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The Relationship Between Lightning Type and Convective State of Thunderclouds

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Thunderstorm case studies and earlier observations are described which illuminate the relationship between cloud vertical development and the prevalence of intracloud (IC) and cloud-to-ground (CG) lightning. A consistent temporal evolution starting with peak IC activity changing to predominant CG activity and concluding with strong outflow (microburst) suggests that ice is responsible for both the electrical (i.e., lightning) and dynamical (i.e., microburst) phenomena. The IC activity is attributed to the updraft-driven accumulation of graupel particles in the central dipole region, and the subsequent CG activity to the descent of ice particles beneath the height of the main negative charge. The subsequent descent and melting of ice particles beneath the height of the 0°C isotherm are associated with the acceleration of the downdraft and outflow. The IC lightning precursor can provide a valuable short-term (5–10 min) warning for microburst hazard at ground level.

1. INTRODUCTION

Convective storms are well recognized to produce two common types of lightning: intracloud (IC) and cloud to ground (CG). Some convective storms are recognized to produce strong downdrafts, often referred to as microbursts, which have been demonstrated to pose a severe hazard to commercial aviation [*Fujita*, 1985]. This study was initially concerned with a search for a practical short-term precursor to the microburst hazard in the cloud electrical development. In the course of this investigation, consistent relationships between the stage of the convective activity and the lightning type became apparent, and tied in closely with earlier electrical observations of thunderstorms and with contemporary observations of microburst precursors in Doppler radar observations [*Campbell*, 1988]. This paper is concerned with a description of these relationships and with an interpretation based on ice-phase microphysics.

2. OBSERVATIONS

Radar and electrical observations of thunderstorm microbursts were carried out in Huntsville, Alabama, during the spring and summer of 1987. Measurements of radar reflectivity and mean Doppler velocity were obtained with the Massachusetts Institute of Technology (MIT) C-band Doppler radar (λ = 5.4 cm, BW = 1.4°, P_τ = 250 kW, pulse repetition frequency (PRF) = 921 Hz). The cloud electrical activity was monitored with an array of 10 corona points. The 1-Hz sampling rate allows sufficient resolution to record the discontinuities associated with both IC and CG lightning. The threshold electric field necessary to initiate corona current limits the detection range of these sensors to 10–15 km for isolated thunderclouds. This feature was found to be beneficial, for in horizontally extensive storms it confined the lightning events to the region over the array where microburst detection with the radar was best defined.

The investigation of the CG subset of the total lightning rate (CG and IC lightning cannot be differentiated unambiguously on the basis of corona point records alone) was made possible by the East Coast Lightning Network [*Orville et al.*, 1983]. The detection efficiency of this network in the vicinity of Huntsville is estimated to be 80%. The accuracy in CG location (5–10 km) is usually sufficient to assign lightning events to a particular storm identified by radar.

3. CASE STUDIES

The microburst-producing clouds in this study were almost invariably air mass thunderstorms in weakly sheared environments and exhibited peak lightning rates greater than or equal to three flashes/min. The IC lightning dominated over CG lightning in the early stages of vertical development. The observed temporal relationship between the peak lightning rate and the peak outflow velocity was very systematic in the storms studied. The evolution of total lightning rate, CG lightning rates (all events located within 20 km of the Doppler radar), and maximum differential velocity at the ground are recorded for several case studies, which are discussed briefly in chronological order. The velocity differential across all outflows reported here exceeded 20 m/s. A headwind-tailwind change of 10 m/s is of concern to commercial aviation, while the largest microburst velocity differentials observed by Doppler radars have been roughly 40–50 m/s. All lightning rates were tabulated in 1-min time intervals. All microbursts studied were classified as "wet"

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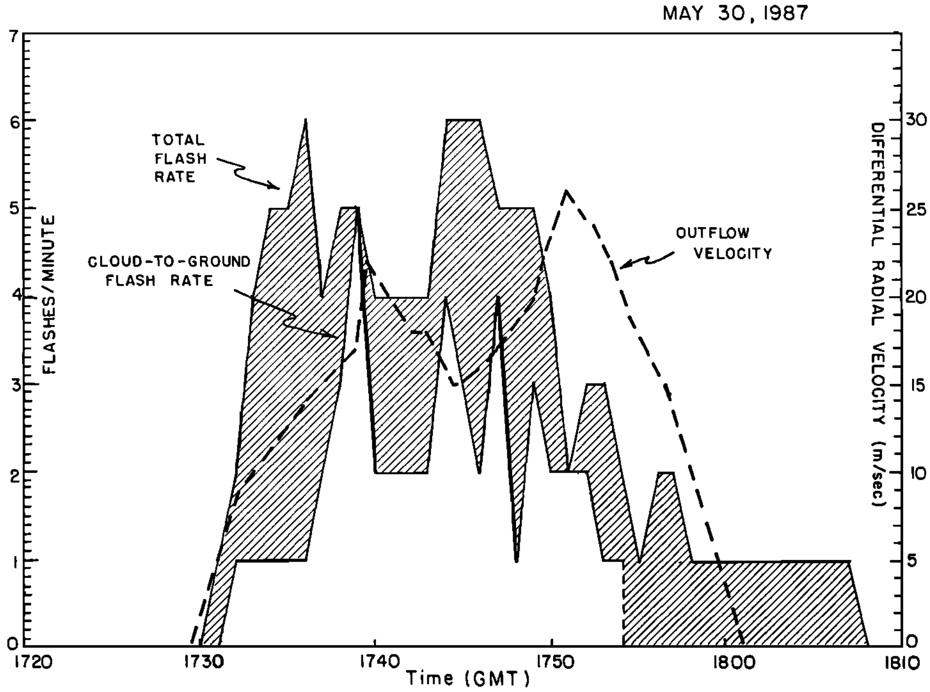

Fig. 1. Evolution of total lightning flash rate, cloud-to-ground flash rate, and differential radial velocity associated with the double microburst on May 30, 1987.

(surface reflectivity ≥30 dBZ) and were characterized by low-level reflectivity values of 55–65 dBZ.

May 30, 1987

As shown in Figure 1, this air mass thunderstorm, situated on the northwest edge of the corona point network, produced an outflow with a double maximum. The total flash rate increases rapidly (at a rate of 1 flash/min/min) after 1730 UT, and exceeds the CG rate by fivefold. The peak in total lightning rate leads the initial outflow maximum by 4 min. A well-defined peak in CG lightning is associated with this initial outflow, and at this time the CG component dominates the total lightning activity. A second peak in total lightning (1746 UT), again dominated by IC activity, precedes the second outflow by 7–8 min. Both types of lightning have diminished by this time (1752 UT), but again the CG component is more prevalent on a relative basis.

The peak flash rates of 6 min^{-1} were typical for the Huntsville storms whose maximum radar cloud heights were almost invariably in the range of 13–14 km msl; the environmental air temperature at this altitude was −65°C to −70°C.

June 1, 1987

This long-duration outflow has a somewhat broader maximum (peak value 23 m/s) which lags the initial IC activity by about 8 min, as shown in Figure 2. Again the IC rate dominates the CG rate by factors of 3–7. The largest CG rate (two flashes/min) is roughly centered on the time of maximum outflow (1804 UT). Earlier lightning activity (1740–1750 UT) was associated with other nearby cells which did not exhibit microburst activity.

June 23, 1987

The cell which produced this microburst was embedded in a widespread area of reflectivity to the west of the network, and the total lightning rate was obtained on the basis of a single corona point record. The evolution of parameters is shown in Figure 3. In this example, a sufficient number of range-height indicator (RHI) scans was obtained to follow the evolution of radar cloud top height as well, and this information is included in Figure 3. The peak lightning rate (four flashes/min) occurs at 0018 UT, at approximately the time of cloud top apogee. The outflow develops in close association with the descent of the cloud top. The maximum outflow velocity (23 m/s) lags the peak flash rate by 7 min. Again, CG activity is generally more prevalent during the later outflow stage than during the earlier upward development.

July 20, 1986

The systematic electrical outflow behavior illustrated by the case studies described thus far is further supported by independent analyses [*Fujita and Black*, 1988; *Goodman et al.*, 1988] of an isolated thunderstorm in the same location but one summer earlier. Figure 4 shows the time-height evolution of this storm, taken from *Fujita and Black* [1988], but supplemented with additional information related to this study. The approximate height of the −10°C isotherm is shown as an indication of the height of the main negative charge region [*Krehbiel*, 1986]. Also shown in Figure 4 are the evolution of the 0 and 56 dBZ reflectivity contours, and Doppler radar-derived estimates of the motions of precipitation particles. The maximum vertical development occurs at about 1317 UT, and it is therefore little surprise that the peak total lightning rate (23 flashes/min) occurs at 1317–1318 UT [*Goodman et al.*, 1988]. This time precedes the microburst "touchdown" by 3 min, and precedes the maximum outflow by 6 min. All CG lightning occurs after the initial IC activity at 1313 UT.

The systematic nature of this phenomenon is further substantiated by overall microburst statistics from the 1987 Huntsville study. During 4 months of observations (May–

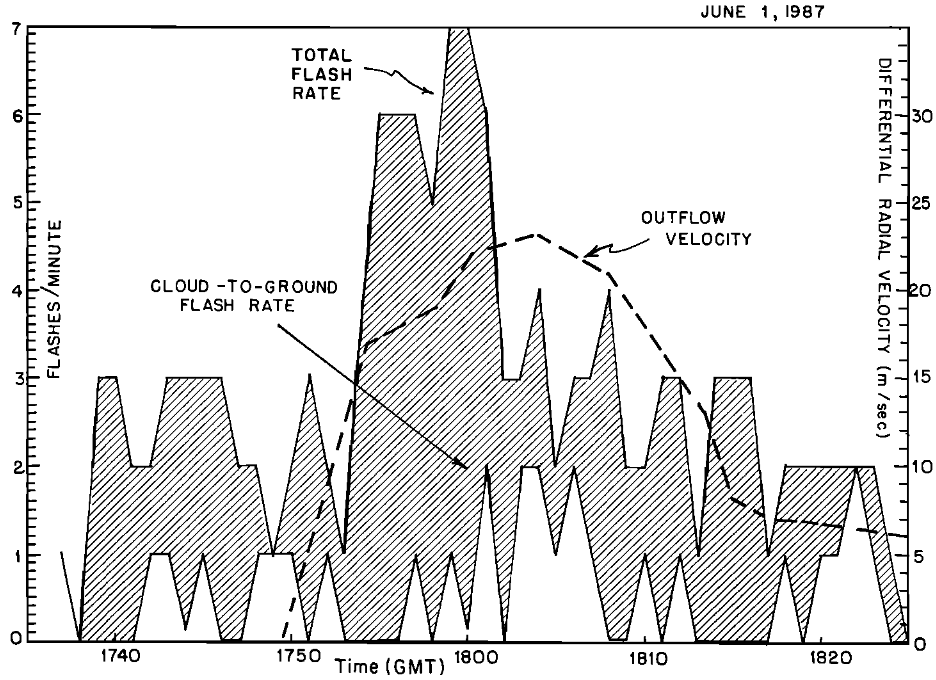

Fig. 2. Evolution of total lightning flash rate, cloud-to-ground flash rate, and differential radial velocity associated with the outflow on June 1, 1987.

August), 25 microbursts were observed in thunderstorms within 10 km of the Doppler radar. Only about 10 of these were sufficiently close to corona point stations to permit electrical documentation. All but one of the latter set of storms exhibited the intracloud lightning precursor. The exception had a radar top of only 11–12 km and produced only three lightnings (all intracloud). A 50-dBZ echo was observed above the melting level 5 min prior to the time of maximum outflow in the latter case.

Lightning was also observed in storms for which no microbursts were detected. These storms either showed modest development above the melting level, with lightning rates of two flashes/min or less, or showed substantial vertical development with high lightning rates in strongly sheared environments. All Huntsville squall lines were in the latter category; the individual cells of a line displayed symmetrical outflows only infrequently.

4. Similar Features in Earlier Results

Emphasis in the Huntsville observations reported here was placed on the identification of electrical precursors to hazardous thunderstorm outflows at ground level. The atten-

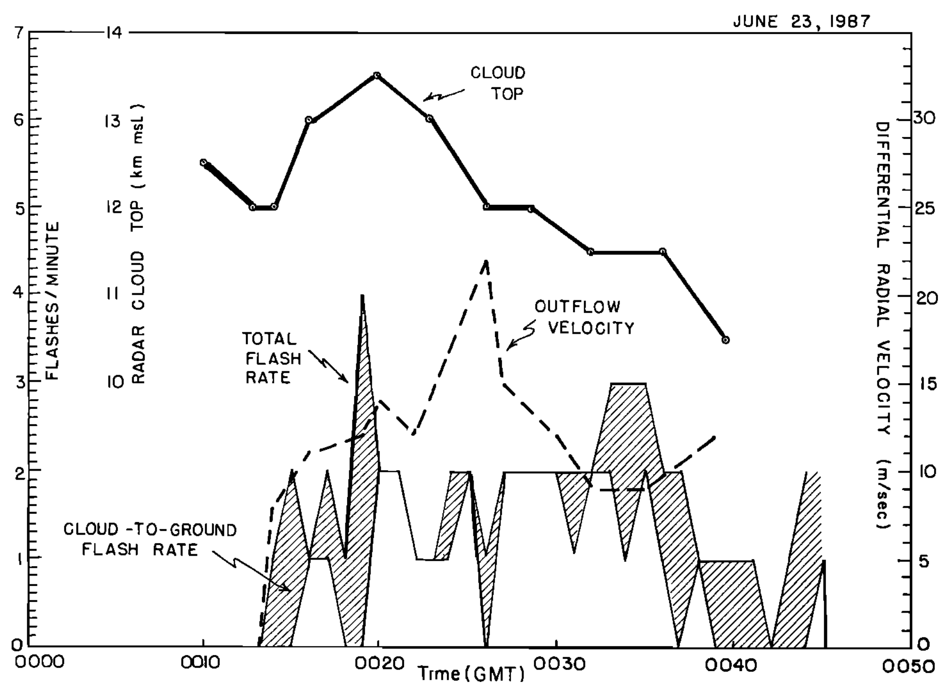

Fig. 3. Evolution of total lightning flash rate, cloud-to-ground flash rate, differential radial velocity, and radar cloud height associated with the microburst on June 23, 1987.

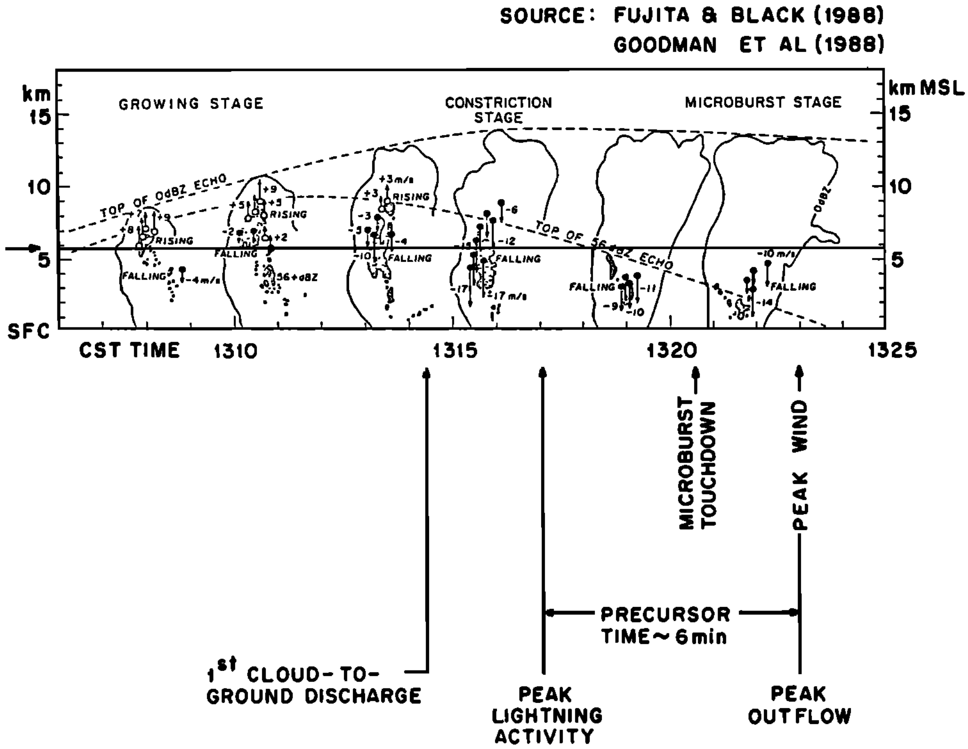

Fig. 4. Time-height evolution of isolated microburst-producing storm on July 20, 1986, studied by *Fujita and Black* [1988] and *Goodman et al.* [1988]. The height of the −10°C isotherm is shown as a rough lower boundary for the central dipole region of the cloud. The time of peak intracloud lightning rate (and peak total lightning rate) is also indicated.

tion naturally focused on storm dynamical features which were not investigated in earlier case studies. Nonetheless, an examination of the earlier published results shows considerable consistency with the present results and supports the thesis that lightning type is strongly influenced by specific features of the convective development.

Workman and Reynolds [1949] documented the consistent precedence of IC lightning during the upward development of convective clouds in New Mexico. The initial IC flash preceded the initial CG flash by 6 min. The first CG flash is shown to appear several minutes into the slumping phase of the radar echo aloft. *Brook and Kitagawa* [1960] show examples of the evolution of IC and CG lightning in New Mexico thunderstorms. Cyclic variations are evident, in which a period of high IC activity and low CG activity is followed immediately by a period of low IC activity and high CG activity.

An examination of lightning detection and ranging (LDAR) data in *Lhermitte and Krehbiel* [1979] indicates that as many as 15 IC flashes precede the first CG flash in the initial stage of a Florida storm. In a second and more vigorous stage of convective development, LDAR radiation sources associated with IC lightning rise in parallel with the vertical development. The later (≈3 min) onset of CG lightning is well correlated with the initial descent of the 55-dB*Z* reflectivity core beneath the level of (inferred) main negative charge. The velocity field associated with this descending reflectivity feature was not investigated, but in light of the Huntsville observations, it appears likely that a strong outflow was produced by this storm.

MacGorman et al. [1986] have investigated IC and CG lightning in a substantially larger storm in Oklahoma which exhibited a mesocyclone and tornado. The IC lightning activity was associated with the tornado period and presumably the period of greatest vertical development and convective vigor. The later decline in IC activity is accompanied by an increase in CG activity. The analysis of radar reflectivity evolution at various heights suggests that large quantities of ice are descending at levels at and below the (inferred) height of main negative charge during the period of predominant CG activity.

Doppler radar studies of a New Mexico thunderstorm [*Lhermitte and Williams*, 1984] show a peak total lightning rate well correlated with the vertical development aloft, and a subsequent descending reflectivity core which arrives at 0 km msl (by extrapolation of the observations) 8–10 min after the peak lightning rate. This time is consistent with the observations in Huntsville described earlier.

Photogrammetric studies of cloud top variations in New Mexico [*Atchley et al.*, 1983] show that cloud top maxima systematically lag the times of peak lightning activity, again supporting the role of upward development in promoting the electrification. Peaks in rain intensity at the ground (3.2 km msl) lag the lightning peaks by about 5 min. An energetic CG discharge with multiple ground contact points occurred in the same storm during a period of cloud top descent as observed with a vertically pointing Doppler radar.

Poehler [1978] correlated CG lightning and radar cloud top variations in a storm in Florida. His results show a peak in CG activity 8–10 min after the time of maximum radar cloud top. IC lightning was not included in this analysis.

The Krehbiel "wedge" storm occurred at Kennedy Space Center on August 8, 1977 [*Krehbiel*, 1981]. The consistency in the inferred heights of the negative charge region constitutes the best single piece of evidence for the constant-altitude nature of this region. The first 13 lightning events in

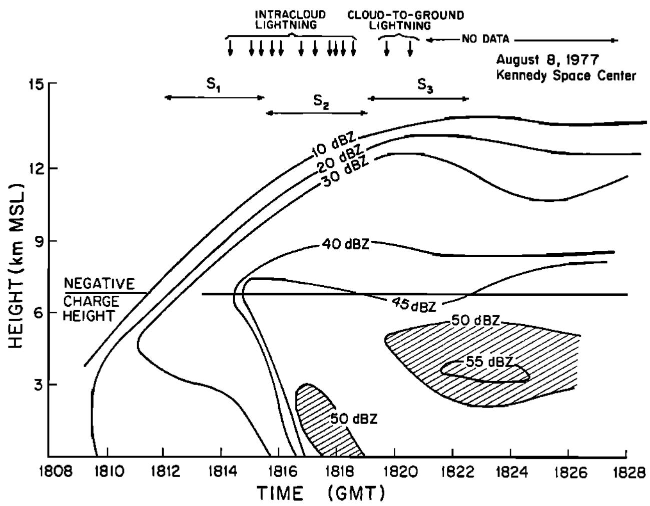

Fig. 5. Time-height evolution of maximum radar reflectivity for the storm on August 8, 1977. Times of IC and CG lightning are indicated.

this storm are well documented by *Krehbiel* [1981]. *Lhermitte and Williams* [1985] subsequently analyzed this storm with triple Doppler radar data. A time-height plot of maximum radar reflectivity (from the NCAR C-band radar) for comparison with the lightning events is shown in Figure 5. The S_1, S_2, and S_3 denote the three periods of triple Doppler analysis. The first 11 discharges are all IC and fall within the developing (S_1) and mature (S_2) stages of the storm. The precipitation particle motions are upward within the initial dipole region throughout the period of intracloud activity. The peak lightning rate at 1818 UT occurs 2 min prior to the time of maximum vertical extent of the 30-dBZ contour. The first CG discharge occurs just as the reflectivity core (above the negative charge height) begins to descend, and larger reflectivity appears at still lower levels (beneath the main negative charge region). This overall behavior bears a close similarity to the earlier results, particularly the evolution depicted by *Fujita and Black* [1988] in Figure 4. The Florida storm may well have produced an outflow after 1828 UT, but such features were not investigated in this earlier study. It is important to note that large reflectivity appeared at lower levels at an earlier time (1816 UT) but was not accompanied by CG lightning. Nor did the associated precipitation originate above the height of the negative charge region, as it almost surely did in the Huntsville microburst examples.

5. Discussion and Interpretation

In the observed systematic relationships between the vertical development of thunderclouds and the prevalent lightning type, it is useful to consider prototype electrostatic structures believed responsible for the two dominant lightning types (IC and CG). Structures originally advocated by *Wilson* [1916] and by *Simpson and Scrase* [1937] are illustrated in Figure 6. These two structures are denoted "dipole" and "tripole," respectively.

A conspicuous electrical feature of thunderclouds is the main negative charge region, which is basic to both dipole and tripole structures in Figure 6. The results of a number of studies suggest that the main negative charge region is correlated with temperature and is 6 km or more from mean sea level. Balloon soundings indicate that the largest vertical fields in thunderclouds are encountered at the upper and

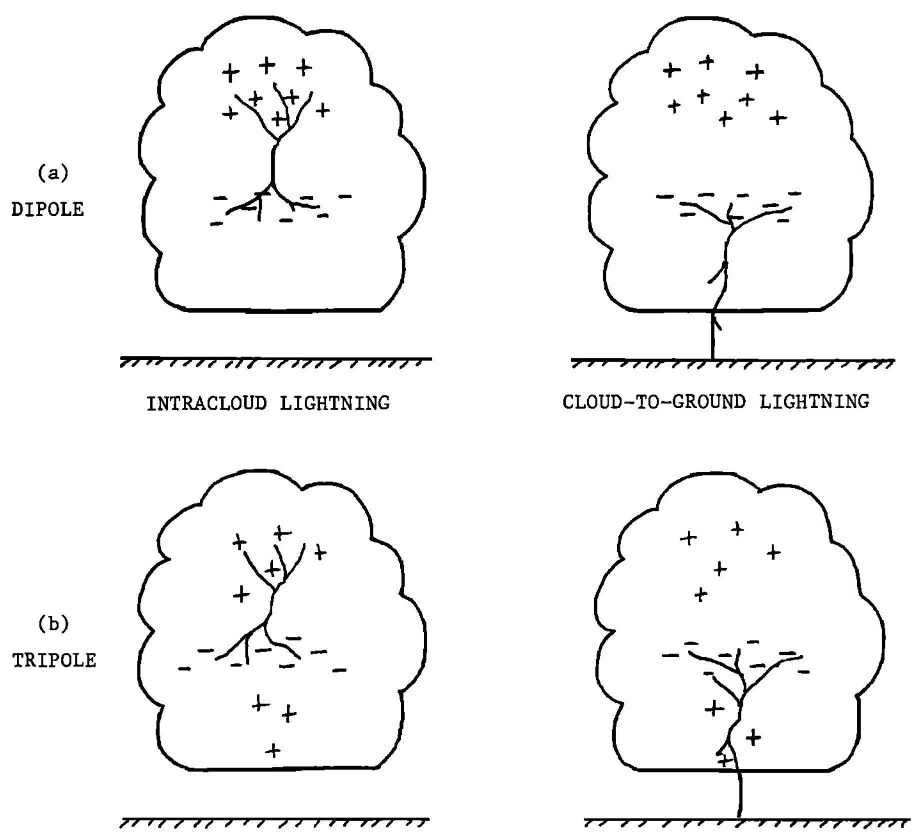

Fig. 6. Depiction of IC and CG lightning in prototype electrostatic structures: (*a*) dipole and (*b*) tripole.

lower boundary of this thin (≤1000 m), stratified region. Evidence from VHF radiation studies [*Krehbiel*, 1981; *Taylor*, 1983] is consistent with the idea that IC and CG lightning are initiated at the upper and lower boundary, respectively, of the main negative charge layer. The time-averaged prevalence of IC lightning is consistent with the balloon observations which show significantly larger vertical fields above this layer than below it [*Weber et al.*, 1982; *Winn et al.*, 1983; *Byrne et al.* 1983, 1987].

There seems little doubt that both the magnitude of the electrostatic field and the distribution of dielectric strength will influence the origin of breakdown and the lightning type. To the extent that dielectric strength is controlled by air density, we again expect a bias for IC discharges at the higher altitude in either the dipole or tripole structure. To the extent that dielectric strength is controlled by precipitation particles, we may expect a bias for CG lightning, in light of the radar observations that the reflectivity associated with precipitation is often diminishing with height at the level of the main negative charge.

The fundamental role of lower positive charge in provoking CG lightning is an old concept [*Clarence and Malan*, 1957]. Qualitative observations of electrical discharges in laboratory-scale space charge structures [*Williams et al.*, 1985] support it. Laboratory discharges were never observed to initiate and propagate away from the edges of unipolar regions of concentrated space charge (as depicted for the dipole-embodied CG discharge in Figure 6*a*) when the initial electrostatic field diminished away from the boundary. However, once discharges had intruded a space charge region of opposite polarity, they were observed to progress for a considerable distance, in some cases the full extent of the space charge region.

The simple dipole structure in Figure 6*a* is often assumed in studies of the charge redistribution by lightning [*Jacobson and Krider*, 1976; *Krehbiel et al.*, 1979; *Krehbiel*, 1981]. It can be shown, however, that these methods are not particularly sensitive to the participation of lower positive charge in lightning unless the field change sensors are very close to the positive charge region [*Williams*, this issue]. When the sensors are close, the lower positive charge manifests itself [*Jacobson and Krider*, 1976; *Poehler*, 1978]. The observations of lower positive charge in thunderclouds [*Simpson and Scrase*, 1937; *Kuettner*, 1950; *Marshall and Winn*, 1982; *Holden et al.*, 1983] show localized structures which may not be well resolved by coarsely spaced field sensor networks.

Local field excursions (from foul weather polarity to fair weather polarity and back again) associated with precipitation (FEAWPS) and downdrafts are observed beneath thunderclouds [*Moore and Vonnegut*, 1977]. Similar phenomena have been observed associated with microbursts in the Huntsville studies [*Weber et al.*, 1987] when the outflow occurs sufficiently close to a corona point sensor. FEAWPS appear to be the electrical manifestation of microbursts and are not accounted for by the simple dipole structure, in Figure 6*a*, with dominant negative charge in the lower part of the cloud.

The peak lightning rate systematically leads the maximum outflow velocity for all but one microburst observed in the Huntsville study, as noted earlier. A consideration of the present results together with the results of earlier studies indicates that the peak electrical activity is well correlated with the cloud vertical development, as quantified variously with radar cloud height, updraft velocity, and radar reflectivity at upper levels. The very consistent temporal relationships between the electrical phenomenon (i.e., the lightning) and the dynamical phenomenon (i.e., the microburst) suggest that the two phenomena have a common cause. Evidence will be presented that this common cause is ice.

A considerable body of evidence has developed, from both field and laboratory studies, that collisions between graupel particles and ice crystals are responsible for the separation of charge which accounts for the main positive dipole. This evidence is reviewed elsewhere [*Williams*, this issue]. IC lightning appears to be most invigorated in the presence of a well-developed updraft in which all the particles (ice crystals, supercooled droplets, and graupel) are moving upward relative to the ground [*Lhermitte and Williams*, 1985], and a particle "balance level" manifests itself at midlevels ($H \approx$ 6–7 km; see, for example, Figure 4, 1309–1314 UT). When the balance level finally disappears, and the ice particles aloft begin to descend, the IC rate (and total lightning rate) slackens. Millions of kilograms of ice are now free to descend and melt on traversing the 0°C isotherm, thereby absorbing the latent heat of fusion. The induced negative buoyancy may be the predominant drive for microburst formation. A simple comparison of the latent heat energy (LM) and the gravitational potential energy (Mgh) of this mass M of ice particles, shows that LM is greater by about a factor of 5. Here we have assumed that all the ice melts prior to reaching the ground, an assumption validated by many observations in the Huntsville area.

The role of melting in driving convective-scale downdrafts is an old idea [e.g., *Normand*, 1946] but often gets less attention than evaporation because of the large contrast in the latent heats of vaporization and melting. The rate of cooling for these two processes is, however, inversely proportional to the respective latent heats; on a particle-by-particle basis, the rate of cooling due to melting exceeds that due to evaporation even at relative humidities as small as 40%. This result is manifest in the numerical calculations of *Srivastava* [1987].

In addition to the electrical observations reported here, a fundamental role for ice in microburst formation is supported by the finding (in the Cooperative Huntsville Meteorological Experiment (COHMEX) and, more recently, in Darwin, Australia) that Doppler radar-observed outflows are uncommon from convective clouds with large reflectivity (50–60 dB*Z*) but inappreciable development above the melting level. All clouds showing large outflows in this study exhibited substantial reflectivity above the melting level, and this aspect we link with the electrical activity.

The average precursor interval (time between peak lightning rate and peak outflow) observed in the various case studies is 7 min. The downward mean Doppler velocity of the ice particles is 10–15 m/s (see Figure 4), so in this time they will fall a distance 4.2–6.3 km. The largest graupel and hail particles will fall at a larger velocity. The resulting displacements are in agreement with the inferred height of the main negative charge center.

The later stage diminishment of IC activity and predominance of CG lightning in the various case studies we attribute to the diminished ice content of the central dipole region and the descent of large numbers of graupel particles beneath the main negative charge region. Both laboratory [*Takahashi*, 1978; *Jayaratne et al.*, 1983; *Illingworth*, 1985] and field measurements [*MacCready and Proudfit*, 1965; *Marshall and Winn*, 1982] suggest the graupel particles will acquire positive charge at levels beneath the main negative charge. The gravitational power associated with the falling positively charged precipitation may promote CG lightning, in agreement with the observations reported here. Further evidence for this interpretation is presented by *Williams* [this issue].

From the practical standpoint of using lightning activity as a precursor to microburst hazard at low levels, these observations and interpretations make it clear that IC rather than CG activity is the superior precursor. A well-defined peak in activity will be more difficult to detect in the comparatively infrequent CG lightning component.

6. CONCLUSIONS

Comparisons between the lightning type and the convective state of thunderclouds in a variety of geographical environments and storm types show three main points of consistency.

1. The IC lightning dominates in early stages and is well correlated with the upward development of the cloud, the growth of ice particles, and radar reflectivity above the inferred negative charge region. Ten or more IC flashes may occur before the first CG event. Precipitation particle velocities are upward in the central dipole region, by virtue of the existence of strong updrafts in the upper part of the cloud.

2. CG lightning activity (less frequent than IC) lags the initial IC peak by 5–10 min, although this behavior is somewhat less systematic than the intracloud behavior. The contours of radar reflectivity aloft are now flat or descending with time. By this time the initial CG activity is associated with the descent of precipitation particles (hail and graupel) beneath the main dipole of the cloud.

3. Strong outflows at ground level in thunderstorms (i.e., microbursts) lag the peak lightning rate (dominated by IC events) by a time of 5–10 min.

The preliminary interpretation of these three observations is as follows.

1. The IC lightning is the result of charge separation by ice particle collisions and differential motions in the upper dipole region. Negative charge is selectively transferred to the larger particles in this region.

2. While negative charge accumulates at midlevels, it may not be energetically favorable to transfer negative charge to ground in CG lightning. The cloud-to-ground lightning may be stimulated by the subsequent descent of ice particles through the level of the main negative charge and the action of charge reversal microphysics which endows the larger ice particles with positive charge. The lower positive charge results in the bias which allows for negative charge transfer to ground in CG lightning.

3. The melting of descending ice particles and the induced negative buoyancy are responsible for accelerating the downdraft and producing the outflow at low levels. The observed 5- to 10-min interval is required for ice particles to transit the distance between the main negative charge region and the ground.

The detection of total lightning activity in deep thunderstorms in weakly sheared environments provides one simple short-term warning for microburst hazard at low levels. In a practical wind shear warning system, this electrical information would be combined with radar-detectable precursors to enhance the probability of a successful forecast. Development and evaluation of this combined wind shear warning approach are under way as one application of the physical relationships described herein.

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