Thunderstorm Electrification by the Inductive Charging Mechanism: II. Possible Effects of Updraft on the Charge Separation Process

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ABSTRACT

There is evidence that the inductive charging process is likely to be efficient in regions of the cloud that contain relatively high concentrations of large ice particles (graupel, hail, etc.) and small ice particles or supercooled droplets, but not in regions where only liquid drops are present. Because of these spatial limitations, the transport of charge centers by updrafts can be expected to affect the direction and efficiency of the inductive charge transfer process. On the basis of some qualitative arguments we come to the following conclusions: 1) updrafts are necessary for the inductive charge separation process to be efficient, and 2) this charge separation mechanism need not always produce a bipolar charge distribution with the positive charge center above the negative charge center, but that in the presence of strong updrafts the negative charge center may extend all the way to the cloud top.

1. Introduction

Recent laboratory experiments (Scott and Levin, 1970; Aufdermaur and Johnson, 1972) show that under some conditions inductive charge transfer during collision between ice particles of different sizes or between large ice particles and splattering (or bouncing) supercooled droplets can be very efficient. The extent to which this occurs inside a cloud is still uncertain. There is some evidence that this charge separation process can be efficient only within a limited region in the cloud. If this is the case, then the transport of charge by updrafts and downdrafts can be expected to affect the direction and efficiency of charge transfer.

Because of the interdependence of particle charges, their fall velocities, and the local electric field strength, a quantitative evaluation of the effects of updraft on this charging mechanism is difficult. At present we shall deal with the problem in a qualitative way only. Our conclusions should therefore be regarded as tentative and subject to further investigation.

2. Spatial limitations of the inductive charging mechanism

In collisions between ice particles polarized in an external electric field, charge is transferred and the charged particles separate under gravity in a direction that increases the existing field. The amount of charge transferred has been theoretically computed for the case of two perfectly conducting spheres by Gordon (quoted by Latham and Mason, 1962). Roughly the same values have been measured by Scott and Levin (1970) for charge transferred in collisions between an ice sphere and natural ice crystals at temperatures in the range of −2 to −4C. [Earlier measurements by Latham and Mason (1962) using laboratory-made pure ice particles showed no measurable charge transfer at the same temperature. Scott and Levin attribute this disagreement to the difference in conductivity between natural ice crystals and pure ice.] Our computations show (Paluch and Sartor, 1973) that if the amount of charge transferred is about the same as the theoretical value for perfectly conducting spheres, then in the presence of relatively high concentrations of precipitation-size ice particles ($\gtrsim 3$ gm m^{-3}) this charge separation process can be very efficient. However, since the conductivity of ice decreases rapidly with temperature (Sartor, 1967), it is possible that at some lower temperatures the amount of charge transferred in a collision becomes very small. At present we do not know what, if any, temperature limitations this charge transfer process may have in clouds.

In collisions between polarized ice particles and supercooled droplets, charge can be separated in a direction that enhances the existing field if partial coalescence occurs and part of the droplet mass splatters off the bottom (but not the top) surface of the ice particle. Experiments by Aufdermaur and Johnson (1972) indicate that such splattering occurs with a frequency of 1–10 events per 1000 collisions. Given that the supercooled droplet concentrations often exceed the small ice particle concentrations by several orders of magnitude, this charge separation process may be just as efficient as the charge separation in ice-ice collisions,

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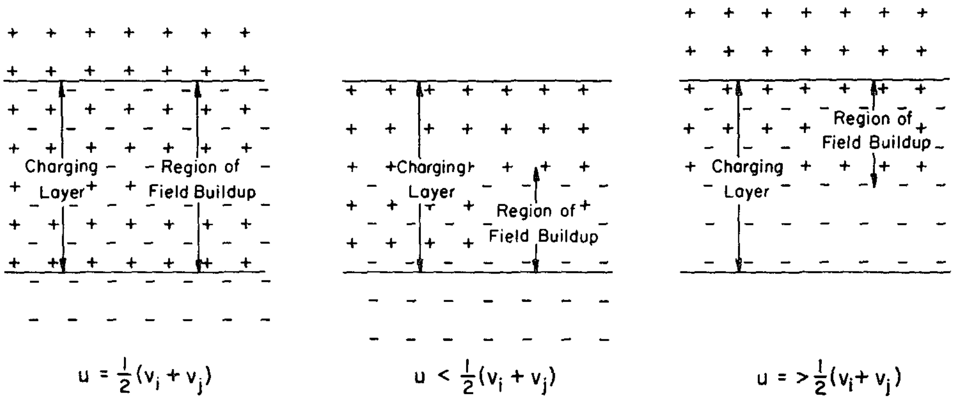

Fig. 1. A schematic diagram of gravitational charge separation at different updraft velocities U in a region containing two kinds of particles whose terminal velocities are V_j and V_i.

provided that relatively high concentrations of precipitation size ice particles are present (Paluch and Sartor, 1973).

In collisions between polarized liquid drops for charge to be separated the drops must temporarily coalesce and then break up again; no charge is transferred if the drops "bounce" without breaking the air film between them (Sartor and Abbott, 1968). When the smaller droplet breaks off the bottom surface, charge separates in a direction that enhances the existing field, whereas the field is decreased if the droplet breaks off the top surface. Thus the two processes tend to counteract each other. If one type of break-off predominates, it could be expected from aerodynamic considerations to be the one where the smaller drop breaks off the top surface (see also Matthews and Mason, 1964). Combined with the fact that temporary drop coalescence and breakup are quite rare events (Whelpdale and Hist, 1971), this suggests that the inductive charging processes for liquid drops will not be effective in separating charge in a rapid systematic way.

We shall therefore proceed from the argument that the inductive charge separation mechanism involves ice-ice or ice-supercooled droplet collisions only. Qualitatively this is compatible with observations. The strongest electric fields are generally observed above the zero isotherm and occur in the presence of ice crystals, rimed aggregates, and supercooled droplets (Latham and Stow, 1969; Mason, 1972).

Thus, we expect the region where inductive charge transfer occurs to be spatially bounded. The lower limit of this region is at the altitude where ice particles melt; the upper limit is at some altitude above which there is an insufficient number of precipitation size ice particles, or above which there are not enough supercooled droplets and the cloud temperature is too low for efficient charge transfer in ice particle collisions to take place. At present we do not know which of these limitations is of primary importance in determining the upper boundary of the charging zone.

3. The effects of updraft velocity on charge separation

The existence of upper and lower boundaries of the region of charge separation implies that only over some limited range of updraft velocities can the generation of electric fields be expected to reach maximum efficiency.

Since the amount of charge transferred in a collision is directly proportional to the local electric field strength, the most efficient charge separation occurs when the charged particles separate in a way that results in a maximum increase in the electric field strength in the region where charge transfer can occur. Thus, the most effective field buildup can be expected to occur when the updraft speed is such that the upward flux of the positive charge equals the downward flux of the negative charge; that is, when the updraft is about half the fallspeed of the large ice particles [more precisely, when updraft $U=\frac{1}{2}(v_j+v_i)$, where v_j and v_i are the mean terminal velocities of the larger and smaller cloud particles, respectively]. If the updraft speed is either too low or too high, charge of one sign will fall or be swept into the charging zone (see Fig. 1) and thus the region where efficient charge transfer and field buildup take place will continuously decrease in depth. If the charging zone is relatively shallow, this process may be of primary importance in determining the time during which the electric field can grow efficiently.

That convection is a necessary condition for electrification has been noted by a number of observers (Vonnegut *et al.*, 1959; Reynolds and Brook, 1956; Workman and Reynolds, 1949; and others). Apart from inductive charging, this is consistent with the convective theory of cloud electrification proposed by Vonnegut (1955).

In regions of the cloud where conditions for electrification are favorable, the inductive charging mechanism is typically expected to produce a bipolar charge distribution with the positive charge center above the negative charge center if initially the electric field is in the direction of the fair weather field (the opposite polarity should result if the initial electric field direction is reversed). Such bipolar charge distribution is often observed in thunderstorms.

However, Malan and Schonland (1951) and Fitzgerald (1972) have observed that in a number of clouds the net negative charge is distributed within a column that extends all the way from the base of the cloud where temperatures are as high as 3C to the very top of the cloud where temperatures are −40C or less. Offhand, this type of charge distribution seems incompatible with the inductive charging mechanism as well as other charging mechanisms that involve gravitational charge separation. Upon closer inspection, however, it appears that a negatively charged column-like structure can, under some conditions, be a consequence of the inductive charge separation process.

As long as the large ice particles are colliding with the smaller cloud particles within the charging zone, their charge will tend to adjust to a value appropriate to the local field strength (Paluch and Sartor, 1973). Estimates show that the relaxation time for charging (and discharging) the larger ice particles by multiple collisions can be quite small. For example: a graupel partical falling at 8 m sec^{-1} through a cloud of 0.5 cm^{-3} small ice particles $50\,\mu$ in radius has a relaxation time of about 20 sec (assuming that collision efficiency, separation probability and charge transfer efficiency are equal to 1).

Let us consider now the electric field produced by a finite bipolar charge distribution. If the field between the charge centers is directed downward, then at the upper edge of the positively charged volume and at the lower edge of the negatively charged volume there is a weak fringe field directed upward. When updrafts are high so that the negatively charged volume lies well within the charging zone, then it can be expected that the large ice particles at the lower edge of the negatively charged volume will transfer their negative charge to the smaller neutral ice particles or supercooled droplets which are carried along with the updraft. Once started, this process of transferring charge will continue while the negative charge center moves upward. Eventually all the negative charge may be transferred to the small cloud particles and carried by the updraft to the upper portions of the cloud.

In regions where updrafts are low, so that the positively charged volume lies within the charging zone, we cannot generally expect a similar charge loss from the small positive particles because the average time between collisions for these particles is on the same order of magnitude or larger than typical growth times for thunderstorm fields. For example, if there are 10^{-5} cm^{-3} graupel particles 0.2 cm in radius falling at 8 m sec^{-1}, then the average time between collisions for a small ice particle is about 1000 sec.

Thus, when updrafts are low or when the thunderstorm cell is in its beginning stages of growth, we expect the positive charge to be attached to the small cloud particles and negative charge to the large ones, producing the typical thunderstorm polarity. On the other hand, if the updraft structure of a thunderstorm cell is (or has been) such that in the core the updrafts are about the same as the fallspeed of the large ice particles, then in the high-updraft regions we can expect the negative charge to be attached to the small cloud particles and carried upward; whereas in adjacent regions where updrafts are lower, negative charge will be carried downward by the larger cloud particles. In this way the negative charge may in time extend to the top and the bottom of the cloud, producing a column-like structure within the updraft region. Fig. 2 gives a rough sketch of what this charge distribution may look like in a single-cell developing cumulonimbus. Multiple-cell storms can, of course, contain all possible combinations of the depicted situations. In such storms discharges can occur between all cloud elements and the charged regions may rearrange in many ways which are too complex to describe.

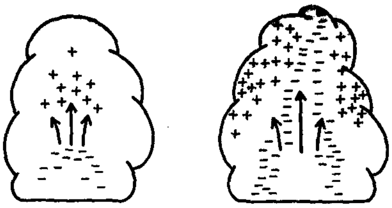
EARLY STAGE LATER STAGE

FIG. 2. A sketch of expected charge distribution due to inductive charging in a single developing thunderstorm cell in the presence of strong updrafts (indicated by arrows).

4. Conclusions

Our preliminary conclusions are that 1) updrafts are necessary for the inductive charge separation process to be efficient, and 2) this charge separation mechanism need not always produce a bipolar charge distribution with the positive charge center above the negative charge center, but that in the presence of strong updrafts the negative charge center may extend all the way to the top of the thunderstorm cell.

A quantitative assessment of the effects of updraft on the inductive charge separation mechanism requires a three-dimensional time-dependent model in which particle charges are computed as functions of time and of their position within the charging zone. To develop such a model we must know the approximate dimensions of the charging zone. This, in turn, requires that we know to what extent the inductive charge transfer efficiency depends on temperature and other factors that may be of importance. Thus, more laboratory studies of the inductive charge transfer process are very much needed.

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