Electric field growth in thunderclouds

By WILLIAM P. WINN and L. G. BYERLEY, III
New Mexico Institute of Mining and Technology, Socorro, New Mexico 87801

(Received 24 March 1975. Communicated by Professor C. B. Moore)

Summary

We have constructed a balloon-borne instrument for measuring the magnitude of the horizontal component of the electric field in thunderclouds. It consists of two hollow, copper spheres 15 cm in diameter held 2 cm apart. The spheres spin about an axis that can be described as the perpendicular bisector of the line segment between the centres of the spheres. The sinusoidally-varying charge that is induced on the spheres by an electric field is amplified and telemetered to ground. The amplitude and telemetry transmitters are located inside one of the spheres. The spheres also serve as the telemetry antenna. The time behaviour of the electric field in the cloud is substantially different than that at the ground. The effects of corona discharge from the ground and of the finite conductivity of the air outside the cloud seem to be negligible in the presence of the intense field near a region of charge inside a cloud. Measurements of electric field intensities inside a cloud just before and after a lightning flash when combined with measurements at the ground can be used to obtain an approximate value for the total quantity of charge in a region of cloud just before it is partially discharged by lightning. In two cases the charge just before lightning was estimated to be $-120 \, \text{C}$ and $-160 \, \text{C}$. During a brief interval in one of our flights the electric field at the balloon reflected the time behaviour of the electric field in the cloud; the electric field increased linearly with time between lightning flashes.

1. Introduction

During the summer of 1974 we measured the magnitude of the horizontal component of the electric field in thunderclouds using instruments carried by free balloons. The balloons were launched from Langmuir Laboratory in central New Mexico. We have simultaneous measurements of the electric field at the ground. The presentation of the data here is centred around three questions: (1) How does the behaviour of the electric field in the cloud compare with that at the ground? (2) What is the total quantity of charge in regions affected by lightning? (3) What is the electric field as a function of time inside a cloud at a point fixed relative to the cloud?

A number of authors have predicted that the behaviour of the electric field in a cloud should be different from that at the ground. The electric field at the ground is affected by point discharge from the ground and by the finite conductivity of the air outside the cloud, particularly the air at high altitudes. This subject is discussed at length by Chalmers (1967) and Illingworth (1971). These effects should make a negligible contribution to the intense field near a region of charge inside a cloud. Our measurements support these predictions.

There is some question about the net quantity of negative charge present inside thunderclouds. Simpson and Robinson (1940), Malan (1952), and Gish and Wait (1950) made estimates ranging from $-20 \, \text{C}$ to $-40 \, \text{C}$ based on electric field measurements at the ground or above thunderstorms. Kasemir (1965) questioned these estimates because they do not take into account the screening charge at the boundary of the cloud resulting from the difference in conductivity inside and outside the cloud, nor the effects of the increase in conductivity with altitude. He proposed, on theoretical grounds, that the amount of negative charge is more likely to be around $-340 \, \text{C}$. Thus even an approximate determination of the amount of charge would be useful. We shall obtain an estimate in the following way: If we knew both the quantity of charge neutralized and the ratio of the charge neutralized to the total amount present in the region affected by a lightning flash, then we could
determine the total. Measurements of the abrupt field changes at the ground accompanying lightning and of the location of the charge that was neutralized together give values for the quantity of charge neutralized (Brook et al. 1962). Our measurements of electric field inside clouds can provide an estimate for the ratio. We need to assume that the fractional decrease in charge is the same as the fractional decrease in electric field at the balloon. We expect this to be true only on the average. For any particular discharge, the fractional decrease in charge may be more or less than the fractional decrease in field, depending on the location of the balloon relative to the neutralized charge and the charge that remains.

A graph of the electric field strength v. time between lightning flashes is often called a recovery curve. We are interested in the shapes of recovery curves inside clouds because a number of theoretical models for thundercloud electrification predict what they should be (Sartor 1967; Mason 1972; Levin and Ziv 1974). Measurements are difficult to obtain because the desired time variation is usually mixed in with the spatial variation from the movement of the vehicle carrying the instrument. However, since balloons and parachutes move rather slowly, they will see mainly the variations of the electric field with time when they happen to be where the field is a slowly varying function of position. During a brief interval in one of our flights (20 August 1974), which we shall discuss at length below, there were frequent lightning flashes and the electric field appears to have been a slowly varying function of position in the vicinity of the balloon.

Figure 1. Electric-field meter. The insulation between the spheres includes two teflon discs to prevent water from forming a conductive bridge. The mass of the assembly, including rod and blades is 2kg; a more recent version has a mass of 1.6kg. The rod is 16mm diameter and about 0.78m long. Each of the four balsa-wood blades is 0.1m wide and 0.32m long; they are held in the hub at a pitch angle of about 7° to induce rotation about the vertical rod. The inverted plastic cup visible above the blades kept water away from a swivel.
Only a few investigators before us have measured electric fields in thunderclouds using slow vehicles (parachutes or balloons). Simpson and Scrase (1937), Simpson and Robinson (1940), Chapman (1953), and Yüan Chen et al. (1965) released free balloons with instruments that measured the corona current through a long vertical wire and were thereby able to deduce the sign of the vertical component of the electric field. They could obtain only a rough estimate of the magnitude of the vertical component because it is related to the corona current by a non-linear function that varies with altitude. Their published records show only a few examples of sudden electric field changes that appear to have been caused by lightning (see Simpson and Scrase 1937, Fig. 6, flights 49 and 67). The records of Evans (1969) from instruments carried by parachutes contain a few examples of sudden electric field changes that may have been caused by lightning flashes (see Evans, Fig. 7), but there are no ground measurements for comparison. Rust and Moore (1974) measured electric fields near the bases of thunderstorms with an instrument suspended from a captive balloon. A short portion of one of their records (14h53m to 15h00m on 31 August 1971) shows an electric field growth pattern similar to one of ours.

2. The electric field meter

Our electric field meter is a version of the 'electrostatic fluxmeter' described in a review by Chalmers (1967). It has been adapted for use on airplanes (Kasemir 1972), rockets (Winn and Moore 1971; and Winn et al. 1974), and balloons (Christian and Few 1974). Our instrument (Fig. 1) consists of two 15cm diameter hollow copper spheres held 1.9cm apart at the bottom end of a vertical dielectric rod. Vertical winds through the blades at the upper end of the rod caused the whole assembly to rotate about the rod. The two spheres are electrically insulated from each other. One sphere is 'ground' for the charge amplifier and other circuits inside it as shown in Fig. 2. The other sphere is connected to the input of the charge amplifier. An electric field component perpendicular to the rod, \( E_z \), will induce equal and opposite charges on the two spheres; the flow of this charge back and forth through the amplifier as the instrument spins causes a sinusoidal voltage at the output of the amplifier. The field component parallel to the spin axis does not contribute to the signal.

![Diagram of the electrical structure of the instrument.](image)

Figure 2. Diagram of the electrical structure of the instrument. The two operational amplifiers (shown as triangles) are industrial grade type 741 integrated circuits; the first one is used as a charge amplifier with \( C = 0.1 \mu F \) and \( R = 1 \Omega \); the second one is a voltage amplifier with a gain of \( -3 \). The switches are in a complementary metal-oxide semiconductor type 4016 integrated circuit; control logic for the switches is not shown. The voltage-controlled oscillator (VCO) is made with an Intersil 8038 function generator. The FM transmitter radiated 40 mW at 400MHz. A thermistor in a bridge circuit and an operational amplifier serve as a temperature sensor.
The perpendicular component, $E_\perp$, is usually the horizontal component of the field. However, when the instrument swings like a pendulum below the balloon, the vertical component makes a contribution to $E_\perp$ at the ends of each swing but not at the bottom, causing a modulation of the sinusoidal signal. The amount of modulation and the instrument's maximum angle of excursion from the vertical (which we do not know in our experiments) could be used to find the vertical component of the field. Our measurements give only the magnitude of the horizontal field, $(E_1^2 + E_2^2)^{1/2}$.

This same method for measuring electric fields could be implemented with a single sphere divided into two insulated hemispheres. We chose to use two spheres instead so they could serve as the two halves of a telemetry antenna. Two spheres are a rough approximation to a biconical antenna, and thus have a characteristic impedance that is mostly resistive at our telemetry frequency of 400MHz. The characteristic impedance of two insulated hemispheres would, unfortunately, have a large capacitive part, making it difficult to match the transmitter to it.

A short segment of one of our records appears in Fig. 3. The frequency of the sine function is the spin rate of the instrument, about 3 s$^{-1}$, and the amplitude of the function is proportional to $|E_\perp|$. The abrupt change in amplitude at 12h26m44s is the result of a lightning flash. The sequence of steps interrupting the sine wave after the lightning flash provides calibration and temperature; switches inside the instrument (see Fig. 2) disconnect the electric field signal every 5 seconds and connect in sequence two reference voltages and the output of the temperature sensor. The reference voltages calibrate the entire telemetry recording system; thus, the amplitude $V_0$ of the sinusoidal voltage at the output of the second operational amplifier (in Fig. 2) can be determined from the trace in Fig. 3.

![Figure 3. A segment of the record from 25 July 1974. The sequence of rectangular pulses near the bottom of the record is a time code. The straight lines are unused channels on the oscillograph.](image)

The value of $|E_\perp|$ can be derived from $V_0$ by solving the electrostatic problem of two spheres in a uniform external field for the relation between $E_\perp$ and the charges $Q$ and $-Q$ induced on the spheres and by analysing the circuit for the relation between $Q$ and $V_0$. We have outlined the derivations in the appendix. The result is that

$$|E_\perp| = -(8.8 \times 10^{11})(1 + (\omega RC)^{-2})A^{-1}CV_0$$

in SI units. The constant $8.8 \times 10^{11}$ volts meter$^{-1}$ Coulomb$^{-1}$ is the ratio of electric field to induced charge for 15cm diameter spheres held 1.9cm apart, $\omega$ is the angular spin rate (radians/s) of the spheres about the vertical rod, $R$ and $C$ are the feedback resistance and capacitance of the charge amplifier (Fig. 2), and $A$ is the gain of the second amplifier.

We can obtain a value for $V_0$, and hence for $|E_\perp|$, for each half revolution of the instrument, which corresponds to a time of less than 0.2s and a vertical ascent (or descent) distance relative to the surrounding air of less than 1 meter.
The unusual shape of this electric field meter is the result of our attempt to make reliable measurements in the hostile environment inside thunderstorms. In the appendix we write about the ways in which our design overcomes some of the difficulties arising from the presence of precipitation particles, high humidity and intense electric fields.

3. Flying the instrument

The electric field meter and its parachute were carried aloft by helium-filled balloons launched from the ground. Initially we tried to use neoprene meteorological balloons, but they often burst before reaching the cloud base, apparently as a result of hail impacts. Balloons made of 0.02mm thick polyethylene worked well. We inflated them to a diameter of about 2.5m, so that the total lifting force was between 1.5 and 2 times the weight of the load; thus the balloon would rise even after accumulating some water or ice. Ascent velocities before entering clouds were typically 3 to 5m/s.

An explosive squib, pressure switch, and battery were arranged to detach the parachute and electric field meter from the balloon at a predetermined altitude. We obtained electric field records both during ascent and descent.

The parachute was placed about 5m above the electric field meter. It was simply a 1.2m × 1.2m square of polyethylene with shroud lines from each corner. The descent velocity was about twice the ascent velocity.

We usually did not attempt to recover the electric field meters, which are relatively inexpensive. Their value is less than the cost of finding and recovering them from the rugged terrain around Langmuir Laboratory.

4. Other instruments

The locations of various ground-based instruments in the vicinity of Langmuir Labora-

![Figure 4. Plan view of the vicinity around Langmuir Laboratory. Instruments pertinent to this paper are shown in parentheses. E stands for upward facing electric field-mills mounted flush in the ground, and M is for microphone arrays. Topographic contours are given in metres above sea level.](image-url)
tory are shown in Fig. 4. Professors C. R. Holmes and C. B. Moore made the electric-field mills using a mechanical design by Professor G. D. Freier. They face upward and are mounted flush in the ground in areas with low grass and no trees. They are calibrated by applying a known voltage to a plate held parallel to the ground. Our sign convention is that a field is positive if it exerts an upward force on a positive charge.

Thunder arrival times and directions are determined with the microphone arrays of C. R. Holmes.

Professors C. B. Moore and C. R. Holmes built the radar, which radiates at 9375 MHz with a peak power output of 225 kW. It makes a vertical scan every 2.7 s and then increases its azimuth for the next scan, covering the whole sky in 132 s.

We tracked the balloons while they were visible beneath the cloud bases with two theodolites on a 1040 m baseline.

5. Observations and Interpretations

In 1974 seven of our balloons carrying instruments for measuring the magnitude of the horizontal component of the electric field drifted into regions of thunderstorms with moderate or intense electric field. A total of 57 sudden electric field changes due to lightning appear in the records. The total includes 13 cases in which the electric field increased as a result of a flash and 44 cases in which it decreased. The 13 increases were not uniformly or randomly dispersed among the decreases; they occurred in groups.

It is not surprising that lightning occasionally causes the magnitudes of the electric field to increase in some locations. This could arise from a number of situations involving more than one region of charge. For example, the electric field between two regions of negative charge would increase if lightning neutralized one of the regions. The electric field will also increase at some locations in the vicinity of two oppositely-charged regions after one of them is neutralized. The fact that the increases were grouped together indicates merely a persistence of the cloud structure and relative location of the balloon causing the increases (or decreases).

For the 44 cases in which lightning decreased the intensity of the electric field, the ratio of the magnitude of the decrease to the initial intensity just before the flash had an average value of 0.4 and a standard deviation of 0.2.

This average value of 0.4 for the fractional decrease in electric field reflects only very approximately the average fractional decrease in the charge of a region affected by lightning. Some of the smaller fractional decreases in field could have been due to a large fractional decrease of a distant charge superimposed on the steady field of a nearby charge center; including such decreases in the total reduces the average value below what it should be. On the other hand, the average value of the ratio is increased over what it should be by not counting the decreases that are so small they become lost in the noise.

We shall describe next two storms in some detail. The two storms were generally similar to other summer storms in the vicinity of Langmuir Laboratory. They were chosen because the records of the electric field at the balloon were relatively simple and indicated the presence of moderate or intense electric fields affected by lightning. The effects of corona from the ground are evident in the records from both storms, more strongly in the second one, and there are significant differences in the behaviour of the electric field at the balloon and at the ground in each case. The first storm was rather weak, with lightning occurring less often than once a minute during the time the balloon was in the active part of the storm. The second storm was more active, producing lightning about twice a minute.
This was a good example of an air mass storm initiated by the thermal and orographic uplifting of air over the Magdalena Mountains. Wind from the west was strong, so that storms were weak, and drifted away from the laboratory.

Electric field records for the entire duration of the storm are shown in Fig. 5. The electric field became strongly positive at the ground (indicating negative charge overhead) around 11h59m MST (Mountain Standard Time). The balloon was launched at 12h04m and encountered a region of moderate electric field, reaching a value of $4 \times 10^4$ V/m, at 12h14m; this region was apparently not affected by lightning while the balloon was there. The balloon encountered intense electric fields affected by lightning between 12h22m and 12h32m MST. After this the storm drifted away from the mountains and became inactive. Electric fields at the ground did not decline, however, because a new storm formed in the northwest, passing over the mountain range about 5km to the north of the laboratory.

The temperature of the balloon-borne instrument is also shown in Fig. 5. We do not understand the jitter. The fact that the temperature became constant for a while at 0°C suggests that water drops were freezing on the instrument. The other possibility is that the balloon was caught in downdraughts whose velocity equalled the ascent velocity of the balloon, but it would be quite a coincidence for these two velocities to become equal just at 0°C. The balloon could not have stopped rising relative to the air around it since the spin rate of the instrument, which depends strongly on the relative air velocity, maintained its normal value.

![Graph showing electric field, temperature, and time](image)

Figure 5. An overview of the storm on 25 July 1974. Mountain Standard Time is shown along the abscissa. Add 7 hours to get Greenwich Mean Time. The noise-like segments of the balloon record are actually oscillations caused by swinging of the instrument; the oscillations are resolved in Fig. 6. The temperature is that of one of the copper spheres.

We estimated altitudes for the balloon by assuming a constant rate of rise and by interpolating between launch altitude and the altitude at which a squib fired and released the instrument from the balloon. Using this method, the temperature sensor on the instrument first became 0°C at an altitude of 5200m above sea level. This is in reasonable agreement with the 5100m altitude of the 0°C isotherm calculated from U.S. Weather Bureau soundings assuming a dry adiabatic lapse rate below the cloud base and a saturated lapse rate above the base.

The part of the balloon record with the most intense fields is shown in Fig. 6 along with the records from two ground stations. The record from the Microphone Hill station is shown twice, once with the same scale on the ordinate used for the balloon record to emphasize the fact that the fields at the balloon were much more intense.

The oscillations sometimes present in the balloon record indicate that the instrument was swinging like a pendulum below the balloon and the vertical component of the field
Figure 6. Electric field records between 12h22m and 12h30m MST on 25 July 1974. The error in the relative values of $|E|_x$—comparing one part of the graph with another part—is less than $10^5$ V/m; the absolute error should be less than 15%.

was significant. The magnitude of the horizontal component, $(E_x^2 + E_y^2)^{1/2}$, can be found by averaging over the oscillations.

Notice that the magnitude of the electric field at the balloon was substantially reduced by each lightning flash. The ratio of the field change to its initial value was 0.5 for flash d and 0.82 for flash f. Thus the ratios for both flashes are greater than the average value mentioned earlier. The electric field just before flash f was $8.7 \times 10^4$ V/m.

There are two indications that corona from the ground was affecting the electric field there: (1) The magnitude of the field at the ground-based mills remained constant (or even declined somewhat at the Microphone Hill station) for a considerable time before flashes e and f. This behaviour is typical for nearby storms. It means that the electric field cannot exceed by much the value at which it causes the corona current to increase rapidly. Notice that as the storm drifted east (after flash f), the fields at the ground-based mills became smaller and continued to grow during the entire interval between flashes; the effects of corona diminished. (2) The electric field became negative (indicating positive charge overhead) for a brief time following flashes e and f. Our interpretation of this is that the positive charge overhead was that emitted by corona, and it dominated the field at the ground for a short time after the negative charge had been partly neutralized. Chalmers (1967) gives an extended discussion of these effects.

Our balloon-borne electric field instruments had no provision for determining the direction of the horizontal component of the electric field relative to the ground. We can, however, find the change in azimuthal direction of the electric field caused by a lightning flash from records like that of Fig. 3 (which is for flash f) by measuring the phase change in the sine wave due to a flash. Changes in direction in degrees are shown for most of the flashes in Fig. 6. The change was variable but in each case it was no greater than 60°. Apparently, the balloon was located where the field was dominated by a single region of charge. In particular, the corona space charge that caused the polarity reversals (180° changes in direction) at the ground did not cause large changes in direction at the balloon.

In order to decide whether or not we can draw conclusions from our records of this storm about the electric field growth $v.$ time inside the cloud between lightning flashes,
we must assess the importance of the motion of the balloon between lightning flashes. We do this in the following way: The peak values of the electric field at the balloon just before each lightning flash varied considerably from flash to flash. The peak value rose from $5 \times 10^4 \text{V/m}$ just before flash e to $8.7 \times 10^4 \text{V/m}$ just before flash f and then declined sharply to $3 \times 10^4 \text{V/m}$ just before flash g. If we assume that the electric field must reach a certain relatively fixed value at the point in the cloud where a lightning discharge is initiated, then the variations in peak values implies that the balloon was changing its position relative to the region of charge. Apparently, the balloon was moving into the region of intense field when flashes d and e occurred, and began to move away from it around the time of flash f. Thus we conclude that part of the apparent temporal behaviour of the field at the balloon was due to the motion of the balloon. In particular, we think that the increasing rate of electric field growth (positive second derivative) preceding flash e and the decreasing rate of growth (negative second derivative) preceding flash f were both at least partly due to the motion of the balloon.

Using similar arguments, we shall conclude that the motion of the balloon was unimportant during an interesting period of the storm we describe next.

(b) Second storm: 20 August 1974

When the balloon was launched, lightning from a thunderstorm just west of Langmuir Laboratory was causing most of the large transients on the electric field at the ground. The balloon, however, went into a different, younger storm, entering the cloud base 2-2km due east of the laboratory. This younger storm began to dominate the electric field at the ground-based field mills after the balloon entered the cloud.

![Figure 7. Radar echoes from a vertical scan at 11h05m06s. Range rings are 2km apart except for the extra ring above 10km, which shows the maximum range for which digital data was obtained. The position of the balloon is indicated by the +. Z = 9000 in the echo 1.5km east of the balloon.](image)

Radar echoes from a vertical scan through the cloud the balloon went into are showing in Fig. 7. The position of the balloon in that figure is reasonably precise; it was determined by assuming the balloon maintained a constant velocity for 2.5 minutes after theodolite tracking terminated when the balloon went into the base of the cloud; its direction had been constant for 2.5 minutes before entering the cloud. The intense portion of the radar echo extends about 9 km above the ground and is about 1.5km wide. Tall and slender precipitation echoes such as this are common in New Mexico thunderstorms. Unfortunately our electric field meter did not include a method for determining the direction of $E_T$. We cannot say whether or not the charge was located in the region of strong echo.
Fig. 8 shows the altitude of the balloon, the temperature of the electric field meter, and electric fields at the balloon and at the ground. The records begin when the balloon was launched and end 24 minutes later when the telemetry signal became weak. The increase in the vertical velocity of the balloon before it reached the cloud base indicates an updraft velocity of about 1.5 m/s. The 0°C isotherm shown in Fig. 8 is based on U.S. Weather Bureau soundings and measurements of temperature and mixing ratio at Langmuir Laboratory. The temperature sensor on one of the copper spheres of the electric field meter indicated 0°C about 15s after the balloon went through the 0°C isotherm; such a lag could easily be due to the heat capacity of the sphere. The increase in temperature of the sphere between 11h07m and 11h08m occurred during the ascent: we can only guess that it was due to the freezing of supercooled water on the instrument. The accelerated decrease in temperature at 11h13m occurred just after the instrument was released from the balloon and began to descend (relative to the surrounding air). This is puzzling. Perhaps the instrument was substantially warmer than its environment and began to approach equilibrium faster during descent because its spin rate increased, increasing the ventilation. The relatively high-frequency oscillations in the amplitude of \( E \) in Fig. 8 were again caused by the simultaneous occurrence of a significant vertical component of the electric field and swinging of the instrument below the balloon. The oscillations are resolved in Fig. 9; they are most evident before and after lightning flashes \( w \) and \( z \).

Fig. 9 gives a closer look at the interesting portion of the record. The largest electric field transient at the balloon (between \( s \) and \( t \)) during this time does not show up at all on the balloon record; it came from a different cloud – the one west of the laboratory.

Again, notice that the magnitude of the electric field at the balloon usually was substantially reduced by each lightning flash. The exceptions are flashes \( r \) and \( u \) and one about midway between \( y \) and \( z \).

We have enough information to calculate the quantities of charge neutralized by
flashes y and z. Since both y and z were cloud-to-ground flashes, the electric field change at the ground, $\Delta E$, and the charge neutralized, $\Delta Q$, are related by

$$\Delta Q = -2\pi\varepsilon_0 \Delta E(H^2 + D^2)^{3/2}H^{-1}$$

(in SI units)

where $D$ is the horizontal distance between the neutralized charge and the point at which $\Delta E$ is measured. $H$ is the height of the neutralized charge above ground, which is assumed to be a flat conductor. The equation takes into account the image charge below the surface of the earth. The electric field change $\Delta E$ at the ground at West Knoll was $-5.8 \times 10^3$ V/m for flash y and $-6.6 \times 10^3$ V/m for z. Thunder arrived at West Knoll 20 ± 0.5s after y and 21 ± 1.5 sec after flash z. Using 332m/s for the velocity of sound, $D = 6600 \pm 170$m for y and 7000 ± 500m for z. The distance $H$ from the ground to the center of the region of charge that was neutralized is the most uncertain quantity. The horizontal fields at the balloon (Fig. 8) were small until the balloon reached an altitude of about 5200m above sea level. The vertical component of the field at the balloon became substantial at about 7000m above sea level, as indicated by the appearance of oscillations between flashes y and z. Thus the charge centre was 5200 to 7000m above sea level. The terrain under the storm is mountainous, varying from 2000 to 3000m above sea level. Therefore $H$ lies somewhere between 2200 and 5000m. Fortunately, $\Delta Q$ is a very slowly varying function of $H$ in the above interval. Graphs for $\Delta Q$ as a function of $H$ for flashes y and z are shown in Fig. 10. $\Delta Q$ was between −37 and −50C for flash y and between −47 and −66C for flash z.

We cannot calculate $\Delta Q$ for other flashes in this storm because we are not sure they were cloud-to-ground flashes.

The nearly constant value of the electric field at the ground except after lightning flashes and the two polarity reversals are evidence of corona from the ground. The situation is confused by the presence of more than one storm.
The changes in direction of the electric field at the balloon due to some of the lightning flashes are shown in Fig. 9. The changes were relatively small, again suggesting that the field at the balloon was dominated by a single charge region and that it was not noticeably affected by the corona space charge so evident at the ground.

The significance of the balloon record from this storm over that of our previous example is that it allows us to say something about the temporal behaviour of the electric field in the cloud between lightning flashes. The fact that the peak value of the field at the balloon changed relatively slowly during the interval between flashes s and z indicates that during that time the balloon did not move far relative to the region causing the lightning. During the much shorter intervals between lightning flashes, we are reasonably confident that the apparent time variation of the electric field was not much affected by the motion of the balloon and that it is a good approximation to the time variation at a fixed point relative to the cloud. We can make only a rough estimate of the gain in altitude of the balloon between flashes because we were not able to track it inside the cloud. The average upward velocity of the balloon between the 0°C isotherm and altitude at which the instrument was released was 7.5 m/s. If it had this velocity during the 35 s interval between flashes s and t, then it would have ascended 260 meters.

Two facts are particularly noteworthy: (1) The growth of the electric field at the balloon between lightning flashes was quite different than that at the ground. At the ground the field quickly returned to its original value soon after each flash and then remained steady until the following flash. In contrast, the electric field at the balloon grew steadily during the entire interval between flashes. (2) The field at the balloon was often nearly a linear function of time. An exception to this pattern occurred in the relatively long interval between flashes y and z, where the electric field at the balloon (after averaging over the oscillations) declined during the latter part of the interval. This interval should perhaps be divided into two since there was a small field change about halfway between flashes y and z.

6. Conclusion

Our measurements support the widely held view that the behaviour of the electric field at the ground is different than that inside the cloud. During the two storms we have just described the electric field at the ground was strongly affected by corona discharge. Similar records from many other storms indicate that corona is important directly under or near a storm, and that its effects diminish with the strength of the electric field away from the storm. At large distances from the storm the effects of corona are negligible, but then the conductivity of the air outside the storm, particularly the air at higher altitudes, influences the behaviour of the field, as described by Illingworth (1971). At some intermediate distance, where the combined effects of corona and high-altitude air are a minimum, the electric field behaviour at the ground is closest to that in the cloud. But even there it may not be representative of the behaviour of the field in the cloud. The linear growth of electric field v. time between lightning flashes during part of the record on 20 August 1974 is not typical of the time behaviour of the field at the ground at any distance from thunderstorms in New Mexico.

According to Brook et al. (1962) the average charge neutralized by a lightning flash in a New Mexico thunderstorm is about —25 C. The average fractional decrease of the electric field recorded by our balloon-borne instrument inside clouds was 0.4. If we assume that the fractional decrease in charge is, on the average, approximately equal to the fractional decrease in field, then the total amount of charge in a region just before a lightning flash is about —60 C. This estimate is very rough because it was obtained by dividing averages from different sets of storms (although both sets were in New Mexico). Furthermore, we
expect the amount of charge to be as variable as other thunderstorm parameters. The variability may be illustrated by the particular flashes y and z on 20 August 1974. The charges neutralized by these flashes were about \(-43\) and \(-56C\) and the fractional decreases in electric field at the balloon were 0.37 and 0.34. Thus we estimate the quantities of charge just before flashes y and z to be around \(-120\) and \(-160C\), respectively.

Perhaps the most interesting feature of our data is that during the 20 August 1974 storm the electric field between discharges at the balloon was often a linear function of time. It would be quite interesting to see what the electric field \(v\) time is like inside storms that are clearly different than those in New Mexico, such as the very large hailstorms over the high plains of the United States and tropical storms whose bases are much lower than the \(0^\circ\)C isotherm.

Measurements of electric field \(v\) time are particularly worthwhile since they can be compared with the predictions of many models for thundercloud electrification. For example, recent models based on the induction charging of small particles rebounding from the undersides of large particles in an electric field (Sartor 1967; Mason 1972; Levin and Ziv, 1974) predict an initial rapid electric field growth which later slows down and becomes self-limiting at values near those believed to be necessary to initiate lightning. Such non-linear field growth does not appear to describe the storm of 20 August 1974.

ACKNOWLEDGMENTS

We thank Professor C. B. Moore for showing us how to use balloons and Professor C. R. Holmes for providing thunder data. Professors Moore and Holmes together provided radar and field mill records. Miss Maura P. J. Kelly helped us assemble instruments and reduced much of the data, for which we are grateful.

We thank Mr. J. Hughes of the U.S. Office of Naval Research and Messrs F. Eden and C. Downie of the U.S. National Science Foundation for their continued support of the study of thunderstorm electrification under the Meteorology and RANN programmes.

REFERENCES


Christian, H. J. and Few, A. A. 1974 ‘The measurement of atmospheric electric fields using a newly developed balloon borne sensor,’ Proceedings of Fifth International Conference on Atmospheric Electricity, Garmisch-Partenkirchen, in press.


APPENDIX

1. ELECTRIC FIELDS i. OUTPUT VOLTAGE

Davis (1964) has solved the electrostatic problem for two spheres. In our application, the charge amplifier maintains the spheres at the same potential, so that the charge $Q$ induced on sphere 1 by $E_1$ is given by Eq. (20) and (21) in Davis; the charge induced on sphere 2 is $-Q$. The maximum value, $Q_0$, of the induced charge occurs when $E_1$ is parallel to the line between the centres of the spheres. For 15cm diameter spheres held 1.9cm apart

$$|E_1|/Q_0 = 8.8 \times 10^{11} \text{ V m}^{-1} \text{C}^{-1}.$$  

This calculation assumes the spheres are embedded in a uniform dielectric with dielectric constant = 1. The dielectric material (mostly Teflon) holding the spheres together should not affect the induced charge because the material is in a region where the electric field is very low. The dielectric material will, of course, increase the capacity between the spheres but this is of no consequence since the charge amplifier maintains the spheres at the same potential.

The charge $Q$ induced on sphere 1 is related to the amplifier output voltage $V$ by

$$\frac{dQ}{dt} = \frac{C}{A} \frac{dV}{dt} + \frac{V}{RA} $$  

where $C$ and $R$ are the feedback capacity and resistance of the charge amplifier and $A = -R_2/R_1$ is the gain of the second amplifier. This equation is easy to solve because $Q$ varies sinusoidally. Let

$$Q = Q_0 \exp(i\omega t)$$

and

$$V = V_0 \exp(i(\omega t + \delta))$$

where $Q_0$, $V_0$, and $\delta$ are real positive. Then

$$Q_0 = -(1 + (\omega RC)^{-2})A^{-1}CV_0$$

and

$$|E_1| = -(8.8 \times 10^{11})(1 + (\omega RC)^{-2})A^{-1}CV_0$$
ELECTRIC FIELD GROWTH IN THUNDERCLOUDS

which is the result quoted earlier. The minus sign appears because the gain $A$ of the second amplifier is negative.

In order to check the above calculation we operated a field meter in the electric field between parallel plates with a known voltage $V$ difference and spacing $d$. Even though the separation $d$ was only 6 sphere diameters (3 times the width of the instrument), the indicated electric field was within 10% of $V/d$.

2. ANALYSES OF DISTURBING ELECTRICAL EFFECTS

The copper balls and the rotator blades may both accumulate a net electrical charge by capturing charged particles, by releasing particles in an electric field, or by going into corona discharge. Since the accumulated charge does not move relative to the instrument it does not contribute to the sinusoidal output voltage.

The collection of a charged particle by one of the copper spheres causes a step increase in the output voltage followed by an exponential decline. Most particles will carry a charge less than 300pC, and would therefore cause a step increase in voltage less than $9 \times 10^{-2}$V, which is too small to resolve on our records and a factor of 100 smaller than the voltage output from moderate ($3 \times 10^4$V/m) thundercloud electric fields. Collisions with many charged particles might cause observable noise-like fluctuations in the voltage, which could be separated easily from the sinusoidal signal. Most of our records are free of noise; the example in Fig. 3 is typical. We think the noise that does appear in a few records stems from the vibration caused by particles hitting the copper spheres. Our FM transmitters are somewhat microphonic.

A precipitation particle breaking away from one of the spheres in the presence of an electric field would carry an induced charge, which would cause a step voltage to appear. Again, the effect is small. A 3mm diameter spherical particle being released in an electric field of $10^6$V/m would carry a charge of 410pC, which would cause a $1.2 \times 10^{-2}$V jump in the output voltage of the second amplifier.

Corona discharge from the smooth copper spheres seldom occurs, but when it does it has two effects: First, the brief, intermittent currents characteristic of corona cause step changes in the output signal. We have a few examples during one flight in 1974 where steps are visible. A few of the steps are large enough to saturate the second amplifier, and some data is lost while the amplifier recovers, but there is no possibility of misreading the value of the electric field because the sinusoidal pattern is distinctive. Second, the corona space charge, once it has been released, gives rise to an electric field that adds (vectorially) to the cloud's field. Fortunately, the relative vertical wind past the instrument carries this space charge up or down where it contributes only to the vertical component of the field, which our instrument does not detect.

Corona discharge from the rotator blades would release space charge to be carried by the vertical wind past the spheres during ascent and would contribute to the horizontal field to which the instrument is sensitive. We have tried to inhibit corona discharge from the blades, which are made of balsa wood, by coating them with a urethane varnish. The high acceleration (10 times that of gravity) at the tips of the blades keeps water from accumulating there.

Since the parachute and balloon subtend a small solid angle above the instrument, any charge they accumulate will contribute only to the vertical component of the field.

We have inserted Teflon discs between the 2 spheres to maintain good insulation in the presence of high humidity and condensed water. Furthermore, the use of a charge amplifier (with an input impedance of about 25 ohms) places minimal demand on the insulation between the spheres.
An accumulation of ice on the spheres would change the shape of the sensors and therefore change the calibration. It would also add mass to the instrument, slow the ascent of the balloon, and decrease the spin rate of the instrument. The spin rates on our records from 1974 flights are usually reasonably constant. Occasionally the spin rate decreases or increases for a short time. This could be due to the accumulation and shedding of ice by the instrument or the balloon, or the result of an acceleration of the balloon upon entering an updraft or downdraft.

In our derivation of Eq. (1) relating the output signal voltage to the charge induced on one of the spheres, we tacitly assumed that the air inside the cloud in the vicinity of the instrument was a perfect insulator. We shall now show that this is a very good assumption. Suppose the air has a conductivity \( \lambda \). Then Eq. (1) must be modified as follows to account for the flow of current away from sphere number 1 (see Fig. 2):

\[
\int \lambda E \cdot n \, dS + \frac{dQ}{dt} = \frac{C}{A} \frac{dV}{dt} + \frac{V}{RA}.
\]

The integral is over a spherical Gaussian surface just outside sphere number 1; \( n \) is a unit vector normal to the surface element \( dS \) and pointing outward from the surface. When there is no corona from the instrument, as is usually the case, \( \lambda \) is independent of position and can be taken outside the integral. Then the integrand becomes \( 1/\varepsilon_0 \) times the surface charge per unit area and the equation reduces to

\[
\frac{Q}{\tau} + \frac{dQ}{dt} = \frac{C}{A} \frac{dV}{dt} + \frac{V}{RA},
\]

where \( \tau = \varepsilon_0/\lambda \) is the relaxation time of the air surrounding the instrument. The steady rotation of the instrument gives rise to sinusoidal solutions. Let \( Q = Q_0 \exp(i\omega t) \) and \( V = V_0 \exp(i\omega t + i\delta) \). Then our equation becomes

\[
Q_0 \left( \frac{1}{\tau} + i\omega \right) = \frac{CV_0}{A} \left( \frac{1}{RC} + i\omega \right) \exp(i\delta).
\]

For our instrument \( RC = 0.1s \) and \( \omega \) is approximately 25 radians/s. Rust and Moore (1974) measured the conductivity inside thunderclouds near their bases and found \( \tau \) to be about 4000s. Thus \( 1/\tau \) is completely negligible, as we earlier assumed. Even if \( \tau \) were as small as 0.1s and we neglected it, our value for \( Q_0 \), and thus for \( |E_1| \), would be only 8% too high.

The purpose of the foregoing discussion is to impart some confidence in measurements made with this instrument. However, in view of the difficult environment, we do recognize the need to accept cautiously all measurements (including ours) of electric fields in thunderclouds.