An Observation of the Relationship between Supercell Structure and Lightning Ground-Strike Polarity

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1 July 1991 and 14 October 1991

ABSTRACT

Cloud-to-ground lightning data are presented from tornadic thunderstorms in Oklahoma, Kansas, and Nebraska on 13 March 1990. The tornadic storms from northern Oklahoma northward into Kansas and Nebraska produced an unusually high percentage of positive cloud-to-ground (+CG) flashes, whereas those in central and southern Oklahoma produced mostly negative flashes. Visual evidence indicates a distinct difference in structure between the northern storms, which produced high +CG rates, and the southern storms, which did not. The storms with high +CG rates possessed characteristics of storms in the low-precipitation (LP) portion of the supercell spectrum. In contrast, visual and radar characteristics indicate that the southern storms with lower +CG frequencies were in the high-precipitation (HP) portion of the supercell spectrum. These findings are consistent with another recent study linking high +CG rates with LP storms. Based on these observations, potential benefits of real-time lightning-strike data to forecast and warning operations are considered.

1. Introduction

Several recent studies of lightning characteristics have examined the role of positive cloud-to-ground (+CG) flashes, i.e., flashes that deliver positive charge to the ground, as opposed to the more frequent negative charge. Many of these studies (Rust et al. 1985; Reap and MacGorman 1989; MacGorman and Nielsen 1991, to name a few) have noted a direct relationship between +CG flash frequency and storm severity. This relationship suggests that real-time data from lightning-detection networks might prove useful in severe–local-storm forecasting and warning operations.

Unfortunately, these studies indicate that the relationship is only a general one; not all severe storms produce elevated +CG rates, and not all storms with high +CG rates are severe. Thus, before we can use lightning polarity data effectively in warning operations, we must learn why only some severe storms produce high +CG rates, and, in particular, *which* storms. Curran and Rust (1991) suggest one possible answer by documenting a case in which high +CG rates were found to be associated with low-precipitation (LP) storms of the type described by Bluestein and Parks (1983). They found a peak in +CG rates during the LP stage of a thunderstorm, followed by a return to mostly negative flashes once the storm evolved from an LP storm into a "classic" tornadic supercell. (For a discussion of the supercell spectrum, see Doswell et al. 1990). This finding could be significant, since LP storms often can appear benign on radar (despite their capacity to produce tornadoes and very large hail) and, thus, can be relatively difficult to identify using radar alone. Although LP storms typically present a striking visual appearance and thus can be identified readily by trained storm spotters, the added information provided by a lightning-detection network could improve the chances of providing advance warning of an LP storm.

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2. Overview of the 13 March 1990 tornado outbreak

An outbreak of severe thunderstorms on the afternoon and evening of 13 March 1990 produced several dozen tornadoes over the central and southern Plains, many of which were rated strong or violent (F2 or greater). The tracks of the tornadoes in Nebraska, Kansas, and Oklahoma are shown in Fig. 1. All but one of the tornado corridors in Fig. 1 were associated with either a single parent thunderstorm or with multiple storms that tracked across the same general area. (Corridor 7, in Kansas and Nebraska, encloses a region of sporadic tornado development that occurred with a squall line.) Details of these corridors are given in Table 1.

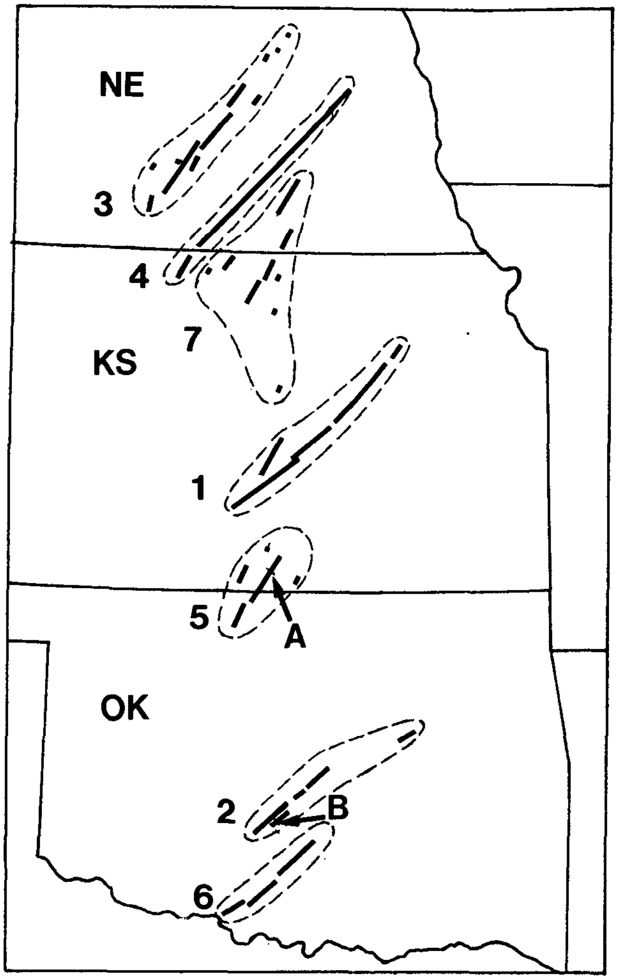

FIG. 1. Tornado tracks (heavy solid) in Nebraska, Kansas, and Oklahoma between 2200 UTC 13 March and 0300 UTC 14 March 1990. Tornado corridors, numbered chronologically according to time of first tornado touchdown, are enclosed by dashed lines. Locations A and B are locations of tornadoes shown in Figs. 2 and 3, respectively.

Cloud-to-ground lightning-strike data from the parent thunderstorms were recorded in real time by the lightning detection network operated by the National Severe Storms Laboratory (NSSL) (see Reap and MacGorman 1989 for details regarding this network). The data reveal a marked tendency for some of the tornadic storms to produce unusually high rates of +CG flashes. (Reap and MacGorman 1989 determined that, overall, about 4% of all warm-season CG flashes in the United States are positive. Hourly +CG percentages during the peak of this outbreak ranged from 16% to 27%, and for some individual storms approached 100%!) The high +CG rates were noted particularly in the tornadic storms from northern Oklahoma northward, while the storms in central and southern Oklahoma contained mostly negative flashes.

Many of the tornadoes were recorded by numerous photographers using still cameras and video equipment. The visual characteristics of the tornadic storms correlate very well with those associated with supercells (Doswell et al. 1990). In particular, the tornadoes occurred within regions of larger-scale rotation (i.e., mesocyclones), with heavy precipitation cores (if any) to the north or northeast of the regions of rotation. However, tornadoes in the storms from northern Oklahoma northward occurred in regions that were remarkably free of significant precipitation; heavy precipitation either was not visible at all or was displaced well to the northeast of the tornadoes. This distinct horizontal separation between rotating updraft and precipitation cascade region is commonly observed with storms in the LP end of the supercell spectrum. In contrast, the storms in central and southern Oklahoma contained significant precipitation within the mesocyclone regions—an observation more typical of high-precipitation (HP) supercells (Moller et al. 1990). Doppler radar observations in Oklahoma support these observations; Imy and Burgess (1991) identified one tornadic storm in northern Oklahoma as an LP storm (through post-analysis of data recorded from the NSSL 10-cm Doppler radar; storm severity and mesocyclone presence could not be detected in real time), and identified the tornadic storms in central and southern Oklahoma as HP storms during their tornadic phases.

3. Lightning data and storm evolution

Initial tornado development was remarkably coincident throughout the three-state area, with four of the corridors becoming active within a 14-min period just prior to 2300 (all times UTC). Lightning-strike data collected in real time by the NSSL network are shown in Fig. 2 for the 1-h period ending at 2300. The heavy concentration of flashes in central Oklahoma was associated with corridor 2; several +CGs occurred in this region but, overall, the region was dominated by negative flashes. Farther north, however, a remarkable concentration of *almost entirely +CG flashes* was seen over southern Kansas associated with the parent storm of corridor 1. Another concentration of flashes, again almost entirely +CG, was seen over southern Nebraska in connection with corridor 3.

TABLE 1. Characteristics of tornado corridors shown in Fig. 1. Type refers to configuration of parent thunderstorms: S—single storm; M—Multiple storms tracking across the same general area; L—Squall line. "First" and "last" refer to times of tornado occurrence (UTC). Max F refers to Fujita Scale.

Corridor number	State(s)	Type	First	Last	Number of tornadoes	Max F	Deaths
1	KS	M	2234	0205	4	5	2
2	OK	M	2244	0210	5	2	0
3	NE	M	2245	0130	10	3	0
4	KS, NE	S	2248	0210	3	4	0
5	OK, KS	S	2315	0035	5	3	0
6	OK	S	0001	0245	3	3	0
7	KS, NE	L	0020	0240	9	3	0

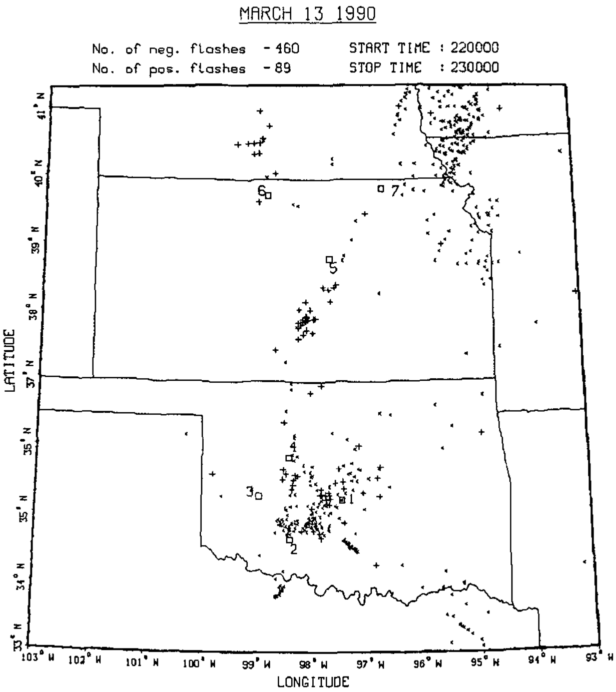

FIG. 2. Cloud-to-ground lightning strikes detected in real time by the NSSL lightning-detection network, 2200–2300 UTC 13 March 1990. Negative flashes indicated by < symbols; positive flashes by plus signs. Numbered squares (1 through 7) are locations of direction-finding equipment; NSSL is at location 1.

Between 2300 13 March and 0000 14 March, corridors 1 through 4 remained very active, while tornado development began in corridors 5 and 6. Lightning data from this period are shown in Fig. 3. Positive flashes continued to dominate from north-central Oklahoma northward into central Nebraska, while flashes farther south in Oklahoma were mostly negative. Heavy concentrations of +CG flashes in south-central Nebraska and central Kansas were associated with corridors 4 and 1, respectively. A massive (F4), long-track tornado was in progress during most of this period in corridor 4, while the parent thunderstorm in corridor 1 produced two F5 tornadoes (the first to be recorded in the United States in nearly five years) and two fatalities. Concentrations of +CG flashes also were seen in Nebraska with corridor 3, and near the Kansas–Oklahoma border with newly developed corridor 5. Concentrations of mostly negative flashes were seen in central Oklahoma (corridor 2) and near the Oklahoma–Texas border, where the parent storm of corridor 6 was moving into the range of the NSSL network.

The photographs in Figs. 4 and 5 were taken during the period represented in Fig. 3. From the many still photographs and video segments taken on this day, these photographs are representative of the difference in storm structure between the northern and southern storms. Figure 4 shows the structure of the storm near the Kansas–Oklahoma border (corridor 5), revealing the visual appearance of an LP storm, as described by Bluestein and Parks (1983). In contrast, the developing tornado in Fig. 5 is accompanied by a large area of heavy precipitation wrapping around the south side of the funnel. Heavy precipitation obscured the funnel about one minute after the photograph was taken, despite the proximity of the funnel (less than 2 km).

Lightning-strike data from the period 0000 to 0100 14 March (Fig. 6) shows a continued trend of very high +CG rates in the northern storms, while negative flashes prevailed from central Oklahoma southward. Clusters of almost entirely +CG flashes were seen in Nebraska and near the Kansas–Oklahoma border associated with corridors 3, 4, and 5. All three corridors were producing severe weather during this period, although corridor 5 became nontornadic after 0035. A heavy concentration of flashes in east-central Kansas, associated with corridor 1, also maintained a high frequency of +CGs, but negative flash rates began to increase in this area. A new region of concentrated flashes, mostly positive, was seen in north-central Kansas in connection with a developing squall line that became tornadic (corridor 7) during this period. Meanwhile, concentrated flash regions in southern Oklahoma (corridors 2 and 6) continued to display a higher frequency of negative flashes.

Only corridors 6 and 7 remained active after 0210. Lightning data from the period 0100 to 0200 (Fig. 7) show the demise of corridors 3 (Nebraska) and 5 (southern Kansas). High flash concentrations remained, however, in central and southern Oklahoma

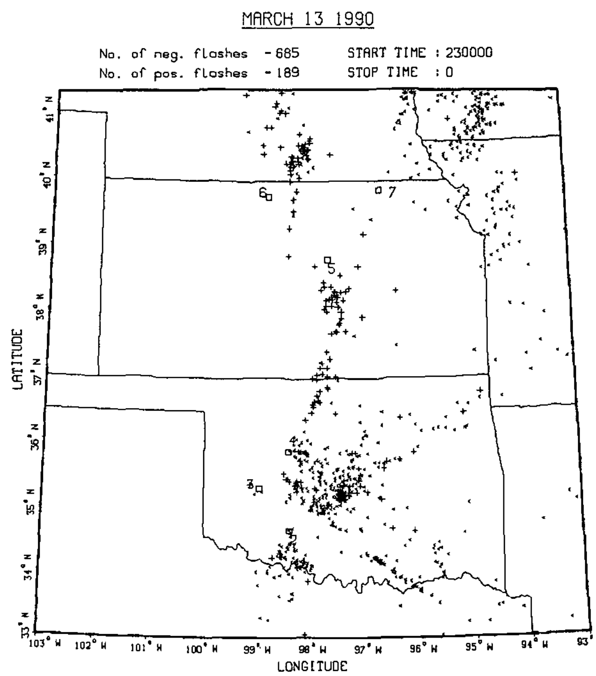

FIG. 3. As in Fig. 2, except for the period 2300 UTC 13 March–0000 UTC 14 March 1990.

FIG. 4. Photograph of tornado and parent thunderstorm, looking west from near South Haven, KS, at approximately 0028 UTC 14 March 1990. Tornado is at location A in Fig. 1, and is approximately 20 km from the photographer. Photograph courtesy of J. McKinney.

(corridors 2 and 6), as well as in northeastern Kansas (corridor 1). The parent thunderstorm associated with corridor 1 showed a trend toward lower +CG rates than previously, coincident with a marked decrease in tornado intensity. (Tornado production ceased with this storm after about 0130, except for a short-lived F1 tornado shortly after 0200.) The cluster of +CG flashes formerly associated with corridor 4 in Nebraska merged with the elongated cluster associated with the squall line and corridor 7; +CGs continued to prevail in these areas.

Lightning data after 0200 (not shown) showed that only corridors 1, 6, and 7 were associated with concentrated flashes. Flashes in northeastern Kansas (corridor 1) became entirely negative after 0200. Corridor 6 continued as in previous periods, with a few +CGs but a predominance of negative flashes. The squall line from central Kansas northward into Nebraska, which produced several tornadoes in corridor 7 during this period, continued with a high +CG rate.

4. Discussion

Several investigators have noted that high +CG rates tend to occur in regions of the thunderstorm outside of the heaviest precipitation. These regions include the downwind anvil, especially well away from the main storm tower (Rust et al. 1981; MacGorman and Nielsen 1991), from the rear of the main cell (Rust et al. 1981), and in decaying storms when precipitation rates are decreasing (Fuquay 1982; Orville et al. 1983). The bipolar pattern observed in some mesoscale storm systems (Orville et al. 1988; Stolzenburg 1990) typically consists of a maximum negative flash density near the region of heaviest precipitation, with maximum +CG density centered downwind in a region of lower precipitation intensities. One hypothesis advanced in these investigations is that +CG flashes occur when the positively charged upper (anvil) portion of the thunderstorm is laterally displaced from the negatively charged precipitation core, creating a tilted dipole (Brook et al. 1982). Such a situation can occur during the decaying stage of a thunderstorm, when the precipitation core (and hence its shielding effect) weakens. It also can occur when the primary updraft and downdraft regions of a thunderstorm are separated horizontally by a considerable distance, an occurrence routinely observed in most classic supercells and, in particular, those storms tending toward the LP end of the supercell spectrum. And "true" LP storms, through their char-

FIG. 5. Photograph of developing tornado, looking west from Criner, OK, at 2331 UTC 13 March 1990. Tornado is at location B in Fig. 1, and is approximately 2 km from the photographer. Note area of heavy precipitation (left) wrapping around south side of funnel; this precipitation (rain and small hail) reached the photographer's location and obscured the funnel within 2 minutes after photograph was taken. Photograph by M. Branick.

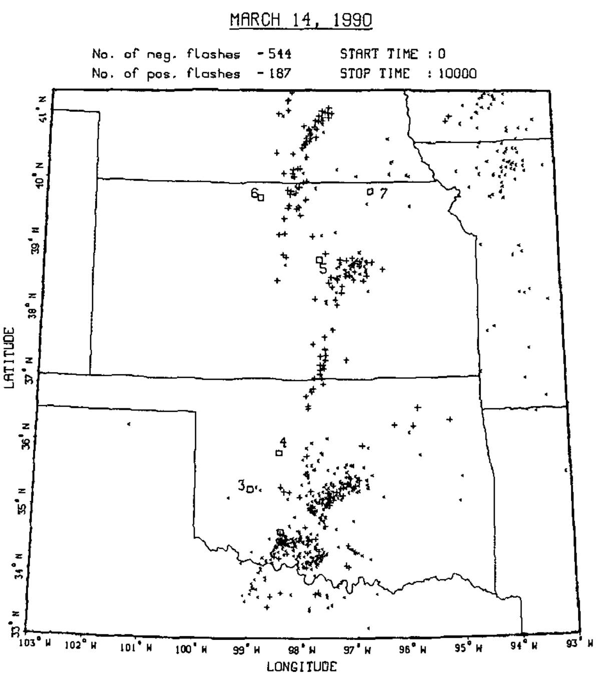

FIG. 6. As in Fig. 2, except for the period 0000–0100 UTC 14 March 1990.

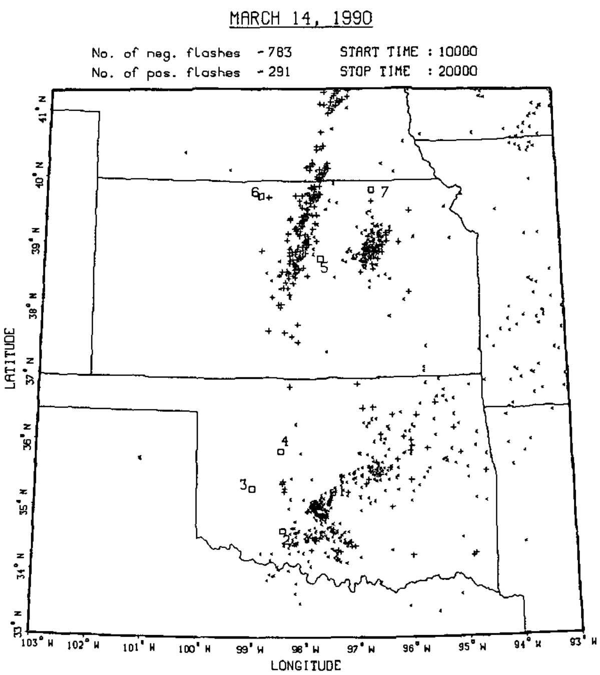

FIG. 7. As in Fig. 2, except for the period 0100–0200 UTC 14 March 1990.

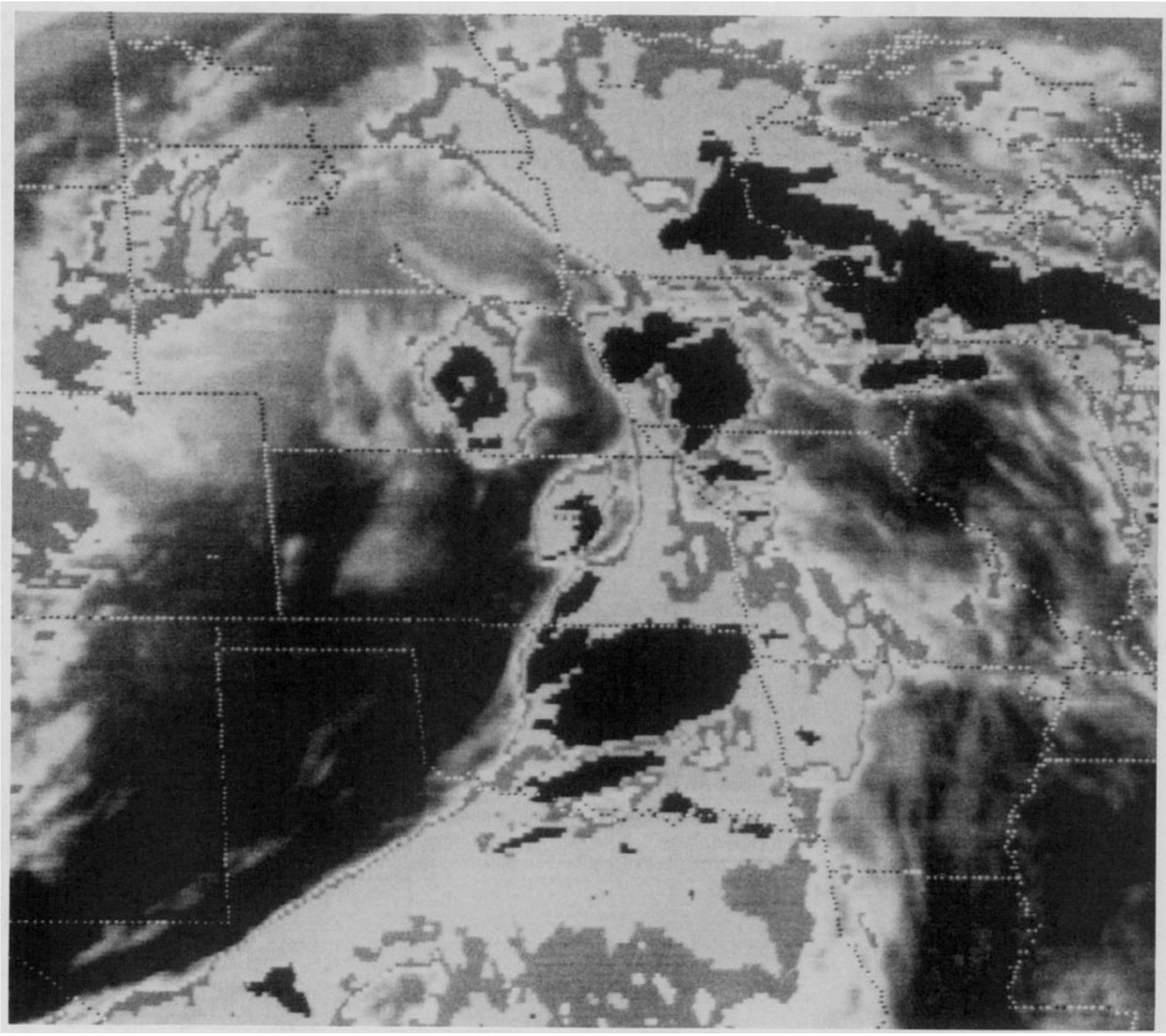

FIG. 8. Enhanced infrared satellite photo (MB enhancement curve) at 2300 UTC 13 March 1990.

acteristic shortage of heavy precipitation, may lack the negative charge shielding necessary to prevent a large number of +CG flashes. Thus, our observation of elevated +CG rates with LP supercells supports the findings of Curran and Rust (1991).

The reasons for the northern storms tending toward LP, versus the southern storms tending toward HP, is beyond our ability to answer. However, we offer what perhaps is an intriguing clue found in satellite imagery. Figure 8 shows an enhanced-infrared satellite view at the time when four of the tornado corridors were active. The sharp northwestern edge of the cirrus shield from western Texas to eastern Kansas gives a remarkably good representation of the dividing line between LP-type storms to the north and HP-type storms to the south. This observation leads us to speculate that something in the upper troposphere contributed to the differences in supercell structure. A difference in upper-tropospheric moisture content certainly was evident between the northern and southern storms, while the sharpness of the cloud edge suggests the presence of a jet-stream axis lying just to the northwest of the cloud edge (most likely along the axis of smaller cloud elements stretching from extreme western Texas northeastward into the Texas Panhandle). Extrapolation of this feature northeastward would place the LP storms in Kansas and Nebraska in a region of stronger upper-tropospheric winds, and stronger speed shear, than the HP storms further south in Oklahoma.

5. Forecast applications and future research

A validated relationship between supercell type and +CG frequency could be of use in real-time forecast and warning operations. Although LP storms can be visually spectacular, they can appear quite benign on radar (Doswell et al. 1990; Bluestein and Parks 1983). This situation increases the potential for contradictory information to reach the forecaster, who must make a warn/no-warn decision nonetheless. A real-time lightning-detection system capable of determining flash polarity could provide the added information needed to make the proper warning decision. However, the use of this relationship in severe-storm warning operations is wholly dependent on whether or not the correlation between elevated +CG rates and supercell type can be demonstrated *routinely* and *reliably*. We hope that additional studies of similar events in the future will provide further insight into this apparent correlation.

Acknowledgments. The authors wish to thank Mike Eilts, Don MacGorman, Richard Orville, and Ronald Reap for their helpful comments and reviews of the manuscript. We also thank Brian Curran and Dave Rust for helpful discussions related to their work on the event of 26 April 1984. Don MacGorman provided the lightning ground-strike data. Robert Prentice and Gene Rhoden were instrumental in collecting the many hours of video footage taken of the storms on 13 March. Thanks also to the many individuals who shared their home videos and still photographs of the events of 13 March.

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