The effect of electrical conductivity on the growth of the electric field in a thunderstorm

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(Manuscript received May 13; in final form October 28, 1974)

ABSTRACT

The effect of the electrical conductivity on the electrical development of the cloud is investigated. By the use of a numerical model which couples the growth of the electric field and the precipitation development it is demonstrated that as long as the conductivity varies between values which are smaller than the fair weather conductivity and values of up to 100 times the fair weather conductivity, the polarization charging mechanism is powerful enough to generate fields large enough to create lightning.

Introduction

For some time there has been disagreement as to the magnitude of the electrical conductivity inside thunderclouds. The popular belief is that the electrical conductivity within the thunderstorm is *less* than the electrical conductivity of the surrounding air (see Wilson, 1956; Chalmers, 1967; and Mason, 1971). Supposedly the cloud droplets capture the free ions, effectively lowering the number of mobile charges, and reducing the electrical conductivity. However, the high electrical field within the thunderstorm is responsible for the formation of space charge due to point discharge at the ground and assorted discharge effects from irregular particles (ice crystals) and effects during the interactions of water drops (see Dawson, 1970; Pisler & Atkinson, 1971). Hence one might expect an increase in the electrical conductivity as the field builds.

Freier (1962) analysed the recovery curves of potential gradient following lightning flashes; his results indicated that the conductivity of the cloudy air inside these well developed thunderstorms was about twenty times the conductivity of the environmental air. Later, Freier (1963, 1968) developed simplistic models of the thunderstorm which suggest that the conductivity of the cloudy air in the thunderstorm is larger than the conductivity of the surrounding air, but he also suggested that perhaps there is a non-conducting layer near the cloud boundaries.

If either the cloud proper is a poor conductor or this non-conducting layer resides at the cloud edges one expects a space charge to exist in regions where the conductivity changes occur. In the case of an insulating cloud in a conducting medium, a charged layer of opposite sign should exist in the environmental air surrounding the charge centers. The properties of such a screening layer have been modeled by Brown et al. (1971). However, in reality, the existence of such screening layers has not been established, though direct measurements of space charge and spatial variations of electric field have suggested their existence (see Moore et al., 1959, 1961; Vonnegut et al., 1959, 1962). Obviously, indirect measurements of electric field variations and space charge have not established the relative magnitude of the conductivity of cloudy air.

The available data taken in situ (see Evans, 1969) indicate that the well-electrified cloud has a range of conductivities that are generally 10 to 100 times the value of the surrounding air. However, the standard conductivity data taken with ground-based instrumentation located on mountain tops within the thunderstorms (see Moore, 1972) indicate the reverse, that the conductivity of the cloudy air is less than that expected for clear air. There is much confusion as to what the appropriate values of conductivity are. However, a reasonable reconciliation of the data is possible if the cloud initially has a lower conductivity than its environment, but that as the cloud becomes more electrified its conductivity increases dramatically.

This paper is intended to consider the effect of such electrical conductivity variations on electrical field growth in a numerical model of the thunderstorm which includes both the development of the electrical field and the development of precipitation.

It focuses on the question recently posed by Muchnik (1974): If there is indeed a high conductivity within the cloud in the regions where most of the charge is generated (say temperatures between 0°C and −20°C), how, indeed, can the charge be separated in the first place? The argument is that the cloud proper must act effectively as an insulator in order that the large electric dipole can form. Scott & Levin (1974) present the view that it is all a matter of degree. If the charge generating mechanism is powerful enough, the conductivity of the thundercloud is unimportant. This paper attempts to substantiate this view quantitatively with specific examples.

The electrical cloud model

The model used is adequately described by Ziv & Levin (1974). It is a time-dependent model of the whole cloud which considers the cloud as a large capacitor within which charge is generated by the polarization charging mechanism. Simultaneously, precipitation develops by a continuous collection process in which the larger drops collect the smallest cloud droplets and water is added to maintain the cloud droplet–raindrop distribution in a form resembling that found in nature. The basic equation of electrical field growth is given by Mason (1971, 1972), Paluch & Sartor (1973) and Ziv & Levin (1974):

$$d\mathbf{F}/dt = -4\pi\left(\sum_i n_i Q_i \mathbf{V}_i + \mathbf{j}\right) \tag{1}$$

The source current flux $\Sigma_i n_i Q_i \mathbf{V}_i$ is the contribution to the charge separation (commonly referred to as generation) of cloud particles of size index i, concentration n_i, charge Q_i, and velocity $\mathbf{V}_i$. The charges are computed by simultaneous integration of the differential equations for polarization charging of each particle size. This set of ordinary differential equations includes eq. 1 and a continuous collection equation for particle growth by collection. The fall velocities $\mathbf{V}_i$ are computed considering the levitating effect of the electric field. The different characteristics of water and ice are simulated by using different prescribed particle densities, collection efficiencies and charge transfer coefficients. Horizontal gradients as well as effects of electric field on the aerodynamics and coalescence of particles are ignored; the vertical dimension only appears implicitly in consideration of charge continuity of the cloud as a whole, the gathering of charge in the upper and lower charge centers, and the updraft velocity.

The discharge currents

Of special concern is the discharge current flux j. In simplistic form it can be considered as a sum of two terms: (1) the current flux linear with respect to the electric field which is written in terms of Ohm's law as

$$j' = \lambda F \tag{2}$$

and (2) the current flux non-linear with respect to the electric field, resulting from discharge and corona effects.

$$j = j' + j'' \tag{3}$$

To treat the problem empirically, Sartor (1967, 1970) assumed that the discharge currents are given by the form

$$j = \frac{-\lambda F}{2} - \frac{\lambda F^k}{2F_0^{k-1}} \tag{4}$$

where k took on values of 1, 2, 3, and 4; λ is the conductivity of cloudy air; and F_0 is the initial value of the electric field. Mason (1972), however, attempted to fit the scanty data with an exponential form,

$$j = A\,(\exp \beta F - 1) \tag{5}$$

where $A = 10^{-3}$ and $\beta = 0.2$ when e.s.u. are used. Note that Mason used a conductivity of cloudy air that is approximately one-third the fair weather value (6×10^{-4} e.s.u. at 5 km altitude)

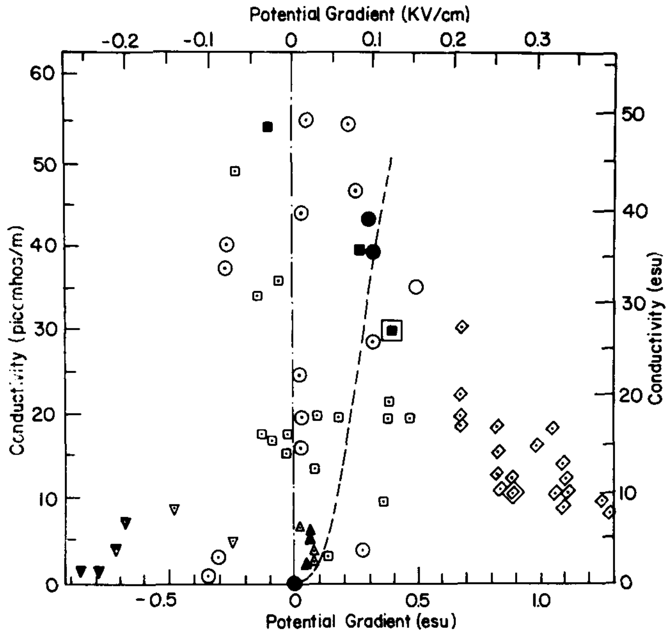

Fig. 1. A composite of Evans' electrical conductivity data: ▽, dropsonde C-50; □, dropsonde C-12; ○, dropsonde C-41; △, dropsonde C-25; ◇, dropsonde C-49. The closed circle at the origin corresponds to dropsonde 7; mean altitude 5 km. Dashed curve represents the best fit of the dark data points and corresponds to eq. 6.

at low electric fields and approaches the fair weather value at $F \simeq 5$ Kv/cm.

Note that the discharge currents used by both Mason & Sartor are greater than the values expected by Wilson (1956). His calculations predict that the conductivity should be about 1/10 the clear air values until the electric field intensity is greater than 30 v/cm. At larger fields the conductivity would be even lower. Important is the fact that ion production by electrical corona (see Dawson, 1970) was omitted in the calculation and since such mechanisms become important at altitudes of 5 km, one expects a higher conductivity.

However, it appears that the only data available that were actually acquired within electrified clouds are those of Evans (1969). The data were acquired from parachuted electric field mills which utilized a rather unique technique of obtaining both the electric field and the conductivity utilizing the dynamic response characteristics of the instrument. As a result, the author claims that the data are only valid when the field is rather high and the changes in the field are small. Evans' data are presented on Fig. 1. The data points represented by the dark symbols are those which Evans considered reliable; those which were considered unreliable are represented by open symbols. The indicated reliability of the best data points is $\pm 50\%$. However, apart from the unreliability of the data (see Vonnegut, 1969) is the fact, emphasized by Evans, that the conductivities are at least 10 to 100 times the values normally found at that altitude. In an attempt to use the most reliable points, we fitted them to a parabolic form, represented by the dashed curve:

$$\lambda(\text{e.s.u.}) = 6 \times 10^{-4} + 3.2(F - F_0)^2 \qquad (6)$$

which presumes the conductivity is equal to the fair weather value initially.

Fig. 2 shows the way several of the discharge currents change as the electric field builds (specific forms for the discharge currents are tabulated in Table 1). It is demonstrated that eq. 6 leads to discharge currents four to five orders of magnitude larger than those obtained by eq. 5.

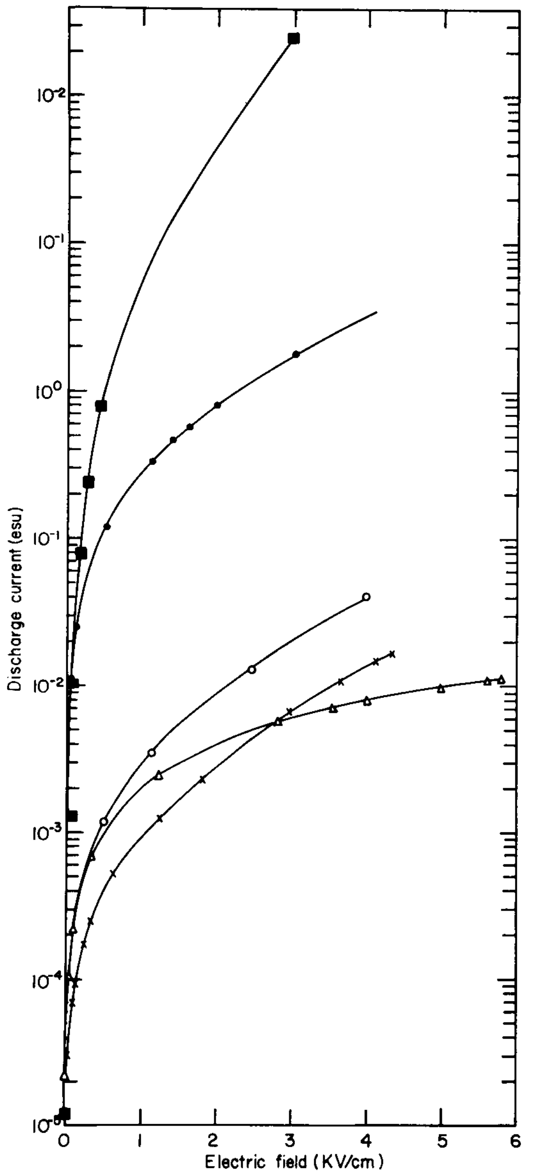

Fig. 2. Variations of the discharge currents with electric field. ×, Exp. 1; ○, Exp. 4; ●, Exp. 6; △, Exp. 10; ■, Exp. 11 (see Table 1).

Expected cloud properties

Fig. 3 is a diagram of the expected cloud properties in three possible cases; they represent the cloud at the *initial state,* before charges have developed on the cloud particles, or the condition where the effect of the charged particle flux is small: in case *a*, the cloud has a conductivity below the conductivity of the environment or the cloud acts as an insulator in a conducting medium. Then the initial fair weather current flux through the cloud is diminished (cared for later, eq. 13, by considering alterations in the cross sectional area of the flux tube). At the same time, the electric field is enhanced due to the buildup of static charge at the upper and lower cloud boundaries. The opposite effects occur when the cloud has a higher conductivity than its environment, case *c*. Here, one expects that, due to the convergence of the fair weather current, the initial current flux would be enhanced. Also, inside the conducting cloud, one expects a low electric field.

The initial value of dF/dt also is expected to follow the initial change in F, due to the effect of formation of the cloud and the creation of a region of altered conductivity. However, if the time required for the cloud to establish its initially lower (higher) conductivity is long or the adjustment to this conductivity state is completed before charge generation can be initiated within the cloud, the initial value of dF/dt would be expected to be small or nearly zero.

Rederivation of the equation for field growth

At this point more consideration needs to be given to the initial state of the cloud and eq. 1. Initially, we consider the cloud to be without charge. This means that the first term on the right side of eq. 1 is initially zero, leaving the discharge current as the sole factor in determining the initial time rate of change of the electric field, and making dF/dt unrealistically negative. The reason for this, of course, is neglect of the omnipresent fair weather currents in the original derivation.

Consider Maxwell's equation for the curl of the magnetic field:

$$\nabla \times \mathbf{H} = \frac{1}{c}\frac{\partial \mathbf{D}}{\partial t} + \frac{4\pi}{c}\mathbf{J}_t \tag{7}$$

where $\mathbf{D}$ is the electric displacement and $\mathbf{J}_t$ is the total conduction current, including the current carried on the cloud particles,

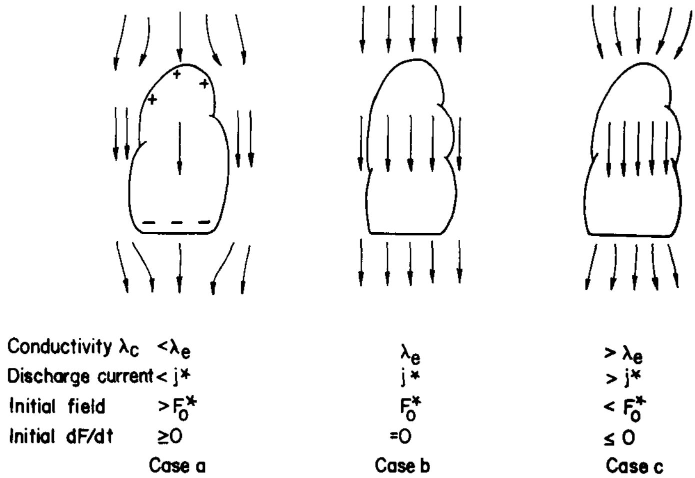

Fig. 3. Expected values of cloud parameters for different values of the conductivity of the cloudy air, λ_c, relative to the conductivity of the surrounding air, λ_e.

$$\mathbf{J}_t = \sum_i n_i Q_i \mathbf{V}_i + \mathbf{j} \tag{8}$$

and c is the velocity of light. The left side of eq. 7 vanishes identically when operated on by the divergence operator. The resulting equation (see Freier, 1963), is

$$\Delta \cdot \left(\frac{1}{4\pi}\frac{\partial D}{\partial t} + \mathbf{J}_t\right) = 0 \tag{9}$$

To obtain a solution to eq. 9 we consider the integral over a closed, stationary volume and use Gauss' theorem:

$$\oint\oint\oint \nabla \cdot \left(\frac{1}{4\pi}\frac{\partial \mathbf{D}}{\partial t} + \mathbf{J}_t\right) dV = \oint\oint \left(\frac{1}{4\pi}\frac{\partial \mathbf{D}}{\partial t} + \mathbf{J}_t\right) \cdot d\mathbf{S} \tag{10}$$

The resulting equation is perfectly general provided there are no moving boundaries (this may be justified as long as the electrically active region lies well within the chosen boundaries); it relates the displacement current $(1/c \cdot \partial D/\partial t)$ to the total conduction current that flows through the closed surface S:

$$\oint\oint \left(\frac{1}{4\pi}\frac{\partial \mathbf{D}}{\partial t} + \mathbf{J}_t\right) \cdot d\mathbf{S} = 0 \tag{11}$$

Now, let us simplify this equation and apply it to our cloud model. Consider the volume shown in Fig. 4 which considers the cloud to be less conductive than its environment. (This use of a poorly conducting cloud does not detract from the generality of the development. Other cases can be treated by simply distorting the control volume.) The sides of the surface are current flux lines, the top surface is far removed from the cloud, and the bottom surface cuts the cloud at the region of interest. Along the flux lines, on the sides of the control volume, the two terms in eq. 11 vanish; over the top area $\partial D/\partial t$ is negligibly small and there is no flux of cloud particles. Therefore eq. 11 becomes

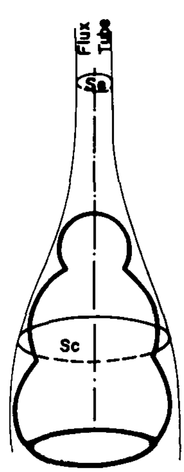

Fig. 4. The volume considered in the derivation of eq. 13.

$$\oint\oint\left(\frac{1}{4\pi}\frac{\partial \mathbf{D}}{\partial t}+\mathbf{J}_t\right)\cdot d\mathbf{S}=\frac{1}{4\pi}\oint\oint\frac{\partial \mathbf{D}}{\partial t}\cdot d\mathbf{S}_c + \oint\oint \mathbf{J}_t\cdot d\mathbf{S}_c - \oint\oint \mathbf{j}\cdot d\mathbf{S}_e \qquad (12)$$

Ignoring polarization charges,[1] approximating the dielectric constant of the cloudy air by that of a vacuum, and defining the appropriate averages over the areas S_c and S_e, eq. 12 becomes much simpler:

$$\frac{1}{4\pi}\frac{\partial \overline{F}}{\partial t}S_c+\overline{J}_t S_c - j^* S_e = 0$$

or

$$\frac{1}{4\pi}\frac{\partial \overline{F}}{\partial t}+\sum_i \overline{nQ_i V_i}+\overline{j}-j_0\frac{S_e}{S_c}=0 \qquad (13)$$

where only the vertical components are considered and where j^* is the mean current flux into the upper side of the surface.

Initially j^* is the fair weather current flux j_0; in this treatment, for lack of better observational values, we will assume that j^* is approximately j_0 throughout the lifetime of the thundercloud. Of course, when the electric field within the thundercloud becomes great enough, the ratio S_e/S_c may approach zero and, indeed, the direction of j^* reverses so that the cloud acts as a current source for replenishment of the charges in the ionosphere and maintenance of the global fair weather electric field. This effect, though perhaps of major importance to the maintenance of the fair weather currents (see Dolezalek, 1972) is assumed to be small in comparison to the large discharge currents within the thundercloud in its mature stage. This assumption is substantiated by the results of this model.

Note that now eq. 13 contains the additional term $j(S_e/S_c)$, the contribution of the fair weather current that was omitted from eq. 1. As mentioned, it is assumed that this term is

[1] This assumption seems incompatible with the use of polarization charging as a prime mechanism for field growth. To demonstrate that the contribution of the polarization **P** to the electric displacement **D** is negligible, take the worst case when there are 10 g/m³ or 10^{-5} g of liquid water per cm³. Then $|4\pi P/F| \sim 3\times10^{-5}$ if the Clausius-Mossotti relation is used to calculate the polarizability (see, for example, Panofsky & Phillips, 1953).

Table 1. *Electrical parameters utilized in the electrical cloud model*

	F_0 (v/cm)	Expression for $J=\lambda F$ (e.s.u.)	λ_c/λ_v at $F=F_0$	λ_c/λ_v at $F=F_{max}$	$\partial F/\partial t$ at $t=0$ (e.s.u.)	F_{max} (v/cm)	Time to reach F_{max} (sec)	Comments	$\Sigma n_i Q_i v_i$ at F_{max} (e.s.u.)
Exp. 1	2	10^{-3} (exp $0.2F-1$)	1/3	2.00	0	4 380	388	Mason's expression	2.2×10^{-1}
Exp. 2	5	10^{-3} (exp $0.2F-1$)	1/3	1.83	0	4 188	365	Mason's expression	1.92×10^{-1}
Exp. 3	0.1	10^{-3} (exp $0.2F-1$)	1/3	2.61	0	4 930	454	Low F_0	3.13×10^{-1}
Exp. 4	0.1	3×10^{-3} (exp $0.2F-1$)	1	5.26	0	4 099	473	$\lambda = 3\times$ Mason's	5.42×10^{-1}
Exp. 5	0.1	3×10^{-2} (exp $0.2F-1$)	10	31.6	0	2 975	676	$\lambda = 30\times$ Mason's	2.34
Exp. 6	0.1	3×10^{-1} (exp $0.2F-1$)	100	207	0	> 1 971	> 880	$\lambda = 300\times$ Mason's	10.26
Exp. 7	0.01	3×10^{-2} (exp $0.2F-1$)	10	34.1	0	3 150	690	Very low initial field	2.70
Exp. 8	2	10^{-3} (exp $0.2F-1$)	1/3	1.96	2.5×10^{-5}	4 338	385	Positive $\partial F/\partial t\|_{t=0}$	2.1×10^{-1}
Exp. 9	0.1	3×10^{-2} (exp $0.2F-1$)	10	35.1	-2.5×10^{-5}	3 206	710	Negative $\partial F/\partial t\|_{t=0}$	2.81
Exp. 10	0.1	$6\times10^{-4}F$	1	1	0	5 850	472	Constant λ	1.46×10^{-1}
Exp. 11	0.1	$6\times10^{-4}F+3.2(F-0.1)^2$	1	> 10^5	0	> 120	> 720	Evans' data	> 1.5

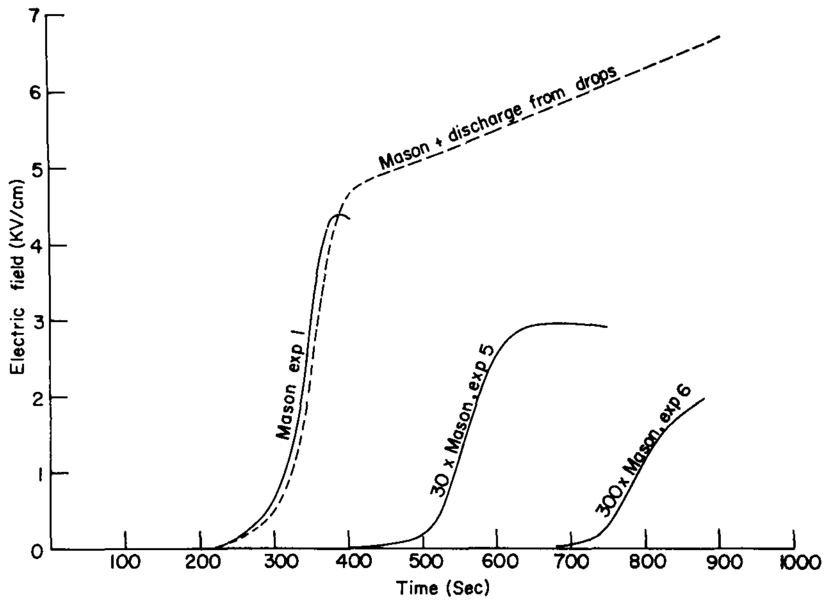

Fig. 5. The effect of different conductivities on the growth of the electric field. The dashed curve includes the effect of drop discharge.

small; however, it may have a marked effect in specifying the initial conditions for field development. Its importance will be considered in the following section.

The growth of the electric field

There are many different ways one can perturb the terms of eq. 13 and still conform to the criteria set forth in Fig. 3. The terms $j_0(S_e/S_c)$ is significant only in the initial stages of electrification and should be less than (greater than) j_0 if the cloud is relatively non-conducting (conducting). However, since its actual value is not known and in the solution of eq. 13 it automatically conforms to these criteria, in the following calculations it will only be considered indirectly. Also, initially it is reasonable that $\partial F/\partial t|_{t=0} = 0$, though it may be positive (negative) if the cloud is relatively non-conducting (conducting).

In the other models (Sartor, 1970; Paluch & Sartor, 1973; Mason, 1972), the cloud has generally been considered to be less conducting than its surroundings, at least in the initial stages of development. So, following Mason (1972), let us use the development of the electric field in this case as a reference. Using Mason's expression (eq. 5) for the conductivity and the other parameters as specified in Table 2, a numerical experiment was run for the values of the parameters listed in Table 1, Experiment 1. Then other experiments were conducted using other parameters to describe the electrical conductivity, as presented in Table 1. Fig. 5 presents the growth of the electric field for a few selected experiments from Table 1. As the field evolves the value of the generating current $\Sigma n_i Q_i V_i$ changes. It first increases due to the increase of V and Q but then decreases due to the effect of the electrical forces on V (see Ziv & Levin, 1974). Table 1 also presents the value of the generating current when the field reaches its maximum value.

Experiments 1, 2, and 3 show the effect of varying the initial value of the electric field. The effect is slight; lowering the electric field delays the time of awakening of the electric field but, as shown, a larger value of the maximum electric field is obtained. This effect, as mentioned by Ziv & Levin (1974), is due to the precipitation development. The delayed electric field build-up simply allows the particles to grow larger before they are levitated so that a larger value of the electric field can be obtained.

Table 2. *Cloud parameters used in the electrical cloud model (see Ziv & Levin, 1974)*

Parameter	Symbol	Value
Separation efficiency	E_3	0.3
Precipitation density (Graupel)	ϱ_p	0.6 g/cm³
Cloud water density	ϱ_c	1.0 g/cm³
Initial liquid water content		
In precipitation particles	W_p	1.0 g/m³
In cloud particles	W_c	1.0 g/m³
Initial mean radius of precipitation particles	R_4	200 μ
Radius of cloud particles	R_1	10 μ
Effective contact angle	θ	45°
Charge transfer coefficient	$1-\exp(-tc/\tau)$	1.0

Specifying a non-zero initial value of $\partial F/\partial t$ has a similar effect. If the initial $\partial F/\partial t$ is greater than zero (corresponding to $S_e/S_c < 1$ in eq. 13 or case of a conducting cloud in Fig. 3), the field growth has an initial boost but, again, the particles have less time to grow so that the final maximum value of the electric field is less (compare Experiments 1 and 8). Alternately, if the initial $\partial F/\partial t$ is less than zero (corresponding to $S_e/S_c > 0$ in eq. 13 or case *c* of a conducting cloud in Fig. 3), the initial growth of the electric field is hindered and the maximum value of the field is increased (compare Experiments 5 and 9). Note that a non-zero value of the initial time derivative could arise from any overriding electrical effects. For instance, if the cloud were developing in the lee of another developing storm, this simplistic argument would suggest that the electric field development of the cloud would be hindered.

But, in reality, all of these effects are small; the actual size of the maximum field is little altered by reasonable variations in either F_0 or the initial time derivative. The effect is primarily one of altering the time of awakening of the field; merely shifting the origin gives approximately the same net field growth. It is more interesting to consider the effect of the absolute magnitude of the conductivity, retaining a given expression. For this purpose we have adopted the empirical expression of Mason. If one uses different values of the pre-exponential factor the net effect of discharge currents on the maximum value of the electric field is simulated (see Experiments 1, 4, 5, and 6). It is apparent that a large increase in the discharge current (corresponding to the factors of 30 or 300, values greater than suggested by Evans) does not have an overwhelming effect on the field that can be attained. A factor of 300 increase in the conductivity decreases the maximum electric field by only a factor of two (see Fig. 5). The extreme case of a cloud of high conductivity, corresponding to the empirical fit to Evans' data (Experiment 11) does show a marked effect, however. Yet even in this case, the field grows despite the fact that the electrical conductivity is a factor of 10^6 greater than the fair weather value. A maximum was not obtained in 720 seconds, but at that time the field was still increasing and had obtained a value of 120 v/cm, a field comparable to that measured by Evans (see Fig. 1). The computation was terminated at that time because the indicated precipitation rate was becoming too large ($\sim$300 mm/h). A similar effect occurred in Experiment 6.

This indicates the power of the polarization charging mechanism in the development of the electric field. Also, the controversy regarding the conductivity effect is somewhat resolved as reasonable values of the conductivity can create large electric fields. It remains that the interaction between the electric field and the precipitation elements are important both in the formation of the electric field and in the development of precipitation (see Ziv & Levin, 1974; Levin & Ziv, 1974).

Drop discharge effect

However, the question of how the electric charge on the hydrometeors is conducted away through the discharge currents is unanswered. For a complete treatment of this problem the effective potential in the environment of the drops is required and this can only be calculated when we have incorporated a vertical dimension explicitly into the model. The effect has not yet been included in any of the models but bears consideration as (1) the charge produced on the drops could be quickly conducted away, or (2) in a stagnant parcel, the air might lose its mobile charges and become non-conductive.

In an attempt to simulate the effect to first order we have superimposed an approximate depletion term;[1]

$$\left.\frac{dQ}{dt}\right|_{\substack{\text{loss by}\\ \text{conditon}}} = -4\pi\lambda Q \qquad (14)$$

upon the equation for charge build-up on the individual particles as presented by Ziv & Levin (1974).

The resulting effect of this discharge is illustrated in Fig. 5 (dashed curve). The additional term has only a slight effect on the field development until the field growth slows. After that point discharge from the drops appears to reduce the levitation effect, allowing further drop interactions and continuation of the field growth. This indicates that loss of charge from the particles is beneficial to fie'd growth.

[1] Assumes that the discharge effect reaches a quasi-steady state. This necessitates that $1/4\pi\lambda$ must be greater than the characteristic time for field development. In reality this is true only for a conductive cloud because $1/4\pi\lambda_c \sim 2$ minutes.

Summary

The effect on electric field development of varying the electrical conductivity inside the cloud is considered. It is found that the initial state of the cloud is important in establishing the time of awakening of the electric field but the initial state of the cloud has a relatively little effect on the field development. The conductivity of the cloud, when contained within reasonable bounds, is not all important in consideration of field development. Noteworthy is the fact that a conductivity increase of a factor of 10 only lowers the maximum electric field by 25%. Field development by the polarization charging mechanism is extremely effective; it seems to be mostly dependent on parameters related to the development of the precipitation.

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ВЛИЯНИЕ ЭЛЕКТРОПРОВОДНОСТИ НА РОСТ ЭЛЕКТРИЧЕСКОГО ПОЛЯ В ГРОЗОВОМ ОБЛАКЕ

Изучается влияние электропроводности на развитие электрических условий в облаке. С помощью численной модели, в которой совместно рассматриваются рост электрического поля и развитие осадков, показано, что если проводимость меняется между величинами, меньшими, чем проводимость при хорошей погоде и величиной в 100 раз большей последней, то механизм поляризации зарядов достаточно эффективен для генерации полей, способных вызывать молнии.