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INFINITE CLOUD MODEL OF ELECTRIFICATION BY THE PRECIPITATION
MECHANISM IN THE PRESENCE OF HIGH RATES OF ION GENERATION

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INFINITE CLOUD MODEL OF ELECTRIFICATION BY THE
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OF ION GENERATION

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ABSTRACT

We have extended a simple, infinite-cloud, precipitation-mechanism model of thundercloud electrification to include effects due to the presence of radioactive aerosol particles. These effects involve ion generation, currents due to motions of ions and charged aerosol particles, and collection of ions and aerosol particles by hydrometeors and cloud droplets. Our conclusion is that an ion-pair generation rate $G \geq 10^{12} \text{ m}^{-3} \text{ s}^{-1}$ will prevent significant electric-field growth.

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INTRODUCTION

Consideration of the electrical aspects of rainout requires self-consistent determination of the electric field in the presence of high rates of ionization. The processes of attachment of ions to radioactive aerosol particles and cloud drops of various sizes and of attachment of radioactive particles to drops depend on the ambient electric field; the time development of the electric field in turn depends on the currents associated with the motions of the various charged objects in the cloud. In this paper we examine the extent to which the ionization associated with a radioactive aerosol will limit electric-field growth in a thundercloud within the context of a simple cloud model.

There is not agreement on the mechanism by which large fields are generated in natural thunderstorms. Favored theories in recent years involve the charge separation produced by charged solid precipitation falling away from oppositely charged cloud droplets that move with the updraft. The charging of these two types of object with opposite sign arises from collisions of cloud droplets with precipitation hydrometeors. Mechanisms proposed for this collision charging include an inductive mechanism involving polarization of the hydrometeor by the ambient electric field and several non-inductive mechanisms involving differential charge transport along a thermal gradient or differences in the work functions of ice surfaces. The details of various simple models based on precipitation theories of electrification have been worked out, for example, by Kamra [1970], Mason [1972, 1973], Paluch and Sartor [1973], Ziv and Levin [1974], Scott and Levin [1975], and Illingworth and Latham [1975, 1977]. Starting from a fair-weather field the order of 100 Vm^{-1} , these calculations

yield fields greater than 10^5 Vm^{-1} in times of from 50 to 1000 seconds, depending on the particular values of various parameters that are used.

Precipitation theories for cloud electrification have been criticized on various counts, particularly by Moore [1974, 1975a, 1975b, 1976]. However, the few quantitative models of cloud electrification based on alternative theories have so far not proved capable of explaining the development of thunderstorm fields in a reasonable amount of time [Chiu and Klett, 1976].

Most precipitation-theory models of thunderstorm electrification have in common the assumption of an infinite cloud with neither horizontal nor vertical space dependence of its properties. Exceptions are recent work by Illingworth and Latham [1975, 1977] on a simple cylindrically symmetric, finite-cloud model and by Chiu and Orville [1977] on a more elaborate model of this type. The electric field and the droplet and hydrometeor velocities are assumed to have only vertical components. The evolution of the electric field in time is obtained by solving

$$\frac{dE}{dt} = - \frac{J}{\epsilon_0}, \quad (1)$$

where the current density J has contributions from the motions of charged droplets, charged hydrometeors and in some cases ions.

Our first attempt to assess the effect of high ion-production rates on electric-field growth has been to extend a simple, infinite-cloud, precipitation-theory model to include effects due to the presence of radioactive aerosol particles. Before describing this model, we present a rough estimate of the rate of ionization that we expect will prevent field growth. Suppose that during its growth, in the absence of significant ionization, the electric-field strength is roughly an exponential function of time.

$E \approx E_0 \exp(\xi t)$. Then from Eq. (1) we have $-J/\epsilon_0 = dE/dt \approx \xi E$. Suppose it takes a time $\Delta t \approx 100$ s for the field strength to grow from 100 Vm^{-1} to $3 \times 10^5 \text{ Vm}^{-1}$; then $\xi = \Delta(\ln E)/\Delta t \approx 0.08 \text{ s}^{-1}$. Thus, the magnitude of the current density that the field-building process can generate is roughly $|J| \approx \epsilon_0 \xi E \approx (7.1 \times 10^{-13} \text{ C}^2 \text{ J}^{-1} \text{ m}^{-1} \text{ s}^{-1}) E$.

Let n_1 and n_2 be the number densities of positive and of negative ions, respectively, and w_1 and w_2 be the corresponding mobilities. If $n_1 \approx n_2 \equiv n$, we have for the current density due to the ions that $J_{\text{ions}} \approx ne(w_1 + w_2)E$, where e is the magnitude of the electronic charge. Thus, if the field is to grow in the presence of the ions we must have $\epsilon_0 \xi > ne(w_1 + w_2)$, or $n < \epsilon_0 \xi / e(w_1 + w_2) \approx 1.2 \times 10^{10} \text{ m}^{-3}$, where for the mobilities we have used $w_1 = 1.8 \times 10^{-4} \text{ m}^2 \text{ V}^{-1} \text{ s}^{-1}$ and $w_2 = 2.0 \times 10^{-4} \text{ m}^2 \text{ V}^{-1} \text{ s}^{-1}$ [Mohnen, 1974].

To estimate the generation rate G for electron--positive-ion pairs (hereafter called simply the ion-generation rate) associated with this number density, we insert $n = 1.2 \times 10^{10} \text{ m}^{-3}$ into Eq. (C11) of the report by Rosenkilde [1976, Appendix C] and solve for the ion-generation rate. If we use Rosenkilde's estimates for the attachment coefficients, we obtain for the case where $E = 3 \times 10^5 \text{ Vm}^{-1}$ and the droplet number density is $2.0 \times 10^8 \text{ m}^{-3}$ that $G \approx 1.4 \times 10^{11} \text{ m}^{-3} \text{ s}^{-1}$. If we assume that the field growth occurs in the shorter time $\Delta t \approx 20$ s, we obtain $G \approx 7.3 \times 10^{11} \text{ m}^{-3} \text{ s}^{-1}$. We anticipate that an ion-generation rate of roughly this magnitude will prevent electric-field growth.

DESCRIPTION OF MODEL

We start with a simple, infinite-cloud, precipitation-theory model of thunderstorm electrification. We assume that the cloud is spatially homogeneous and that the electric-field development is governed by Eq. (1). The macroscopic electric-field strength, the current density, and the velocities of all cloud objects are assumed to have only vertical components; downward is taken as positive.

We consider one size of spherical cloud droplet for each of three droplet categories: droplets that have had zero (virgin droplets), one, and two collisions with hydrometeors. The probability of rebound from a third collision is assumed to be zero. We include a parameter representing a constant rate of gain in the number of virgin droplets per unit volume to account for condensation. Rather than attempting to deal with a distribution of droplet charges within each category, we assume that the total charge available for each category of droplets at each step of the computation is uniformly distributed over the droplets in the category. [Scott and Levin, 1975]

We consider one size of spherical hydrometeor. The number of hydrometeors per unit volume is assumed constant; the size of the hydrometeors grows in time because of accretion of colliding droplets that do not rebound and accretion of a fraction of the mass of rebounding droplets. Aufdermaur and Jansson [1972] give experimental evidence that a supercooled liquid droplet undergoing a rebounding collision with a hail pellet will leave some of its mass behind on the pellet. Hydrometeors and droplets are assumed to move vertically with their terminal velocities as determined by electrical, gravitational, and air viscosity effects. We compute the terminal velocities as suggested by Ziv and Levin [1974]. Geometrical cross sections are used to describe

droplet-hydrometeor collisions; droplet-droplet collisions are ignored.

For the inductive mechanism the charges on a droplet and a hydrometeor immediately after a collision depend on their charges just before the collision, their radii, the ambient electric-field strength, and the angle θ between the electric-field direction and the line joining the centers of the spheres through the point of contact according to the equations of A. N. Gordon as reported by Latham and Mason [1962].

The probability that a droplet will rebound from a collision with a hydrometeor will depend on θ ; however, it is not feasible to follow each collision with its individual value of θ . We introduce as a parameter applicable to all collisions an average rebound probability $\overline{\alpha(\theta)}$. To describe the amount of charge exchanged in a collision via the inductive mechanism we also need a parameter representing the average value of the product of the rebound probability and the cosine of θ divided by the average value of the rebound probability, $\overline{\alpha(\theta)\cos\theta} / \overline{\alpha(\theta)}$, which we represent by $\langle\cos\theta\rangle$.

In order to represent one type of non-inductive charging mechanism we introduce a parameter Δ representing a constant amount of charge exchanged in each rebounding droplet-hydrometeor collision. The sign of Δ is such that the hydrometeor gains negative charge.

We must add to this basic model a number of effects associated with the presence of radioactive aerosol particles: (1) Contributions to the current density due to the motions of ions, free electrons, and charged aerosol particles. (2) Contributions to the charging of droplets and hydrometeors due to collection of ions and free electrons. (3) Collection of ions by aerosol particles. (4) Ion-ion recombination. (5) Augmentation of ion and free electron number densities due to decay of the radioactive aerosol. (6) Attachment of free electrons to air molecules forming ions. (7) Collection of aerosol particles by droplets and hydrometeors.

Radioactive aerosol particles are described by parameters representing their concentration, radii, and an activity that gives the desired ion-generation rate. Particle mobilities were estimated using the empirical formula given by Fuchs [1964, p. 27]. We assume that each beta decay of the radioactive aerosol material produces a 0.5 MeV beta particle that generates 1.5×10^4 electron--positive-ion pairs. Rates for significant processes involving free electrons have been estimated based on information given by Phelps [1969] and by Biondi [1969].

We take the ion-ion recombination coefficient to be $1.6 \times 10^{-12} \text{ m}^3 \text{ s}^{-1}$. The hydrometeors, droplets, and aerosol particles collect ions via convective diffusion with both fluid and electrical forces. To describe the currents of positive and negative ions to the collectors we use the equations of Whipple and Chalmers [1944] or of Klett [1971], depending on whether the parameter eEa/kT has magnitude greater than or less than 4.0, respectively, as suggested by Klett. Here e is the magnitude of the electronic charge, a is the radius of the collecting object, k is Boltzmann's constant, T is the absolute temperature, and E is the electric-field strength far from the collector. Ionic mobilities are based on an article by Mohnen [1974].

Free-electron drift velocities are computed using the formula given by Rosenkilde [1976, Appendix B] based on a tabulation given by Huxley and Crompton [1974]. In an early version of the model, collection of free electrons was described using the same equations as used for collection of ions. The concentration of free electrons is always very small compared to the concentration of ions, and the results with electron collection included were insignificantly different from the results without electron collection. Therefore, collection of free electrons was not included in subsequent versions of the model.

It is difficult to make even a crude model of the collection of aerosol particles by hydrometeors and droplets. Theoretical calculations by Grover [1976] for particle radii of from 0.5 to 10 μm indicate that for a droplet-sized collector the collision efficiency will depend strongly on the particular electrical conditions. We have made two preliminary investigations concerning particle collection. (1) For small aerosol particles the collection formulas should not be grossly different from those for ion collection. In one version we included collection of particles by droplets and hydrometeors following the same equations as used to describe collection of ions. (2) In another version we included a constant rate of depletion of the number density of particles; the charges of removed particles were assigned equally to hydrometeors and virgin droplets so that the model continued to conserve charge. Our conclusion from these studies is that collection of a few particles $\text{cm}^{-3}\text{s}^{-1}$ will affect the electric-field strength by at most a few percent over a time of several hundred seconds. By this time we can answer the question of whether or not the electric-field strength grows to large values; therefore, we have ignored collection of aerosol particles for most of our computations.

Based on these assumptions, we have developed a system of twelve coupled first-order ordinary differential equations that govern the time development of the electrical conditions of our model cloud. These equations are presented in detail in a report by Spangler [1978]. We have solved these equations for various choices of parameters and initial conditions using the version of the Gear differential equations solving code developed by Hindmarsh [1974].

CHOICE OF PARAMETERS

There are many parameters that can be varied. Since our major concern is to assess the effect of radioactive aerosol particles on electric-field growth, we have given most attention to consideration of various values of the ion-generation rate G .

We have investigated three cases for the charge separation accompanying rebound of droplets colliding with hydrometeors: 1) inductive mechanism only, 2) non-inductive mechanism only, and 3) both inductive and non-inductive mechanisms acting simultaneously. Several non-inductive mechanisms that might be operative in ice-ice or ice-water collisions have been proposed; the experimental evidence is contradictory. Reynolds, Brook, and Courley [1957] reported a charge separation the order of $1.7 \times 10^{-13} \text{C}$ per ice crystal collision when ice crystals of about 50 microns radius and supercooled liquid droplets collided with a simulated graupel pellet of 2 mm radius. Latham and Mason [1961] found a charge separation of only $1.7 \times 10^{-18} \text{C}$ per rebounding collision when ice crystals of 50 microns radius collided with a simulated hail pellet under conditions similar to those of Reynolds et al. This discrepancy is supposedly resolved by noting the smoothness of the hail pellet used by Latham and Mason compared to that of Reynolds et al. [Stow, 1969]. Buser and Aufdermaur [1974] reported a charge separation the order of $2 \times 10^{-15} \text{C}$ per collision for ice crystals of 20 μm diameter impacting on ice targets. Marshall et al. [1978] have suggested that the charge transfer per rebounding collision Δ for ice crystals of diameters d of from 10 to 300 μm can be expressed roughly by the relation $d = k\Delta^2$, where k has the value $5 \times 10^{-6} \text{Cm}^{-2}$. This leaves a wide range of values that might exist in an actual thundercloud. We have tried values of Δ of from $1.5 \times 10^{-13} \text{C}$ to $1.5 \times 10^{-17} \text{C}$. The largest

value gave electric-field strength growth for small G that seemed unrealistically abrupt. Most of our runs to investigate non-inductive charge separation have been made with $\Delta = 1.5 \times 10^{-14} \text{ C}$ since an actual hydrometeor in a cloud is likely to be rough, and we want to investigate the effect of ion generation in the presence of the most puissant feasible charging mechanism.

There is not any experimental data directly relating rebound probability and θ for ice-ice or ice-water collisions. Aufdermaur and Johnson [1972] reported that in collisions of supercooled liquid droplets with a simulated hail pellet there were only 1 to 10 rebounds per 1000 collisions. On the basis of these data, Moore [1975b] argued that rebound occurs only for essentially grazing collisions. The report of Scott and Levin [1970] infers a considerably larger rebound probability for collisions of snow crystals with an ice sphere; however, Moore [1975b] suggests that an ice crystal may slide around the surface of the pellet and make its departure from near the equatorial zone. Values often used in other models of this type have been $\langle \cos \theta \rangle = 0.707$ and $\overline{\alpha(\theta)} = 1$. Moore [1975b, 1976] has asserted that appropriate values are $\langle \cos \theta \rangle = 0.088$ and $\overline{\alpha(\theta)} = 0.01$, or even smaller. Mason [1976] has expressed disagreement with Moore's arguments. All in all, the literature permits great freedom in choosing these parameters. The question is confounded because the surfaces may not be smoothly spherical, and the rebound probability may depend on the topography near the point of contact. There is evidence [Marshall et al., 1978] that for ice-ice collisions the rebound probability may depend significantly on the relative velocity of impact. We have made some runs using the values $\langle \cos \theta \rangle = 0.088$ and $\overline{\alpha(\theta)} = 0.01$ suggested by Moore; we have made a larger number of runs using $\langle \cos \theta \rangle = 0.2$ and $\overline{\alpha(\theta)} = 0.3$.

Choices for other parameters have been made guided by the values used in

other models and by what seems representative of actual thunderclouds. For altitude-dependent quantities we have used values appropriate for an altitude of approximately 4 km. A list of typical parameter values is given in Table 1.

We have assumed that at time zero a fully developed cloud exists with typical hydrometeors and droplets. We do not attempt to describe how the cloud became infected with the radioactive aerosol. The initial charges on the hydrometeors, droplets, and particles are assumed to be zero, and the electric-field strength and the ion densities are assigned normal fair-weather values. We also have made some runs with a negative (i.e. upward directed) initial electric field.

RESULTS

Results obtained for the electric-field strength as a function of time for various ion-generation rates and two hydrometeor concentrations are shown in Figs. 1-4. Figures 1-3 all are for $\bar{\alpha} = 0.3$ and $\langle \cos\theta \rangle = 0.2$. Fig. 1 shows results when only the inductive mechanism is considered; Fig. 2 shows results when only the non-inductive mechanism is considered; Fig. 3 shows results when the inductive and non-inductive mechanisms are acting simultaneously. Figure 4 is for $\bar{\alpha} = 0.01$ and $\langle \cos\theta \rangle = 0.088$. Since the model does not include any dissipation effects arising from corona and the development of lightning, the plots of electric-field strength are terminated at 10^6 Vm^{-1} if they reach that value.

In Fig. 1 we see that with only the inductive mechanism operating, a value of $G > 10^9 \text{ m}^{-3} \text{ s}^{-1}$ is required to have a significant effect on electric-field growth. Increasing G beyond this value causes increasing delay in the attainment of a large field. If $G > 10^{11} \text{ m}^{-3} \text{ s}^{-1}$, there is no field growth within 600s.

In Fig. 2 we see that with only the non-inductive mechanism operating and with a charge exchange per collision of $\Delta = 1.5 \times 10^{-14} \text{ C}$, a value of $G \approx 3.2 \times 10^{11} \text{ m}^{-3} \text{ s}^{-1}$ is required to have a significant effect on electric-field growth. The delay in field growth with increasing G is much less than in Fig. 1; if the field strength grows beyond 10^5 Vm^{-1} , it does so within about 80s. The ultimate field strength is smaller than in Fig. 1; this is because field growth occurs while the hydrometeors are smaller and more readily levitated. A value $G = 2 \times 10^{12} \text{ m}^{-3} \text{ s}^{-1}$ prevents field growth.

With $\Delta = 1.5 \times 10^{-15} \text{ C}$ the curves are like those in Fig. 2 but shifted somewhat to the right and reaching somewhat greater field strengths. A curve like 8 is reached for $G = 10^{12} \text{ m}^{-3} \text{ s}^{-1}$. With $\Delta = 1.5 \times 10^{-16} \text{ C}$ the curves are again similar to those in Fig. 2, but with a more gradual termination of field growth

and a slightly greater shift to the right. A curve similar to 8 is reached for $G = 10^{11-3} \text{ m}^{-3} \text{ s}^{-1}$. With $\Delta = 1.5 \times 10^{-17} \text{ C}$ the curves are again similar to those of Fig. 2 but shifted somewhat to the right and with a more gradual termination of field growth. In this case the largest field strength attained is only slightly greater than 10^5 Vm^{-1} . A curve similar to 8 is reached for G less than $10^{11-3} \text{ m}^{-3} \text{ s}^{-1}$ but greater than $10^{10-3} \text{ m}^{-3} \text{ s}^{-1}$.

The curves of Fig. 3 are much like those of Fig. 2, indicating that the non-inductive mechanism dominates for $\Delta = 1.5 \times 10^{-14} \text{ C}$. This domination by the non-inductive mechanism continues down to $\Delta = 1.5 \times 10^{-16} \text{ C}$. However, with $\Delta = 1.5 \times 10^{-17} \text{ C}$ the curves obtained for both mechanisms operating simultaneously are similar to those of Fig. 1.

The shape of the curves in Fig. 4 for both mechanisms operating simultaneously is much like that of the curves in Fig. 3; however, the value of G required to prevent field growth is about an order of magnitude smaller. The curves of Fig. 4 for the inductive mechanism operating alone are very different from the curves of Fig. 1. In Fig. 4, as G is increased from zero there is at first field growth at earlier times and to greater ultimate field strength. This trend continues to beyond $G = 10^{9-3} \text{ m}^{-3} \text{ s}^{-1}$. Further increase in G leads to delay in the onset of field growth, a more abrupt termination of field growth, and lower ultimate field strength. Finally by $G = 10^{11-3} \text{ m}^{-3} \text{ s}^{-1}$ field growth is prevented. This is essentially the same value of G that prevents field growth in Fig. 1.

The stronger field growth in Fig. 1 is associated with greater growth of hydrometeor charge, which we would expect for larger $\bar{\alpha}$ and $\langle \cos \theta \rangle$. The initial trend to greater field growth as G is increased in Fig. 4 is associated with the development of significant positive droplet charges, particularly when $(n_1 - n_2)$ becomes a significant fraction of $(n_1 + n_2)$. This behavior can also be traced in the cases of Fig. 1, but it is masked there by the greater current

due to charged hydrometeors.

We also made some computations with an initial field strength of -100 Vm^{-1} rather than $+100 \text{ Vm}^{-1}$. Examination of the equations of the model under the condition that the initial values of the droplet and hydrometeor charges and of the electric-field strength are changed in sign reveals the following:

(a) The expressions for the inductive charging mechanism are reversed in sign; i.e., the mechanism will tend to produce positive hydrometeors and negative droplets, and hence to build an electric field of negative sign.

(b) The equations for the collection of ions by various objects show the same kind of symmetry to the extent that $n_1 \approx n_2$ and $w_1 \approx w_2$. These relations are only roughly valid in our model; therefore, we expect that the situation if the electrical initial conditions are reversed in sign will be more complex than simply building a negative field in cases where ion collection is important.

(c) The expressions for the charge exchanged in a collision via the non-inductive mechanism are independent of the electrical conditions. Therefore, this mechanism tends to build a positive electric field regardless of the change in sign of the initial electrical conditions.

(d) The expression for the contribution to aerosol particle charging that is directly due to β -decay is not affected by the change in sign of the initial electrical conditions.

Our results are consistent with these observations. The computations made with $E(t=0) = -100 \text{ Vm}^{-1}$ and the non-inductive charge-separation mechanism operating with $\Delta = 1.5 \times 10^{-14} \text{ C}$ produced virtually identical results after the first seconds to those for $E(t=0) = +100 \text{ Vm}^{-1}$. If only the inductive charge-separation mechanism is operating, the results obtained depend on the value of G . With only background ion production the results for $E(t=0) = -100 \text{ Vm}^{-1}$, except for the virgin droplet charge q and the aerosol particle charge q_p ,

are essentially identical to those for $E(t=0) = +100 \text{ Vm}^{-1}$ except the charges and the electric field have their signs reversed. Thus, in this case a negative electric field is produced. With the exceptions of q and q_p , which are very small in magnitude compared with the other charges, the greatest difference in magnitude of any quantity for the two cases after 125 seconds is about 0.6%.

With $G = 10^9 \text{ m}^{-3} \text{ s}^{-1}$, the inductive mechanism with an initial field of $E(t=0) = -100 \text{ Vm}^{-1}$ again results in the building of a large negative field. With the exception of q and q_p , after 600s the greatest difference in the magnitude of any quantity from the case for a positive initial field is about 5% (the difference in the field magnitudes is 0.14%), and the charges and the electric field have opposite signs for the two cases.

If G is increased to $10^{10} \text{ m}^{-3} \text{ s}^{-1}$, the inductive mechanism with $E(t=0) = -100 \text{ Vm}^{-1}$ produces a positive field. After 600s all quantities have values virtually identical to those produced when $E(t=0) = +100 \text{ Vm}^{-1}$.

Most references describe the electrification of thunderclouds as if only clouds of positive electric field (according to our sign convention of down as positive) exist. Clouds of opposite polarity have been reported for example in a review by Imyanitov and Shifrin [1962], and by Takeuti and Nakano [1974], though the latter authors have more recently concluded that they are observing clouds of normal polarity that are highly distorted by wind shear. [Takeuti, et al., 1978] Illingworth and Latham [1977] report measurements by H. Kasemir showing reversal in sign of the vertical electrical field component within single clouds. If instances of clouds with regions of large negative electric field exist but are rare, this would be an argument favoring the proposition that a non-inductive charge-separation mechanism commonly but not universally operates at least in the early stages of cloud electrification. If negative electric fields are common, this would favor the inductive charge-separation mechanism usually acting alone.

DISCUSSION AND CONCLUSIONS

Our results with only a background ion-generation rate are consistent with what has been obtained with other models of this sort. Both the inductive and the non-inductive charging processes give potent electrification mechanisms, and acting separately or simultaneously they provide tenable explanation of the origin of large electric-field strength in thunderclouds. Field strengths in excess of 10^5 Vm^{-1} are readily produced even for small rebound probability.

As the ion-generation rate is increased, we find that eventually electric-field growth is suppressed. The range of values of G required to prevent field growth for the various cases considered is consistent with the rough estimate made earlier in this paper.

Our treatment has a number of limitations; important among these are the absence of any space dependence, consideration of only vertical field components and only vertical motions of cloud objects, use of only one size and one charge for droplets and one size and one charge for hydrometeors, limitation to spherical droplets and hydrometeors, and a tentative and very simplified treatment of aerosol particle collection. We do not believe that refinement of the model in any of the areas of limitation will alter the basic conclusion that, although there is some variation with choice of parameters and charging mechanism, a conservative estimate is that an ion-generation rate $G \geq 10^{12-3} \text{ m}^{-3} \text{ s}^{-1}$ will prevent significant electric-field growth.

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TABLE 1. Typical Parameter Values

Rate of condensation of virgin droplets per unit volume	$5.0 \times 10^6 \text{ m}^{-3} \text{ s}^{-1}$
Initial electric-field strength	$\pm 100 \text{ V m}^{-1}$
Fraction of mass of droplet left behind on hydrometeor after a rebounding collision	0.1
Background ion-pair generation rate per unit volume	$10^7 \text{ m}^{-3} \text{ s}^{-1}$
Number density of hydrometeors	$10^3 \text{ m}^{-3}, 10^2 \text{ m}^{-3}$
Initial hydrometeor radius	10^{-3} m
Absolute temperature	260K
Ion-ion recombination coefficient	$1.6 \times 10^{-12} \text{ m}^3 \text{ s}^{-1}$
Initial number density of virgin droplets	$2.0 \times 10^8 \text{ m}^{-3}$
Initial number density for other droplet categories	0
$\langle \cos \theta \rangle$	0.2, 0.088
Number density of aerosol particles	10^{10} m^{-3}
Initial number density of positive and of negative ions	$2.5 \times 10^9 \text{ m}^{-3}$
Virgin droplet radius	$2.0 \times 10^{-5} \text{ m}$
Aerosol particle radius	10^{-7} m
Mobility of positive ions	$1.84 \times 10^{-4} \text{ m}^2 \text{ V}^{-1} \text{ s}^{-1}$
Mobility of negative ions	$2.00 \times 10^{-4} \text{ m}^2 \text{ V}^{-1} \text{ s}^{-1}$
$\overline{a(\theta)}$	0.3, 0.01
Droplet mass density	1000 kg m^{-3}
Hydrometeor mass density	600 kg m^{-3}

TABLE 2. Ion-Generation Rate and Hydrometeor Number Density for the Curves of Fig. 1.

Curve	Ion-Generation Rate $G(m^{-3} s^{-1})$	Number Density of Hydrometeors $N(m^{-3})$
3	0	10^3
e	10^9	10^3
d	10^{10}	10^3
c	10^{10}	10^2
1	3.2×10^{10}	10^3
b	5.6×10^{10}	10^3
a	10^{11}	10^2
2	10^{11}	10^3

TABLE 3. Ion-Generation Rate and Hydrometeor Number Density for the Curves of Fig. 2.

Curve	Ion-Generation Rate $G(m^{-3}s^{-1})$	Number Density of Hydrometeors $N(m^{-3})$
7	0	10^3
k	10^{11}	10^3
l	3.2×10^{11}	10^3
m	5.6×10^{11}	10^3
9	10^{12}	10^3
n	10^{12}	10^2
s	1.8×10^{12}	10^2
u	2.4×10^{12}	10^2
r	3.2×10^{12}	10^2
o	10^{13}	10^2
8	10^{13}	10^3
p	10^{15}	10^3

TABLE 4. Ion-Generation Rate and Hydrometeor Number Density for the Curves of Fig. 3.

Curve	Ion-Generation Rate $G(m^{-3}s^{-1})$	Number Density of Hydrometeors $N(m^{-3})$
4	0	10^3
j	10^9	10^3
6	10^{11}	10^3
i	10^{11}	10^2
h	10^{12}	10^2
5	10^{12}	10^3
w	1.1×10^{12}	10^2
v	1.2×10^{12}	10^2
t	1.3×10^{12}	10^2
q	1.8×10^{12}	10^2
g	3.2×10^{12}	10^2
f	10^{15}	10^3

TABLE 5. Ion-Generation Rate and Charge-Separation Mechanism for the Curves of Fig. 4.

Curve	Ion-Generation Rate $G(\text{m}^{-3} \text{s}^{-1})$	Charge-Separation Mechanism
B	0	both ($\Delta = 1.5 \times 10^{-14} \text{C}$)
F	10^{10}	both ($\Delta = 1.5 \times 10^{-14} \text{C}$)
D	10^{11}	both ($\Delta = 1.5 \times 10^{-14} \text{C}$)
C	10^{12}	both ($\Delta = 1.5 \times 10^{-14} \text{C}$)
A	0	inductive
J	10^7	inductive
I	10^8	inductive
G	10^9	inductive
E	10^{10}	inductive
L	3.2×10^{10}	inductive
H	10^{11}	inductive

FIGURE CAPTIONS

Fig. 1: Development of the electric-field strength with time when only the inductive charge-separation mechanism is operative. All curves are for $\bar{\alpha} = 0.3$ and $\langle \cos\theta \rangle = 0.2$. The ion-generation rates and hydrometeor number densities for the various curves are given in Table 2; values of all other parameters are given in Table 1.

Fig. 2: Development of the electric-field strength with time when only the non-inductive charge-separation mechanism is operative. All curves are for $\Delta = 1.5 \times 10^{-14} \text{ C}$, $\bar{\alpha} = 0.3$ and $\langle \cos\theta \rangle = 0.2$. The ion-generation rates and hydrometeor number densities for the various curves are given in Table 3; values of all other parameters are given in Table 1.

Fig. 3: Development of the electric-field strength with time when the inductive and non-inductive charge-separation mechanisms operate simultaneously. All curves are for $\Delta = 1.5 \times 10^{-14} \text{ C}$, $\bar{\alpha} = 0.3$ and $\langle \cos\theta \rangle = 0.2$. The ion-generation rates and hydrometeor number densities for the various curves are given in Table 4; values of all other parameters are given in Table 1.

Fig. 4: Development of the electric-field strength with time when $\bar{\alpha} = 0.01$ and $\langle \cos\theta \rangle = 0.088$. All curves are for $N = 10^3 \text{ m}^{-3}$. Ion-generation rates and charge-separation mechanisms are given in Table 5; values of all other parameters are given in Table 1.

Fig. 1

Fig. 2

Fig. 3

Fig. 4