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Notes and Correspondence

Comments on the paper 'The electrification of thunderstorms' by John Latham (Q. J. April 1981, 107, 277–298)

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Future studies of the charged particles in thunderclouds and how they are carried about by the movement of the air may eventually justify Latham's statement (1981), that the convective process is unlikely to be of importance in thunderstorm electrification. The arguments on which he bases this conclusion do not.

His premise, that strong electrification and lightning can take place in a developing storm before the space charge produced by corona from the ground could be carried by updraughts into the upper part of the cloud, is undoubtedly correct. His conclusion, that the convective mechanism would therefore be incapable of producing lightning in the absence of corona-produced space charge from the ground, is unwarranted.

According to the convective mechanism, the primary electrification process takes place on the upper surface of the cumuliform cloud at the discontinuity in electrical properties between the clear air about the cloud and the cloud itself. Under the influence of an electric field, ions move freely in the clear air about the cloud. However, inside the clouds the ions rapidly become attached to the water substance particles of the cloud and thereby lose their mobility. This process results in the formation of a screening layer (Brown *et al.*, 1971) that is carried to lower levels and accumulates to form a region of charge within the cloud.

In the original presentation of this idea, Grenet (1947) suggested that the electric field at the upper cloud surface responsible for the movement of the ions was produced by fair weather space charge from lower levels carried by updraughts into the cloud. He showed that the resultant process could be capable of producing lightning through the action of electric fields produced at the top of the cloud by this charge alone. Later, Vonnegut (1955) independently proposed the same mechanism and suggested, in addition, that space charge produced by other sources, such as falling precipitation and point discharge from corona, could also provide important contributions to the electric field at the top of the cloud. While sources of space charge other than corona may play the primary role in the early stages of convective electrification, there is reason to suppose that space charge produced by corona could become important later on.

The experiments carried out in central Illinois (Vonnegut *et al.*, 1962) show that positive space charge released near the ground from a horizontal wire maintained at a high voltage is readily carried by updraughts into the upper portions of fair weather cumulus clouds and causes them to become weakly electrified. There is reason to suppose that the same process would take place in a thunderstorm and that the much larger flux of space charge produced naturally by corona from objects on the ground would eventually also be carried by updraughts into the upper cloud. Here it would supplement other sources of positive space charge and help to maintain and intensify the electrification of the mature thunderstorm.

Latham's suggestion, that in the absence of corona the electrification process would ultimately become self-extinguishing, may well be correct. Because much higher electric fields are required to produce corona over water than over land (Toland and Vonnegut, 1977; Griffiths *et al.*, 1973), it is probable that corona may not take place under many maritime thunderclouds. The absence of a continuous flux of corona-produced positive space charge when the storm is over water may be one of the reasons that less lightning is produced over the oceans than over land as has been reported by Orville (1981).

Latham does not state why he concludes that the convective electrification process is incompatible with his Fig. 7. Presumably it is because he doubts that downdraughts would be capable of carrying the negative charge arriving at the top of the cloud down to the locations where negative charge is shown in his illustration. Conceivably he may be correct. Future studies of the circulation in the upper portion of the cumulus may show that the descending currents of air on the upper surface of the cloud do not penetrate this far down into the cloud. At present, however, this is not precluded by what is known about thunderclouds. In fact, there are various pieces of evidence to

suggest that downdraughts would be capable of carrying negative charge and causing it to accumulate in the locations illustrated in Fig. 7.

Measurements made from high altitude aircraft show that the strong electric fields above thunderclouds are confined to the overshooting cumuliform towers penetrating into the stable atmosphere above the anvil (Vonnegut *et al.*, 1966). The fact that the cloud is able to sustain these strong electric fields for many minutes even though the electrical relaxation time at these altitudes is of the order of tens of seconds suggested that the convective motions of the upper cloud surface are carrying away the negative charge brought by conduction as fast as it flows to the surface of the cloud.

Time lapse motion pictures made looking down on clouds from high-altitude balloons (Vonnegut and Atkinson, 1958) show a divergent flow on the cloud top. This would be capable of carrying the charge that arrives on the cloud surface radially outward and then downward on descending currents of air at the outer surfaces of the cloud turret.

Airplane traverses at 13 km through a thunderstorm cloud whose top was at 15 km show downdraughts reaching speeds as high as $35\,\mathrm{m\,s^{-1}}$ (Steiner and Rhyne, 1962), presumably produced by descending air from overshooting turrets. Such strong downdraughts carrying space charge should be capable of penetrating deeply into the cloud before they lose their momentum.

Experiments with artificially electrified clouds simulating the circulation in the top of an overshooting cumulonimbus turret demonstrate phenomena predicted by the convective electrification mechanism. Laboratory experiments conducted with a dense cloud of electrified water droplets suspended in gaseous carbon dioxide (Eden and Vonnegut, 1965) demonstrate that under stratiform conditions negligible electric currents flowed from ionizing electrodes suspended above the cloud. When convective circulation similar to an overshooting cumulus cloud was introduced into the cloud, a continuous flow of current occurred. This current, analogous to that flowing to the thunderstorm from the electrosphere, is predicted by the convective mechanism.

Similar experiments on a much larger scale (Vonnegut *et al.*, 1962) were carried out by inoculating fair weather cumuli approximately 2 km in height with artificially produced positive space charge. As predicted by the convective mechanism, negative charge was attracted to the upper cloud surface and then carried to lower levels by downdraughts.

In comparison with the thunderstorm, the artificially produced electrification of the fair weather cloud was trivial in intensity. However, if the rate of electrical energy production varies by as much as the fifth power of the cloud dimensions (as has been suggested by Vonnegut (1963)), there is reason to believe that in a large thundercloud convective electrification could be adequate to produce lightning.

It is not sufficient that a theory describe only the electrical currents responsible for causing lightning. Any theory, to be considered satisfactory, must also describe the other electrical currents that are associated with the thunderstorm (Vonnegut, 1963). Particularly important are the charge motions that maintain the global fair weather electrical process by transferring negative charge from the upper atmosphere to the earth (Wilson, 1920).

To repeat an earlier query (Vonnegut, 1965), 'If Dr. Latham and proponents of electrification mechanisms based on the falling of charged precipitation find the assumed patterns of charge movement in the convective mechanism elaborate or improbable, what alternative explanation do they propose for what happens to the negative charge carried to the top of the cloud by the conduction current and to the positive charge released from the earth under the cloud by point discharge?'

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Reply by J. LATHAM

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Dr Vonnegut's long-standing, lucid and balanced advocacy of the convective theory of thundercloud electrification has been, in my view, extremely helpful to fellow-scientists in that it has provided the sceptical and self-critical climate necessary for unequivocal resolution of this challenging problem.

I would agree with him that a definitive explanation has not yet been provided – and I would not seek either to minimize the crucial role of convection in charge transport or to assert that the convective mechanism does not contribute to field-growth within thunderclouds. However, for the reasons outlined below, I feel that the circumstantial case for the general dominance of a precipitation-based mechanism involving ice is strong.

Figure 7 in my paper is a reproduction from Krehbiel *et al.* (1980) which demonstrates that the negative charge centres found in thunderclouds studied in three locations – Florida, New Mexico and the Sea of Japan – were confined within the same narrow temperature band, −10 to −25°C, despite the fact that cloud-based temperatures and cloud depth were very different. These findings are strongly suggestive of a temperature-controlled charging mechanism involving ice. The extremely comprehensive field studies of Krehbiel *et al.* (1979) reveal an association between precipitation and the locations from which cloud-to-ground flashes originate. In combination, these investigations point to a charge transfer process in which precipitation (probably small hail) interacts with ice crystals. Evidence for the efficacy of a non-inductive version of such a process is presented in my paper.

I agree completely with Dr Vonnegut's contention that vigorous downward motions are generally found in cumuliform clouds at more-or-less all levels. Paluch (1979) and others have provided incontrovertible evidence for the importance of penetrative downdraughts in such clouds. In fact, these negatively buoyant plumes will often penetrate well below the −10°C level; which fact appears to militate against their having a major role in charge transport.

In answer to Dr Vonnegut's final query I would suggest that the conduction currents flowing to the thundercloud act to inhibit field growth, but that generally they are unable to prevent the production of breakdown fields.

It is seventeen years since Dr Vonnegut and I debated these questions in the pages of this journal. In my view a substantial amount of evidence has accumulated in this period to consolidate the case for a precipitation-based mechanism of thunderstorm electrification; while the convective mechanism has not received further experimental support. The question remains open, however. Perhaps, when it is re-assessed in 1999, it can be resolved.

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Book Reviews

Dynamical Meteorology. An Introductory Selection. Edited by B. W. Atkinson. Methuen 1981. Pp. ix + 228. £5.95 paperback; £11.50 hardback. Special price to Royal Met. Soc. Members £5.00. (paperback)

It is greatly to the credit of the Editor of this book that, towards the end of his record seven year period as Editor of 'Weather', he yet retained the enthusiasm to plan and bring to fruition a series of commissioned articles designed to help the non-expert, in particular one with little or no formal mathematics, towards an understanding of meteorological dynamics. The series appeared in 1978 and 1979 and proved to be a popular feature. With some additions it comprises this book of fifteen chapters, by ten authors from the U.K. and U.S.A. For good measure the Editor himself contributes an introductory chapter and two others.

Early chapters, by H. A. Panofsky and R. S. Harwood, deal with broad principles of the dynamics and thermodynamics of the atmosphere. These authors plainly have their brief firmly in mind and seek successfully to clarify basic concepts and relationships by frequent recourse to simple physical analogy. Here, as generally throughout the book, little attempt is made to 'prove' in the formal mathematical sense.

There follow three notable 'new' chapters, by M. A. Pedder, which describe kinematic and dynamical methods of analysis, of varying sophistication, aimed at revealing the three-dimensional structure and development of synoptic-scale systems. Also, in a particular case study the analysis is related to conventional dynamical theory. A feature of these chapters, though one more suited to instructors than to uninitiated readers, is the unusual and commendable emphasis placed by the author on the nature and effects of errors of all kinds, and of the steps which the analyst may take to mitigate them.

A further interpolated chapter, by the Editor, repairs an omission in the original series by providing a discussion of waves. He describes the physical characteristics and mathematical formulation of wave motion in general, followed by a cursory discussion of atmospheric waves—specifically sound, gravity, inertia, Rossby, baroclinic. Remarkably, there is no mention of either frequency or wave number, despite the prominence afforded to the latter in modern discussions of large-scale dynamics, the 'waves' in question being those obtained by 'spectral decomposition' of geopotential or temperature time series.

Following a review, by B. W. Atkinson, of the historical development of dynamical meteorology, there are contributions on the spectrum of motions (E. R. Reiter), on turbulence (A. Ibbetson), on energetics (A. A. White), on transfer properties of large-scale eddies (J. S. A. Green), and on short range numerical weather prediction (A. J. Gadd). The concepts and to some extent the level of mathematics of these more specialist topics are at a more advanced level than in earlier chapters. Plainly, however, the authors exert themselves to accommodate the non-specialist reader and succeed very well in doing so. The book ends with a thoughtful general perspective of the topic by J. A. Smagorinsky.

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The electrification of thunderstorms

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(Symons Memorial Lecture, delivered 16 May 1979)

1. Introduction

The overall goal towards which this article is directed is to identify the mechanism or mechanisms responsible for electric field development within thunderclouds, culminating in the production of lightning. It will not be fully achieved. Examination of existing evidence will reveal that despite substantial progress over the past few years, especially within the Thunderstorm Research International Programme (TRIP), we have not yet performed sufficiently comprehensive and precise field experiments in order to discriminate uniquely between competing mechanisms. However, this evidence is already sufficient to permit us to discard several theories as being inconsistent with the behaviour and properties of thunderstorms in general – though some of these may have specific importance, in relation, for example, to volcanic or warm-cloud lightning; and to reveal the very strong links that exist between the electrical, dynamical and microphysical development of thunderclouds.

In the belief that the major obstacle to progress in this area has been the dearth of reliable field evidence we focus major attention in this article upon recent field experiments, although scant attention is devoted to the details of the technological developments responsible for this recent progress. Consideration is also given to selected laboratory and computational experiments which appear to have assisted our understanding in some important way or to form the basis of crucial future work.

This article is idiosyncratic and incomplete. It presents a personal view of the current state of the art with respect to the problem of thunderstorm electrification. It has been necessary to eliminate specific reference to a large number of significant papers which have nevertheless contributed in a substantial way to the evolution of the arguments and standpoints advanced herein – and which have assisted greatly the attempt to define those future experiments which appear to be most urgently required.

2. Some requirements of an acceptable theory

Thunderstorms are highly variable in their complexity and intensity. Thus it is unjustifiable to attempt to provide quantitative values for parameters important in thunder-

storm electrification without recognizing their wide range. This situation underlines the need for detailed *case studies*, since average values cannot be regarded as appropriate for specific cases. However, given these reservations, it is useful, in attempting a provisional assessment of theories of thunderstorm electrification – and rejecting some of these – to try to develop a skeletal list of conditions and parameter values with which any generally acceptable theory must be consistent. Such a list was presented by Mason (1953) and appears valid now, to a considerable extent: the mature stage of a thunderstorm cell of moderate intensity – characterized by lightning activity, strong vertical air motions and the presence of precipitation – lasts for about 30 minutes, during which time the average current (negative charge downwards) is in the region of 1 ampere; the first lightning stroke usually occurs within 20 minutes of the formation of precipitation within the cell; the basic electrical structure is that of a dipole, positive charge being located at higher altitudes than negative. This statement is not inconsistent with the observations made by Takeuti *et al.* (1978) and others, of *positive* charge being brought to ground by lightning in certain localities and situations – this results generally from highly sheared air-flow. In fact, Ogawa and Brook (1969) and others have shown that the dipole vector within thunderclouds is often at a substantial angle to the vertical. Mason's other primary conditions – the location of the negative charge at $-5\,^{\circ}$C and the association of field-growth with the development of soft hail – are discussed more fully in the following section, in the light of recent research, but appear largely acceptable.

A further condition, which research over the past decade permits us to define with reasonable precision, concerns the magnitude of the fields required to initiate and to propagate the positive corona streamers that trigger the onset of lightning; positive streamers are much more likely to initiate lightning than negative ones because they can propagate in substantially lower fields. The experiments and calculations of Phelps (1974), Griffiths and Phelps (1976) and others have added greatly to our understanding of the energetics and physics of positive streamer propagation, and indicate that this can occur when the reduced field exceeds a critical value around $6\,\mathrm{kV\,cm^{-1}\,torr^{-1}}$; this corresponds to a field of 3 to $4\,\mathrm{kV\,cm^{-1}}$ at altitudes pertaining to the central regions of thunderstorms.

Since the breakdown field in dry air at normal atmospheric pressure in the absence of particles is about $30\,\mathrm{kV\,cm^{-1}}$, while the largest fields that have been recorded within thunderstorms are around $4\,\mathrm{kV\,cm^{-1}}$ (Gunn 1948, Winn and Moore 1971 and others) – and indeed, as several workers have shown (for example Gay *et al.* 1974), field-driven currents would extinguish field-growth in substantially higher fields – it is clear that hydrometeors must provide the sites for corona initiation, as a consequence of the concentration of electrical stress at their extremities. Early work on corona initiation from ice and water (Bandel 1951, Richards and Dawson 1971), indicated that ice could not sustain corona, and that even for optimally charged large raindrops corona could not be initiated – via electrohydrodynamic bursting – in fields below about $5{\cdot}5\,\mathrm{kV\,cm^{-1}}$. However, Griffiths and Latham (1974) showed that ice can initiate and sustain corona at temperatures warmer than about $-20\,^{\circ}$C; the surface conductivity of ice is too low at lower temperatures. Figure 1 displays their measured relationship between corona onset field and pressure for ice particles of various shapes and sizes. It is seen that the critical field for corona initiation from hailstones or snowflakes within thunderstorms can be as low as 3–$4\,\mathrm{kV\,cm^{-1}}$.

Crabb and Latham (1974) examined the possibility that positive corona can be initiated in low ambient fields from the highly deformed surfaces of raindrops during their collision and temporary union. They found that when drops of radii 2·7 mm and 0·65 mm made glancing collisions at their appropriate relative velocities positive corona was initiated in fields as low as $2{\cdot}5\,\mathrm{kV\,cm^{-1}}$ from the tip of the spike formed momentarily as the drops separated. Figure 2 illustrates this process and Fig. 3 shows how the critical field varies with

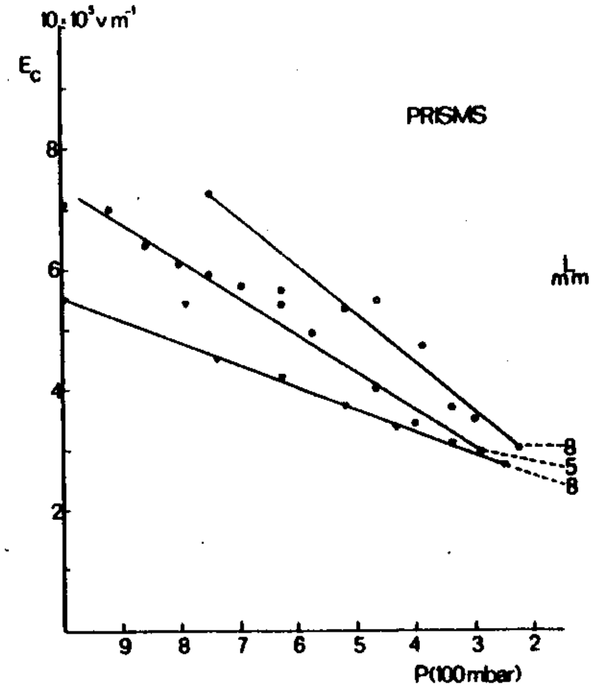

Figure 1. The measured variation with pressure P of the critical field E_c required to produce corona from prismatic ice crystals of length L (mm) at a temperature $T = -12\,^{\circ}\mathrm{C}$ (from Griffiths and Latham 1974).

Figure 2. Filament produced when water drops of radii 2·7 mm and 0·65 mm make a glancing collision at a relative velocity of $5{\cdot}8\,\mathrm{m\,s^{-1}}$ (from Crabb and Latham 1974).

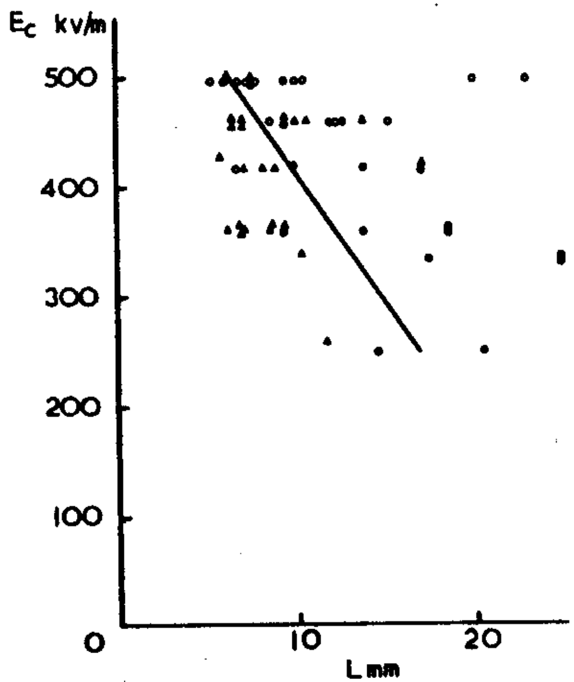

Figure 3. The measured variation of the critical field E_c required to produce corona with L, the maximum distance between the vertical extremities of the blob of water produced by the temporary coalescence of a pair of drops of radii 2·7 mm and 0·65 mm colliding with relative velocity $5{\cdot}8\,\mathrm{m\,s^{-1}}$. ○: corona accompanying the collision; ▲: no corona; ——: line above which 80% of (○) and 25% of (▲) points lie (from Crabb and Latham 1974).

impact parameter – the ratio of the perpendicular spacing of the trajectories of their centres to the sum of their radii.

It is clear that positive corona can be initiated from solid hydrometeors or colliding raindrops and can subsequently propagate in fields below about $4\,\mathrm{kV\,cm^{-1}}$. Thus an additional requirement of a satisfactory theory of thunderstorm electrification is that a positive field of this magnitude should be generated within the central regions of a thunderstorm within about 20 minutes of the formation of precipitation.

The various requirements identified in this section are sufficiently demanding to enforce the elimination of several theories of thunderstorm electrification as being of general importance. However, certain competing mechanisms appear to be consistent with these requirements, and in order to discriminate between them we need to examine recent field evidence concerning the relationships between the electrical, microphysical and dynamical characteristics of thunderstorms, together with more specific questions such as the relationship between the charge and size of individual hydrometeors. In section 3 we review the recent evidence and in section 4 we attempt to determine which, if any, of existing theories of thunderstorm electrification are consistent with it, and the requirements already established.

3. Some recent field investigations

During the past few years several ground-based techniques have been utilized to locate some segment of a lightning flash. Krider and Noggle (1976) developed a system for locating the strike point of a cloud-to-ground flash from the initial rise in the magnetic wave-form of a return stroke. Szymanski and Rust (1979) examined radar echoes from lightning in order to locate channels occurring within a stationary radar beam. Krehbiel *et al.* (1979) made multi-station measurements of the electric field change induced by lightning, and located the equivalent charge centres neutralized by ground flashes. More detailed information on the structure of lightning has been provided by acoustic and VHF mapping techniques. Few (1970), Few and Teer (1974), Winn *et al.* (1978) and others developed a system based on the recording of thunder by an array of microphones spaced 30 to 100 m apart. Proctor (1970) developed a system which employed an array of antennas separated by 10 to 15 km for mapping lightning from its VHF radiation. A similar technique was utilized by Lennon (1975). In the system developed by Taylor (1978) an array of antennas separated by 13·74 m was used to determine the azimuth and elevation of VHF signals; two arrays were employed in order, by triangulation, to determine the three-dimensional location of the source of a signal. Warwick *et al.* (1979) and Hayenga and Warwick (1980) described an interferometric technique for measuring the VHF radio centroid of nearby lightning flashes at 5 μs intervals. An example of the positional detail provided by this technique is given in Fig. 4. In the following paragraphs we discuss particular findings emanating from these various new techniques. We concentrate on those which appear to apply most directly to the problem of thunderstorm electrification.

A rigorous and comprehensive analysis of the charge structure of lightning discharges to ground was conducted, in New Mexico, by Krehbiel *et al.* (1979). Sources of charge for the individual strokes of four multiple-stroke flashes to ground on 23 August 1971 were determined using measurements of the electrostatic field change obtained at eight locations

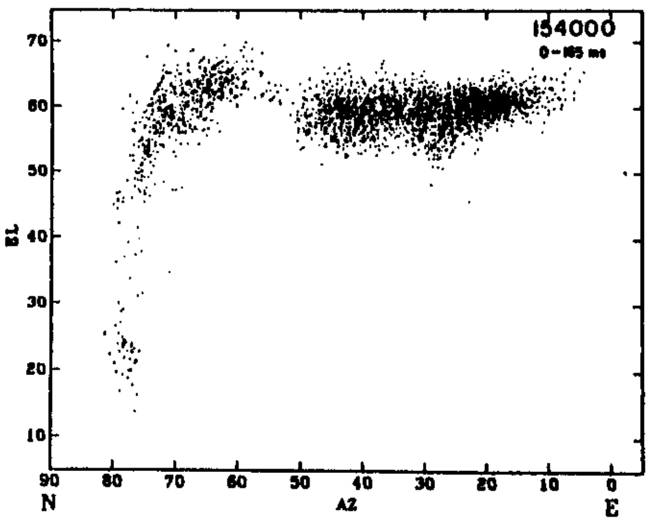

Figure 4. Azimuth *AZ* and elevation *EL* angles in degrees derived for individual radiation sources for the initial portion of lightning flash 152902 on 29 August 1978 (from Hayenga and Warwick 1980).

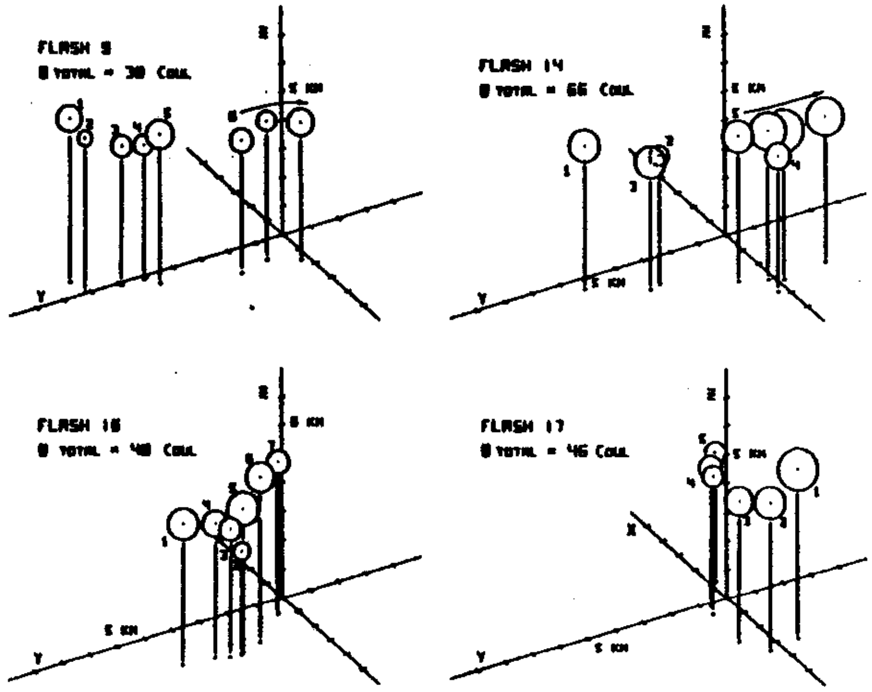

Figure 5. Summary of ground stroke charge structure for flashes 9, 14, 16 and 17 on 23 August 1971. The circles denote the size of spherical volumes which would have contained the individual stroke charges at a uniform density of 20 C km^{-3}. (Charge volumes for the continuing current of flash 14 are cumulative from the beginning of the discharge, except for the last volume.) From Krehbiel *et al.* (1979).

on the ground beneath the storm. The resulting charge locations were compared with 3-cm radar measurements of precipitation structure in the storm. The field changes of individual strokes were found to be reasonably consistent with the lowering to ground of a localized or spherically symmetric charge in the cloud. The centres of charge for successive strokes of each flash developed over large horizontal distances within the cloud, up to 8 km, at more or less constant elevation between the −9 and −17 °C clear-air temperature levels, as illustrated in Fig. 5. Comparison with the radar measurements showed that the discharges developed through the full horizontal extent of the precipitating region of the storm and appeared to be bounded within this extent. In one instance where cellular structure of the storm was apparent, the strokes selectively discharged regions where the precipitation echo was the strongest, as shown in Fig. 6. The vertical extent of the stroke charge locations was small in comparison with the vertical extent of the storm. The field changes in the intervals between strokes were found to exhibit many of the features which Malan and Schonland used to infer that ground flashes discharge a nearly vertical column of charge in the cloud. This and other evidence is used to show that their observations, which were made at a single station, could instead have been of horizontally developing discharges. The inter-stroke field changes have been analysed using a point dipole model and found to correspond to predominantly horizontal charge motion that was closely associated with the ground stroke sources for the flashes. The interstroke activity served effectively to transport negative

Figure 6. Vertical cross-section in north–south plane of the radar precipitation echo from the thunderstorm of 23 August 1971, obtained 1 minute after flash 9. Sources of charge for the flash 9 strokes are superimposed on the returns and progressed from left to right. North is left. Total charge destroyed ~ 30 C (from Krehbiel *et al.* 1979).

charge in the direction of earlier stroke volumes and often persisted in the vicinity of an earlier stroke volume, while subsequent strokes discharged more distant regions of the cloud. Long-duration field changes that sometimes preceded the first stroke of a flash have been analysed and found to correspond to a series of vertical and horizontal breakdown events within the cloud, prior to development of a leader-to-ground. These events were associated in part with the negative charge region that became the source of the first stroke and effectively transported negative charge away from the first stroke charge volume and from the charge volumes of subsequent strokes. Several continuing current discharges were found also to progress horizontally within the cloud and sustained currents in the range of 580 A to less than 50 A. The continuing current field changes were consistently better fitted by the monopole charge model than the field changes of discrete strokes within the same flash.

The general conclusion of Krehbiel *et al.* that the negative charge centres within a thundercloud are located within a supercooled region of relatively small vertical dimension is consistent with the work of Workman *et al.* (1942), Reynolds and Neill (1955), Jacobson and Krider (1976), Taylor (1980) and others. Further confirmation of the generality of this conclusion is provided by the field-change and radar studies conducted in Florida, in the summers of 1976, 1977 and 1978, as part of the TRIP, by Krehbiel *et al.* (1980). They found that the sources of negative charge for successive strokes of a discharge to ground lie within a relatively limited height range between about the −10 and −25 °C temperature levels, and coincide predominantly with precipitation at these levels. Figure 7 presents the striking result from their studies in Florida, New Mexico and Japan – where convective winter storms were investigated – that the temperatures at which the negative charge centres were located are similar in all three studies, even though the cloud bases are at very different levels. The implications of this important conclusion with respect to the mechanism of

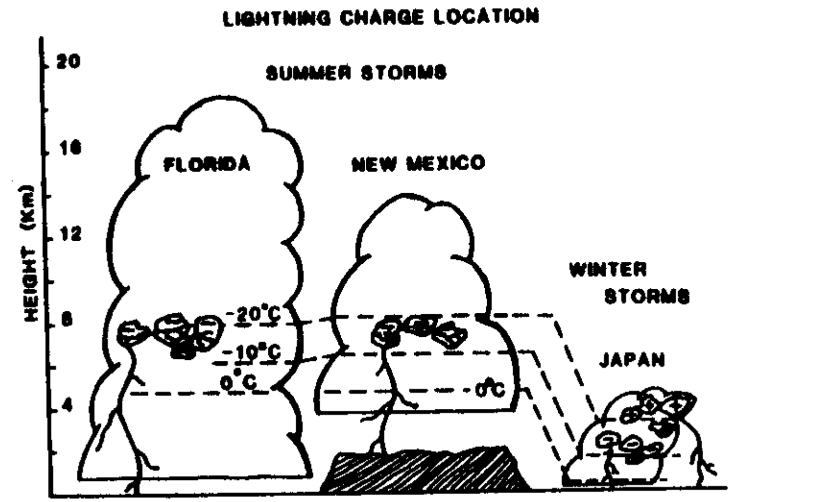

Figure 7. Schematic diagram illustrating the levels and distribution of ground-flash charge sources observed in thunderstorms in summertime in Florida and New Mexico and in wintertime in Japan (from Krehbiel *et al.* 1980).

thunderstorm electrification are discussed in section 4. Krehbiel *et al.* (1980) found that in one storm system for which Doppler-derived wind-field data had been obtained, the onset of lightning activity in one of the storm cells followed the development of a strong (45 dBZ) precipitation echo above the 0 °C level, and coincided with a rapid increase (to 25 m s^{-1}) in the speed of the updraught carrying this precipitation. The discharge rate for the entire storm thereupon increased to 60 min^{-1}. The electric field measurements indicate that most of these were small-amplitude intracloud discharges. The bold arrow in Fig. 8 shows that the moment change associated with one of these discharges – identified with the newly active cell – was aligned with and in the region of the updraught, the positive charge source being upwind of the precipitation echo.

Some similar but not identical results were obtained in 10-cm radar and VHF space-time mapping studies of thunderstorms by Taylor (1980) and MacGorman *et al.* (1980), the latter experiments being supplemented by acoustic location measurements. This work was performed in Oklahoma and in Florida. In both studies it was found that lightning activity is generally located in close proximity to, but not within, the high reflectivity regions of storms. Taylor observed that most lightning activity is confined to the temperature range −5 to −20 °C. Figure 9 presents a typical example from his work of a discharge superimposed on Doppler radar reflectivity contours for a storm in the vicinity of Norman, Oklahoma. Each (+) corresponds to an impulse source of radiation occurring within the 3 to 4 km altitude band. It is seen that the discharge was associated with a developing region of a storm located south-west of older storm regions; and that there is a general association between radar reflectivity and radiation bursts. Closer examination (not evident from the figure) shows that the impulse sources concentrate in the vicinity of strong horizontal wind shear. MacGorman *et al.* (1980) presented clear evidence showing that in all four thunderstorms studied in their 1979 summer research programmes in Oklahoma, although lightning was closely associated with regions of sustained high reflectivity it was completely outside those of reflectivity exceeding about 50 dBZ. They observed that as new regions of high

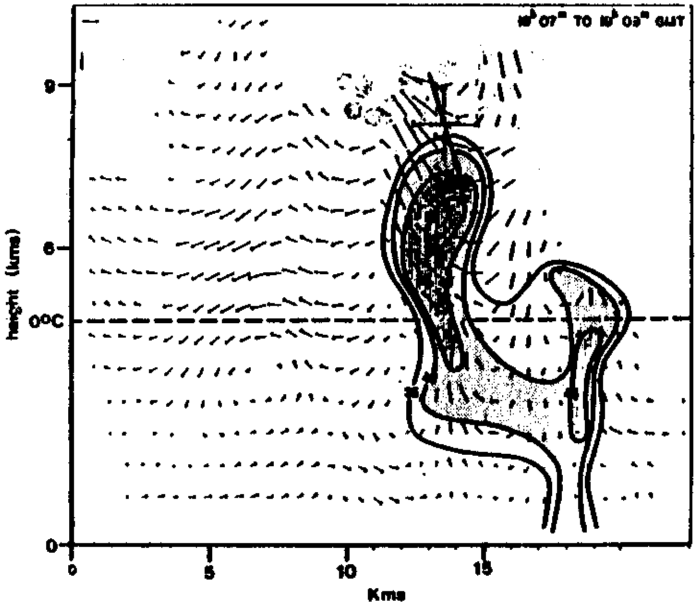

Figure 8. Reflectivity contours and projected wind field in a vertical plane through a cell at the time of a peak in the cell's electrical activity, on 23 August 1978. The hatched circles denote the initial radiation sources from discharges near the analysis plane during the two-minute time interval 1907–1909. The bold arrow indicates the direction of effective positive charge transfer for an intracloud discharge within the plane at time 190718. 5 C km total moment change occurred during two distinct 15 ms events. (The dipole extent shown assumes 2·4 C charge transfer.) An upper-level downdraught within the right-most radiation sources was associated with a larger, overhanging cell situated behind the analysis plane that was also electrically active at the time of the data. A third cell is seen developing on the southern (right) edge of the storm. Reflectivity values are in dBZ units; wind vectors are at 600 m grid points, with 10 m s^{-1} speed denoted on the upper left (from Krehbiel *et al.* 1980).

reflectivity formed and old ones dissipated, the location of the lightning moved towards these newer regions. In two storms observed with single Doppler radar, lightning tended to occur in or near regions of cyclonic shear, usually associated with updraughts in Oklahoma storms. In one storm observed with dual Doppler radars, lightning was prone to occur in regions of weak updraught ($<$ 10 m s^{-1}) or adjacent to downdraughts. These conclusions are illustrated in Fig. 10.

A clearer understanding of the roles of precipitation and the inductive theory in the electrification of thunderstorms formed in summertime in the region of the Langmuir Laboratory on the summit of South Baldy Mountain in the Magdelena Range in New Mexico, has arisen from the airborne studies of Gaskell *et al.* (1978) and Christian *et al.* (1980), which were conducted in 1976 and 1977 respectively. The vehicle employed in these studies was the ONR/NMIMT research aeroplane, which was equipped to measure, in addition to basic meteorological parameters, all three components of the electric field E and the charge Q and size d of individual precipitation elements. In 1976 penetrations were confined to the lower regions of the thunderclouds (around the 0 °C isotherm), while in 1977 it was possible to traverse the clouds at all levels below about the -10 °C isotherm. In 1977 the airborne measurements were supplemented by: a rain-gauge network surrounding

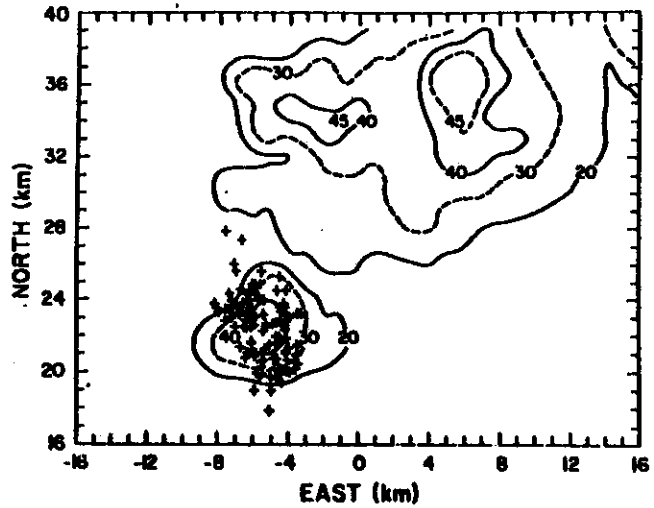

Figure 9. Example of impulse sources (+) for one lightning discharge superimposed upon Doppler radar reflectivity contours (dBZ) for an altitude of 3·5 km (from Taylor 1980).

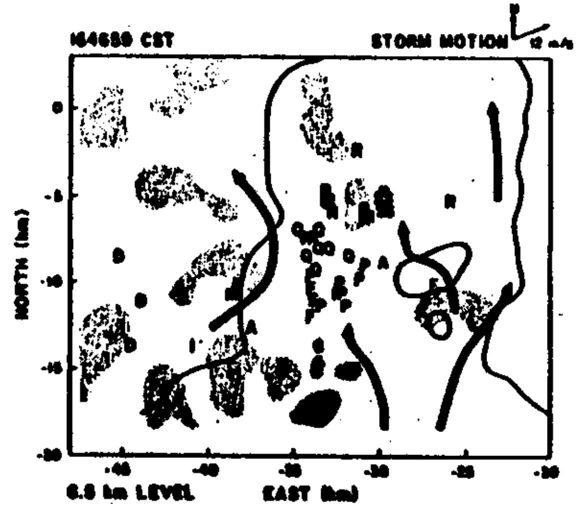

Figure 10. Radar data superimposed on VHF source locations for a flash at 164659 CST in an Oklahoma storm on 6 June 1979. Radar data are shown at the 6·5 km level of a grid made from a series of radar scans at 1644–1648 CST. The outer contour line is 30 dBZ. The inner, heavier contour is 45 dBZ. Winds were calculated using data from two Doppler radars. Arrows indicate stream lines in the horizontal wind. Dotted shading indicates areas of downdraught (mostly 5 m s^{-1} or smaller). Striped shading indicates areas having updraughts greater than 10 m s^{-1}. The calculated locations of sources of VHF impulses are denoted by letters. Impulses were received during the first 15 ms interval from sources coded 'A', during the second 15 ms interval from sources coded 'B', and so on (from MacGorman *et al.* 1980).

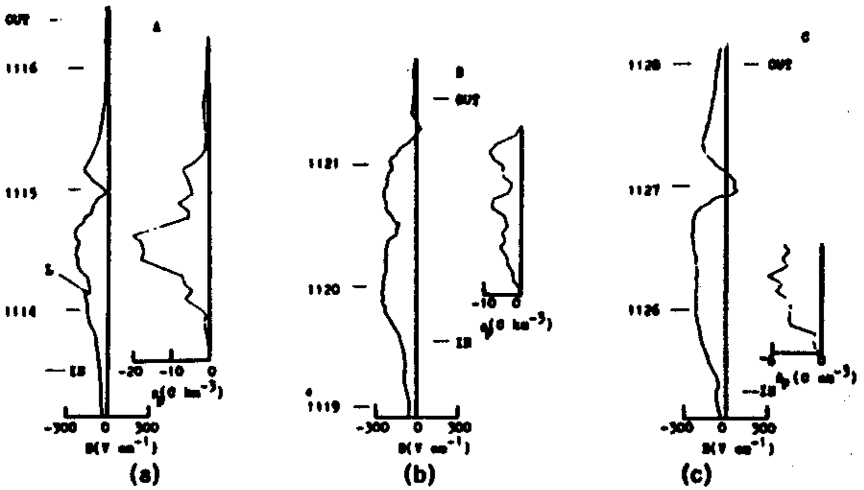

Figure 11. Variations with time of vertical electric field E and precipitation charge density ρ_p during three penetrations of a thunderstorm on 9 August 1976. The penetrations were at 13 000 ft (+2 °C). (a) penetration 3; (b) penetration 4; (c) penetration 5. The sudden field change at L in (a) is probably due to lightning (from Gaskell *et al.* 1978).

Langmuir Laboratory; a 3-cm radar; an acoustic system for locating lightning channels; and a ground-based field-change meter for counting and recording the time of occurrence of lightning strokes.

The main conclusions of the 1976 studies were as follows: Volume charge densities on precipitation, ρ_p, were often around $-5\,\mathrm{nC\,m^{-3}}$ over horizontal distances of several kilometres, as illustrated in Fig. 11. ρ_p was almost always negative, but positive charge densities, of lower magnitude, were occasionally observed over shorter distances. The major contribution to the measured values of ρ_p was made by particles of size around 1 mm or smaller. Simultaneous measurements of Q and d showed that no simple relationship existed between them. Charges of about 100 pC were commonly observed on particles around 1 mm in size. These are much too large to be explicable in terms of the inductive theory. Positive and negative charges were found to coexist, except when the precipitation rate, p, was very low. However, charge of one sign (almost invariably negative) was always strongly dominant. Values of p could be estimated crudely from the d pulses. In regions of high ρ_p they were rarely in excess of $10\,\mathrm{mm\,h^{-1}}$; on some occasions when ρ_p was substantial p was below $1\,\mathrm{mm\,h^{-1}}$.

The same broad picture resulted from the 1977 airborne studies, but the more comprehensive facilities available in this second year permitted more detailed and specific conclusions to be drawn. In a thundercloud studied on 6 August 1977 the first cell produced precipitation at the ground but no lightning. Vertical fields, E_z, of up to about $50\,\mathrm{kV\,m^{-1}}$ and precipitation charge densities ρ_p of up to $-0{\cdot}5\,\mathrm{C\,km^{-3}}$ were recorded within the cloud. The second cell, which grew as the first one decayed, produced 7 lightning strokes in 9 minutes during which time the radar revealed vigorous vertical growth in a narrow zone containing precipitation. Thunder reconstructions showed the acoustic sources for the first flash of this cell to be very near the top of the cloud at an altitude of 10 km above m.s.l. The subsequent flashes produced acoustic signals from progressively lower in the cloud, as shown

in Fig. 12. The acoustic sources were generally coincident with regions of higher reflectivity. When the radar echo reached its maximum height lightning activity ceased. E_z values of up to about $50\,\mathrm{kV\,m^{-1}}$ and ρ_p values of up to $-1\,\mathrm{C\,km^{-3}}$ were measured. ρ_p was consistently negative, individual charges being less than ± 40 pC. Q values were within the inductive limit for a thundercloud at breakdown but no systematic relation between Q and d was found. Six penetrations were made through the thundercloud of 15 August 1977 which produced only two lightning strokes. The E_z records were indicative of a (±) dipole located near the cloud top, at around −13 °C. Fields of up to about $100\,\mathrm{kV\,m^{-1}}$ and ρ_p values

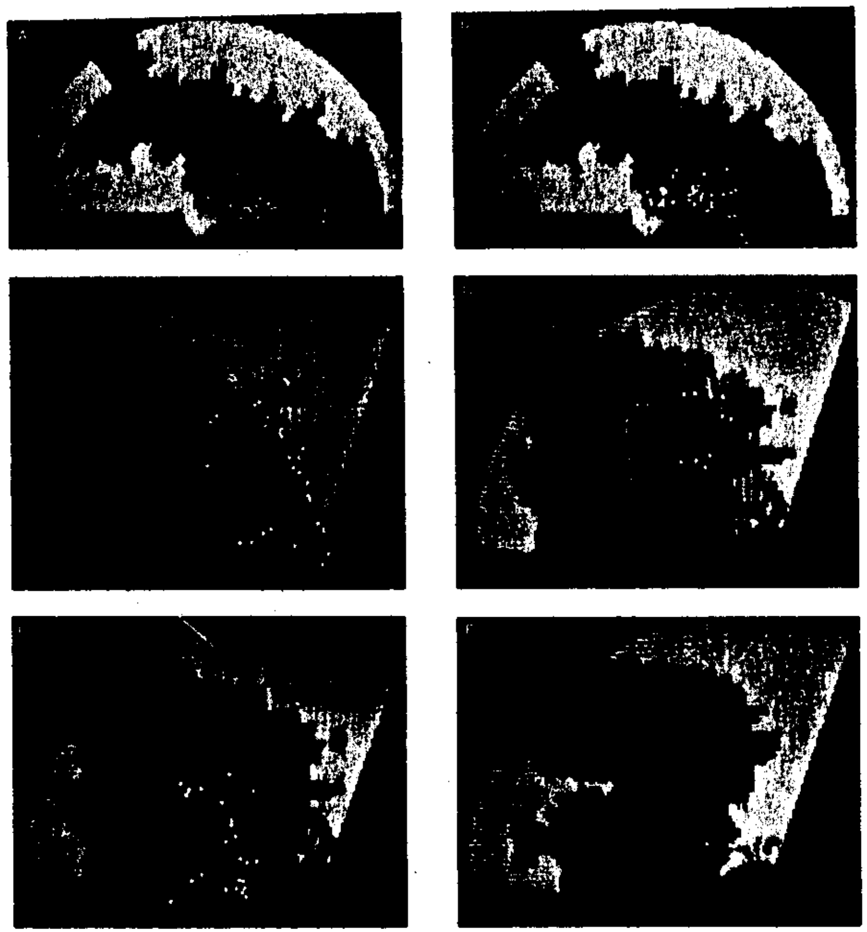

Figure 12. Thunder sources from cell II on 6 August 1977 superimposed on CAPPI and RHI displays for various altitudes (z) and azimuths (ϕ) (from Christian *et al.* 1980).
(A): z = 6·1 km; 1203–1205 MST: ▼, flash 1205–1212, ×, 1207–1209, ○, 1200–1211
(B): z = 6·1 km; 1203–1205 MST: ○, 1210–1228 and 1211–1245, □, 1214–1229
(C): ϕ = 164°; 1204–1254 MST: ×, 1205–1212, ○, 1207–1209
(D): ϕ = 158°; 1209–1217 MST: ○ 1208–1211
(E): ϕ = 158°; 1209–1217 MST: ○, 1210–1228 and 1211–1245
(F): ϕ = 97°; 1217–1227 MST: ○, 1214–1229

(positive and negative) of around $-5\,C\,km^{-3}$ were measured. Q values of up to $\pm 250\,pC$ were recorded, with charges around $\pm 50\,pC$ being commonly found. No systematic Q/d relation was revealed, and smaller precipitation particles frequently carried charges (positive or negative) in excess of the inductive limit, as shown in Fig. 13. On both days estimated precipitation rates were of order $10\,mm\,h^{-1}$ and on most occasions the pilot reported precipitation particles to be either 'ice' or 'mixed liquid water and ice'.

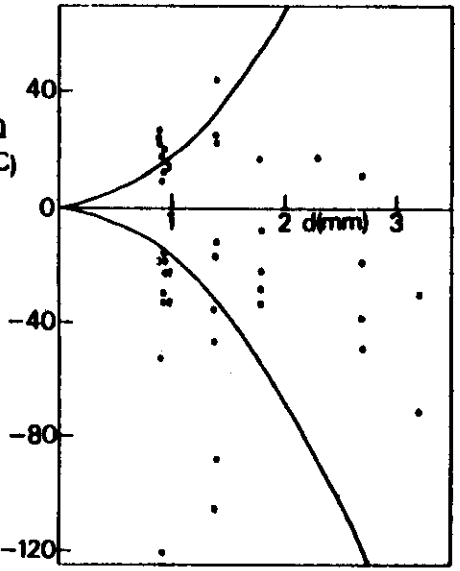

Figure 13. Charge-size (Q–d) coincidences measured in the 65 seconds of penetration B on 15 August 1977. The solid lines are theoretical maxima for the inductive mechanism operating in a breakdown field $\pm 300\,kV\,m^{-1}$. The numbers attached to certain points are the numbers of observations at those points (from Christian *et al.* 1980).

The primary conclusions to be drawn from these studies, conducted in 1976 and 1977 with the ONR/NMIMT Schweitzer aeroplane, are that: the charges and currents carried by precipitation elements are often substantial; the particles carrying these large charges in the central regions of thunderclouds are generally solid; the charges on individual precipitation elements are not explicable in terms of the inductive mechanism; lightning activity within a cell is associated with upward motion of precipitation, as revealed by radar; breakdown fields can be developed efficiently in cells where the precipitation rate does not exceed a few millimetres per hour.

Instrumented balloons afford an additional insight into cloud electrification because, in general, as distinct from airplanes, they permit the *time-development* of electrical characteristics to be studied in a particular location. This feature enabled Winn and Byerley (1975) to examine the nature of the field growth in the intervals between lightning strokes in New Mexican thunderstorms. They found that it was linear, which is inexplicable in terms of the inductive mechanisms of thundercloud electrification. Winn *et al.* (1978) described a detailed case study in which radar, an acoustic system for the location of points on lightning channels and an instrumented balloon were used to examine the electrical and dynamical

structure of a weak thunderstorm over the Langmuir Laboratory. It revealed negatively charged downdraughts, positive charge at higher levels, screening layers at cloud boundaries, and strong associations between the field structure and the air motions.

4. Examination of theories of thunderstorm electrification

The evidence presented in the preceding two sections (especially in Fig. 7) is strongly suggestive of the role of small hail in carrying the charges that constitute the negative pole of a thundercloud. Thus it appears likely that the primary charging process or processes within thunderclouds involve the collision of small hail with either supercooled droplets or ice crystals. In this section we concentrate attention on such processes and consider also those other mechanisms which appear potentially powerful and/or have received considerable attention in recent years.

Various workers (for example Wilson 1929, Takahashi 1977 and Wahlin 1977) have proposed that the differential capture of ions by hydrometeors, as a consequence of polarization, mobility differences, the state of the surface of the particle, or differences in electrochemical potential can lead to the development of breakdown fields. However, Wormell (1953) pointed out that the rate of ion production by cosmic rays is far too small. This is true even at the highest levels within thunderclouds, when account is taken of the dominant role of recombination in regions where particle concentrations are small. However, it seems possible that the production of fields of moderate intensity ($\sim 100\,V\,cm^{-1}$) in warm clouds may be a result of selective ion-capture by polarised raindrops, as proposed by Wilson.

Vonnegut (1955) proposed a feedback mechanism in which negative ions from the highly conducting atmosphere flow to the cloud top, and are carried to the lower regions of the cloud by downdraughts at the vertical boundaries – while positive ions produced by point discharge at the surface of the earth are carried by updraughts to higher levels within the cloud. In this way the observed $\pm$ polarity develops. However, the time required for ions to travel from the earth's surface to the central regions of the cloud is too long (around 20 minutes) for this process to be important, especially when account is taken of the fact that point discharge can be initiated at the ground only when the field inside the cloud is close to breakdown. Penetrative downdraughts produced by entrainment at the cloud summit may provide an efficient mechanism of downward transport of negative charge, but in the absence of an upward flow of positive charge this process will ultimately become self-extinguishing. Perhaps the strongest reason for concluding that this convective process is unlikely to be of primary importance in thunderstorm electrification is its incompatibility with Fig. 7.

This figure is also suggestive of the unimportance, in most thunderclouds, of the version of the inductive mechanism in which rebounding collisions between large and small water particles polarised in the electric field of the cloud cause the larger drops to acquire negative charge. As these fall beneath the smaller droplets carrying a compensating positive charge a field of the observed polarity develops. Since the magnitude of the charge transfer is proportional to the strength of the electric field E we have a positive feedback mechanism, which is an attractive feature of the inductive theories. Computations by several workers (for example, Sartor 1961, 1967, Latham and Mason 1962, Mason 1972 and Scott and Levin 1975), indicate that inductive mechanisms can produce breakdown within the available time if α ($= \Sigma\, p(\theta)\cos\theta$), the sum, over all interactions, of products of the probability of separation, p, and the cosine of the angle θ between the line of centres at impact and the field vector, is significant. However, the experiments of Jennings (1975) indicate that, for water-water collisions, $p \to 0$ as E rises above about 250 V cm^{-1}, while those of Whelpdale and List (1971), performed in the absence of an electric field, show that separation occurs only when $\cos\theta \to 0$. Thus we conclude that this form of the inductive process is not of major importance in thunderstorm electrification.

Workman and Reynolds (1948, 1950), Lodge *et al.* (1956) and others have shown that during the freezing of supercooled water or dilute aqueous solutions large potential differences may be developed across the ice-water interface, as a result of the selective incorporation of ions of one sign. Although the sign and magnitude of the potential was found to be sensitive, in these studies, to the concentration and constitution of the solute the charge transferred in laboratory experiments (Workman 1969, Shewchuk and Iribarne 1971, Latham and Warwicker 1980) in which solution droplets splashed from an artificial hailstone at velocities appropriate to interactions within clouds was found to be an insensitive function of these parameters. Workman and Shewchuk and Iribarne found values of charge transfer of around 10^{-11} C, while Latham and Warwicker's values were about three orders of magnitude lower. The reason for this discrepancy is not known, although it may be relevant to note that in the latter experiments the drops were in thermal equilibrium at a range of temperatures below 0 °C. This Workman-Reynolds process could operate within thunderclouds either by shedding supercooled water during wet-growth of hail or by splashing collisions between hailstones and supercooled drops. The former process is unlikely to be important in thunderstorm electrification in view of the frequent observations of lightning from clouds with low precipitation rates and only small hail. In the latter case Latham and Warwicker found that an imposed electric field in excess of about 100 V m^{-1} dominated the charge separation process and that – for the drop size employed in their experiments – the process was dissipative of the electric field since the colliding drop retained contact with the hailstone whilst swinging past its equator to depart from its upper surface. Their calculations indicated that this process is insignificant quantitatively. It seems likely that induction will always dictate the sign and magnitude of the charge transfer involving the separation of liquid from a hailstone or raindrop, once the electric field has risen to a rather modest level.

Latham and Mason (1961) reported a powerful process of charge transfer associated with ice-splinter production during the growth of rime, but subsequent work has revealed that this mechanism occurs only over a restricted range of conditions. Hallett and Mossop (1974) and Mossop (1976, 1978) have shown that ice crystals are produced in significant quantities during riming within the temperature range −5 to −8 °C provided that the supercooled droplet spectrum is broad. When operating optimally (Chisnell and Latham 1976) this process can increase ice particle concentrations in the warmer regions of supercooled cloud by a factor of up to about 10^4 in 10 to 15 minutes. It thus has important implications with respect to rainfall modification. Hallett and Saunders (1979) have found that charge is transferred during the ejection of splinters. However its magnitude, for conditions pertaining to thunderclouds, is substantially less than that produced by hailstone-ice crystal collisions, and it occurs over such a narrow range of conditions that it appears unlikely to be of primary importance in thunderstorm electrification.

Aufdermaur and Johnson (1972) showed that when an artificial hailstone is exposed to a stream of supercooled water droplets in the presence of an electric field a small fraction ($\sim 10^{-3}$) separate after collision, transferring charge in accordance with the inductive mechanism. Their suggestion that only glancing collisions result in separation was confirmed by Gaskell (1979) and Gaskell and Illingworth (1980). In this case the product α is small, though not necessarily inadequate, in view of the high concentrations of droplets and the fact that for highly aspherical hailstones the geometrical and electrical 'equators' may be significantly different. It is important, in examining further this mechanism, to establish the

sensitivity of α to the value of electric field E. However, the field observations, outlined in the previous section, that precipitation elements in thunderclouds in New Mexico carry charges which are not related to their size in the manner dictated by the inductive theory, and which are often larger than this mechanism can explain, indicates that this process is unlikely to be of major importance in thunderstorm electrification. A further disadvantage, pointed out by Moore (1976), is that there exists a high probability that charged droplets would be captured by precipitation elements, thus reducing the efficiency of field growth.

The same restrictions militate against the possibility that the version of the inductive theory in which ice crystals collide with and separate from hailstones is the dominant charging process. A more severe limitation of this process is that when these solid hydrometeors collide with contact times representative of those existing in thunderclouds (for example Latham and Mason 1962, Buser and Aufdermaur 1971, Aufdermaur and Buser 1977, Gaskell 1979) the magnitude of the charge transfer is either unaffected or only marginally affected by the application of strong electric fields. This is presumably because the relaxation time for charge redistribution is much longer than the time of contact; calculations presented by Gaskell (1979) support this view.

The final mechanism to be discussed, which appears to be consistent with the evidence and requirements identified in sections 2 and 3 is non-inductive charge transfer between ice crystals and small hail. Results from laboratory experiments have been variable since the classic studies of Reynolds *et al.* (1957) revealed large charging (hailstone negative) when ice crystals and supercooled droplets coexisted in the cloud through which the hailstone was moving. Marshall *et al.* (1978) confirmed the efficiency of this charge transfer process when ice crystals rebounded from a rimed target and showed that the results of more or less all previous experiments gave, over a wide range of crystal size, a value of charge transfer roughly proportional to the square of the diameter of the crystal. This conclusion is illustrated in Fig. 14. More recent work, by Gaskell (1979), Hallett and Saunders (1979), Caranti and Illingworth (1980) and others again reveals strong charging during ice-ice contact and appears to support the suggestion of Buser and Aufdermaur that the sign and magnitude of the charge transfer is governed by surface potential differences between the colliding ice particles.

Crude calculations by Illingworth and Latham (1977) indicate that this ice-ice mechanism is capable of producing breakdown fields within the available time and with modest precipitation rates if the average concentration of ice crystals throughout the charging zone is of order 10 per litre. Since the negative charge centre within a thundercloud is generally located between about −10 and −25 °C it is clear that the concentrations of ice-forming nuclei are inadequate to produce the ice crystal concentrations required – and that some secondary process would have to be operative. Although no definitive studies have been made of the simultaneous electrical and microphysical properties of thunderclouds the work of Hallett *et al.* (1978) demonstrates that the Hallett-Mossop multiplication process is operative in summertime thunderclouds in Florida, while the measurements of Dye (1980) show that the conditions for its occurrence exist in the thunderclouds studied in New Mexico during the TRIP experiments. Latham and Stow (1969) measured ice crystal concentrations of up to about 100 per litre at temperatures around −10 °C in thunderclouds in Northern Arizona. These observations, and those of other workers, indicate that the required concentrations of ice crystals often exist, at the appropriate temperatures, within thunderclouds in regions in which some major electrical experiments have been conducted.

This ice-ice process is compatible with Fig. 7, which shows that the negative charge centres in clouds of greatly different vertical depth and base temperature (in Florida, New Mexico and Japan) are located at essentially the same temperature level (between −10 and −25 °C). Rough calculations show that microscopically sized crystals ejected at around

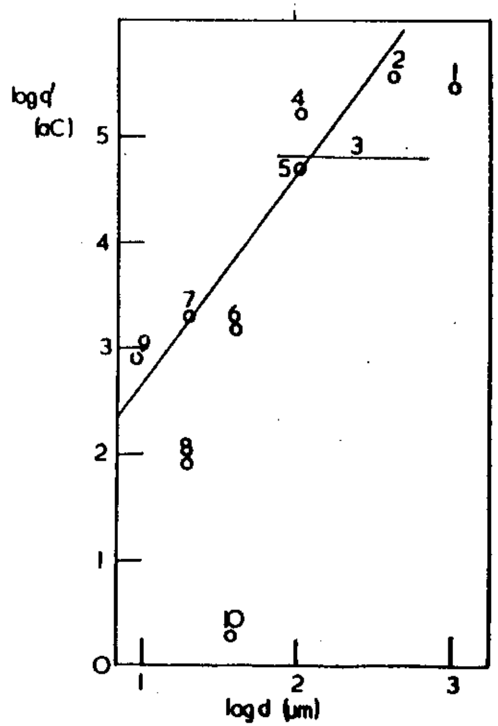

Figure 14. The variations of q', the charge transfer per rebounding event, with ice crystal size, d, derived from the experiments of several workers. 1, Latham and Miller (1965); 2, Latham and Montagne (1970); 3, Latham and Stow (1969); 4, Reynolds, Brook and Gourley (1957); 5, Aufdermaur and Johnson (1972); 6 and 8, Church (1966); 7, Aufdermaur and Buser (1977); 10, Latham and Mason (1961); 9, Marshall *et al.* (1978). In 3, only a range of sizes was quoted. Marshall (1976) has argued that point 8 is probably underestimated by about one order of magnitude (from Marshall *et al.* 1978).

−6 °C by the Hallett–Mossop process will grow by diffusion, as they ascend in the updraught, to become efficient in charge transfer by collision with hail by the time they have risen to the −15 to −20 °C isotherms. Given the variability of the processes involved it appears that the observed locations of the negative charge centre fit well with the suggestion that the major charging mechanism is the non-inductive transient collision of small hailstones with ice crystals produced at relatively warm temperatures by the Hallett–Mossop process. An alternative mechanism by which ice crystals may exist in sufficiently high concentrations in the lower regions of thunderclouds is transport in penetrative downdraughts produced by entrainment at the top of a growing cloud (Squires 1958, Telford 1975, Raymond 1979, Paluch 1979). The observations, mentioned in the preceding section, that lightning tends to originate in regions of moderate radar reflectivity is consistent with the facts that smaller precipitation elements have a higher surface/volume ratio than larger ones and can therefore transport charge more efficiently; and that the ice–ice mechanism would not operate if a hailstone was sweeping out supercooled water sufficiently rapidly to engage in wet-growth.

5. Discussion

It should be stressed that the conclusions emanating from the analysis presented in the preceding section are highly provisional. Field studies conducted to date have been insufficiently comprehensive unequivocally to conclude either that the ice–ice non-inductive process is predominant or that other mechanisms do not play a major role in thunderstorm electrification. The strongest competitor to this ice–ice process would appear to be the inductive ice–water mechanism. Although several disadvantages of this mechanism have been identified, in the previous section, a definitive assessment must wait on much more detailed information on the charge/size/field relationship for precipitation elements in thunderclouds. However, the observation made in balloon studies by Winn and Byerley (1975) and Winn, Standler *et al.* (1980) that the rate of field growth dE/dt within a thunderstorm is approximately constant (rather than proportional to E) favours a non-inductive rather than an inductive mechanism.

It may be of interest to attempt to establish the time variation of the location of the negative charge centre within a thunderstorm cell. It might be expected – if a precipitation mechanism is dominant – that as the electric field develops the negative charge centre will increase in altitude as updraughts carry the precipitation particles (and ice crystals, if the Hallett–Mossop process is operating) to higher levels. Thus, if a new cell forms in the vicinity of an established one the electric field in the region of the early interactions of precipitation and smaller hydrometeors will be negative, i.e. of opposite polarity to that normally found in the central regions of thunderstorms. It follows that if an inductive mechanism is operating the electric field that develops within this new cell will be negative – and that adjacent cells within an assemblage that form a thundercloud may be of opposite polarity. There appears to be no evidence in favour of this prediction and therefore it appears likely that a non-inductive rather than an inductive process is generally dominant in thunderstorm electrification.

If the non-inductive ice–ice process is of major importance then one might expect to find significant differences in the rates of field development – and especially the location of the negative charge centre – between clouds in which the Hallett–Mossop ice production process operates and those in which it does not. Specifically, it would be interesting to compare these locations in thunderclouds in Montana, to be studied in the CCOPE experiment in 1981 – since these clouds are believed not to exhibit this splintering phenomenon – with those in New Mexico and Florida, discussed in section 3, where splintering does occur.

It is apparent that over the past few years there have been considerable technological advances, mentioned in section 3, that permit the performance of much more powerful and comprehensive field studies of thunderstorm electrification than have been performed to date. The more important of these developments include: various techniques for the location of charge centres and sources of electromagnetic radiation; fast-scanning and dual-doppler radar for observation of the three-dimensional structure of the air motions and precipitation; airborne devices for the measurement within clouds of electric field strength and the charge and size of precipitation elements; and optical instruments for the measurement of the shape, phase, size and concentration of hydrometeors of all types. Experiments, preferably conducted at more than one location, in which these techniques were fully integrated into a coordinated field programme, would go far to resolve some of the existing uncertainties which this article has attempted to identify. This would be further assisted if a technique could be devised for the measurement of individual charges on smaller hydrometeors. Specific problems which such a programme might address are: the association between charge centres, electric fields, precipitation and the airflow; the structure of the electric field and the characteristics of the hydrometeors throughout the evolution of the cloud from its formation to its production of lightning; the exchange of charge between the cloud and its environment, and the field structure within the latter; and the charge/size/field relationships for individual precipitation elements. It would appear sensible, at first, to direct emphasis to the stage of the electrical development that culminates with the first lightning stroke, since the work of Winn, Moore *et al.* (1980) and others indicates that lightning may modify significantly the electrical characteristics of thunderstorms. The performance of such a coordinated experiment should then permit optimal benefit to be derived, in attempting to explain thunderstorm electrification, from the comprehensive models of cumulonimbus convection and electrification which have been described, for example by Chiu (1978), Chiu and Orville (1978), Helsdon (1980) and Rawlins (1980). No doubt, also, the information derived from these field experiments would guide the refinement of these models.

Mason (1969), in a comprehensive review of the current status of cloud physics, isolated three major unresolved problems; the evolution of cloud droplets in cumulus, leading to the formation of embryonic raindrops; the glaciation of shallow supercooled cumulus; and the electrification of thunderstorms. It appears possible that the solutions to each of these problems are intimately related. The calculations of Baker and Latham (1979), Telford and Chai (1980) and Baker *et al.* (1980) have shown that the inhomogeneous nature of the mixing between a turbulent cloud and entrained environmental air produces droplet spectra which fit well with observation and results in the formation of embryonic raindrops several times faster than is predicted classically. Such enhanced growth-rates could cause the largest droplets required for the operation of the Hallett–Mossop splintering process to be available at significantly higher temperatures than classical theory would predict. Since this process operates only within the -5 to -8 °C temperature band it is possible that in some circumstances the splintering process would not occur if the rate of growth by condensation of the largest droplets in the spectrum was not significantly increased. This may well apply to the thunderstorms studied in New Mexico, which have relatively cold bases. The Hallett–Mossop process has been shown (for example, Chisnell and Latham 1976) to be capable of producing the observed rapid glaciation of cumulus, giving rise to ice crystal concentrations required (according to estimates outlined in the previous section) for the ice-crystal/hailstone non-inductive mechanism of thundercloud electrification to produce breakdown fields within the available time. As mentioned earlier, an alternative mechanism for producing the ice crystal concentrations required at relatively warm temperatures for effective charge separation is transport from higher altitudes in the penetrative downdraughts caused by turbulent entrainment and droplet evaporation at the top of the growing cloud – the first stage of the process which leads to spectral broadening and the generally observed sub-adiabatic water contents.

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