Lightning and Related Phenomena in Isolated Thunderstorms and Squall Line Systems

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During the past few years, cooperative research on storm electricity has yielded the following results of both basic and applied interest from isolated severe storms and squall line systems: 1) the intracloud to cloud-to-ground flashing ratio can be as great as 40:1; 2) as storm cells in a squall line dissipate, flashes of longer horizontal extent become predominant; 3) two vertically separated centers of lightning activity exist: one at a height of about 5 km and another at about 12 km; 4) storms can produce lightning in their upper regions at a high rate; 5) positive cloud-to-ground flashes occur in the severe stage of isolated storms and in trailing precipitation during the later, well-developed stage of squall line storms; 6) mesoscale convective complexes have been observed to have cloud-to-ground flashing rates of ≥ 48 min^{-1}; and 7) the electric field in anvils several tens of kilometers away from the main storm core can be very high (≥ 94 kV-m).

Introduction

IN 1978 the National Severe Storms Laboratory (NSSL) began coordinated measurements of the electricity, airflow kinematics, and precipitation associated with the large and often severe thunderstorms that form over the Great Plains of the United States. This research effort has incorporated cooperative studies with several universities and other U.S. government agencies. Our goal is to develop an understanding of the electricity and coexisting dynamics and precipitation in storms[1] that can be applied to such problems as forecasting and nowcasting of lightning hazards and development of design criteria for aircraft and ground-based systems.

While lightning can be a hazard to aviation regardless of where or in what type of storm it is encountered, this paper is divided into isolated thunderstorms, both single and multicell types, and squall-line systems. The maximum radar reflectivity and potential damage (hail, wind, lightning, etc.) in these two broad categories can be the same. It is their horizontal dimensions, however, that can make them significantly different, both as a threat to aviation and as a subject for data acquisition. The problems posed to aviation are obviously different; for instance, aircraft enroute can generally circumnavigate isolated storms, but squall lines are often of such extent that they must be penetrated. Relative to data acquisition, it is possible to observe a significant part of an isolated storm but not a whole squall line.

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Instrumentation

Measurements of electrical phenomena are made with both fixed and mobile facilities (Fig. 1). The fixed facilities include a lightning discharge mapping system[2] that yields the three-dimensional location of vhf (very high frequency, specifically 30-80 MHz here) radiation sources from lightning at rates of up to 16,000 per second and out to a range of about 60 km. The vhf sources are the result of a change in current moment in the lightning channels, caused by breakdown processes or channel tortuosity. Electric field changes are measured with sensors that allow the entire flash to be characterized by its electrostatic field change and other sensors that allow the recording of the detail in return strokes and other rapid changes. Additional recorded parameters include the atmospheric electric field, optical waveforms from lightning, location of CG (cloud-to-ground lightning) flashes within about 400 km (Fig. 2), and corona current. Clouds and lightning are documented with television recordings and 35 mm still and streak-film cameras. Radar echoes from IC (intracloud lightning, i.e., any flash not striking Earth) and CG lightning[3,4] can be recorded with both Doppler and conventional radars. Meteorological information is obtained from soundings of the atmosphere and a surface meteorological network.

A van has been equipped as a mobile laboratory to measure most of the electrical parameters mentioned above. Use of a mobile laboratory allows us to place and maintain instrumentation in a position approximately fixed relative to the storm. In addition, we are able to acquire data on storms whose range from our fixed base would otherwise prohibit quantitative study.

Radar information on storms is obtained with one conventional and two Doppler radars, all S-band (radar with a transmitted wavelength of about 10 cm) radars. The arrangement of Doppler radars forms a primary dual-Doppler data acquisition area about 200 km in length and aligned from southwest to northeast, the predominant direction of move-

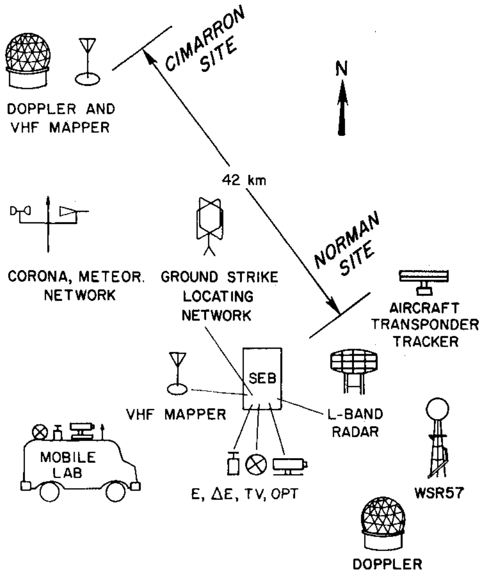


Fig. 1 NSSL storm electricity research facilities. Both sites have a vhf lightning mapping system and an S-band Doppler radar. The main recording site for storm electricity parameters is the storm electricity building (SEB). The University of Mississippi/NSSL mobile laboratory has much of the same instrumentation as the SEB. The L-band radar is used to acquire echoes from lightning. Aircraft positions can be superimposed on the WSR-57 radar display.

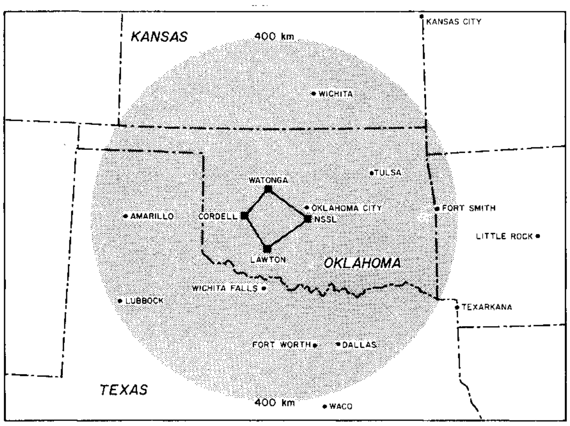


Fig. 2 Cloud-to-ground strike locating network. The four squares denote site locations, which are about 100 km apart. The nominal range of detection is within a radius of about 400 km of NSSL. All sites are capable of detecting both positive and negative flashes to ground.

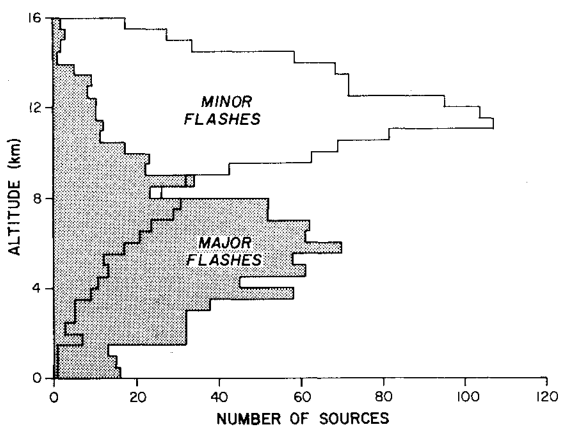


Fig. 3 Altitude distributions of vhf lightning impulse sources from 30-min interval in storm 1, June 19, 1980.

ment of springtime storms. Dual-Doppler data are obtained by scanning up through a selected storm region. Each tilt sequence through a storm region usually takes 4-5 min. Because of the increasing height of the radar horizon and the degradation of radar resolution with range, useful quantitative Doppler radar data can be obtained to ranges of about 300 km.

Logistic support and guidance for the mobile laboratory, balloon launches, and aircraft are provided by radio communication. Research aircraft can be controlled from and tracked at the NSSL Doppler radar facility, making possible real-time assessment of precipitation, turbulence, and lightning, which aids selection of desired flight paths for various aircraft experiments.

Lightning in Isolated Thunderstorms

Studies have been made of several isolated thunderstorms, which ranged from nonsevere to supercell. Examples of the interactions between lightning and storm structure are found in the following summary of storms on June 19, 1980.

Deep convection began to the southwest of Norman around 1930 CST. Between about 2215 and 2400 CST, four isolated storms developed within about 50 km of NSSL and were studied. The lighting flashes mapped in these four storms are divided into two categories: major and minor. Major flashes are defined here as those that produced >30 vhf impulse signals at each mapping station, with minor flashes having between 5 and 30. (In general, the number of signals chosen for each category has no physical significance and could vary among storms as well as being a function of range and system sensitivity settings. Also, initial results indicate that the two categories often, but not always, exist in storms.) From electric field changes that occurred simultaneously with the vhf signals, all minor flashes appear to have been intracloud. Identification of major flash type was accomplished in the same way. Electric field changes for major flashes indicate they included both IC and CG flashes, with 20-30% being CG. Although this percentage of flashes is reasonable, the major flash rates were far below those usually observed.[1,4] The ratio of the number of minor to major flashes was greater than 17:1. The flashing rates of the minor flashes varied from 18-36 min^{-1} and averaged 26 min^{-1}. The average time interval between flashes in these storms was 2.3 s. However, time intervals were log-normally distributed with a median of 1.4 s.

We now examine the altitude distribution of the mapped vhf sources for the four storms; storm 1 is typical and is shown in Fig. 3. Most major flashes occurred at lower altitudes, and most minor flashes at higher altitudes. There were a few exceptions, causing the slow "trail-off" of the overlapping distributions. For all four storms, lightning sources in the major flashes were concentrated between altitudes of 4-6 km, while the minor flashes peaked between 11-13 km.

The horizontal extent of lightning previously has been reported to be greater than the vertical by a factor of 3 or more.[5] Such a tendency is of concern to aviation since it indicates that lightning hazards are not limited to the initiation region (near or in the main storm core). The horizontal extent of the major flashes from these storms was about 16 km, with 20% of the major flashes exceeding 20 km in extent. The horizontal extent of minor flashes averaged about the same, but with 33% greater than 20 km.

The initiation height of lightning is relevant because it indicates the height at which breakdown fields could be encountered by penetrating aircraft. The initiation height is determined from the data presented herein by the height of the first mapped impulse source. (This may not always be the first point in the breakdown, but it should be close.) The initiation height for major flashes was just below 7 km, and the minor flashes began at about 10 km, corresponding to clear air temperatures of -16 and $-38°C$, respectively.

It is difficult to produce an easily understandable composite of lightning activity and radar-derived storm parameters in two dimensions. An example of results obtained by combining lightning location, precipitation, and air motions for storm 1 is presented, and the general interrelationships of these parameters for all four storms are summarized. At the sacrifice of detail and secondary relationships, only two heights where associations between lightning location and storm structure are the most obvious are presented (Fig. 4). It is found that the location of lightning sources conforms best with the radar reflectivity at 5 km for major flashes and with the divergent horizontal wind pattern at 13 km for minor flashes.

Superposed onto the plan view of reflectivity and horizontal streamlines at 5 km in Fig. 4a are the vhf sources of major flashes occurring at all altitudes. It is clear that the lightning sources were concentrated in the high reflectivity region. The vhf source density of the major flashes within the 50 dBZ areas was three times greater than that in the area containing 40-50 dBZ. The horizontal winds tended to curve through the lightning activity area. The main updraft area for this part of the storm, centered at (-4 km, 41 km), generally occurred near and within the areas containing 50% of the vhf sources. Updraft velocities were 10-20 m-s^{-1} at this level and exceeded 20 m-s^{-1} above 6 km. In addition, a line through the core centers at each radar analysis level deviates horizontally only 2 km between the ground and 14 km, thus indicating very little vertical shear in the horizontal wind. It was evidenced that these severe storms were less vigorous than most by their relatively low updraft speeds and major flashing rate.

Minor flashes at all attitudes are superposed onto the reflectivity contours and horizontal streamlines at 13 km in Fig. 4b. The plan view distribution of minor flash sources was very patchy and distributed over a much larger area than the major flashes; no single region of concentration was found. Therefore, 13 separate areas that contain 80% of the sources are shown. The lightning sources of minor flashes do not align with any one reflectivity feature, and lightning is evident in low reflectivities ($\leq$ 10 dBZ). The sources seem associated with the divergent, outflowing winds at the top of the storm, and thus with the top of the updraft.

Similarities exist among the four isolated storms examined. Usually a single high reflectivity core in excess of 50 dBZ dominated each storm, with 60 dBZ observed occasionally. Multicellular structure was also apparent. Lightning characteristics in these storms were also similar. Our conclusions for these storms, including results from data not discussed here, are summarized as follows:

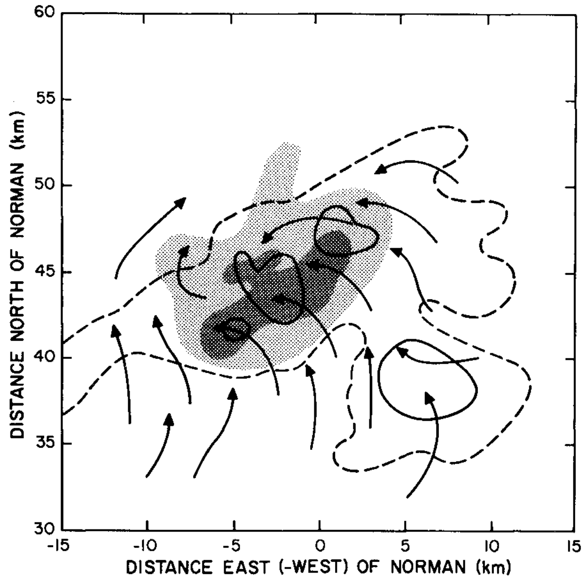
1) There is a class of minor IC flashes that formed a large canopy to an altitude of at least 16 km over the main updraft.

2) Minor flashes produced almost a continuum of lightning activity centered at 11-13 km altitude and have no apparent temporal association with the major flashes that occurred sporadically in the lower portions of storms.

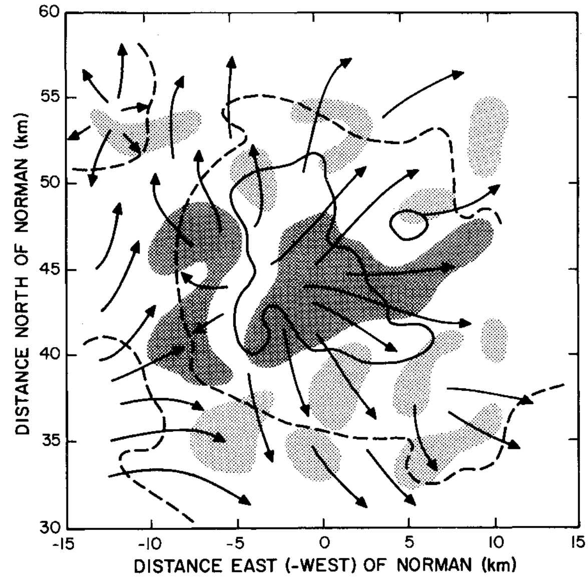
3) Major flashes overlapped high reflectivity cores or occurred near and downwind of the cores. Major flash sources were concentrated at 4-6 km altitudes, and seldom extended above 10 km.

4) Lightning initiation heights for the major and minor flashes were at 7 km and 10 km, respectively.

5) A minimum of vhf sources occurred at about 9 km altitude, where the environmental temperature was about -30°C.



a) vhf sources of major flashes at all altitudes are superposed onto the 40-dBZ (dashed contours) and 50-dBZ (solid contours) radar reflectivity and Doppler-derived horizontal wind streamlines (arrows) at 5 km altitude. The total shaded area contains 80% of all mapped sources, while 50% are within the darker shading. The radar scan time was 2222-2227 CST, and the lightning occurred between 2219-2227 CST.



b) vhf sources of minor flashes at all altitudes are superposed onto the 10-dBZ (dashed contours) and 30-dBZ (solid contours) radar reflectivity and horizontal wind streamlines (arrows) at 13 km altitude. The total shaded areas contain 80% of all mapped sources, while 50% are within the darker shading. The radar and lightning time intervals are as in 4a.

Fig. 4 Plan views of vhf sources, radar reflectivity, and Doppler-derived wind streamlines, storm 1, June 19, 1980.

Electric Field in a Severe Thunderstorm Anvil

A previous study in isolated storms in Florida shows that electric fields in thunderstorm anvils only a few kilometers from the main storm core are quite small (1-10 kV-m^{-1}). On May 30, 1982, the first flight into the downshear (leading) anvil of a multicellular severe storm was made with a free balloon carrying a standard radiosonde and a meter for measuring the vector electric field. The balloon entered the bottom of the anvil at a height of 5.5 km, about 65 km from the storm's main precipitation and updraft core. From the earlier Florida study, small electric fields were expected there. Instead a peak field of 94 kV-m^{-1} was measured between a negatively charged screening layer (at $\sim$5.5 km) and a thin ($\sim$600 m) positive layer at 7.3 km. Data transmission ceased at 8.6 km MSL (mean sea level) when the balloon was above the positive layer, and the field was still 75 kV-m. (The anvil top exceeded 13 km.) Such intense electric fields so far from the storm core suggest a significant probability of lightning strikes to aircraft flying through anvils and raise intriguing questions with regard to the distribution of charge and the production of lightning in the anvils of large storms.

Lightning in Squall Line Storms

Although the location of lightning flashes can be determined with a variety of techniques, the use of radar has been found to be a very effective way to locate intracloud portions of lightning. Radar is particularly well suited to the study of lightning in squall line storms, where the storm extent and propagation of lightning can exceed 100 km.[6] One excellent radar for this purpose is the uhf-band radar (ultra high frequency radar with transmitter wavelength of 70.5 cm) at the Wallops Flight Facility (WFF) in Virginia. The results from initial studies with this unique radar on the lightning structure in a squall line storm are summarized here.

The immediate need for determining the distribution of lightning activity with altitude was recognized when faced with the problem of how to guide the NASA F-106B research airplane into storms so that it would be struck by lightning as part of the NASA Storm Hazards Program.[7] An S-band radar was used to determine precipitation reflectivity while the uhf-band radar was used to locate lightning flashes in a manner depicted in Fig. 5. Both radars were operated in the RHI mode (range-height indicator mode of displaying radar data). The uhf-band radar was held at a constant azimuth while its elevation was stepped in 2.5 deg increments with acquisition for 30 s at each elevation step. The S-band radar was scanned continuously within the 2.5 deg azimuth sector of the uhf-band radar. A complete vertical scan of nearby storms with the uhf radar at a single azimuth usually took about 5 min. Presented here are the results of the observation of a storm situated south of WFF on August 11, 1982. This storm was one of several within a squall line. The lightning activity is characterized by the flash density, defined here as the number of flashes per minute observed in each kilometer interval along the radar beam ($\text{min}^{-1}\ \text{km}^{-1}$).

From 1403-1408 EST two centers of lightning density that are vertically separated were present in the storm. An example of lightning and precipitation structure is shown in Fig. 6. The lower center, at 6-8 km altitude, was associated with the leading (relative to storm motion) side of the 50-dBZ precipitation core, while the rear portion of this core had no lightning activity at all. The upper lightning density maximum was at about 13 km and near the top of the 40-dBZ reflectivity contour. During the period 1417-1423 EST, the upper lightning density maximum and the top of the 40-dBZ reflectivity region descended from 13.5 km to less than 12 km. The lower lightning density maximum was then found in both towers in the 50-dBZ reflextivity. In the third period, 1451-1456 EST, the upper lightning density maximum was again prominent at about 13 km. The lower maximum moved downward slightly and appeared to be associated with the heavy precipitation region (60 dBZ). These results clearly show the presence of two centers of lightning activity similar to that observed in the isolated storms in Oklahoma. The authors have observed that lightning activity in the upper regions of a storm is comparable to the activity in the lower regions, as measured by the number of vhf sources and the radar echoes from lightning. High-altitude lightning appear to be a hazard to aircraft operating in the upper portion of storms. Some confirmation of this is provided by the large number of strikes to the NASA F106B at high altitudes (temperatures of -30 to $-40°C$).

In other studies of lightning with radar, a squall line was observed in Oklahoma on May 20, 1980. There the authors used an L-band radar to locate lightning and observed 1055 flashes during a 46-min period. The IC:CG flash ratio was at least 40:1. With an S-band Doppler radar, the precipitation was also recorded in four cells along the squall line. From this study[4] the following can be inferred about lightning in squall lines: 1) there is a tendency for most lightning to have at least some portion of each flash near the leading edge of the precipitation core; 2) throughout the electrically active life of cells there are both short and long flashes (up to >100 km in horizontal extent); as a cell develops and lightning activity increases, shorter horizontal flashes predominate, while the longer ones dominate the activity as a cell dissipates; and 3)

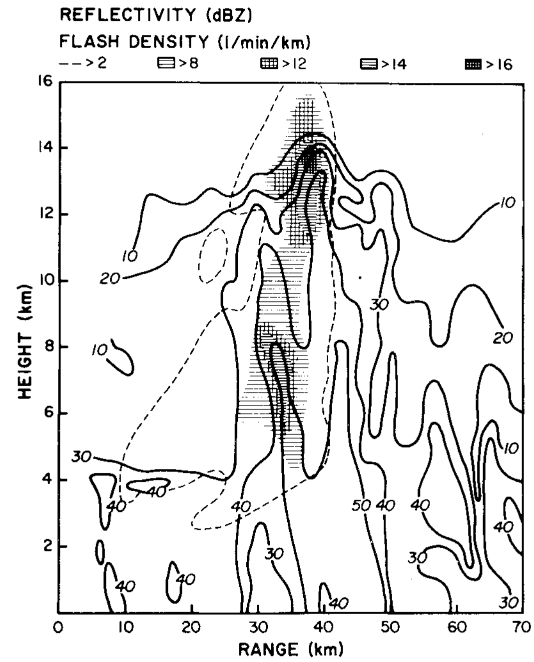


Fig. 6 Vertical storm structure and lightning flash density, August 11, 1982, for a 5-min interval. Solid lines are radar reflectivity in dBZ from the S-band radar. Lightning densities (see shading code at top of figure), obtained with the uhf radar at WFF.

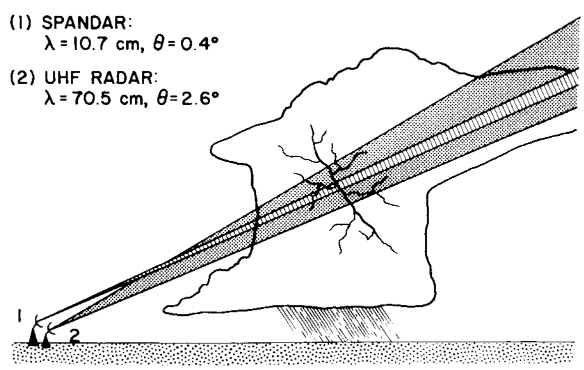


Fig. 5 Relative position of the antenna patterns of the S- and uhf-band radars used to map the vertical structure of storms and lightning.

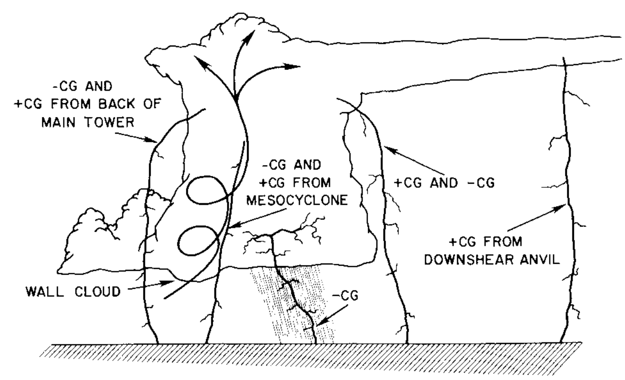


Fig. 7 Composite sketch of observed locations of CG flashes based on observations of 31 confirmed +CG and numerous −CG flashes in several isolated, severe storms.

lightning often propagates through low-reflectivity regions away from the precipitation cores.

Cloud-to-Ground Lightning in a Mesoscale Convective Complex

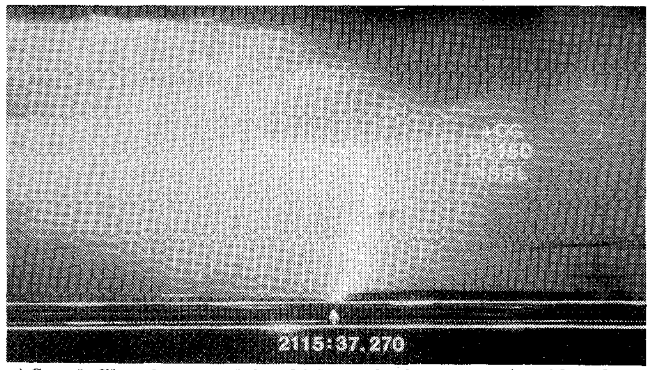
A mesoscale convective complex (MCC)[9] is a meteorologically significant event because it persists for many hours, covers large areas, can produce severe weather, often has large embedded storms and squall lines, produces large numbers of lightning flashes, is very hard to forecast, and affects aviation throughout the region in which it occurs. We have analyzed an MCC that occurred May 27-28, 1982. This MCC contained two easily identifiable squall lines that moved from Texas into Oklahoma. The CG lightning has been compared with visual and infrared satellite observations and with lightning measurements made by a NASA U-2 airplane that overflew portions of the system. For a period of 7 h, the average CG flash rate recorded in the MCC was 48 min^{-1}, with a minimum of 38 min^{-1} and a maximum of 61 min^{-1}. Obviously, if IC as well as CG lightning could have been recorded, the flashing rate for the MCC would have been even greater. From the U-2 overflights, it was also observed that CG lightning flashes have optical components at cloud top may tens of kilometers from the ground strike points. In analyzing CG flashes in several MCC's, it was found that CG rates appear higher than in other severe storms. For example, the CG flashing rate in the tornadic storm in Wichita Falls, Texas, in 1979 was 50 times less than a storm in this MCC. The total number of flashes to ground has varied by a factor of 3 in four MCC's, but appears to be independent of total MCC size.

Positive Cloud-to-Ground Flashes

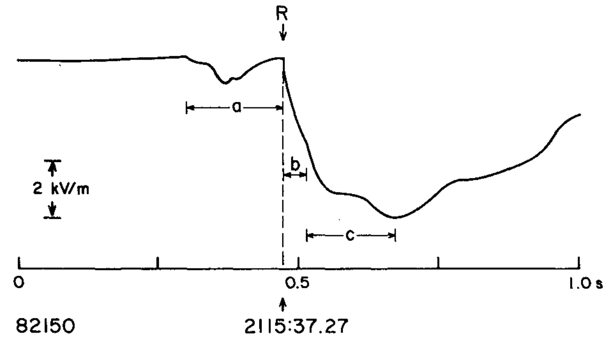
Prior to the late 1970's, most of the studies of flashes that lower positive charge to ground (+CG) were of flashes to tall structures. In these studies it was noted that positive flashes, while numbering only a few percent of all CG flashes, often had very large peak currents. These flashes were termed "triggered" because they had upward-propagating leaders from tall structures, rather than downward leaders from the cloud to the ground. It has been found, however, that +CG flashes are present during some isolated storms and squall lines and that they occur naturally by downward propagation from the cloud. Owing to their occurrence in both categories of storms and their possible importance to aviation, a summary of the characteristics of these flashes and their storm environments is presented here.

+CG flashes have been observed to emanate from regions of isolated severe storms as indicated in Fig. 7. Depicted in the figure is the classical supercell[10] thunderstorm. Of the CG flashes observed within isolated severe thunderstorms, only negative charge has been lowered to ground by flashes within the heavy precipitation regions. Those from under the upshear anvil at the rear of the storm and from the downshear (leading) anvil near the main storm tower can lower charge of either polarity, but usually lower negative charge. Of the few flashes observed to emanate from the mesocyclone, confirmed by the presence of a rotating wall cloud, two +CG flashes have been documented. Nearly all of the flashes to ground from the downshear anvil and well away from the storm tower have been positive. Most of the +CG flashes emerged from high in the storm, the notable exception being those apparently rare flashes from the lowered wall cloud.

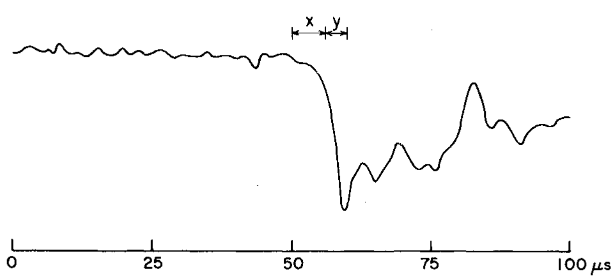
Single-stroke +CG flashes, which apparently are the vast majority of positive flashes, have a rather typical, but not unique, electrostatic field change[11] as shown in Fig. 8. Usually the flash shows substantial preliminary activity (averaging 240 ms) followed by a return stoke whose amplitude averages about one-tenth of the total field change. The presence of continuing current is suggested by the large, relatively slow field change after the return stroke.



a) Streak-film photograph in which continuing current is evident from the continuous smearing of luminosity. It lasts for about 60 ms; the associated continuing current field change can be seen in Fig. 8b from R to the first "break" in the curve, i.e., interval b.



b) Electrostatic field change for the flash shown above. The return stroke is labeled R and shows that it lowered positive charge. Interval a denotes the preliminary activity prior to the return stroke. Interval b is the confirmed continuing current, and c is either additional continuing current or subsequent intracloud breakdown.



c) A highly expanded electric field waveform for the return stroke, R. Interval *x* is the slow rise and *y* the more rapid rise to peak observed in both negative and positive CG flashes.

Fig. 8 +CG flash recorded at NSSL on 30 May 1982, approximately 2115:30 CST.

Simultaneous electric field, photographic, and television recordings have been obtained for a few +CG flashes, such as the example in Fig. 8. Notice the blurred channel luminosity that verifies continuing current is present during interval b of the field change. The four +CG flashes for which streak camera or TV images have been obtained show the presence of continuing current. Based on the high percentage of single-stroke +CG flashes that have very similar field changes and these few with confirmed continuing current, it is believed that continuing current is very common in +CG flashes. The high time resolution electric field waveform, recorded with a bandwidth of 1 MHz and shown in Fig. 8, has a zero-to-peak rise time of about 4 μs. Faster +CG return-stroke rise times have been observed, with the fastest in the submicrosecond range. Such fast rise times indicate the possibility of significant effects due to signal induction on aircraft wiring and circuitry by coupling through apertures.[12]

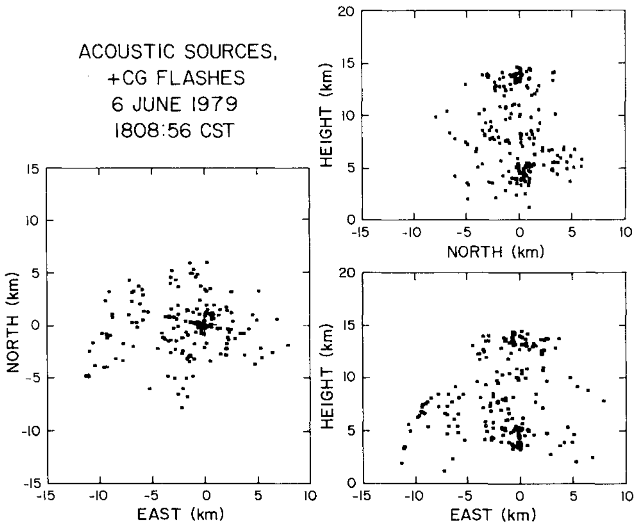


Fig. 9 Map of nearby thunder acoustic sources for +CG flash. Coordinates are relative to NSSL. Significant discharge activity extended to a height of about 15 km. The freezing level was at about 4 km.

TV recordings and photographs of several +CG flashes have also been obtained that clearly show downward branches, thus indicating downward leader propagation. Of the +CG flashes observed in Oklahoma storms, there is no evidence of upward propagation, which would be indicative of tall structure triggering. Thus, it appears as if +CG flashes do occur naturally to relatively flat terrain.

+CG flashes are found not only in the mature and late stages of supercells, but they have been observed also from the trailing side of squall lines. The locations of acoustic sources from two +CG flashes have been mapped using the thunder technique for mapping lightning channels.[13] Shown in Fig. 9 are the reconstructed, nearby thunder source locations for one of six positive flashes that occurred in the trailing part of a squall line during an 8-min period on June 6, 1979. From visual observations and a time-to-thunder measurement, it is inferred that the flash struck ground about 8 km west of the laboratory. Due to the range limitations of thunder recording, the horizontal extent of this flash probably exceeded 20 km indicated. Other, more qualitative, observations indicate that +CG flashes in squall lines propagate very long distances before coming to ground. Many thunder sources were located at or just above the freezing level, approximately 4 km above ground (or 4.7 km MSL). However, there were a significant number of sources, and therefore, channels, above 11 km.

Data from an NSSL Doppler radar show that the acoustic sources lower than 5 km were located in reflectivities of <17 dBZ, while those above 11 km were located in even weaker reflectivities of <9 dBZ. The portion of this flash containing the channel to ground was tens of kilometers from the closest large precipitation core of ≥ 50 dBZ, and the flash came to ground beneath the broad region of light precipitation behind the squall line.

There are several aspects of +CG flashes in need of further study to ascertain to what extent they pose a threat to aviation. Areas for study include: 1) the presence of very fast return stroke rise times, 2) the presence of large peak currents, 3) the frequent occurrence of continuing current in the return stroke channel, 4) the tendency for the +CG flashes to be in low-reflectivity regions of squall lines and anvils, both of which can appear relatively innocuous on radar displays, and 5) their very large spatial extent.

Concluding Remarks

We believe that several facets of our research are relevant to lightning hazards to aviation. Study areas the authors are currently addressing include: 1) peak currents and rise times in channels of both −CG and +CG flashes, 2) assessment of whether +CG flashes pose unusual hazards, 3) lightning location relative to turbulence and updrafts within storms, 4) the location of lightning relative to storm features in different storm types, and 5) procedures for real-time guidance of research aircraft.

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