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Preliminary Study of Lightning Location Relative to Storm Structure

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Lightning is being studied relative to storm structure using a VHF space-time discharge mapping system, radar, a cloud-to-ground flash locator, acoustic reconstruction of thunder, and other instrumentation. The horizontal discharge processes within the cloud generally propagate at speeds of 10^4-10^5 m/s. We have found horizontal extents of lightning up to 90 km. In an analysis of a limited number of flashes, lightning occured in or near regions of high cyclonic shear. Positive cloud-to-ground flashes have been observed emanating from several identifiable regions of severe storms. Lightning echoes observed with 10-cm radar are generally 10-25 dB greater than the largest precipitation echo in the storm.

Introduction

DURING the past three years, we have been developing the capability of making quantitative electrical measurements on severe storms. A variety of electrical measurements have been made. We have analyzed portions of three storms to correlate lightning activity with radar reflectivity and Doppler-derived wind fields. We have also analyzed a small fraction of the recorded lightning flashes to investigate various characteristics of lightning discharge processes.

Instrumentation

Components of our facility and instrumentation used by cooperating groups are depicted in Fig. 1. The three-dimensional location of lightning discharges within storms is accomplished through the use of a wideband VHF system (20-80 MHz) capable of resolving 16,000 electromagnetic impulses per second (Fig. 2). Time differences of arrival at a pair of horizontally spaced antennas and a pair of vertically spaced antennas define, respectively, azimuth and elevation angles to ±0.5 deg accuracy. The arrival times, measured to 16 μs relative accuracy between two stations—National Severe Storms Laboratory (NSSL) and Cimarron (CIM)—are used to identify and select impulses observed at each station as having been produced by a common source and also to obtain the temporal structure and progression speeds of the lightning processes. A real-time azimuth-elevation display is available for monitoring the lightning activity. Details of the instrumentation and the initial test of this technique on Florida thunderstorms in 1976 are reported by Taylor.[1]

Two other systems are used to provide additional data on the location of lightning. Information on cloud-to-ground (CG) flashes and their strike points at the ground within about 200 km is provided by a crossed-loop location system.[2] Lightning is also located through the use of a 23-cm aircraft-tracking radar modified to have circular polarization to substantially reduce the echoes from precipitation and thus facilitate the detection of radar echoes from lightning. The purpose of the radar is twofold: 1) a study of the physical processes of lightning and 2) location of lightning activity within severe storms out to long ranges (≃200 km) and throughout extended periods (1-4 h) of the lifetime of a storm.

A number of other parameters are measured to provide additional electrical information. To identify lightning type (that is, CG or intracloud (IC) flashes), we record the electric field change from lightning. Other measurements we make include the atmospheric electric field, optical transients from lightning, corona current, electrical current carried on precipitation, and acoustic signals of thunder. Television and movie recordings of clouds and lightning are made. Environmental data are obtained from meteorological soundings of the atmosphere and a surface network that measures wind, pressure, temperature, and humidity. Storm structure and kinematics are determined with data from our two 10-cm Doppler radars.

Results

Since we have acquired data on only portions of a limited number of storms, our results are fragments of a more complete description of the electrical life history of a storm that awaits additional data and analyses. We present our results in categories determined primarily by the technique used to make the measurements.

A. Space-Time Mapping of Lightning Within Storms

An example of the complexity of lightning activity as seen with the VHF mapping system is shown in Fig. 3. Each letter indicates an elevation and azimuth angle of a VHF impulse obtained from a wide line of thunderstorms to the west of the NSSL station. Impulses designated by the same letter all occurred within a common 100-ms interval, marked sequentially from A to Z. The absence of letters indicate an absence of impulses during those corresponding periods. It is difficult to comprehend the discharge structure from Fig. 3a, but some order in the configurations is apparent by viewing curves drawn around letter groups (Fig. 3b). Note that some of the impulses are not included in these major groups. Five discharge areas were clearly separated and can be recognized. Observations from the other mapping station (CIM), although not presented here, were used to determine range. The discharge on the right: 1) began in group H at a height of about 12 km, 2) propagated toward the NSSL station at high elevation angles within the anvil cloud (upper group I), 3) propagated away from the station (lower group I), and 4) then produced VHF sources in groups J, K, and L. The discharge lasted about 500 ms and involved a cloud region whose horizontal diameter was about 15 km. (Note: We report our results in height above ground for simplicity and consistency with the analysis of both mapping and dual-Doppler data. Approximate altitude can be obtained by adding 0.4 km, the local terrain altitude.) The discharge confined to group N lasted less than 100 ms, extended 1.5 km horizontally, and extended 4.7 km vertically. Duration of each of the other three discharges, E through H, T through W, and V through Y, was less than 400 ms, and the maximum horizontal dimension of each region was less than 6 km.

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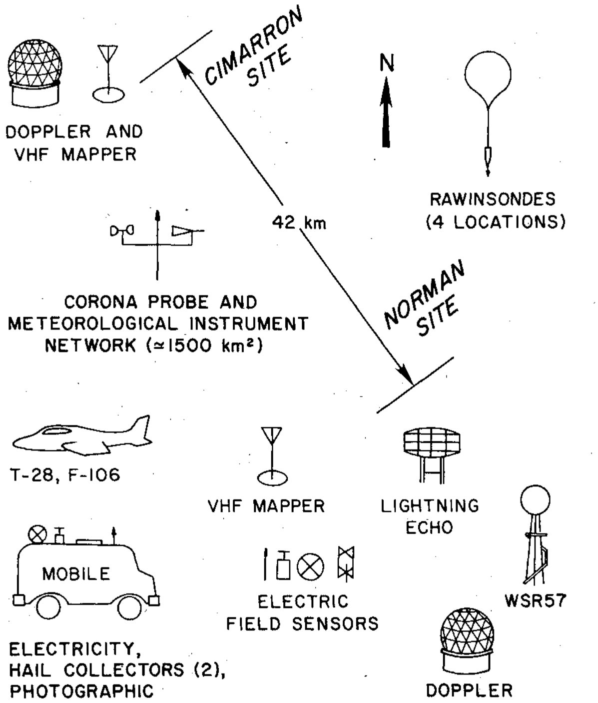

Fig. 1 Facilities and instrumentation used in severe storm research.

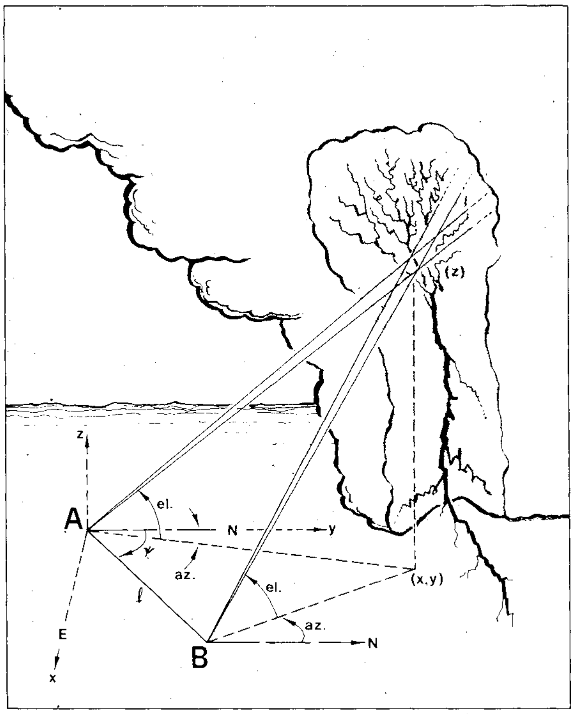

Fig. 2 Location of lighning impulses using two observing stations.

Most lightning activity observed by the VHF mapping technique originates from discharge processes within the cloud, and only a few impulses are observed from return stroke channels. An excellent example of this is shown in Fig. 4 by the azimuth-elevation display from a single station. The time interval for each letter designation is 75 ms. The two CG flashes (mostly A through C's and X's) occurred with a time separation of about 1.7 s. (Note that in the terminology here a CG *flash* is an entire lightning event within which there are separate return *strokes* to ground.) A single letter A at 112 deg azimuth and 2 deg elevation and two X's at about 82 deg azimuth and 2 deg elevation represent impulses from the lower few hundred meters of the return strokes of these CG's.

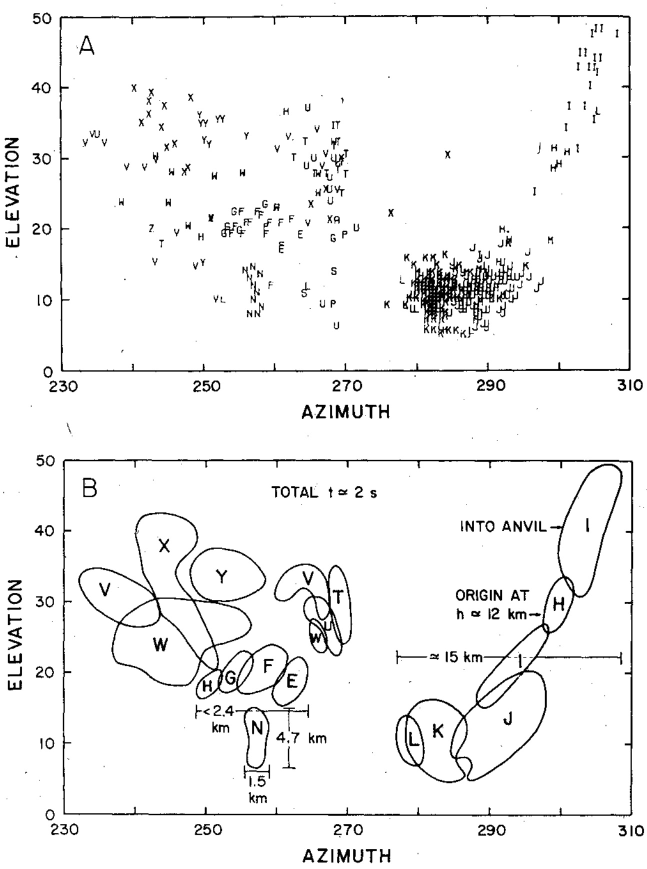

Fig. 3 Example of complex lightning activity showing azimuth and elevation in degrees viewed from a single VHF mapping station: a) each letter designation indicates impulse-source elevation and azimuth angles during successive 100-ms periods progressing from A to Z; b) groups of impulses comprising five discharge areas within a 2-s period.

The crossed-loop direction finding system detected two single-stroke flashes whose time of occurrence corresponds with these low elevation impulses. The azimuthal directions of these impulses agree within 2 deg of the direction to locations from the loop system. By triangulation from data recorded at both stations, we located the center of the discharge on the right, letters A, B, and C, at a range of 14 km with a median impulse height of 5.2 km and horizontal extent of about 6 by 10 km. Corresponding values for the discharge represented by the X's are 15, 5.1, and 3 by 7 km.

An intracloud discharge extending 28 km across another squall line is presented in Fig. 5 as a very good example of systematic progression of discharge processes. Each letter designation in Fig. 5a indicates impulses viewed from the NSSL station during successive 50-ms time periods. General progression of the discharge is from left to right in the figure and from front to back across the squall line. The discharge starts with a group of C's centered near 183 deg azimuth and moves into a group of D's centered near 202 deg. There is a pause of about 250 ms before a single J is observed at 176 deg followed by a few K's at 187 deg; the apparent main discharge then begins with L's and progresses to increasing azimuth as shown by the M's through the P's. A few Q's at about 203 deg and a single R at about 197 deg finally terminate the discharge some 200 ms after the L's. The total discharge time was about 800 ms.

When we analyze the time sequence of arrival of the sources represented by each idividual letter, it is possible to delineate the channel structure of this discharge as shown in Fig. 5b and 5c. Circles replace the letters used in Fig. 5a and coded lines indicate a possible structure of the discharge channels. The line codes change to assist in identifying sources with letter

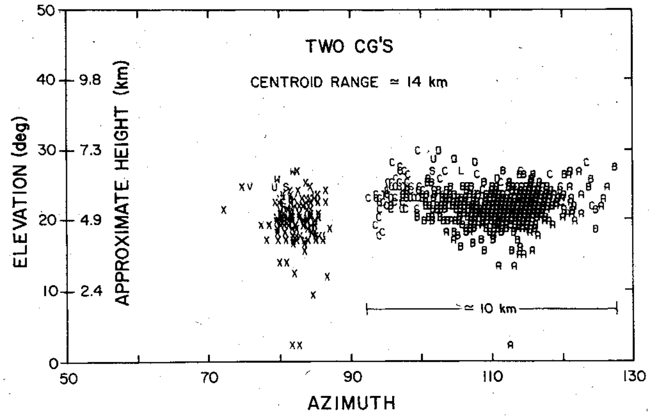

Fig. 4 Two single-stroke CG flashes, one represented by letters A, B, and C, the other by the letter X. (A few other letters are also scattered through these regions.) Each letter indicates the azimuth and elevation angle of impulse sources during successive 75-ms time periods.

designations used in Fig. 5a. Arrows are placed on some of the lines where space permits to show the direction of discharge movement. The channel structures shown here are not unique solutions for the impulse sequence, and subjective decisions were made in ordering the channel progressions. Construction of the discharge channels is difficult where multichannels are present because the impulses are often produced by sources along simultaneously active channels. Consecutive impulses are not necessarily adjacent in space because there is no ordered sequence in which the sources from different channels radiate. Thus, the indentification of an impulse to be used in furthering a channel's progression depends upon the proximity in time and space of this impulse with the previous impulse used in constructing the channel. Figure 5b presents only the sources previously indicated by the C's and D's, and Fig. 5c includes the L's through P's with a few K's and Q's at the beginning and ending, respectively.

We infer that this discharge was not comprised of a single interconnected flow of current made up of many channels and branches, but was composed of several closely related discharges. Initiation points of these component discharges are shown by solid dots in Figs. 5b and 5c. The first initiation impulse was at 180 deg azimuth (Fig. 5b). After a lengthy pause, the next initiation impulse occured at 186 deg (Fig. 5c). Other initiation points for the major component discharges consisted of one at 197 deg and two at 216 deg. Proctor[3] observed similar disjointed discharges in storms in South Africa.

Having observed the complex nature of channel development, we now examine where in the storm the initial electrical breakdown for each discharge occurs. This is of fundamental importance to understanding where very high electric fields occur in storms and may well indicate the region of highest risk to aircraft penetrating the storm. For a first approximation, we assume the discharge initiation height to be the first impulse recorded by the VHF mapping equipment. The heights of the first impulses of 63 discharges from a storm in central Oklahoma on 20 May 1979 were partitioned into CG, IC, and U (unidentified) categories. Classification was made through interpretation of measured electric field changes. A discharge was placed into the unidentified category whenever the field change amplitude was too small to interpret. Twenty-eight flashes were classified as CG, 16 as IC, and 19 as U. (The data suggest that most, if not all, of the U's were IC flashes.) The median initiation height for the CG flashes was 5.5 km (associated with a clear air temperature of $-13°C$) and is considerably below the 7.0-7.4 km ($-22°C$) median heights for the IC and U flashes.

The speed of individual channels cannot be calculated because of constraints mentioned previously, but we have calculated the progression speed of discharges from the gross

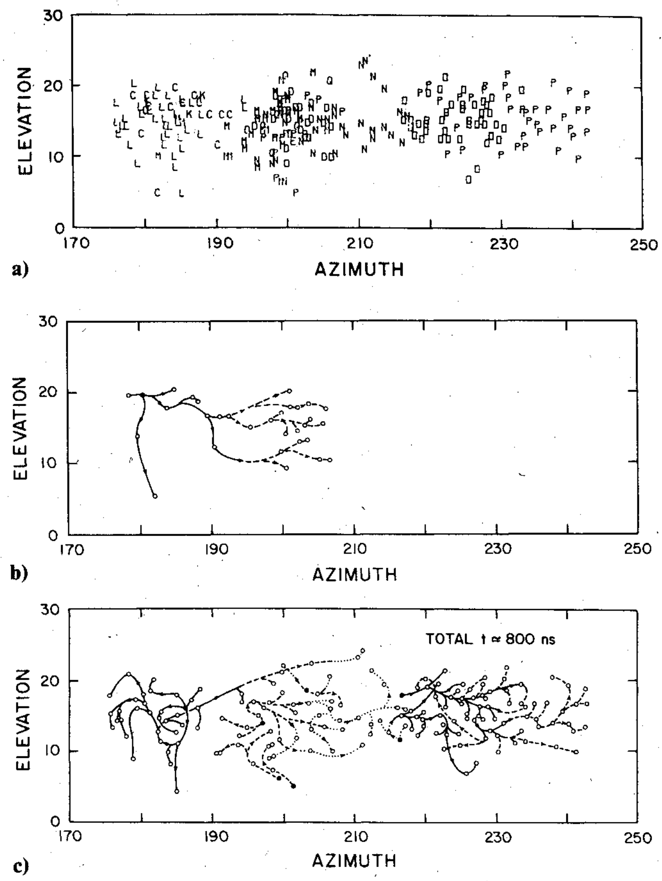

Fig. 5 Systematic progression of an IC flash: a) each letter designation is for successive 50-ms periods; b) early parts of the discharge represented by C and D in Fig. 5a. The initiation impulse is indicated by ●; all other impulses shown as ○. Line codes change to assist identification with letters in Fig. 5a. Arrows indicate direction of discharge; c) later parts of discharge represented predominately by L through P in Fig. 5a with coding same as for Fig. 5b.

movement of groups of pulses. Results for a few flashes indicate that the in-cloud portion of CG flashes propagate faster than do IC flashes. IC flashes tend to have greater horizontal extent than CG flashes. In addition to these 63 flashes, many of the others we have mapped show significant horizontal extent. Other investigators have also observed this feature in storms.[4-6] The horizontal extent of flashes often exceed 10 km in large storms; we have documented flashes of 90-km length with radar (more details are given in part B of this section). A summary of the features of the 63 flashes discussed here is given in Table 1.

We are particularly interested in lightning relative to radar reflectivity and wind fields. A few examples of mapping data that demonstrate our initial findings are presented. Flashes, as depicted by VHF impulse source locations typically avoid the highest reflectivity in a cell as in Fig. 6. MacGorman[7] studied lightning in a severe storm in Colorado using acoustic techniques; a few sources from the 35 flashes he mapped occurred within 45 dBZ contours, but none within 50 dBZ. In the limited number of flashes we have analyzed, some VHF sources have occurred within the most intense radar reflec-

Table 1 Median discharge characteristics inferred from VHF space-time mapping of 63 flashes

Parameter	CG	IC	U
Initiation height, km	5.5	7.0	7.4
Discharge center height, km	4.3	5.9	5.0
Progression speed, 10^4 m/s	6.6	5.5	5.0
Extent of discharge, km	9.7	17.0	15.0

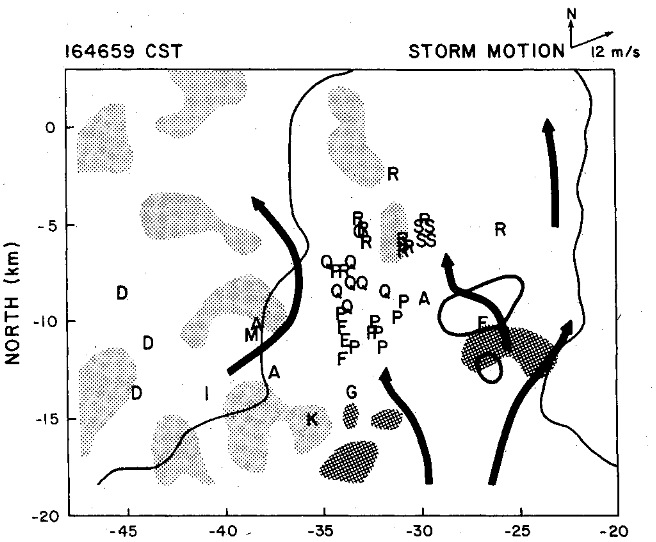

Fig. 6 VHF source locations superimposed on radar data for a flash at 1646:59 CST, June 6, 1979. Radar data are at 6.5 km. The outer contour is 30 dBZ; the inner ones are 45 dBZ. Winds are from dual Doppler. Arrows indicate streamlines in the horizontal wind. Light shading indicates downdraft, usually ≤5 m/s. Dark shading indicates updrafts >10 m/s, while no shading indicates 0-10 m/s updrafts. VHF source locations are denoted by letters, each for a successive 15-ms interval. Distances are from NSSL.

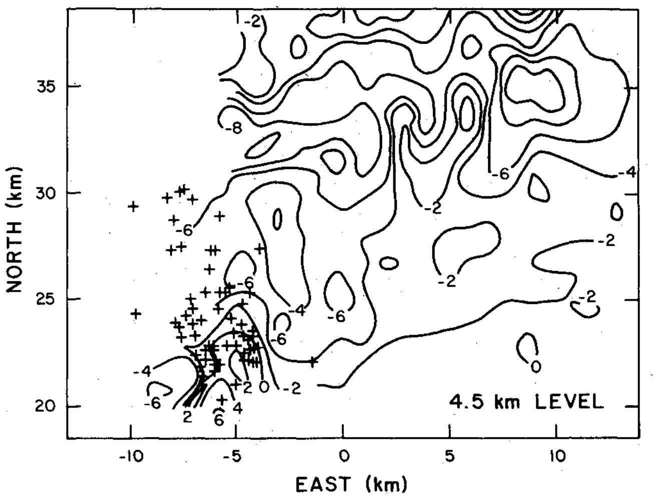

Fig. 7 VHF source locations at 4-5 km superimposed on radial Doppler velocity contours for a flash at 1515:36 CST, June 1, 1978. Velocity data are for a height of 4.5 km. Positive velocities indicate outward motion. Distances are from NSSL.

tivity; most observed sources, however, have been in lower reflectivities.

Doppler radar data allow us to study the location of lightning relative to air motions within the storm. We operate two 10-cm wavelength Doppler radars, one located at the NSSL site and the other 42 km to the northwest (CIM). This arrangement forms a primary dual-Doppler data acquisiton area that is approximated by a figure 8 shape, about 200 km in length and 100 km in width, with its major axis from southwest to northeast,[8] which is generally the direction of movement of springtime storms. Precipitation reflectivity and useful single-Doppler information, i.e., the radial component of velocity toward or away from the radar, can be obtained to ranges greater than 300 km. Dual-Doppler data are usually obtained by coordinating scans up and through a selected region of a storm. Each tilt sequence usually takes about 4-5 min. This scanning technique and dual-Doppler data synthesis allow meaningful information on the structure and dynamics of large storms to be obtained.[9] The Doppler at NSSL and a recently installed 23-cm wavelength conventional radar are further utilized to acquire radar echoes from lightning.

We have analyzed Doppler-derived air motions from portions of three storms. In a storm on June 1, 1978, the locations of VHF impulses tended to be concentrated in and near cyclonic shear deduced from single-Doppler measurements (Fig. 7). The region of cyclonic shear was inferred to be an area of updraft from the reflectivity structure and from a known association between cyclonic shear and updrafts in Oklahoma storms. In a storm on June 20, 1978, most impulses were also found in the vicinity of the cyclonic shear. On June 20, however, the shear was considerably stronger and satisfied the criteria for cyclonic circulation.[10]

Dual-Doppler radar data were taken during a squall line storm of June 6, 1979, so estimates of all three components of wind can be derived. We have analyzed a portion of the squall line for a half-hour period as it approached from the west. A cluster of cells forms the "storm" of interest, which is outlined in Fig. 8 within the 60 deg sector (dashed lines). The inner storm contour contains reflectivities of >45 dBZ. The 60 deg sector is that from which impulses were received with the mapping system. This storm is grossly categorized as severe owing to its hail and straight-line winds in excess of 25 m/s, but it had no significant rotation or tornado. The VHF impulse locations in this storm tended to occur in updraft regions of <10 m/s and were often adjacent to regions of downdraft as shown in Fig. 6. Updraft cores, which we define as areas with vertical velocities >10 m/s, were south and southeast of the lightning. At the level of the lightning, the horizontal wind within the storm generally flowed from the reflectivity and updraft cores back toward the area of lightning.

We also are attempting to correlate various aspects of total lightning activity with storm development. Flashes have been divided into 4-min time intervals that coincide (approximately) with the dual-Doppler data acquisition periods. Frequency of occurrence plots are shown in Fig. 9. We have examined various radar-determined parameters such as maximum reflectivity, areas of high reflectivity, areas of significant updraft, maximum updraft, and radar cloud top height. Maximum reflectivity and updraft are shown in the figure. The total flash activity coarsely follows the trend in a maximum updraft speed. A similar trend in a Florida storm has been reported by Lhermitte and Krehbiel.[11]

B. Radar Observations of Lightning

Radar offers unique opportunities to study and locate lightning, especially out to relatively long ranges. Ligda[6] presented excellent examples of the horizontal extent of lightning from his observations of flashes extending hundreds of kilometers. A preliminary analysis of 19 lightning radar echoes observed during a severe summertime storm has been reported by Szymanski and Rust.[12] Lightning radar echoes were detected at ranges from 30-180 km and at altitudes of up to 10 km. The lightning echoes generally had peak signals 10-25 dB greater than the largest precipitation echoes, but they generally observed the lightning echoes where precipitation reflectivities were less than maximum. This agrees with lightning locations observed by Proctor[4] and MacGorman[7] using other techniques. The location of flashes reported by Szymanski and Rust may be biased, however, since very intense precipitation echoes can obscure the presence of lightning. To reduce substantially the radar return from precipitation, present experiments at NSSL are utilizing a second, longer wavelength (23 cm) radar with circular polarization.

When combined with our simultaneous measurements of electric field changes and VHF impulse locations, lightning

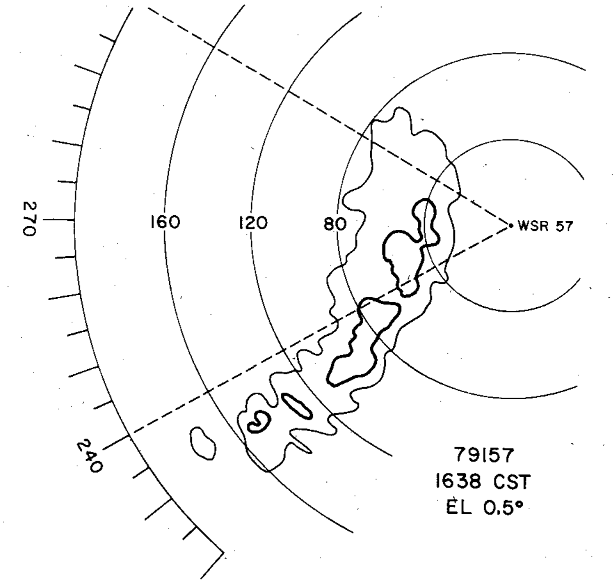

Fig. 8 Outline of squall line at 1638 CST, June 6, 1979. The "storm" of interest is within the dashed lines that denote the 60 deg sector of the discharge mapping system. The inner contours contain >45 dBZ reflectivity. Range rings are labeled in km.

radar echoes offer the possibility of not only locating lightning within storms but also understanding its propagation. Other aspects of our present study include continued lightning echo measurements with the Doppler and VHF mapping of storms overhead to correlate lightning and changes in precipitation size and velocity spectra. Radar has the ability to make remote observations of lightning strikes to aircraft. Using the 23-cm radar, we have had some success in skin-tracking aircraft into storms and detecting flashes that apparently struck the aircraft.

C. Positive CG Flashes in Severe Storms

Other investigators have observed positive CG flashes in mountainous terrain and to tall structures, e.g., Berger,[13] but positive CG flashes to level terrain are generally thought to be rare. On the other hand, Takeuti et al.[14] have observed a predominance of +CG flashes in the highly sheared winter storms in the Hokuriku coastal region of Japan. Interest in these flashes arose partially because of frequent reports of aircraft being struck by them, even though they occurred infrequently.[14] Occasional +CG flashes at the end of a storm have also been observed by other investigators, e.g., Fuquay.[15]

We have observed +CG flashes during severe storms. Those documented as CG flashes by visual or television records in addition to field change records number less than 100 (prior to 1980), but we have obtained numerous other waveforms suggestive of +CG flashes during both the severe and final stages of storms. During a 7-min interval of the June 6, 1979, storm, 5 +CG flashes were documented. We think (from a limited number of visually confirmed CG's) that CG lightning emanating from high on the main storm tower under the upwind anvil and those from the mesocyclone region of severe storms can be positive.[16] During the active stage of one severe storm, the few flashes emanating from well out in the downwind anvil were positive, while those from the downwind anvil, but close to the main tower, were of both polarities (Fig. 10).

+CG flashes to tall structures generally have greater currents and total charge transfer than negative ones.[13] Recently, Brook et al.[17] have reported that the +CG flashes in Japan often transfer large amounts of charge to ground and involve very high currents. The percentage of +CG flashes appears small; nevertheless, they are worthy of study

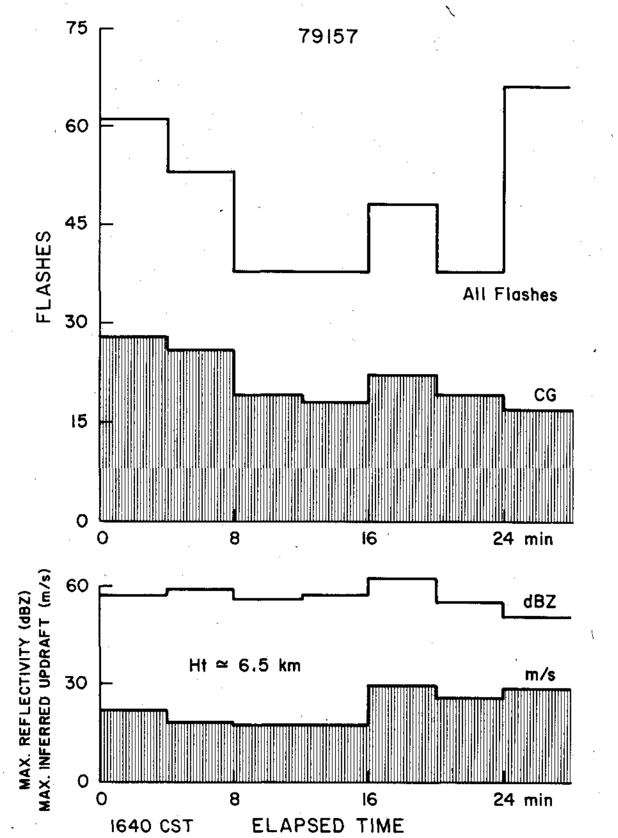

Fig. 9 Lightning activity and radar-determined parameters, June 6, 1979.

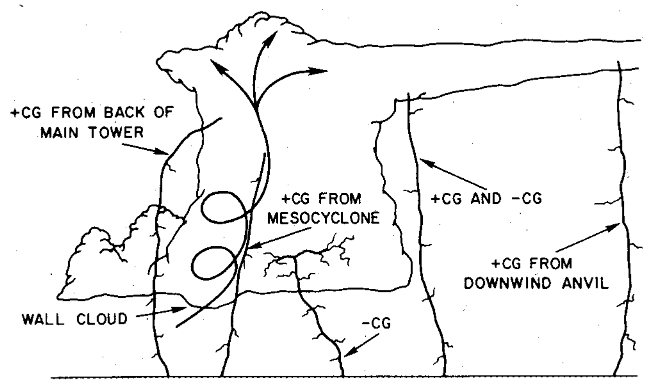

Fig. 10 Sketch of observed locations and polarities of CG flashes from severe thunderstorms. The spiral denotes the region of intense updraft and rotation.

not only because of the scientific curiosity they invoke, but also because they may have important engineering and aviation implications.

Summary

Most lightning activity observed by the VHF mapping technique originates from discharge processes within the cloud and exhibits a greater horizontal than vertical dimension. A discharge's space-time structure is very complex. The fine detail and interrelationships of impulse sources are not readily revealed because the VHF radiation is not produced spatially in ordered sequence, although the gross features of a discharge can be easily identified and tracked through the storm. Lightning seems to progress along multiple branches in a wide front at progression speeds of about 6×10^4 m/s. Lightning is closely associated with regions of high radar reflectivity, but tends to avoid the cores of high reflectivity. The median values of initiation and discharge center heights of lightning processes associated with cloud-to-ground discharges in one Oklahoma storm were about 1.5 km lower than the corresponding parameters for intracloud discharges. The progression speed of intracloud discharges was found to be about 20% slower, yet the discharges extended horizontally almost twice as far, relative to cloud-to-ground discharges. There is often an admixture of large and small discharges producing widely varying numbers of impulses sensed by the VHF mapping system. This admixture is apparently typical of intracloud lightning activity during severe storms.

The use of radar to observe lightning, especially in studies utilizing aircraft, is most encouraging to us. Radar is probably the best instrument for studying the "long" flash, i.e., those exceeding a few tens of kilometers.

Relating lightning location with storm reflectivity and internal wind structure is one of our major efforts within the Storm Electricity Group at NSSL. We plan to continue developing new techniques and expanding our data base to address some of the fundamental scientific and engineering questions concerning the role of lightning in severe and nonsevere storms and to assist the meteorological community to forecast, detect, track, and warn of weather hazards through the use of lightning observations.

Acknowledgments

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