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Effects of coronae on electric fields beneath thunderstorms

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SUMMARY

Intense electric fields beneath thunderstorms produce electrical discharges (coronae) at the tips of trees, bushes and other sharp objects attached to the surface of the earth. We find typical corona current densities of about 1 nA m$^{-2}$ in an 8 kV m$^{-1}$ field at the ground. The ions released into the air limit the magnitude of the field at the ground to about 10 kV m$^{-1}$. Our measurements beneath thunderstorms with a balloon-borne electric field meter show that the magnitude of the field a hundred metres above the ground is several times larger than at the ground; in one case the field 300 metres above ground was 6 times that at the ground. The substantial thickness of the space charge layer and the speed with which it vanishes when the electric field strength declines imply that the charge carriers have substantial velocities (0.4 m s$^{-1}$) rather than being carried by air motions.

Coronae also influence the time behaviour of the electric field at the ground. The field at the ground often changes rapidly after a lightning flash. The rate of change decreases as the field approaches the value it had prior to the flash. In contrast, the field a hundred metres above the ground, which is often above most of the influence of space charge produced by coronae, increases more uniformly (linearly) during the time interval between lightning flashes. This behaviour is similar to that of the field farther aloft in the interior of the cloud. Our numerical simulations of the shapes of recovery curves indicate that the corona current density is more accurately described by a cubic function than by a quadratic function of the electric field strength at the ground.

Despite strong influences of coronae, three properties of the field at the ground accurately reflect what happens above the space charge layer. First, the rapid changes in electric field during a lightning flash are not usually affected by corona space charge. Second, when the field at the ground is nearly constant it usually has the same polarity as the field above the space charge layer. And third, when the field strength at the ground is nearly zero, and when certain other conditions are met, the time rate of change of the field at the ground is the same as that above the space charge layer.

1. INTRODUCTION

The strength of the electric field at the extremities of sharp, grounded, elevated objects can be many hundred times that of the ambient field. Ions are produced by coronae when the magnitude of the ambient field exceeds a few kV m$^{-1}$. Schonland (1928) and Wormell (1930) concluded that coronae can transfer more charge between the earth and thunderstorms than lightning or falling charged precipitation. More recently Livingston and Krider (1978) concluded that coronae transfer more charge than lightning when lightning is infrequent. Vonnegut (1955) and Wilson (1956) have suggested that the corona ions produced at the surface of the earth are transported into thunderstorms and are partly responsible for their electrification. Information about the concentration of ions and their mobility might help us to evaluate the importance of this process. Furthermore, if there is a significant space charge released by corona discharge, measurements of the electric field at the ground, often reported by investigators of thunderstorm electricity, may be a highly misleading indicator of the behaviour of the electric field inside the thundercloud. Wilson (1920), Wormell (1939), Tamura (1954), Freier (1962) and others have studied the time variation of the electric field at the ground following lightning in order to make inferences about thunderstorm processes.

Wormell (1953), Gunn (1954) and Vonnegut (1963) have remarked that the absolute value of the field at the ground is usually less than 10 kV m$^{-1}$. However, field changes at the ground due to lightning often have magnitudes several times greater than this limiting value.
This led Whipple and Scrase (1936) and Wormell (1953) to conclude that the field at the ground is the superposition of two fields, one from charges in the thundercloud and the other from space charge near the ground. Elevated, grounded conductors will usually have the same polarity of charge on their surface as the ground does, and ions released by corona have the sign of the surface charge. Thus ions from corona must reduce the absolute value of the field at the ground. When the magnitude of the electric field exceeds the onset field strength, the rate of production of ions by corona is a rapidly increasing function of the electric field. Hence, corona is a likely mechanism to limit the absolute value of the electric field at the ground. A layer of space charge released by corona would explain why the field at the ground sometimes changes sign during a lightning flash while the field aloft does not. Still another effect of corona on the surface field is the initial rapid recovery observed when a field change due to lightning increases the absolute value of the surface field beyond about 10 kV m\(^{-1}\).

There will also be instances when corona have negligible effect on the electric field at the surface. The magnitude of the field at the surface far from a thunderstorm will be less than that required for corona discharge. In this situation Illingworth (1971, 1972) has concluded that the time variation of the field at the ground after a lightning flash is influenced by the conductivity of the air surrounding the cloud as well as by the separation of charge inside the thundercloud. Another interesting situation occurs over water surfaces. Whipple (1938) recognized that corona might be insignificant at the surface of oceans and lakes because of a lack of sharp, elevated objects there. Thus the electric field should behave differently over water than it does over land. In particular, more intense fields should be present over water, as reported by Toland and Vonnegut (1977).

We report here on our simultaneous measurements of the electric field at the ground and aloft, and of corona discharge and precipitation currents. These experiments were done during July and August 1976 at Langmuir Laboratory in central New Mexico and at Kennedy Space Center on the eastern coast of Florida. After describing our instruments, we first shall present data taken during nearly steady-state conditions when the field was intense. Next we proceed to cases when the field changed rapidly due to lightning flashes. Last we describe some results from calculations that give some insight into the effects of parameters that are difficult to measure. Our goal will be to understand how and when ions from corona modify the electric field near the ground.

2. Measurements

(a) Electric field

The balloon-borne field meter (Fig. 1) measured the induced charge on two metal spheres as they rotated around a horizontal axis with a frequency of about two revolutions a second. The charge on the spheres was proportional to the strength of the electric field. A similar instrument has been described in detail by Winn and Byerley (1975). The captive balloon’s tether was braided nylon which was saturated frequently with silicone oil so that it would not conduct electricity during rain. Any charge that might collect on the tether would produce a field strength at our instrument of less than 2 kV m\(^{-1}\), usually more than an order of magnitude less than observed fields. The instrument was suspended about 35 m below the balloon so that charge on the balloon would not greatly affect the measurement. We estimate the relative error in measurement of the electric field by this instrument to be 5%.

A stationary field mill sensed the field near the ground.

Our sign convention for the vertical component of the electric field is that a positive
test charge has an upward force in a positive field. We denote the strength of the field at altitude $z$ and time $t$ by $E(z,t)$; the field at the ground is $E(0,t)$.

(b) Currents between trees and earth

We also measured currents passing between the earth and small evergreen trees. The trees rested on ceramic high-voltage insulators (Fig. 2) in metal containers filled with soil. In order to detect currents of less than a microampere during rain, we coated the insulators with a chlorosilane and covered them with a rain shield. When guy ropes were required for stability, each one was interrupted by a good insulator with a rain shield. These precautions
were sufficient to maintain a leakage resistance much greater than the 160 kΩ DC input impedance of our ammeter circuit. We used seven trees. Six were equally spaced around the circumference of a circle and were connected in parallel so that the total current flowed through a single ammeter to ground. The seventh tree was at the centre of the circle, and its current passed through a separate ammeter to ground. The tops of all trees were 1.4 ± 0.25 m above the earth. The tops of the containers holding soil and roots were 0.9 m above the earth. The edges of these containers and the tops of the rain shield over the ceramic insulators had a radius of curvature of about 3 mm, blunt enough to make coronae from metal parts negligible compared with that from the trees. The relative error in measurement of currents was less than 5%.

(c) *Rain currents*

We measured the displacement current \( e_0 \frac{\partial E(0,t)}{\partial t} \), plus currents due to falling charged precipitation and ion conduction to earth, with a metal basin of 1.5 m² horizontal area installed in a pit. The basin’s upper edge was level with the surrounding land and was coated with caulking compound to eliminate corona discharge. The basin was supported by ceramic high-voltage insulators. Each insulator had a rain shield, a coating of a chlorosilane, and was heated to prevent condensation of moisture. All precipitation that fell into the basin remained there until the end of the storm to avoid unwanted electrical currents. This basin collected all precipitation intersecting its horizontal cross-section at ground level.

The current from the basin to earth flowed through a resistor, \( R = 100 \, \text{MΩ} \), in parallel with a capacitor, \( C = 0.1 \, \text{μF} \). The capacitor was included so that rapid changes in surface charge on the basin would not saturate the electrometer that sensed the voltage, \( V \), across the resistor and capacitor. To obtain the current density of ion conduction and falling charged precipitation, \( J_t + J_n \), we solved the relation

\[
J_t + J_n + e_0 \frac{\partial E(0,t)}{\partial t} = -\left(1/A\right)(V/R + C \, dV/dt)
\]

using values of the displacement current, \( e_0 \frac{\partial E(0,t)}{\partial t} \), from a field mill. \( A \) is the area of the basin and \( e_0 \) is the permittivity of free space, about \( 8.8 \times 10^{-12} \, \text{F m}^{-1} \). The relative error in measurement of rain current was less than 10%. All equations in this paper are for SI units. Our sign convention is that the current density is positive if positive charge moves upwards (or if negative charge moves downwards). The mobility, \( k \), of an ion has the same sign as the charge on the ion; with this convention, the velocity of both positive and negative ions is \( kE \).

3. **Observations of field increase with altitude**

(a) **Soundings in Florida storms**

Figure 3 shows the electric field at the surface and aloft as a function of time at Kennedy Space Center (KSC) when a large anvil-shaped cloud was overhead. The surface field is that measured by the KSC field mill at site 21, which is 3.1 km northeast of where our balloon was. The KSC field mills have been described by Jacobson and Krider (1976).

At the left edge of Fig. 3 the field meter aloft was about 300 m above the ground and the field there was about 6 times more intense than the field at the ground. When we lowered the field meter to about 200 m, we observed a decline in field strength. We then raised and lowered the field meter between 3 and 120 m for the remainder of the time shown on the graph. The record shows a consistent variation of field strength with altitude during many consecutive soundings. When the balloon-borne meter was near the ground it gave the same reading as the mill on the ground.
Figure 3. Electric field, \( E \), and the altitude of the balloon-borne field meter, \( z \), during a storm at Kennedy Space Center in Florida on 8 July 1976. The dashed line indicates estimated altitude, the dotted line indicates altitude inferred from behaviour of the field meter aloft. The time is given in GMT. The horizontal wind speed, at a site 1-4 km northwest of the balloon, was about 6 m s\(^{-1}\) during this time.

The field at our balloon location crossed zero about three minutes earlier than at the KSC field mill. The difference in zero-crossing times probably reflects a real difference in behaviour of the electric field at two different sites, which were 3-1 km apart.

(b) Soundings in New Mexico storms

We also observed an increase in field strength with altitude during storms over Langmuir Laboratory in central New Mexico. Figure 4 shows the electric field at the surface and aloft as a function of time on 23 August 1976. The surface field is from a field mill mounted
level with the ground plane in a region clear of tall grass, bushes and trees; it was about 150 m south of the balloon winch. The horizontal wind speed was measured at a site 350 m north of the balloon winch.

At the left edge of Fig. 4 the field at 150 m was nearly the same as the field at the surface and the corona current from the trees was low. A few minutes later the magnitude of the surface electric field and the corona current increased and the field aloft began to diverge from the field at the surface. Toward the right edge of Fig. 4 the magnitude of the field at the ground and the corona current decreased and there was less variation of field strength with altitude.

Figure 5 is a particularly fortunate example of the dependence of field on altitude because the field at the ground began a nearly monotonic decline and crossed zero during our soundings. At the left edge of Fig. 5 we see that the field increased with altitude when there was corona current from the trees. During the later part of the record, the time 'a'
until 'b', we held the balloon-borne field meter at 150 m. During this period the electric field aloft was initially greater than the field at the ground, but the electric field at both places and the corona current from the trees decreased. The field at the two altitudes became equal when corona currents in the ring of trees became small. A sounding after time 'b' shows the field was independent of altitude from 3 to 150 m. The small increase in field measured by the balloon-borne field meter at its lowest altitude was probably due to the enhanced field near the winch truck, which was an elevated conductor. We shall refer to Fig. 5 later to show that corona ions were highly mobile.

Figure 6 gives another example of electric field that increases with altitude when the field at the ground is sufficiently strong. However, notice that the electric field became independent of altitude during the last sounding when the field at the ground decreased from 7 to less than 5 kV m⁻¹.

4. Interpretations of Soundings

When the absolute value of the electric field at the ground exceeds about 5 kV m⁻¹ at Langmuir Laboratory or about 3 kV m⁻¹ at Kennedy Space Center, the absolute value of the field increases with altitude. Because the divergence of the electric field is known to be due to space charge (Gauss's law), and our measurements show that current flows into the atmosphere from trees under the same condition required for an altitude dependence of the field, it is clear that the increase in field strength reported here is at least partly due to the space charge of electrical coronae.

Another possibility for creation of a space charge is induction charging of small droplets that are produced when raindrops hit the earth. These charged droplets, like ions from corona discharge, have the same polarity of charge as that on the earth's surface. Since we found evidence of space charge when there was little or no rain and when there was appreciable corona current from trees, we conclude that corona discharge alone can produce space charge of the observed magnitude.

We think the differences in vegetation at the two sites makes the magnitude of the electric field required for coronae less at Kennedy Space Center than at Langmuir Laboratory. There were dense bushes and tall, lush grass at Kennedy Space Center where we estimated (from Fig. 3) that the onset field strength is about 3 kV m⁻¹. Our experiments near Langmuir Laboratory were conducted on a relatively barren mountain ridge: there were isolated clusters of short bushes and sparse grass. From Figs. 4, 5 and 6 we estimate the field strength for onset of coronae to be about 5 kV m⁻¹ in the meadow northwest of Langmuir Laboratory.

(a) Space charge concentration

Using Gauss's law, we calculated the average space charge concentration in horizontal layers above the surface. The boundaries between the layers were dictated by the data we have on the balloon's position. Figure 7 shows space charge concentrations from several soundings. During these and similar soundings the maximum space charge concentration was about 0.8 nC m⁻³ (5000 elementary charges cm⁻³). This value is of the same order as computed by Lutz (1941) and Hutchinson (1951) in the region between the ground and an altitude of about 15 m. Often we found the maximum space charge density to be 30 to 50 m above ground level instead of at ground level. Perhaps this was owing to a decrease in mobility of ions as they attached to aerosol particles.
Figure 7. Space charge concentration as a function of altitude during three soundings. Graph (a) is from data taken at Kennedy Space Centre (Standler 1977). Graphs (b) and (c) are from data shown in Fig. 4 (Langmuir Laboratory), using the two soundings between 14h 44m and 14h 54m.

(b) Ion transport

During several of our flights the corona current at the ground became small (because \( E \) declined) and the variation of \( E \) with altitude soon disappeared. The best example appears in Fig. 5; in the 350 s interval between 'a' and 'b', most of the space charge was removed from the 150 m layer below the balloon. Motion of ions relative to the air by electric forces was probably not the main mechanism of ion removal because a velocity of \( 150 \text{ m/s} / 330 \text{s} = 0.4 \text{ m/s} \), and an electric field strength of 7 kV m\(^{-1}\), imply a mobility of \( 6 \times 10^{-5} \text{ m}^2\text{V}^{-1}\text{s}^{-1} \), which is much too large for ions attached to aerosol particles; ions are believed to attach within 30 s after their creation (Adkins 1959).

Several transport mechanisms are possible. (1) The ions could have been carried vertically by eddies with a characteristic velocity on the order of 0.4 m s\(^{-1}\) and a characteristic size of about 150 m. The eddies could have been driven by convective motions accompanying the thunderstorms and/or by horizontal winds, which were about 4 m s\(^{-1}\) during the interval from 'a' to 'b' in Fig. 5. Raymond and Wilkening (private communication, 1978) have found vertical velocities greater than 0.4 m s\(^{-1}\) during low-level airplane traverses over Langmuir Laboratory at times of convective activity. (2) The net space charge below the balloon may have been carried away by the 4 m s\(^{-1}\) horizontal winds. Since the height around Langmuir Laboratory changes abruptly (200 m in 1 km), horizontal winds could have brought air with low space charge (air not initially near the surface) into the region below the balloon.

Thus the environmental conditions (declining corona current, convection and moderate wind) during the time shown in Fig. 5 are consistent with the relatively rapid decline in space charge from the region below the balloon. During another flight (Fig. 6) in which a decline in space charge was apparent, the horizontal wind velocity was low (about 1 m s\(^{-1}\)) until 10 minutes before the time of interest, when the wind data record ends. If the calm conditions continued, then the most probable ion-transport mechanism would have been vertical transport by eddies driven by convection.

(c) Corona current density

Numerical estimates of corona current density, \( J_c \), are important in assessing charge transfer between thunderclouds and their environment. We can make these estimates in two ways. In this section we compare our data from soundings with a simple theory. Later we analyse our measurements of currents from trees as a function of the distance between them.

Wilson (1925) predicted that under certain conditions, \( E(z) \) will increase with altitude, \( z \), according to the relation

\[
E(z) = \pm [E(0)^2 + (2J_c/(e_0 k))z]^4
\]  

(2)
Figure 8. Electric field as a function of altitude during the three soundings chosen for Fig. 7. The curve is a fit of the data to a steady-state solution of Gauss's law described in the text. The greater spread of points in (b) reflects a change in space charge density during the balloon flight; points to the right of the curve were taken during ascent; points to the left, during descent.

The sign is chosen so that $E(z)$ and $E(0)$ will have the same sign. This relation applies when all the ions have the same polarity of charge, $J_e$ and $E$ neither vary with time nor with location in any horizontal plane, and the ion's velocity is proportional to the electric field. These conditions are sufficient to make $J_e$ independent of altitude. Ion motion due to diffusion or wind is not considered in the derivation of Eq. (2).

We estimated $J_e$ by fitting Eq. (2) to our data from soundings. Because Eq. (2) applies only to time-independent situations, we selected three cases where soundings showed particularly reproducible fields during ascent and descent. Figure 8 shows the electric field as a function of altitude for these cases. Figure 8(a) is from our experiments in Florida. The best fit of field vs. altitude to Eq. (2) by the method of least squares occurs when $J_e/k$ is about $3.5 \times 10^{-6}$ in SI units. If the space charge was composed of small negative ions in dry air, with a mobility, $k$, of about $-2 \times 10^{-4} m^2 V^{-1} s^{-1}$, then $J_e = -0.7 \text{nA m}^{-2}$. If the ions became attached to nuclei, $J_e$ would tend to decrease. However, transport of ions by updrafts and eddy diffusion may have offset this effect. Figures 8(b) and (c) are from soundings over Langmuir Laboratory. We obtain the best fits when $J_e/k = 3.7 \times 10^{-6}$ for Fig. 8(b) and $5.8 \times 10^{-6}$ for Fig. 8(c). Jonassen and Wilkening (1965) found that $k$ for small ions is $-1.9 \times 10^{-4} m^2 V^{-1} s^{-1}$ at Langmuir Laboratory during fine weather. With this value, $J_e$ is $-0.7$ and $-1.1 \text{nA m}^{-2}$ for Figs. 8(b) and (c) respectively.

Sustained corona current densities of $11 \text{nA m}^{-2}$ in a field at the ground of about $91 \text{kV m}^{-1}$ have been estimated by Whipple and Scrase (1936) from measurement of corona current through a metal point. This value, substituted in Eq. (2) with $k = 2 \times 10^{-4} m^2 V^{-1} s^{-1}$, leads one to expect the field at 100 m to be four times the field at the surface. This predicted increase of field with altitude is several times greater than that observed during most of our soundings. Ette (1966), Jhwar and Chalmers (1967) and Stromberg (1971) have found that corona currents through living trees are less than currents through a metal point of the same or lesser height. Measurement of corona current from metal points is not representative of the corona currents from our meadow beneath a thunderstorm.

Schonland (1928) estimated a current density of $40 \text{nA m}^{-2}$ from measurements of corona current through a small tree in an $11 \text{kV m}^{-1}$ field. But Chalmers (1967, p. 245) suggested that the spacing between trees at Schonland’s field site was larger than reported, which would reduce his value of corona current density.

5. CORONA FROM TREES

We measured the current that flowed from the earth into a small tree. To study how this current was affected by neighbouring trees, we also measured the current that flowed
from the earth into six other trees encircling the first tree. Figure 9(a) shows that when the radius of the ring of trees was about twice the height of the trees, the current through the centre tree was nearly the same as the current through each of the trees in the ring. On the other hand, when the radius of the ring was less than the height of the trees, the centre tree produced at least an order of magnitude less current than each tree in the ring, as shown in Fig. 9(c). Figure 9(b) shows that for intermediate values of the radius of the ring of trees, the ratio of current in the centre tree to the current per tree in the ring usually varied between zero and one.

These results are easy to explain. When the trees were near each other, the centre tree was partially electrostatically shielded so the field strength at its extremities was not enhanced enough to ionize air. As the trees became more widely spaced the enhancement of the electric field at the centre tree increased asymptotically to the value it would have had were the other trees not present.

The scatter of data in Fig. 9 may have been due to wind at the ground. Corona current from metal points is proportional to wind speed when the magnitude of the field is sufficiently great (Large and Pierce 1957). Corona current from the perimeter trees could have been more strongly affected by wind than the current from the centre tree, which was somewhat shielded from wind.

We can estimate an upper bound for corona current density from trees of this size and type under a thunderstorm. If we assign half of the ring radius in Fig. 9(a) to the centre tree, corona current from that tree is to be divided by a 6·2 m² area. The largest sustained current observed during our experiment was about 600 nA per tree in an electric field of 12 kV m⁻¹. This gives a current density of about 100 nA m⁻². This is an estimated upper bound for current density from trees of this size, type and exposure under a thunderstorm. Since ΔQ is not necessarily a maximum when the current is a maximum, it is possible that even larger corona current densities can occur when trees are slightly farther apart than our small trees were when the centre tree was not shielded, so we would expect a forest to have a similar upper bound.

The data for Fig. 9 were taken when the electric field was not changing rapidly with time. Thus we could neglect any current owing to varying surface charge (displacement current). We can calculate the displacement current, \( I_d = \varepsilon_0 S \partial E(0,t)/\partial t \), after determining the collection area, \( S \). We determined the collection area by measuring the charge transfer, \( \Delta Q \), between the tree and the earth during an electric field change of magnitude \( E \). If the tree had no corona discharge both before and after the field change, then \( S = \Delta Q/(\varepsilon_0 \Delta E) \). We find that the collection area for both the centre tree and average tree in the ring (when the ring of trees had a radius of 2·8 m) was 1·5 ± 0·5 m². For the data in Fig. 9, \( |\partial E(0,t)/\partial t| < 50 \text{ V m}^{-1} \text{s}^{-1} \); thus the displacement current was less than 1 nA per tree, which is smaller than our ammeter circuit could detect.
6. Observations of Recovery Curves

Thus far we have presented data on the effects of coronae during nearly steady-state conditions at the ground. We now discuss the consequences of coronae when there are sudden field changes due to lightning. When the field changed rapidly with time during our experiments, we held the balloon-borne field meter at a constant altitude for relatively long times to reduce the number of variables.

Figure 10 shows the electric field at the ground and aloft, along with the corona current per tree in the ring, as a function of time during a vigorous thunderstorm at Langmuir Laboratory. In this example the field at the ground almost always changed from positive to negative as a result of a lightning flash, whereas the field aloft usually did not change sign. We attribute this difference to a layer of positive space charge below the balloon-borne field meter. The field at the ground increased after each lightning flash until it ‘recovered’ its value of about 10 kV m\(^{-1}\). When the interval between lightning flashes was long (e.g. between flashes ‘a’ and ‘c’, ‘j’ and ‘k’) the field aloft continued to increase after the field at the ground became constant. The field at the ground was limited by corona discharge. The field aloft was limited by corona ions only after they had had time to migrate above the balloon-borne field meter.

In Fig. 10 the field changes due to lightning were about 50% larger on the ground than aloft. Initially we thought this was due to the curvature of the mountain ridge from which we flew the balloon – the field being greater nearer the surface. The ridge has a radius of curvature of 300 ± 100 m. From this we would expect the field at the ground to be from 40 to 75% greater than at 150 m. However, this explanation does not agree with our observation that the field was independent of altitude when no corona was detected in our trees (see Figs. 5 and 6). It is possible that the 50% difference was due to the 150 m horizontal separation of the two instruments. There can be significant horizontal variations in a distance of 150 m when lightning is nearby.

The remainder of this flight is presented in Fig. 11. The arrival of positively charged hail coincided with a reversal of polarity of the field, although the slope of the field aloft remained positive between lightning flashes. The effects of corona current and the resulting
space charge are particularly striking between lightning flashes 'l' and 'q'. The field aloft had a positive slope of about 300 V m⁻¹ s⁻¹ between flashes, while the field at the ground was essentially constant between flashes. Furthermore, immediately after each flash the field at the ground had an exceedingly rapid recovery which was not present in the field's behaviour aloft.

The field, both aloft and at the ground, reversed polarity after flash 'l' as positively charged precipitation fell. This phenomenon has been described by Moore and Vonnegut (1977), and labelled a “field excursion associated with precipitation (FEAWP)”.

7. INTERPRETATION OF RECOVERY CURVES

To obtain a relation between $E$ at the ground and $E$ aloft, we take the divergence of Maxwell’s equation involving the curl of $H$,

$$\nabla \cdot (\nabla \times \mathbf{H}) = \nabla \cdot (\mathbf{J} + e_0 \partial \mathbf{E}/\partial t)$$

(3)

The left hand side is zero because the divergence of any curl vanishes. We then integrate over a volume enclosed by a Gaussian surface whose bottom is just above the surface of the earth, whose top is horizontal, and whose sides are vertical. It will greatly simplify the analysis if $\mathbf{E}$ is vertical in the region of the Gaussian surface. In order to avoid significant horizontal components of $\mathbf{E}$ at the vertical portion of the Gaussian surface, we specify: (1) that the top of the surface is at some altitude, $z$, which is small compared with the distance from the cloud's charge to the ground; and (2) there are no bushes or trees in or near the Gaussian surface. After converting the volume integral to a surface integral, Eq. (3) becomes

$$0 = \int \mathbf{J} \cdot d\mathbf{S} + e_0 \partial E/\partial t \int \mathbf{E} \cdot d\mathbf{S}$$

(4)

Since $\mathbf{J}$ and $\mathbf{E}$ are nearly constant over the upper and lower boundaries,

$$0 = J(z, t) - J(0, t) + e_0 \partial E(z, t)/\partial t - e_0 \partial E(0, t)/\partial t$$

(5)

We have assumed that horizontal components of $\mathbf{J}$ are constant in every horizontal plane.
This assumption is justified if the distance between elevated objects is not too great, allowing turbulence, diffusion and horizontal wind to produce a nearly uniform horizontal distribution of space charge. For convenience we split the current density at the ground, \( J(0,t) \), into three terms: (1) the corona current density, \( J_c \), which is carried by ions travelling upwards away from the ground; (2) the current density due to ions migrating towards ground, \( J_l \); and (3) the current density due to falling charged precipitation, \( J_r \). Then Eq. (5) becomes

\[
\varepsilon_0 \partial E(0,t) / \partial t = \varepsilon_0 \partial E(z,t) / \partial t + J(z,t) - J_c - J_l - J_r
\]  

(6)

Now we can see why the slope of the electric field aloft will usually be different from that at the ground. The current density terms on the right hand side of Eq. (6) will usually not cancel each other because they arise from fundamentally different processes. For example, the corona current density, \( J_c \), is highly sensitive to changes in \( E(0,t) \) above onset, whereas the rain current density aloft (contained in the term \( J(z,t) \)) is insensitive to changes in \( E(0,t) \).

There are, however, times when the current density terms in Eq. (6) either cancel each other or are zero. During these times the slope of the field aloft will be the same as the slope of the field at the surface, and field mills at the surface will briefly indicate the behaviour of the thundercloud rather than the behaviour of the thin space charge layer from corona. When \( E(0,t) \) is zero the flux of corona ions, \( J_c \), and the flux of downward moving ions, \( J_l \), will also be zero. Under these conditions and when there is no charge brought down by precipitation, Eq. (6) becomes

\[
\varepsilon_0 \partial E(0,t) / \partial t = \varepsilon_0 \partial E(z,t) / \partial t + J(z,t)
\]  

(7)

Now the total current density aloft, \( J(z,t) \), will be negligible when the space charge concentration is small at altitudes near \( z \), or when ions at this altitude are mostly large ions with correspondingly small mobilities and when there is insignificant ion transport by a vertical wind. When these conditions on \( J(z,t) \) and \( E(0,t) \) are met (quite frequently we suspect), then

\[
\partial E(0,t) / \partial t \approx \varepsilon_0 \partial E(z,t) / \partial t
\]  

(8)

The charge flux on precipitation, \( J_r \), may not always be negligible. If the charge on precipitation is nearly constant between altitude \( z \) and the ground (which implies that \( J_r \) is nearly independent of time and there is little or no ion capture by rain), the term \(-J_r\) in Eq. (6) will cancel the part of \( J(z,t) \) due to precipitation current density aloft. When this is true, and when \( E(0,t) \) is zero, and the part of \( J(z,t) \) due to the motion of ions is negligible, we again obtain Eq. (8) from Eq. (6).

The field at the ground often passes through zero between lightning flashes. When \( E(0,t) \) is zero between flashes in Fig. 10, the slope of the field at the ground is a factor of two different from the slope of the field aloft, perhaps because \( J(z,t) \) is not small enough to be neglected. We have other examples (Standler 1977) in which the slope of the field at the ground is within 20% of the slope of the field 40 to 120 m above the ground.

8. MODEL OF RECOVERY PROCESSES

To understand further the effect of coronae on recovery curves, we have performed some calculations to relate the electric field aloft, \( E(z,t) \), to the field at the ground, \( E(0,t) \). We regard the field aloft as a known ‘driving’ field, assume a relation between \( J_c \) and \( E(0,t) \), and then use Eq. (6) to deduce the field at the ground. The effects of all the charge-separation processes inside the thunderstorm are contained in the function we choose for \( E(z,t) \).
We shall assume that \( E(z,t) \) is not affected by the motion of ions from coronae at the ground; this assumption is reasonable if the altitude, \( z \), is greater than the product of the average upward velocity of corona ions and the age of the storm. There is an often conflicting requirement that the altitude, \( z \), be relatively small so that \( E(z,t) \) is nearly vertical to satisfy the assumptions underlying Eq. (6). Thus our analysis will apply only in certain circumstances. We further restrict our analysis to situations when there is no rain and no significant current density at altitude \( z \); thus, \( J_z = J(z,t) = 0 \).

We assume the corona current density, \( J_c \), to be a function only of \( E(0,t) \). Jhwar and Chalmers (1967) have shown that a relation of the form

\[
J_c = \begin{cases} 
0 & \text{for } |E(0,t)| \leq E_0 \\
(c E(0,t) |E(0,t)| - E_0)^2 & \text{for } |E(0,t)| > E_0
\end{cases}
\]

(9)

describes corona current from trees. We shall describe below the effects of using another relation between \( J_c \) and \( E(0,t) \). The parameter \( E_0 \) is the minimum magnitude of electric field for which coronae occur, and \( c \) is a function of the number of discharging objects per unit horizontal area and the relationship between the current and electric field. We estimate \( E_0 = 5 \text{kV m}^{-1} \) and \( c = 2 \times 10^{-20} \text{A m V}^{-3} \), from soundings at Langmuir Laboratory. We have not included the effects of wind speed and the differences between the two polarities of coronae.

We integrated Eq. (6) with respect to time on a digital computer by a finite difference method. Initially we let \( k = 1.5 \times 10^{-4} \text{m}^2 \text{V}^{-1} \text{s}^{-1} \) for the mobility of the positive ions and \(-2.2 \times 10^{-4} \text{m}^2 \text{V}^{-1} \text{s}^{-1} \) for negative ions. Later we shall let the mobility of each ion decrease as it becomes older, to simulate attachment.

(a) Dependence of \( E(0,t) \) upon \( E(z,t) \)

Figure 12 shows three different assumed forms of driving function \( E(z,t) \) and the calculated \( E(0,t) \) and \( J_c \) for each. The driving functions have a discontinuity at \( 60 \text{s} \) to simulate the effect of lightning. In each case \( E(z,t) \) is zero at time zero, \(+30 \text{kV m}^{-1} \) just before the discontinuity, and \(+10 \text{kV m}^{-1} \) just after it. One driving function was chosen to have a linear slope between lightning flashes, which may be typical of the behaviour of some

![Figure 12. Calculated values of \( E(0,t) \) v. time and of \( J_c \) v. time for three forms of \( E(z,t) \):](image-url)

- Before discontinuity
  - (a) \( 500t \)
  - (b) \( 8.333t^2 \)
  - (c) \( 3 \times 10^4(1 - \exp(-t/10)) \)

- After discontinuity
  - (a) \( 500(t - 40) \)
  - (b) \( 8.333(t - 25 - 358)^2 \)
  - (c) \( 3 \times 10^4(1 - \exp(35 - 945 - t)/10)) \)
thunderstorms (Winn and Byerley 1975). The other two driving functions are for extreme cases, one with an increasing slope and the other with a decreasing slope. The three calculated functions \( E(0,t) \) in Fig. 12 are quite similar despite major differences among the driving functions. The principal difference in \( E(0,t) \) is at the left edges of Figs. 12(a), (b), (c), where each trace resembles the \( E(z,t) \) trace that generated it. This resemblance is an artifact of the model, since the initial conditions are: (1) the absence of space charge; (2) zero field at both the ground and altitude \( z \). These initial conditions make \( E(0,t) \) identical with \( E(z,t) \) until \( E(0,t) \) increases beyond \( E_0 \). At this time the production of space charge makes \( E(0,t) \) behave differently from \( E(z,t) \).

The differences among the three computed \( E(0,t) \) traces are small because \( E(0,t) \) is weakly dependent upon \( E(z,t) \) when the magnitude of \( E(0,t) \) exceeds the field strength for onset of corona discharge, \( E_0 \).

(b) Relations between \( J_c \) and \( E(0,t) \)

To explore the relation between corona current density, \( J_c \), and \( E(0,t) \) we have repeated the above calculations using another corona current function that appears in the literature. Cobine (1941, p. 261) cites a relation first found by Warburg (1899) as descriptive of corona current from a metal point to a plane:

\[
J_c = \begin{cases} 
0 & \text{for } |E(0,t)| \leq E_0 \\
(\alpha E(0,t)) \left( |E(0,t)| - E_0 \right) & \text{for } |E(0,t)| > E_0.
\end{cases}
\]  

(10)

We chose the parameter \( \alpha \) so that Eqs. (9) and (10) both give \( J_c = 5 \text{nA m}^{-2} \) when \( E = 10 \text{kV m}^{-1} \).

Figure 13 shows the response of \( E(0,t) \) to the same \( E(z,t) \) when \( J_c \) is quadratic and cubic in \( E(0,t) \). The two \( E(0,t) \) curves are remarkably similar.

Changing the function \( J_c \) has a more dramatic effect when the discontinuity in \( E(z,t) \) makes the magnitude of \( E(0,t) \) greatly exceed \( 10 \text{ kV m}^{-1} \). The driving function \( E(z,t) \) in Fig. 14 simulates the field aloft when a lightning flash increases the local electric field. This happened, for example, at the flashes 'm' to 'q' in Fig. 11. In the intense field immediately after the field discontinuity in Fig. 14, the cubic relation gives 5 times more corona current than the quadratic relation between \( E(0,t) \) and \( J_c \). This larger current produces the much faster 'recovery' of \( E(0,t) \).

A quadratic relation between \( J_c \) and \( E(0,t) \) does not describe both the relatively small

![Figure 13. Effect of corona current function on calculated \( E(0,t) \). The same driving function, \( E(z,t) \), (upper plots) was used in both (a) and (b). In (a) we used a cubic relation (Eq. (9)) with \( E_0 = 5 \text{kV m}^{-1} \) and \( \alpha = 2 \times 10^{-20} \text{Am V}^{-2} \), in (b) we used a quadratic relation (Eq. (10)) with \( E_0 = 5 \text{kV m}^{-1} \) and \( \alpha = 1 \times 10^{-18} \text{Am V}^{-2} \).](image-url)
values of $J_c$ inferred from our soundings in Fig. 8 and the much larger values of $J_c$ inferred from 'recovery' curves in Fig. 11. We conclude that relations for $J_c$ that are quadratic in $E(0, t)$ are less realistic than relations that are cubic.

(c) Effect of mobility on recovery curves

We simulated the effects of attachment of ions by decreasing their mobility as a function of their age, $(t-t_0)$, according to the relation

$$k = k_0 \exp(- (t-t_0)/1.41)$$

where $k_0 = +1.6 \times 10^{-4} \text{m}^2 \text{V}^{-1} \text{s}^{-1}$ for positive ions, and $-2.2 \times 10^{-4} \text{m}^2 \text{V}^{-1} \text{s}^{-1}$ for negative ions.

The mobility will decrease from that of a small ion, $k_0$, to that of a large ion, $\pm 10^{-7} \text{m}^2 \text{V}^{-1} \text{s}^{-1}$, in about 10 seconds. Figure 15(b) shows the calculated 'recovery' curve with the rapid decrease of mobility. For comparison, Fig. 15(a) shows the recovery curve for constant small-ion mobility. The two $E(0, t)$ traces in Fig. 15 are nearly the same. Thus mobilities of ions have little effect on the shape of recovery curves at the ground.

Figure 15. The same form of $E(x, t)$ v. time (upper plots) is used to calculate $E(0, t)$ v. time under two different conditions on mobility. On the left, (a), the mobility is constant at the value for small ions; on the right, (b), the mobility is rapidly decreased as described in Eq. (11).
9. Conclusion

The space charge produced by coronae at the ground often has a dominant effect on the electric field at the ground beneath thunderstorms. On one occasion we observed that the field at the ground was only 1/6 of the field at 300 m altitude. Furthermore, the shape of the 'recovery' curve at the ground can differ markedly from the 'recovery' curve several hundred metres aloft.

There are several interesting lines of research raised by this work. (1) Contrary to predictions, we found no evidence that ions are immobilized in the lowest few hundred metres of the atmosphere. It would be of interest to measure mobility of ions as a function of altitude and time beneath a thunderstorm to see under what conditions corona ions remain small ions. Measurements of vertical wind near the ground beneath thunderstorms are important to describe the role of convective transport of corona ions. (2) A study of $J(z,t)$ might identify conditions when it could be neglected in Eq. (7). This would allow better accuracy in the estimation of the time rate of change of the field aloft from measurements of the field at the surface. (3) Droplets generated by splashing rain are another source of space charge that may modify the field at the ground. However, in order for droplets generated in this manner to rise to appreciable altitudes, they must be small and highly charged. We would like to know if splashing rain produces such droplets.

We measured steady-state corona current densities of the order of $1 \text{nA m}^{-2}$. A current density of this magnitude over a 10 km square gives a current of 0.1 A. For comparison, a lightning flash transfers a charge of about 20 coulombs (Chalmers 1967, p. 303). If we assume one lightning flash per minute, we get an average current of 0.3 A. This is slightly greater than the estimate for corona current. Thus corona currents near the ground may be an appreciable contribution to the charge budget of a thunderstorm.

More measurements of corona current density are needed to determine a representative value for the total current from coronae near the ground. We think the most interesting problem concerning corona ions is to understand where they go and what effect they have on the electrical structure of the thundercloud.

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