Characteristics of Cloud-to-Ground Lightning Associated with Violent Tornadoes

ANTONY H. PEREZ, LOUIS J. WICKER, AND RICHARD E. ORVILLE

Cooperative Institute for Applied Meteorological Studies and Department of Meteorology, Texas A&M University, College Station, Texas

(Manuscript received 13 February 1996, in final form 2 May 1997)

ABSTRACT

Cloud-to-ground (CG) lightning patterns were analyzed in 42 violent tornado-producing (F4, F5) supercells that occurred between January 1989 and November 1992. The purpose of this analysis was to identify potential correlations between CG lightning patterns and tornadogenesis. Lightning characteristics were analyzed for a 30-min period before, during, and 30 min after each tornado's lifetime. Thirty-one of the storms were characterized by a peak in CG flash rate preceding tornado formation; 20 storms displayed a decrease in CG flash activity coincident with tornado touchdown. Six of the 42 storms exhibited a polarity reversal, from positive to negative, in the sign of the charge lowered to ground. Storms exhibiting a majority of positive flashes were generally associated with long-track tornadoes, F5 damage ratings, or severe weather outbreak conditions. The total number of flashes associated with each storm had no correlation with tornadogenesis (total number of flashes ranged from 16 to 3394).

Based on this analysis, it appears that using CG lightning flash patterns exclusively to detect tornado formation is not practical. The amplitudes of the flash rate changes are too variable to be used as a prognostic tool. The flash rate trends do, however, suggest a recurring relationship to tornado formation. Therefore when used in conjunction with other operational tools, CG flash rate analysis may provide additional information useful in identifying changes in thunderstorm intensity.

1. Introduction

Recent observations by Kane (1991), Seimon (1993), and Knapp (1994) suggest that the use of cloud-to-ground (CG) data from the National Lightning Detection Network (NLDN) in the United States (e.g., Orville 1991, 1994) may be used to assist in identifying tornadogenesis. Kane describes the CG lightning characteristics associated with two tornadic supercells and observes a peak in the CG flash rate 10–15 min prior to tornado touchdown. Seimon describes an anomalous polarity reversal in the CG lightning associated with the Plainfield, Illinois, tornado on 28 August 1990. The polarity of the charge lowered to ground by lightning switched from positive (positive lightning) to negative (negative lightning) near the time of the tornado touchdown. Knapp (1994) studied CG flash rate trends in 264 tornadic thunderstorms and found a pulsing tendency in the number of flashes prior to tornado formation. Furthermore, Knapp described a nowcasting technique used to predict dangerous storms. The results of Kane and Seimon, although only for three storms, suggest that the electrical and dynamic properties of thunderstorms may be related. At the very least, their results deserve further examination to determine if any relationships exist and what they may be. Using a methodology similar to Kane, this study analyzes a large sample of tornado-producing storms to determine in a broader setting the overall nature of these relationships.

The study of lightning and tornadoes has a long history going back at least four decades or more. This research includes the electromagnetic wave studies of Jones (1951), Dickson and McConahy (1956), Kohl (1962), and Kohl and Miller (1963). They conclude that there is evidence that intracloud (IC) lightning occurs more frequently in tornadic thunderstorms than in nontornadic storms. Visual observations by Davies-Jones and Golden (1975) found little electrical activity in an area near the tornado vortex itself but noted significant lightning activity in adjacent rain shafts in several storms. More recently, MacGorman and Nielsen (1991) conclude that the CG lightning flash rate is not related to tornadogenesis but found possible correlations between IC flashes and mesocyclone development. These studies suggest that electrical activity plays a varying role in tornadic thunderstorms. Although CG flash activity may not be directly related to tornadoes themselves, flash trends may be a reflection of the larger dynamical–microphysical processes that make up the larger tornadic thunderstorm.

Many results published to date concentrate on the

Current affiliation: National Weather Service Office, Flagstaff, Arizona.

Corresponding author address: Dr. Richard E. Orville, CIAMS, Dept. of Meteorology, Texas A&M University, College Station, TX 77843-3150.
E-mail: rorville@tamu.edu

analysis of single storms (Kane 1991; Seimon 1993) and leave open the question of whether the results can be applied in general to severe tornadic storms. To this end, Knapp (1994) observes a peak–lull–peak flash rate pulsating trend within an hour before tornado report time. This pulsing trend is more pronounced in storms dominated by positive flashes, with the most significant amplitudes approximately 20 min before tornado report time. Furthermore, storms dominated by negative flashes show an increase in positive flash polarity immediately after tornado occurrence. In a similar approach, we analyzed 42 violent tornadic thunderstorms, reported to reach the F4 and F5 class on the Fujita damage scale (Fujita 1981), that occurred between January 1989 and November 1992. Tornadoes of this magnitude are associated with wind speeds greater than 332 km h^{-1} and are almost always associated with intense, long-lived supercell storms.

The strong, continuously evolving, and long-lived updrafts and downdrafts associated with violent tornadic thunderstorms helped to facilitate the process of identifying which lightning flashes corresponded to the thunderstorm in question. An analysis of CG flash locations over time resulted in an identifiable collective of CG flashes that were isolated from surrounding clusters. Since tornadic and nontornadic thunderstorms are often both present, it is increasingly difficult to correlate flash locations with shorter-lived, weaker tornadic storms (Kane 1991). Therefore, our study focused exclusively on supercell storms in which violent tornadoes were reported by *Storm Data.*

2. Data and analysis methods

Data for this research were acquired from the National Severe Storms Forecast Center [NSSFC, now the Storm Prediction Center (SPC)] database and the NLDN archive maintained at Texas A&M University in cooperation with Global Atmospherics, Inc., Tucson, Arizona (formerly GeoMet Data Services, Inc.). Tornado times and locations were originally obtained from the former source and CG lightning flash locations were obtained from the latter. The tornado reports were confirmed by publication in *Storm Data.*

a. Tornado times and locations

The NSSFC database contains entries for 48 F4 and F5 tornadoes that occurred between January 1989 and November 1992. Six of these reports could not be confirmed with *Storm Data,* perhaps due to typographic or interpretation errors, and were omitted from our analysis. The report times for weather in this archive have a nominal time error of ±15 min. The database is an archive of severe weather events reported since 1954 and is updated continually [Hart (1993); this data is available on the SPC Web site at http://www.nssl.noaa.gov/~spc/archive/tornadoes/index.html]. Since lightning detection equipment first became operational across the contiguous United States in 1989 (Orville 1991), we chose this as the first year to collect tornado reports. Each tornado report in the NSSFC database is listed in a ‘‘segment’’ format in which the tornado path is divided into sections corresponding to different storm locations. Each entry, or segment, includes the date, start time, end point coordinates, mean path width, pathlength, F-scale rating and other nonmeteorological information. Since individual entries contain only the beginning time of a segment, the dissipation time, or the end time of the final segment of a tornado track, must be determined from another source. By comparing each tornado occurrence with its respective entry in *Storm Data,* an end time for the final segment was obtained. Table 1 contains the reported touchdown locations and the dates and times of the 42 tornadoes used in this investigation. Several tornado reports each presented a unique set of problems in conducting the analyses. Most common and problematic were those events in which one thunderstorm produced multiple tornadoes or events in which several tornadoes occurred in close proximity to one another. Since the objective of this research was to identify overall lightning trends associated with a large sample of tornadic thunderstorms, individual case study analyses were not performed and were beyond the scope of the intended research.

Multiple events presented unique challenges in the analysis. For example, the Hesston tornado event (case 12) actually consisted of two separate tornadoes that merged into one. The first tornado reached F5 intensity and moved through Hesston, Kansas, around 1700 UTC. Around this time, a second tornado formed approximately 1 mi to the north and paralleled the first tornado. The two tornadoes merged at around 1703 UTC and a more destructive F5 tornado devastated the town of Goessel, Kansas. Although two separate tornadoes are reported in *Storm Data,* they were analyzed together since it was difficult to separate the individual tornadic events from each other. A different set of problems emerged in analyzing cases 34 and 35. These two tornadoes not only occurred in close proximity to one another but their report times overlapped from 1618 to 1625 UTC.

b. Lightning data

Lightning flashes associated with the 42 supercells were analyzed using data from the NLDN. A network of over 100 direction finders recorded CG lightning flashes during the period of the tornado occurrences from January 1989 to November 1992 (Orville 1994). The principles of the network have been previously described (e.g., Mach et al. 1986; Orville et al. 1987; Orville 1991) and will not be discussed here. The CG lightning flash data include the time of the flash, the location, peak signal strength, polarity of charge lowered to ground, and the multiplicity (number of strokes

TABLE 1. Violent tornado occurrences between January 1989 and November 1992.

Case	County/town	State	Date	Time of tornado* (LST)	Time of tornado* (UTC)
1	Wabash/Allendale	IL	7 January 1989	1719–1748 CST	2319–2348
2	Spartanburg/Chesnee	SC	5 May 1989	1720–1735 EST	2220–2235
3	Cleveland/Lawndale	NC	5 May 1989	1754–1821 EST	2254–2321
4	Union/Monroe	NC	5 May 1989	1901–1918 EST	0001–0018
5	Kinney/Bracketville	TX	16 May 1989	2308–2330 CST	0508–0530
6	Adams/Corning	IA	24 May 1989	1711–1854 CST	2311–0054
7	Hamilton/Stratford	IA	24 May 1989	1720–1922 CST	2320–0122
8	Hardin/New Providence	IA	31 May 1989	1850–1920 CST	0050–0120
9	Montgomery/Ames	NY	10 July 1989	1327–1355 EST	1827–1855
10	New Haven/Hamden	CT	10 July 1989	1630–1640 EST	2130–2240
11	Madison/Huntsville	AL	15 November 1989	1630–1650 CST	2230–2250
12**	Harvey/Hesston	KS	13 March 1990	1634–1730 CST	2234–2330
13	Linn/Prairieburg	IA	13 March 1990	1653–1725 CST	2253–2325
14	Webster/Red Cloud	NE	13 March 1990	1705–2010 CST	2305–0210
15	Parker/Weatherford	TX	25 April 1990	1544–1603 CST	2144–2203
16	Pecos/Iraan	TX	1 June 1990	1620–1730 CST	2220–2330
17	Wayne/Rinard	IL	2 June 1990	1645–1722 CST	2245–2322
18	Jasper/Newton	IL	2 June 1990	1707–1720 CST	2307–2320
19	Hamilton/Aden	IL	2 June 1990	1720–1945 CST	2320–0145
20	Lawrence/Bryantsville	IN	2 June 1990	1950–2015 EST	0050–0115
21	Jackson/Clear Spring	IN	2 June 1990	2020–2045 EST	0120–0145
22	Dearborn/Bright	IN	2 June 1990	2200–2305 EST	0300–0405
23	Hitchcock/Statton	NE	15 June 1990	1800–1845 CST	0000–0045
24**	Kendall/Oswego	IL	28 August 1990	1415–1450 CST	2015–2050
25	Reno/Hutchinson	KS	26 March 1991	1845–1920 CST	0045–0120
26**	Butler/Andover	KS	26 April 1991	1657–1810 CST	2257–0010
27	Osage/Garber	OK	26 April 1991	1730–1855 CST	2330–0055
28	Pawnee/Skiatook	OK	26 April 1991	1910–2027 CST	0110–0227
29	Rogers/Oologah	OK	26 April 1991	2045–2053 CST	0245–0253
30	Christian/Nixa	MO	29 November 1991	1805–1825 CST	0005–0025
31	Sharkey/Panther Burn	MS	9 March 1992	2140–2215 CST	0340–0415
32	Pittsburg/Kiowa	OK	11 May 1992	1500–1525 CST	2100–2125
33	Mitchell/Tipton	KS	15 June 1992	1830–1838 CST	0030–0035
34**	Nobles/Leota	MN	16 June 1992	1600–1625 CST	2200–2225
35	Murray/Wilson	MN	16 June 1992	1618–1625 CST	2218–2225
36	Hutchinson/Four Way	TX	27 June 1992	1831–1930 CST	0031–0130
37	Copiah/Hopewell	MS	21 November 1992	2327–0201 CST	0527–0801
38	Harris/Chennelview	TX	21 November 1992	1527–1606 CST	2127–2206
39	Smith/Mize	MS	22 November 1992	0014–0114 CST	0614–0714
40	Cobb/Powder Springs	GA	22 November 1992	1144–1234 EST	1644–1734
41	Putnam/Eatonton	GA	22 November 1992	1645–1720 EST	2145–2220
42	Carroll/Worthville	KY	22 November 1992	1652–1750 EST	2152–2250

* Tornado touchdown and dissipation according to *Storm Data.*
** F5 tornado on the Fujita (1981) scale. All other tornadoes in this list were F4.

in each flash). During the period of data collection, the NLDN had an estimated detection efficiency of 70% (Orville 1994). The primary sources of error in the NLDN data are changes in terrain and man-made structures that interfere with the detected signals. Direction finder spacing, network configuration, and flash position within the network also affect flash detection accuracy. During the time our data was collected, the average location accuracy for the NLDN configuration was between 2 and 4 km (Holle and Lopez 1993).

c. Lightning analysis method

The lightning flash locations were superimposed upon the tornado path to reconstruct the CG lightning distribution near the tornado environment. The flash selection process was performed in two steps. The coordinates of the tornado track were used as reference points to begin an objective flash selection process in the larger domain. First an outer boundary was defined around the tornado path with a spatial extent of 100 km in the four cardinal directions. Since 100 km is large enough to track the features associated with long-lived supercells, the lightning flashes detected within this region were retained for further selection and analysis. Second, clusters of lightning were separated from each other by subjectively determining which flashes corresponded to individual thunderstorm cells by examining graphically the horizontal distribution of CG lightning. The flash locations of each case were plotted, both spatially and temporally, and those flashes that appeared as outliers from the storm in question were discarded. To aid in discrimi-

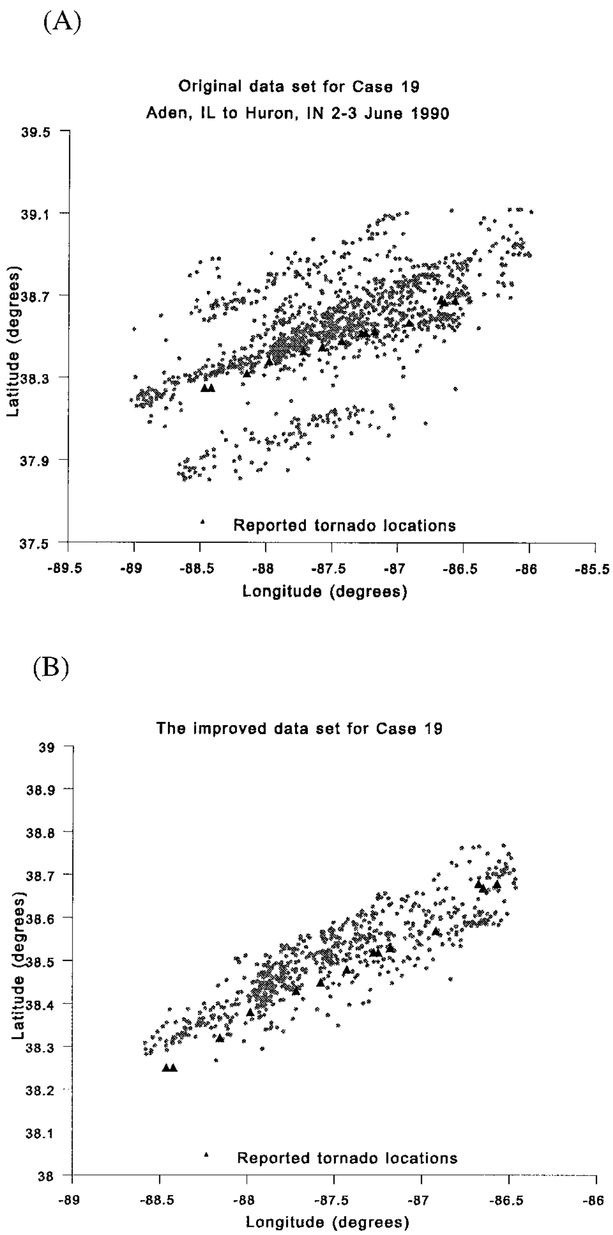


FIG. 1. Result of two-step lightning flash selection method. (a) Flashes associated with multiple storm cells. (b) Improved dataset after subjectively removing flashes associated with other thunderstorm cells.

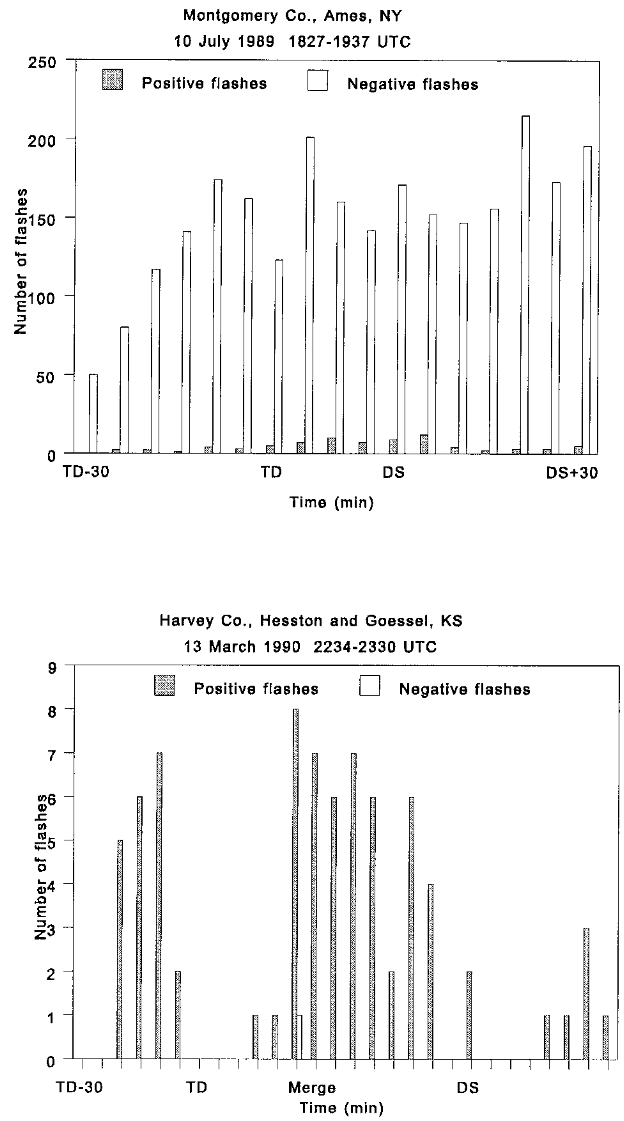


FIG. 2. Examples of two storms showing a peak CG flash rate several minutes before tornado touchdown. Bars represent the number of flashes detected during 5-min intervals; TD represents the time of tornado touchdown; DS the time of dissipation. (a) Peak flash rate 5–10 min before touchdown. (b) Peak rate in positive flashes 10–15 min before touchdown in the Hesston, KS, tornadic supercell. Two tornadoes merged at the time indicated in the figure. The merger was accompanied by an increase in the CG flash rate.

nating between thunderstorms, the National Weather Service Radar Summary charts were used to identify different cells by noting the storm echo boundaries; however, the marginal time and spatial resolution of these maps limited their usefulness. Properly identifying which flashes corresponded to particular convective cells was, and continues to be, one of the greater and time-consuming challenges in lightning research. As noted by Kane (1991), the lightning associated with dissipation and intensification of other cells masks the true relationship between flash frequency and a severe storm. Knapp (1994) analyzed lightning in his large sample by similarly separating CG flashes from surrounding cells subjectively. The difficulty in assigning flash locations grows smaller with the operational network of WSR-88D radars and the archived digital data.

The lightning flashes composing our final sample were plotted and coded with respect to the tornadic phase of each storm: before touchdown, during the tornado, and after dissipation. Figure 1a shows the lightning associated with the Hamilton County, Illinois, thunderstorm of 2 June 1990. Figure 1b shows the resulting cluster of flashes after subjectively isolating and removing surrounding flashes. The tornado track is indicated by the triangle symbols (▲). Each of the resulting lightning datasets was examined for flash rate trends, polarity signatures, and the total storm CG lightning flash rate.

The NLDN data were analyzed in 5-min intervals for each tornado to examine temporal CG flash signatures. Ten and fifteen-minute intervals were also tested but did not adequately resolve flash rate changes. Cloud-to-ground flash data were collected and analyzed during an observation period beginning 30 min before touchdown and ending 30 min after the reported dissipation time. Using this procedure, the following features were identified: 1) a peak in the CG flash rate preceding tornado formation, 2) a local minimum in CG flash rate corresponding to tornado touchdown, and 3) the overall peak flash rate with respect to each tornado occurrence. Several cases revealed interesting polarity characteristics such as lowering predominantly positive charge to ground for the duration of the observation period or switching the predominant polarity during the observation period.

TABLE 2. Tornado pathlength and flash characteristics for all cases. The average flash rate in column 4 was computed by dividing the total number of flashes detected by the storm observation period.

Case no.	Pathlength (km)	Total no. of flashes	Average flash rate (flashes min^{-1})	Positive polarity (percent)
1	35	133	1.5	3.0
2	24	17	0.2	17.7
3	22	16	0.2	31.3
4	21	180	2.3	1.7
5	27	40	0.5	0
6	79	297	1.8	23.6
7	106	463	2.5	16.4
8	18	388	4.3	0
9	68	3394	26.1	3.2
10	5	3258	54.3	2.6
11	30	572	7.2	3.2
12	112	77	0.8	98.7
13	30	124	1.0	10.5
14	198	176	0.7	83.5
15	16	153	1.9	7.2
16	35	755	5.8	0.7
17	37	173	1.8	7.5
18	20	735	10.1	5.7
19	170	604	3.0	2.2
20	18	188	2.2	2.1
21	29	106	0.7	3.8
22	53	292	2.3	2.7
23	45	126	1.2	88.1
24	26	1026	6.4	23.4
25	21	180	1.9	93.3
26	74	259	2.0	69.9
27	106	462	3.2	24.0
28	51	764	5.6	0.9
29	6	518	7.6	1.4
30	16	178	2.2	36.5
31	32	347	3.7	9.5
32	16	366	4.3	4.1
33	5	594	9.1	1.4
34	26	41	0.4	91.1
35	11	28	0.4	92.9
36	32	446	3.8	1.4
37	206	1017	4.8	9.0
38	32	560	5.7	4.8
39	64	1205	10.0	5.2
40	41	71	0.7	25.4
41	51	133	1.4	20.3
42	43	435	3.7	1.2
Mean	49	498	5	22
Std dev	47	696	9	31

3. Results

a. Tornado track characteristics

All tornadoes used in this study were rated F4 or F5 on the Fujita damage scale (Fujita 1981). The track lengths (Table 2) varied from 5 km (cases 10 and 33) to 206 km (case 37). The mean track length was 49 km with a standard deviation of 47 km. The geographic distribution of these tornadic events resulted in two-thirds of the supercells located in the Great Plains and the Midwest. The remaining supercells were located throughout the Southeast except for two tornado reports in New York and Connecticut. It was reassuring that this distribution resembled the climatological distribution of violent thunderstorms that occurred between 1950 and 1976 (Kelley et al. 1978).

b. Lightning characteristics

The CG lightning flashes associated with each storm were analyzed for flash rate, percent positive polarity, flash rate tendencies, and significant polarity changes during the storm observation period. The results are summarized in Tables 2 and 3.

Table 2 contains the total number of flashes, average flash rate, and the percentage of flashes in the storm that lowered positive charge to ground (positive flashes). To compute the average flash rate for each tornado, the total number of CG flashes recorded during the storm observation period is divided by the tornado report time, found in Table 1, plus 30 min before touchdown and after dissipation. Table 2, column 4, shows the average flash rate varied from less than one flash per minute (e.g., cases 2, 3, 5, 12, 14, 21, 34, 35, and 40) to 54 per minute (case 10). The mean rate is 5 flashes min^{-1} with a standard deviation of 9. The percentage of positive flashes, column 5, is seen to vary from 0% (cases 5 and 8) to 98.7% (case 12) with a mean rate of 22%. Seven storms were characterized as predominantly positive since over 50% of the CG flashes in these storms lowered positive charge to ground.

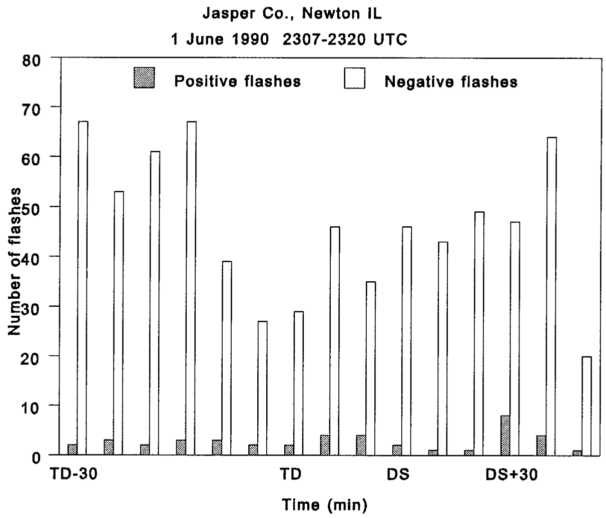
Table 3 summarizes the flash rate tendencies and the observations of polarity shifts, if they occurred in the storm. A local peak flash rate before tornado touchdown (column 2) was detected in 31 cases. The average lag time between the local peak flash rate and tornado touchdown was 17 min with a standard deviation of 7 min. This is comparable to Kane's (1991) observation. Figure

TABLE 3. Lightning characteristics associated with tornado-producing storms.

Tornado no.	Local peak flash rate before tornado touchdown	Local min flash rate coincident with tornado touchdown	Overall peak flash rate relative to tornado lifetime	Polarity shift
1			Before	
2	x	x	Before	
3			Before	
4			Before	
5			After	
6			After	Postive to negative
7			After	Postive to negative
8	x		During	
9	x	x	During	
10	x		Before	
11	x		After	
12	x	x	During	
13			Before	
14			After	
15	x	x	Before	
16	x	x	During	
17	x	x	During	
18	x	x	Before	
19	x	x	During	
20	x		Before	
21	x		During	
22	x	x	Before	
23	x	x	After	
24	x	x	After	Positive to negative
25	x	x	Before	
26	x		Before	Positive to negative
27	x		After	Positive to negative
28		x	During	
29	x	x	Before	
30	x		Before	
31		x	Before	
32	x	x	After	
33	x		After	
34	x		Before	
35			Before	
36	x		During	
37	x	x	During	
38	x		During	
39	x	x	After	
40	x	x	During	Positive to negative
41	x		During	
42	x	x	During	

2 shows examples of this trend in two storms. Figure 2a shows the CG flash rate trends for an F4 tornadic storm in Ames, New York, on 10 July 1989. The tornado was on the ground from 1827 to 1855 UTC. The bars in each graph represent the number of flashes for a 5-min interval for both positive and negative flashes. In this event, there was a peak CG flash rate (34 flashes min^{-1}) about 10 min before tornado touchdown (TD in the figures). After the tornado formed, the CG flash rate assumed a pulsing tendency, reaching a minimum of 24 flashes min^{-1} and a maximum of 48 flashes min^{-1}. After the tornado dissipated (DS in the figures), the CG flashes continued with varying frequency. Figure 2b shows a similar trend in CG activity, but for positive flashes, associated with two tornadoes reaching F5 intensity which moved through Hesston and Goessel, Kansas, on 13 March 1990. These tornadoes were on the ground from 2234 to 2330 UTC and merged near Hesston around 2300 UTC. The CG flashes associated with this storm reached a local peak flash rate 10–15 min before the first tornado touched down. Flash activity ceased for approximately 10 min during the early stages of the first tornado's lifetime. The CG flashes were predominantly positive throughout the observation period. It is interesting that the flash rate increased significantly around the time the second tornado formed and merged with the first. The CG flash rate decreased significantly after the Goessel tornado dissipated.

In Table 3, column 3, 20 supercells were identified with a local minimum CG flash rate that was coincident with tornado touchdown. Implicit in this column is the information that 22 tornadic supercells did not have a



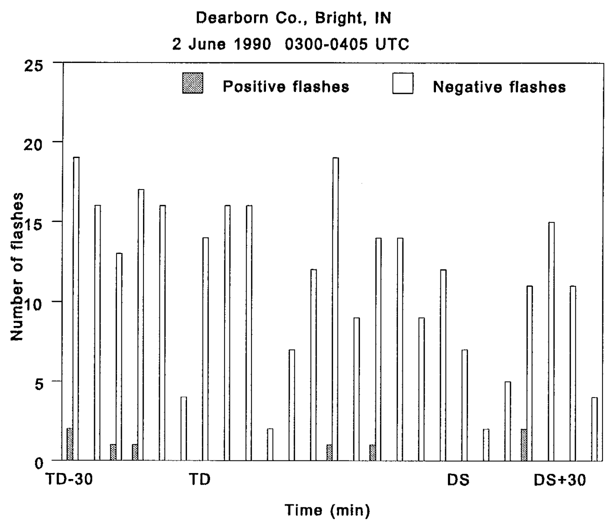


FIG. 3. Same as in Fig. 2 except for cases showing a decrease in CG flashes coincident with the 5-min interval during tornado touchdown. (a) Decrease in CG activity from a maximum over 13 flashes min^{-1} several minutes before touchdown to around 6 flashes min^{-1} at the time of touchdown. (b) A more dramatic example of this trend, with the average flash rate near 3 flashes min^{-1} several minutes before touchdown, then decreasing to less than 1 flash min^{-1} near tornado touchdown.

local minimum flash rate at the time of touchdown. Figure 3 shows two examples of this trend. Figure 3a shows the CG flash rate associated with an F4 tornado in Newton, Illinois, on 2 June 1990. This tornado was on the ground from 2307 to 2320 UTC. The CG flashes in this example displayed a significant decrease in lightning activity within 5 min around the time the tornado formed. The average flash rate reached a peak of approximately 13 flashes min^{-1} 10–15 min before touchdown. At touchdown, the average flash rate decreased to less than 6 flashes min^{-1}. During the tornado, both positive and negative flashes increased, then decreased, and the pulsing trend continued after the tornado dissipated. Figure 3b shows a similar minimum flash rate near the time of touchdown for an F4 tornado in Bright, Indiana, on 2 June 1990. This tornado was on the ground from 0300 to 0405 UTC. Five to ten minutes before touchdown, the average CG flash rate was over 3 flashes min^{-1}. During touchdown, the flash rate dropped to about 0.8 flashes min^{-1}. Within 5 min after this time, the flash rate increased again to approximately 2.6 flashes min^{-1}. During the remainder of the tornado and after dissipation, the flash rate fluctuated and only four positive flashes were detected during the same time period. Thirteen additional storms produced a detectable minimum flash rate within 10 min of touchdown, but not during the 5-min interval corresponding to the reported touchdown time. These events were not as clearly associated with tornado touchdown but were indicative of a potential correlation given the time errors possibly associated with the tornado report times. The events in this category included cases 4, 8, 13, 14, 20 21, 26, 27, 30, 33, 34, 36, and 38. These cases are not shown in Table 3 as having a local minimum flash rate coincident with tornado touchdown but indicated a lesser flash frequency within 10 min of the reported tornado formation. Thus, over 75% of the storms analyzed produced a minimum CG flash rate within 10 min of reported tornado touchdown, but only the 50% indicated in Table 3 were clearly coincident with touchdown.

In Table 3, column 4, it is clear the overall peak flash rate relative to the tornado lifetime has no predictable tendency. The maximum flash rate occurred before, during, or after the tornado lifetime with almost equal probability—with 17, 14, and 11 cases, respectively.

The last column in Table 3 shows which storms displayed a polarity shift in the dominant sign of the charge lowered to ground by lightning. Note that six of the supercells had a polarity shift; the remaining 36 did not. In all six cases, the polarity shift was from positive to negative CG flashes. Case 24, studied in detail by Seimon (1993), is included in this list. Figure 4 shows two examples of the CG flash rate trends in this type of case. Figure 4a is associated, with an F4 tornado, which occurred in Corning, Iowa on 24–25 May 1989. The tornado was on the ground from 2311 to 0054 UTC. Predominantly positive flashes characterized this storm with the greatest number of flashes near the time of touchdown. Within 5–10 min after the tornado dissipated, the frequency of negative flashes significantly increased and was the predominant charge lowered to ground. In this event, the number of negative flashes immediately after tornado dissipation increased to two to three times that of the positive flashes before and during the tornado's lifetime. Ten minutes after tornado dissipation, the frequency of negative flashes steadily decreased. Figure 4b shows another example of CG flashes switching the predominant sign of charge lowered to ground. Unlike the example in Fig. 4a, this case, an F4 tornadic storm in Garber, Oklahoma, on 26 April

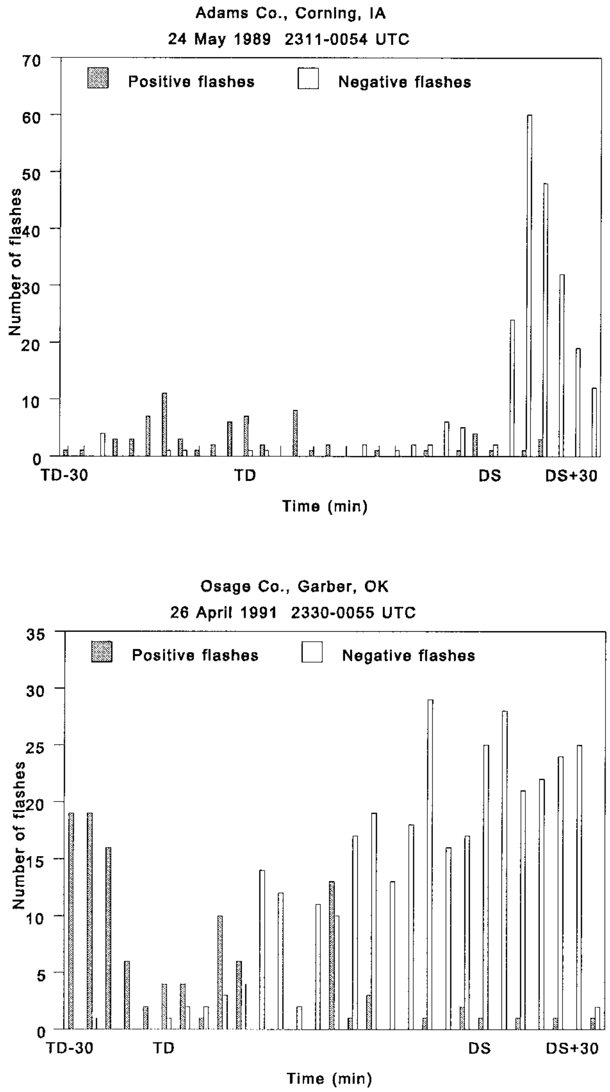


FIG. 4. Same as Fig. 2 except for cases showing a positive to negative polarity reversal. (a) A few positive flashes preceding and during the tornado lifetime. Several minutes before the tornado dissipated, negative flashes began and significantly increased after dissipation. (b) A decrease in positive flashes until the tornado touched down. After the tornado formed, negative flashes began and became predominant during the tornado's lifetime. After dissipation, negative flashes dominated and at a higher average rate than the previous positive CG flashes.

1991, produced a higher flash rate during tornadic stage. This tornado was on the ground from 2330 to 0055 UTC. The number of positive flashes decreased, from approximately 3.8 flashes min^{-1} to 0.4 flashes min^{-1}, until 10 min before touchdown, then fluctuated for 15 min into the tornado lifetime. Near the time of touchdown, the number of negative flashes gradually increased, with some fluctuation, and became the predominant sign of charge lowered to ground about halfway through the tornado's lifetime. As in Fig. 4a, the number of negative flashes during this period was higher than the number of positive flashes, which was the dominant polarity prior to and during the tornado.

4. Discussion

Sferics research indicates that lightning activity increases prior to tornado formation (e.g., Jones 1951; Kohl and Miller 1963). Generally, these sferics signals were of higher frequencies and indicative of IC flash processes. In a more contemporary study, Kane (1991) noted similar decreases in the CG lightning flash rate. He found the lag time between the local peak flash rate and tornado formation to be 10–15 min. The analysis here showed that 31 of the 42 tornadic storms had a similar pattern and the average lag time for these cases was 17 min. Following this peak, there is a general decrease in the CG activity until the tornado touched down.

A possible explanation for this behavior may be hypothesized from our current understanding of updraft dynamics associated with tornadogenesis. Wicker and Wilhelmson (1995) show that in a simulated tornadic supercell tornado formation is preceded by significant increases in updraft intensity in the low to midlevels of the storm. Updraft intensification is also noted in radar observations of tornadic supercells. Doppler radar analyses of the Del City tornado (Johnson et al. 1987) indicate significant increases in the storm's low-level updraft several minutes prior to tornado formation. Both simulation and observational results are consistent with cloud processes inferred from sferics research results. MacGorman et al. (1989) hypothesize that lightning discharges are related to microphysical interactions associated with relative vertical velocities in thunderstorms. This suggests that as upward vertical velocity increases, IC flash production may be enhanced. The enhancement may come about by elevating the regions of electrical potential associated with flash production. In this event, IC flashes may occur more readily and with greater frequency than CG flashes.

Approximately half of the storms in this study were characterized by a decrease in the 5-min CG lightning flash rate coincident with tornado formation. Sferics research reveals a peak in detected signals of IC lightning near the time of tornado formation (Taylor 1973; Johnson et al. 1977; Brown and Hughes 1978). Other observational evidence from MacGorman et al. indicates that IC flashes generally continue, usually with a higher frequency, despite changes in the CG flash rate. Consequently, the decrease in CG flash rate observed in 22 storms may imply an increase in IC flashes or possibly an increase in the ratio of IC to CG flashes.

Mechanisms that potentially enhance IC lightning are found in Lemon and Doswell's (1979) conceptual model of supercell structure. They theorize that while reflectivity increases in the weak echo region (WER), as water and ice particles fill the volume otherwise occupied by strong updrafts, the center of the midlevel cyclone shifts from the WER to a location between the updraft and downdraft. Since F4 and F5 tornadoes are generally formed by the most intense vortices, it follows that the changes in microphysical processes along or near the updraft–downdraft interface can have a significant impact on the local electrical structure. That is, the IC flash rate may be enhanced by decreasing the distance between primary negative and positive charge regions in response to a changing or pulsed updraft. The CG flash rate tendency changes on the order of minutes, perhaps in response to the pulsing updraft. Since the center of the mesocyclone is positioned along the updraft–downdraft interface (Lemon and Doswell 1979), it is possible for either the updraft or the downdraft to dominate the vertical flow. An intensifying updraft, for example, may reduce CG flashes by raising negative charge centers (MacGorman et al. 1989), resulting in a decrease in the distance between the negative and positive charged regions in a thunderstorm.

Also noteworthy are those storms lowering positive charge to ground. Seven storms had a percent positive polarity greater than 50%. Observational studies show that supercells with similar lightning characteristics are often associated with high shear environments (Rust et al. 1985; Curran and Rust 1992), with increased storm severity (Rust et al. 1985; Reap and MacGorman 1989), or in environments ripe for severe weather (Knapp 1994). Six other storms showed a polarity reversal, in all cases the change was from positive to negative flashes. Seimon (1993) observes a polarity reversal coincident with the formation of an F5 tornado in Plainfield, Illinois (case 24 in this paper). He suggests that the observed polarity reversal may be related to tornado-producing dynamics. Doswell and Brooks (1993) caution that generalizations such as this may be premature for an individual storm as similar electrical changes are observed to coincide with different features in other storms. In any case, a polarity reversal must be associated with some microphysical or dynamical change within thunderstorms. The observations of polarity reversals in this study showed that in 36 of the F4 and F5 tornadoes there was no polarity change. MacGorman and Burgess (1994) note that large hail occurred in polarity switching storms when positive flashes dominated. This may also be true of storms with a majority of positive flashes. Knapp (1994) developed a nowcasting technique for identifying potential severe weather associated with positive flash thunderstorms and reports excellent severe weather detection accuracy with his method.

The overall peak CG lightning flash rate (Table 3, column 4) appears to have little correlation with the different stages of tornadogenesis (before, during, or after). Of the 42 storms in this study, the peak CG flash rate occurs before, during, and after tornadoes in 17, 14, and 11 cases, respectively. Many observations in the literature take note of the peak flash rate with respect to tornadic phase. In two tornadic storms, ground flash rates increase after the tornado dissipates (Orville et al. 1982; MacGorman et al. 1989). In three studies, ground flash rates peak during tornadoes (Kane 1991; MacGorman and Nielsen 1991; Keighton et al. 1991). It appears from our study and from previous work that the overall maximum CG flash rate offers no predictive value for tornadogenesis.

The total number of CG flashes in the 42 cases (Table 2, column 3) during the storm observation period showed a variation from 16 to 3394 flashes. Unfortunately, the total number of flashes, CG and IC, is unknown. Clearly, the overall CG flash rate is quite variable in these sample thunderstorms and unsatisfactory for the prediction or identification of a tornadic storm.

5. Conclusions

Cloud-to-ground lightning patterns were analyzed in 42 violent tornado-producing supercells that occurred between January 1989 and November 1992. There appeared to be a correlation within the supercells between CG lightning flash trends and tornadogenesis. Two different flash rate trends were found, one trend was a peak in the CG frequency 15–20 min prior to tornado formation, the other was a relative decrease in CG activity in conjunction with tornado touchdown. The total number of CG flashes 30 min before and after tornado occurrence offered little indication of tornado formation or dissipation. Similarly, as a singular diagnostic, the occurrence of a peak CG rate provided little predictive value for tornadogenesis in this sample of thunderstorms. There were, however, several cases in which storms displayed a polarity reversal or lowered mostly positive charge to ground that appear to merit further study. Six of the 42 storms reversed the predominate polarity of charge lowered to ground, from positive to negative. No storms were observed to shift from negative to positive. Seven thunderstorms lowered primarily positive charge to the earth's surface as indicated by a dominance of positive flashes over negative flashes.

Cloud-to-ground flash rate trends, when used in conjunction with other observational tools such as Doppler radar, may assist in determining changes in a storm's intensity and/or its potential for producing a tornado. As an exclusive monitoring tool, however, it seems unlikely that forecasters can identify in real time the relevant flash rate trend that may precede tornado formation. A local peak CG flash rate occurred in 31 storms (74%) and preceded tornado formation by an average of 17 min. A second trend occurred in 20 (48%) of the storms observed and consisted of a local minimum flash rate coincident with tornado formation. An additional 13 cases (31%) displayed a local minimum CG flash rate within 10 min of touchdown, but this trend was not as distinct as the previous 20 storms.

The results of our study suggest that CG flash rate trends may be associated with dynamical processes within severe thunderstorms. The next step in this study would be to identify and group storms by storm type and conduct similar analyses for thunderstorms associated with lesser intensity tornadoes, severe nontornadic storms, and nonsevere, nontornadic storms. This will provide a more comprehensive view of the relationships between the electrical, microphysical, and dynamical components within thunderstorms.

Acknowledgments. The lightning data used in this analysis were obtained from GeoMet Data Services, Inc. (now Global Atmospherics, Inc., Tucson, Arizona). The material in this paper is based on a master's thesis by A. Perez in partial fulfillment of the graduate degree requirements at Texas A&M University. This study is part of a lightning research program at Texas A&M University supported by the National Science Foundation through Grants ATM-9213787 and ATM-9318994 and by the National Oceanic and Atmospheric Administration through Contract NA37WA0543.

REFERENCES

Brown, R. A., and H. G. Hughes, 1978: Directional VLF sferics from the Union City, Oklahoma, tornadic storm. *J. Geophys. Res.,* **83,** 3571–3574.

Curran, E. B., and W. D. Rust, 1992: Positive ground flashes produced by low-precipitation thunderstorms in Oklahoma on 26 April 1984. *Mon. Wea. Rev.,* **120,** 544–552.

Davies-Jones, R. P., and J. H. Golden, 1975: On the relation of electrical activity to tornadoes. *J. Geophys. Res.,* **80,** 1614–1616.

Dickson, E. B., and R. J. McConahy, 1956: Sferics readings on windstorms and tornadoes. *Bull. Amer. Meteor. Soc.,* **37,** 410–412.

Doswell, C. A., and H. E. Brooks, 1993: Comments on ''Anomalous cloud-to-ground lightning in an F5-tornado-producing supercell thunderstorm on 28 August 1990.'' *Bull. Amer. Meteor. Soc.,* **74,** 2213–2218.

Fujita, T. T., 1981: Tornadoes and downbursts in the context of generalized planetary scales. *J. Atmos. Sci.,* **38,** 1511–1534.

Hart, J. A., 1993: SVRPLOT: A new method of accessing and manipulating the NSSFC Severe Weather Database. Preprints, *17th Conf. on Severe Local Storms,* St. Louis, MO, Amer. Meteor. Soc., 40–41.

Holle, R. L., and R. E. Lopez, 1993: Overview of real-time lightning detection systems and their meteorological uses. NOAA Tech. Memo. ERL NSSL-102, 681 pp. [Available from National Technical Information, 5385 Port Royal Road, Springfield, VA 22161.]

Johnson, H. L., R. D. Hart, M. A. Lind, R. E. Powell, and J. L. Stanford, 1977: Measurements of radio frequency noise from severe and non-severe thunderstorms. *Mon. Wea. Rev.,* **105,** 734–747.

Johnson, K. W., P. S. Ray, B. C. Johnson, and R. P. Davies-Jones, 1987: Observations related to the rotational dynamics of the 20 May 1977 storms. *Mon. Wea. Rev.,* **115,** 2463–2478.

Jones, H. L., 1951: A sferic method of tornado identification and tracking. *Bull. Amer. Meteor. Soc.,* **32,** 380–385.

Kane, R. J., 1991: Correlating lightning to severe local storms in the northeastern United States. *Wea. Forecasting,* **6,** 3–12.

Keighton, S. J., H. B. Bluestein, and D. R. MacGorman, 1991: The evolution of a severe mesoscale convective system: Cloud-to-ground lightning location and storm structure. *Mon. Wea. Rev.,* **119,** 1533–1556.

Kelly, D. L., J. T. Schaefer, R. P. McNulty, C. A. Doswell III, and R. F. Abbey Jr., 1978: An augmented tornado climatology. *Mon. Wea. Rev.,* **106,** 1172–1183.

Knapp, D. I., 1994: Using cloud-to-ground lightning data to identify tornadic thunderstorm signatures and nowcast severe weather. *Natl. Wea. Dig.,* **19,** 35–42.

Kohl, D. A., 1962: Sferics amplitude distribution jump identification of a tornado event. *Mon. Wea. Rev.,* **90,** 451–456.

——, and J. E. Miller, 1963: 500 kc/sec sferics analysis of severe weather events. *Mon. Wea. Rev.,* **91,** 207–214.

Lemon, L. R., and C. A. Doswell III, 1979: Severe thunderstorm evolution and mesocyclone structure as related to tornadogenesis. *Mon. Wea. Rev.,* **107,** 1184–1197.

MacGorman, D. R., and K. E. Nielsen, 1991: Cloud-to-ground lightning in a tornadic storm on 8 May 1986. *Mon. Wea. Rev.,* **119,** 1557–1574.

——, and D. W. Burgess, 1994: Positive cloud-to-ground lightning in tornadic storms and hailstorms. *Mon. Wea. Rev.,* **122,** 1671–1697.

——, ——, V. M. Mazur, W. D. Rust, W. L. Taylor, and B. C. Johnson, 1989: Lightning rates relative to tornadic storm evolution on 22 May 1981. *J. Atmos. Sci.,* **46,** 221–250.

Mach, D. M., D. R. MacGorman, W. D. Rust, and R. T. Arnold, 1986: Site errors and detection efficiency in a magnetic direction-finder network for locating lightning strikes to ground. *J. Atmos. Oceanic Technol.,* **3,** 67–74.

NCDC, 1989: *Storm Data.* Vol. 31, National Climatic Data Center. [Available from National Climatic Data Center, Federal Building, 151 Patton Ave., Asheville, NC 28801.]

——, 1990: *Storm Data.* Vol. 32, National Climatic Data Center. [Available from National Data Climatic Data Center, Federal Building, 15 Patton Ave., Asheville, NC 28801.]

——, 1991: *Storm Data.* Vol. 33, National Climatic Data Center. [Available from National Data Climatic Data Center, Federal Building, 15 Patton Ave., Asheville, NC 28801.]

——, 1992: *Storm Data.* Vol. 34, National Climatic Data Center. [Available from National Data Climatic Data Center, Federal Building, 15 Patton Ave., Asheville, NC 28801.]

Orville, R. E., 1991: Lightning ground flash density in the contiguous United States—1989. *Mon. Wea. Rev.,* **119,** 573–577.

——, 1994: Cloud-to-ground lightning flash characteristics in the contiguous United States: 1989–1991. *J. Geophys. Res.,* **99,** 10 833–10 841.

——, M. W. Maier, F. R. Mosher, D. P. Wylie, and W. D. Rust, 1982: The simultaneous display in a severe storm of lightning ground strike locations onto satellite images and radar reflectivity patterns. Preprints, *12th Conf. on Severe Local Storms,* San Antonio, TX, Amer. Meteor. Soc., 448–451.

——, R. A. Weisman, R. B. Pyle, R. W. Henderson, and R. E. Orville Jr., 1987: Cloud-to-ground lightning flash characteristics from June 1984 through May 1985. *J. Geophys. Res.,* **92,** 5640–5644.

Reap, R. M., and D. R. MacGorman, 1989: Cloud-to-ground lightning: Climatological characteristics and relationships to model fields, radar observations, and severe local storms. *Mon. Wea. Rev.,* **117,** 518–535.

Rust, W. D., D. R. MacGorman, and S. J. Goodman, 1985: Unusual positive cloud-to-ground lightning in Oklahoma storms in 13 May 1983. Preprints, *14th Conf. on Severe Local Storms,* Indianapolis, IN, Amer. Meteor. Soc., 372–375.

Seimon, A., 1993: Anomalous cloud-to-ground lightning in an F5-tornado-producing supercell thunderstorm on 28 August 1990. *Bull. Amer. Meteor. Soc.,* **74,** 189–203.

Taylor, W. L., 1973: Electromagnetic radiation from severe storms in Oklahoma during April 29–30, 1970. *J. Geophys. Res.,* **78,** 8761–8777.

Wicker, L. J., and R. B. Wilhelmson, 1995: Simulation and analysis of tornado development and decay within a three-dimensional supercell thunderstorm. *Frontiers in Tornado Research,* C. Church, Ed., Amer. Geophys. Union, 75–88.