1983). Not all of the CG lightning flashes in a storm can be detected and there is some error in determining the exact location of each flash. Various studies [e.g., Mach et al. (1986);
Fig. 2. Soundings at 1900 CDT (0000 UTC, 1 June 1990) 31 May 1990 at (a) Dodge City, Kansas (DDC), and (b) Amarillo, Texas (AMA). Temperature (solid line) and dewpoint (thick dashed line) given in degrees Celsius by the skewed scale, read at the bottom. Pressure in millibars given at the right; water vapor mixing ratio (thin dashed line) given in grams per kilogram. Winds plotted at far right; half, whole, and flagged wind barbs denote wind speeds of 2.5, 5, and 25 m s$^{-1}$, respectively. Tens unit of wind direction plotted at end of wind barbs; height of wind observation in MSL plotted to the right of each observation.
FIG. 3. Hodographs for 1900 CDT (0000 UTC, 1 June 1990) 31 May 1990 at (a) Dodge City, Kansas (DDC), and (b) Amarillo, Texas (AMA). Points on hodographs denote heights MSL of the wind observations at selected places along each hodograph. Wind speed scales along the $u$ and $v$ axes shown in increments of 2.5 m s$^{-1}$. 

(a)

DDC

1 JUN 90
0000 Z

REGULAR CAPE = 1909.1 J/kg
MOIST CAPE = 1408.6 J/kg
D-6 KM SHEAR = 13.3 m/s
REGULAR BBN = 21.4
MOIST BBN = 16.7
D-6 KM M/RN U = 7.9 m/s
D-6 KM M/RN V = 10.5 m/s
D-3 KM HEL. BNN = 0.5121
D-6 KM HEL. BNN = 0.2179
D-12 KM HEL. BNN = 0.1365
D-3 KM TOT. HEL. = 0.0230 m/s
D-6 KM TOT. HEL. = 0.1212 m/s
D-12 KM TOT. HEL. = 0.0051 m/s
D-3 KM SWIFT. = 0.0036 /s
D-6 KM SWIFT. = 0.0020 /s
D-12 KM SWIFT. = 0.0011 /s

RMAX = 25 m/s

(b)

AMA

1 JUN 90
0000 Z

REGULAR CAPE = 61.6 J/kg
MOIST CAPE = 49.7 J/kg
D-6 KM SHEAR = 5.3 m/s
REGULAR BBN = 4.3
MOIST BBN = 3.5
D-6 KM M/RN U = 7.2 m/s
D-6 KM M/RN V = 9.4 m/s
D-3 KM HEL. BNN = 0.1522
D-6 KM HEL. BNN = 0.0556
D-12 KM HEL. BNN = 0.0703
D-3 KM TOT. HEL. = 0.0097 m/s
D-6 KM TOT. HEL. = 0.0045 m/s
D-12 KM TOT. HEL. = 0.0002 m/s
D-3 KM SWIFT. = 0.0021 /s
D-6 KM SWIFT. = 0.0006 /s
D-12 KM SWIFT. = 0.0005 /s

RMAX = 25 m/s

Fig. 3. Hodographs for 1900 CDT (0000 UTC, 1 June 1990) 31 May 1990 at (a) Dodge City, Kansas (DDC), and (b) Amarillo, Texas (AMA). Points on hodographs denote heights MSL of the wind observations at selected places along each hodograph. Wind speed scales along the $u$ and $v$ axes shown in increments of 2.5 m s$^{-1}$. 

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Table 1. Severe weather events in the northern Texas panhandle on 31 May 1990. Based upon U.S. Department of Commerce (1990) and the severe weather log for the OU storm-intercept team.

<table>
<thead>
<tr>
<th>Super-cell</th>
<th>Event(s)</th>
<th>Time (CDT)</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>F1 tornado, 4.5-cm-diam. hail</td>
<td>1630</td>
</tr>
<tr>
<td>1</td>
<td>F0 tornado, 2–3-cm-diam. hail</td>
<td>1709</td>
</tr>
<tr>
<td>2</td>
<td>F3 tornado, 7.5-cm-diam. hail</td>
<td>1841–1930</td>
</tr>
<tr>
<td>3</td>
<td>F2 tornado</td>
<td>2015–2030</td>
</tr>
<tr>
<td>3</td>
<td>2–3-cm-diam. hail</td>
<td>2030</td>
</tr>
<tr>
<td>3</td>
<td>F0 tornado</td>
<td>2108</td>
</tr>
<tr>
<td>3</td>
<td>F0 tornado</td>
<td>2114</td>
</tr>
<tr>
<td>4</td>
<td>F2 tornado</td>
<td>2245</td>
</tr>
<tr>
<td>4</td>
<td>F0 tornado, &gt;4.5-cm-diam. hail</td>
<td>2315</td>
</tr>
<tr>
<td>4</td>
<td>F0 tornado</td>
<td>2341</td>
</tr>
<tr>
<td>4</td>
<td>F1 tornado</td>
<td>2358</td>
</tr>
</tbody>
</table>

Krider et al. (1980)] have found that the networks typically detect 70%–90% of the negative CG flashes that occur in warm-season storms, although a smaller percentage may be detected during some periods of storms. We estimate that the average error in ground-strike locations for storms analyzed in this study was approximately 5 km. All positive ground flashes detected by the National Severe Storms Laboratory network were included in our analysis, without regard to the amplitude of their signals. Owing to changes in network instrumentation, data from some networks have been contaminated in recent years by cloud flashes incorrectly identified by the networks as positive ground flashes having small-amplitude signals. However, the data presented in this study predate the changes in instrumentation that caused this problem.

In addition, the quality of the WSR-57 radar microfilm was not good enough to correlate lightning lo-
cation precisely with radar reflectivity features within a storm; for example, it was not possible to determine whether or not lightning locations were inside or outside echo cores, or near hook echoes. Furthermore, since Doppler data were not available yet in 1990, features involving the wind field such as mesocyclones and divergence–convergence signatures could not be identified. However, the quality of the radar data was adequate for determining which cells were associated with each lightning flash.

a. Staccato flashes and positive ground flashes

Rust et al. (1981) were the first to document positive ground flashes in supercell storms. Most ground flashes that they observed in and near the reflectivity cores of supercell storms lowered negative charge to ground. However, Rust et al. noted that many of the ground flashes that occurred beneath the anvil of supercell storms lowered positive charge: Far from convective cells, most ground flashes typically were positive, but near the convective tower, ground flashes were more evenly divided between positive and negative. Almost all positive ground flashes in supercell storms have had only a single return stroke (i.e., a single large current surge from the ground to the cloud); this has also been observed for positive ground flashes overall [e.g., Berger (1977)]. Positive ground flashes typically have constituted an increasing percentage of ground flash activity with increasing peak return-stroke current [e.g., Orville et al. (1987)].

Storm chasers have sometimes observed in supercell storms a class of ground flashes that appear as quick, successive bursts of bright ground flashes in the same general region of the storm. Owing to their appearance, these ground flashes have been labeled as staccato flashes. The unusual brightness and short duration of staccato flashes have led some to hypothesize that they are positive ground flashes. This hypothesis can now be tested, because staccato flashes were occasionally visible beneath the anvil on the east side of storm 2 and ground flash mapping data are available for that storm.

During the most violent tornado produced by storm 2, several staccato flashes were seen, along with other ground flashes closer to the reflectivity core. Images of two of the staccato flashes are shown in Fig. 7. A map of ground flashes detected by the mapping network during the 15-min period in which these two staccato flashes occurred is shown in Fig. 8. The concentration of strike points apparent on the west side of ground flash activity in the north-central Texas panhandle was associated with the main storm cell; the strike points scattered east and north around this concentration occurred under the anvil of the storm. Although the time encoding of the video images was not accurate enough to allow unambiguous identification of a particular flash in the video record with a corresponding flash in the lightning mapping record, all ground flashes detected in storm 2 by the lightning mapping network were negative ground flashes. Thus, the staccato flashes observed under the anvil east of storm 2 either were negative ground flashes or were positive ground flashes missed by the network. (A ground flash may not be detected because it produces an electromagnetic signal whose amplitude is below the detection threshold of the system or because it produces a signal with an unusual waveform that fails acceptance tests designed to eliminate cloud flashes from the system output.) However, since all ground flashes observed beneath the anvil east of convection during this period were classified as staccato flashes, it appears likely to us that at least some staccato flashes were negative.

b. Ground flashes relative to storm characteristics and severe weather

The rate of occurrence of CG flashes exhibits four well-defined peaks, each corresponding to one of the four storms (Fig. 9). Only flashes associated with each storm are counted. The first peak in lightning ground-flash rates near 1700 corresponds to the severe stage of storm 1; the peak in lightning rates around 1900 corresponds to the severe stage of storm 2; the peak in lightning rates about 2100 corresponds to the severe stage of storm 3; the peak from about 2230 to 2300...
corresponds with many of the severe weather events associated with storm 4.

No positive CG flashes at all were detected in the first and second supercells. The tornadoes in the first supercell occurred during periods of relatively low CG flash rates. On the other hand, although the major tornado in the second supercell began during a 5-min lull in CG activity, CG flash rates quickly increased to the highest values observed during any of the four storms while the tornado was occurring. Positive CG flashes were detected, however, in the third and fourth supercells; positive CG flash production preceded peak negative CG flash production in both storms.

The strongest tornado in the third supercell began before any ground flashes were produced in the storm, although three positive CG flashes occurred during the last 5 min of the tornado. Ground flash rates increased later in the storm. In contrast, the fourth supercell produced high positive CG flash rates approximately 25 min after it began and produced its strongest tornado just after the positive CG flash rate had decreased to 0 and before the negative CG flash rate had increased.

We now examine more closely the positive and negative CG flashes produced in storms 3 (Fig. 10) and 4 (Fig. 11). No lightning flashes were detected at all during the first 25 min of the echoes associated with storm 3 (Figs. 9 and 10). During the next 45 min, from 2015 to 2100, only positive CGs were detected; most were detected between 2030 and 2045, just after an F2 tornado had been reported (Table 1). From 2100 to 2115 the positive CG flash rate decreased and the negative CG flash rate dramatically increased. Between 2115 and 2130 the polarity of CGs was overwhelmingly negative. As the storm began to dissipate around 2130–2145, the ground flash rate decreased, while the dominant ground flash polarity switched back to positive. Ground flashes all but ceased during the 2145–2200 period, after which the radar echo associated with the storm disappeared.

Since no radar data were available for the fourth storm, we can only make educated guesses about the storm’s evolution based upon the severe weather reports (Table 1), which must themselves be viewed with some caution since the events took place in a sparsely populated area in the dark. From 2200 to 2245 the storm was dominated by positive CG flashes (Figs. 9 and 11). During this period, ground flash rates became higher than at any other time in any of the four storms: Average positive CG flash rates exceeded 6 min⁻¹ for 10 min. Shortly after positive CG flash rates fell back...
Fig. 7. Lightning from the anvil-to-ground in a tornadic supercell to the west at approximately 1902 CDT 31 May 1990, from a video. The top image occurred a fraction of a second (the time duration of six video frames) before the bottom image (copyright H. Bluestein).
to less than 1 min$^{-1}$, an F2 tornado was reported. This tornado report is supported by damage to two farm houses and equipment over a 4.8 km long swath (U.S. Department of Commerce 1990). The dominant polarity of detected CG flashes changed to negative during the lifetime of this tornado and remained negative through 0000. Three weak tornadoes were reported during the period when the the dominant ground flash polarity was negative. A few positive CG flashes occurred as the storm dissipated after 0000 (Fig. 9).

5. Discussion and conclusions

a. Relationship between staccato flashes and polarity

Because the ground flashes that storm chasers have labeled staccato flashes appear to be unusually bright and brief, it had been hypothesized that they are positive ground flashes. Although staccato ground flashes were observed beneath the anvil of storm 2 during the most violent tornado that the storm produced, all ground flashes detected by the mapping system in storm 2 during this period were negative ground flashes. Thus, the observed staccato flashes either were negative ground flashes or were positive ground flashes missed by the mapping system. However, because all ground flashes seen beneath the anvil east of the con-

b. Relationship between tornadoes and ground flashes

Relationships between the genesis, duration, and severity of tornadoes and the polarity and rate of ground flashes varied widely among the four supercell storms on 31 May 1990. We find this noteworthy because the storms all began in approximately the same region and had many similarities in their life histories. However, in addition to the differences in the relationship between tornadoes and ground flashes among the storms, there were significant differences in the severe weather and precipitation that the various storms produced.

Similar variability in the relationship between tornadoes and ground flashes has also been observed among previously documented storms. For example,
in two tornadic storms, ground flash rates were low before and during tornados (Orville et al. 1982; MacGorman et al. 1989). In four other tornadic storms, ground flash rates peaked while there were tornados, but there was usually a local minimum in ground flash rates when the tornados began (Kane 1991; MacGorman and Nielsen 1991; Keighton et al. 1991; Seimon 1993). In two other storms, tornados occurred after ground flash rates had begun to decrease from their peak, but before they had decreased to a local minimum (Kane 1991; MacGorman et al. 1985). Thirty-four of the 42 tornadoes produced on the four days studied by MacGorman and Burgess (1994) began when ground flash rates were either less than 0.5 min⁻¹ or near a local minimum value. During 7 of the 10 tornadoes that lasted at least 20 min, ground flash rates increased while the tornado was occurring.

On 31 May 1990 the majority of tornados (including all rated at least F2 on the Fujita scale) began near or during the time of a local minimum in the ground flash rate. It is noted, however, that the minimum flash rate at tornadogenesis in storm 3 occurred in a single 5-min period and that in the next 5-min period there was a maximum. This was also the only tornado lasting at least as long as 20 min on 31 May, and like most of the long-lived tornadoes observed by MacGorman and Burgess (1994), ground flash rates increased while this tornado was occurring.

Ground-flash activity in two of the storms on 31 May was dominated for 25–35 min by positive ground flashes, instead of the more commonly observed negative ground flashes. Such storms have been documented previously by Rust et al. (1985), Curran and Rust (1992), Branick and Doswell (1992), Seimon (1993), MacGorman and Burgess (1994), Stolzenburg (1994), and Knapp (1994). In a study of ground flashes in 264 tornadic storms nationwide during a 75-day period in 1991, Knapp (1994) noted that 204 of the tornadic storms produced at least 15 ground flashes, and in 62 of these 204 storms, at least 30% (an average of 56%) of ground flashes were positive.

On the six days studied collectively by Curran and Rust (1992), Branick and Doswell (1992), Seimon (1993), and MacGorman and Burgess (1994), ground flash activity in every tornadic storm whose characteristics were mainly those of low-precipitation supercells was dominated by positive ground flashes (i.e., at least 50% of the ground flashes were positive); ground flash activity in every storm whose characteristics were mainly those of high-precipitation supercells was dominated by negative ground flashes. (More recently, positive ground flashes have dominated ground flash activity in two high-precipitation supercell storms, although these have yet to be documented in the refereed literature.) On 31 May 1990, in contrast, storm 2 was clearly a low-precipitation supercell and yet produced only negative ground flashes. Furthermore, the storms dominated by positive ground flashes produced much heavier precipitation than storm 2. (Storm intercept crews drove through torrential downpours of rain and hail after dark.) Thus, while there appears to be a tendency for ground flash activity in low-precipitation supercell storms to be dominated by positive ground flashes and in heavy precipitation supercell storms to be dominated by negative ground flashes, there are exceptions to this tendency.

c. Relationship between hail and ground flashes

MacGorman and Burgess (1994) and Stolzenburg (1994) also noted that storms having predominantly positive ground flash activity for at least 30 min tended to produce large hail during the period when positive ground flashes were being produced. Although large hail also is produced by storms with predominantly negative ground flash activity, it is produced in only a small percentage of such storms, but appears to be produced in a large percentage of storms with predominantly positive ground flash activity. Furthermore, in storms with predominantly positive ground flash activity, both the frequency and maximum diameter of large hail reports typically has decreased within 30 min of a subsequent switch to predominantly negative ground flash activity. A similar association between predominantly positive ground flash activity and large hail has been noted anecdotally by several operational forecasters (K. Crawford 1995, personal communication) in storms on the Great Plains.

Large hail was reported in storm 3 when positive ground flash activity was dominant, and within 30 min of a switch to domination by negative ground flashes in storm 4; both of these observations are consistent with the observations of MacGorman and Burgess (1994). However, no large hail was reported in storm 4 when positive ground flashes were dominant or during the subsequent lull in ground flash activity. Because storm 4 occurred after dark and in a sparsely populated region, it is quite possible that large hail occurred during this period without being detected. However, it is also possible that this storm provides an exception to the previously reported tendency.

d. Relationship between time of tornados and ground flash frequency

The timing of tornados relative to predominantly positive ground flash activity in these two storms was similar to the timing observed in MacGorman and Burgess (1994). In their study of 15 storms, they reported that the most violent tornado produced by a storm always occurred after the maximum positive ground flash rate, whenever the maximum was at least 1.5 flashes per minute (computed from 5-min flash counts, as in the present study). However, when the maximum positive ground flash rate was less than 1.5 min⁻¹ the most violent tornado sometimes occurred before the maxi-
Fig. 10. As in Fig. 8 but during storm 3 for (a) 2000–2015, (b) 2015–2030, (c) 2030–2045, (d) 2045–2100, (e) 2100–2115, (f) 2115–2130, (g) 2130–2145, and (h) 2145–2200 CDT 31 May 1990.
Cloud-to-Ground Lightning Locations
Date: 53190

(e) 2100 - 2115 CDT

(f) 2115 - 2130 CDT

(g) 2130 - 2145 CDT

(h) 2145 - 2200 CDT

Fig. 10. (Continued)
Fig. 11. As in Fig. 8 but during storm 4 for (a) 2200–2215, (b) 2215–2230, (c) 2230–2245, (d) 2245–2300, (e) 2300–2315, (f) 2315–2330, (g) 2330–2345, and (h) 2345–0000 CDT 31 May 1990.
(e) Cloud-to-Ground Lightning Locations
Date.... 53190  **2300 - 2315 CDT**

![Graph](image)

(f) Cloud-to-Ground Lightning Locations
Date.... 53190  **2315 - 2330 CDT**

![Graph](image)

(g) Cloud-to-Ground Lightning Locations
Date.... 53190  **2330 - 2345 CDT**

![Graph](image)

(h) Cloud-to-Ground Lightning Locations
Date.... 53190  **2345 - 0000 CDT**

![Graph](image)

**Fig. 11. (Continued)**

Total Flashes.... 66 Negative.... 61

Total Flashes.... 29 Negative.... 1

Total Flashes.... 8 Positive.... 8

Total Flashes.... 20 Positive.... 8
mum positive ground flash rate, as in storm 3. Unlike storm 3, storm 4 exhibited what has appeared in several storms to be the most distinctive positive ground flash signature: a large increase in positive ground flash rates followed by a rapid decrease to a rate close to 0 min$^{-1}$. In all such cases observed thus far (e.g., tornadic storms in Plainfield, Illinois, on 28 August 1990 and in Wichita, Kansas, and Red Rock, Oklahoma, on 26 April 1991), if the storm produced a tornado, its most violent tornado began during the lull in ground flash activity following the large peak in the positive ground flash rate. In several of these cases, as in storm 4, the dominant ground flash polarity subsequently switched to negative; all such polarity reversals occurred when ground flash rates increased again after the most violent tornado touched down during the lull in ground flash activity.

e. Relationship between precipitation and polarity

A significant aspect of the storms on 31 May 1990 was the transition of the area and amount of precipitation and the dominant polarity of ground flashes around sunset. Before sunset, much of the precipitation had been in the form of hail and some rain, but had been relatively limited in spatial extent. After dark, the relative amount and areal extent of rain appeared to increase. Before dark, all ground flashes detected in supercell storms 1 and 2 were negative ground flashes. Beginning near sunset, ground flash activity was dominated by positive ground flashes during some periods of 30–45 min in supercell storms 3 and 4.

The increase in precipitation after dark on 31 May 1990 is similar to what was observed in some cases by MacGorman and Burgess (1994). However, increases in precipitation also occurred at other times of day in this earlier study, and the change in the dominant polarity of ground flashes that tended to accompany the change in precipitation was in the opposite direction from what was observed on 31 May 1990. In the cases studied by MacGorman and Burgess, the dominant polarity tended to be positive earlier in the day, when precipitation was less, and negative later, when precipitation was greater. Because of persistent regional patterns in the dominant polarity on each storm day, MacGorman and Burgess (1994) suggested that regional differences in the air mass in which the storms occurred affected the polarity of ground flashes.

It is not yet clear what aspects of the environment of storms affect ground flash polarity. In fact, our observations of storms on 31 May 1990 appear confusing in this regard, when considered with other studies. However, it is still quite possible that changes in the air mass were responsible on 31 May 1990, too, since obvious changes occurred after dark in the region in which the storms occurred. For example, boundary layer temperature decreased and boundary layer moisture increased when winds in the boundary layer backed as the dryline retreated westward after dark. Model simulation experiments may be needed to clarify relationships between the environment of storms and ground flash polarity.

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