A STUDY OF THE QUASI-STATIC ELECTRIC FIELDS OF SEVERE THUNDERSTORMS

By

FELIX JOSEPH BOUDREAUX

Bachelor of Science
Southwestern Louisiana Institute
Lafayette, Louisiana
1941

Master of Science
University of Illinois
Urbana, Illinois
1947

Submitted to the Faculty of the Graduate School of
the Oklahoma State University
in partial fulfillment of the requirements
for the degree of
DOCTOR OF PHILOSOPHY
August, 1959

A STUDY OF THE QUASI-STATIC ELECTRIC FIELDS OF SEVERE THUNDERSTORMS

Thesis Approved:

Herbert L. Jones
Thesis Adviser

A. Naeter

Clark A. Dunn

V. J. Lewis

John E. Hoffman

Robert MacVicar
Dean of the Graduate School

PREFACE

The primary objective of this study is to learn as much as possible about electrical storms in terms of the behavior of the electrostatic fields at the earth's surface due to the electric charge configurations in the cells themselves.

The study was begun by organizing the most generally accepted theories as to electrical structure of the atmosphere, charging mechanism of thunderstorm cells and discharge mechanism of lightning strokes.

Advantage was taken of recent experiments which yielded much information relative to the above topics. Such devices as radar, radiosondes, etcetera have yielded much information that was impossible to obtain prior to their development. Chapter III is devoted to a discussion of these experiments.

The theory of induction, radiation, and quasi-static fields in terms of electric and current dipoles is sketched in Chapter V. The objective of this chapter is to differentiate between the often misinterpreted radiated and static fields and to provide theoretical bases which are later studied experimentally.

Chapter VI describes the instruments constructed for the purpose of investigating slowly- and rapidly-varying quasi-static fields, i.e., the electric fluxmeter and the electric probe. The combination of these two, plus the theory and design of the electric probe, is one of the main contributions arising from this study.

The final chapter contains recordings of the electric fields during electrical storms, accompanied by discussions in terms of the theories discussed and developed in earlier chapters.

Because of the broad expanse of material compassed by this study, brevity has been stressed as much as possible. It has been assumed throughout that the reader has a background of physics and electrical engineering; sufficient theory and references have been given so that further workers in this field may extend this study with minimum difficulty.

This study is by no means complete; probably several years' use of the equipment developed will be made before its full capability is realized and before it will yield the answers to other problems outstanding in this field.

ACKNOWLEDGEMENTS

The writer wishes to acknowledge his indebtedness to:

Professor Albrecht Naeter, Professor and Electrical Engineering Department Head, Emeritus, for convincing the writer that Oklahoma State University was an excellent choice for pursuit of graduate work and for his continual encouragement and assistance throughout the writer's doctoral program.

Professor Paul A. McCollum, for his assistance in locating certain items needed in the construction of the apparatus described herein and for his excellent photography of the results.

Professor George W. Lucky, for his assistance as co-worker in the constructional and operational phases of this research and for his criticisms, which contributed much to the conciseness of the results.

Florence D. Boudreaux, who typed the rough draft of this thesis from the longhand and who aided greatly in its composition.

Miss Barbara Benes, who did the excellent work of preparing the entire thesis in its final form for processing.

The National Science Foundation, whose funds provided the materials and apparatus necessary for the final phase of the research.

Dr. Herbert L. Jones, who suggested the general topic of research and who, as committee chairman, advisor, research director, source of supply, etcetera, aided much to make the overall doctoral program a profitable experience.

TABLE OF CONTENTS

LIST OF FIGURES

CHAPTER I

ATMOSPHERIC ELECTRICITY

For a study of the electrical nature of the atmosphere, it has been found to be of great convenience to regard the earth, its atmosphere, and the ionosphere as a spherical condenser with a leaky dielectric--the earth as the inner conductor, the ionosphere as the outer. In accordance with classical convention, the earth has a negative charge. It could hardly be expected that at any time would there ever be a static condition for this condenser; but for a given location where clear weather is manifest, we may apply the definition of electric intensity to the above convention, and find that the fair-weather electric intensity is normal to the surface of the earth, and pointing into it. Since potential gradient is the negative to electric intensity, it follows that fair-weather potential gradient is a normal outward vector.

The idea of a leaky dielectric arises from the presence of ions in the atmosphere. Conductivity of the air is found to be due almost entirely to small ions, created by cosmic rays, and by radioactive gases emanating from the earth itself. Only these small ions have sufficient mobilities as to account for the apparent conductivity of the atmosphere.

It has been estimated by Gish (1951) that the total leakage current is about 1800 amperes, i.e., about 1800 coulombs per second of negative charge from the earth upward, and that the effective resistance of the atmosphere is about 200 ohms. This gives a potential difference of about 360,000 volts. The potential gradient between the plates of our condenser, however, is not uniform, being about 100 volts per meter at sea level, and decreasing with altitude.

The electrical aspect of thunderstorms, or lightning, plays an important role in this situation. First, our condenser cannot remain charged, because of its leaky dielectric. Its equilibrium appears to be a continual charging process, which is brought about by lightning. This is known to carry predominantly negative charge back to earth. This lightning, though frequently destructive, appears to be one of the forces necessary for the existence of life on our planet, since it oxidizes atmospheric nitrogen into a form that becomes usable by plants. Certainly today we can supply plant nitrogen in sufficient quantity as to make that produced by lightning unnecessary, but it appears that plant life could never have survived the early stages of its evolutionary development without the electrochemical nitrogen cycle that goes on with the aid of the thunderstorm.

The supply current, then, which maintains the charge on our condenser, is brought about by electrical discharges. It has been estimated by Gish (1951) that from 3000 to 6000 electrical storms must be in progress at all times to balance the discharge of the condenser via the atmospheric conduction. Statistical data compiled by Brooks (1925) indicates about 1800 electrical storms are in progress at all times over the face of the earth. Allowing two or three cells per activity meets the recharging requirement.

In passing, it might be mentioned that Linss (1887) estimated that the leakage current due to atmospheric conduction is such that the air-earth condenser could be completely discharged in 120 minutes. Gish and Wait (1950) found by measurement that the average charging current per thunderstorm is from 0.3 to 10.6 ampere. This appears to be consistent with the foregoing estimates and data.

To sum up the foregoing, there appears to exist a continual electric field in the earth's atmosphere which carries negative charge from the earth's surface upward. This process cannot continue indefinitely, of course--there must be some means of re-establishing an electrical equilibrium, at least temporarily. It is believed that the thunderstorm and its accompanying lightning discharges serves this purpose. The best supporting link between thunderstorm activity and the daily regeneration of the earth's electric field is given by Whipple and Scrase (1936), whose curve of the diurnal variation of the area covered by thunderstorms on land areas of the earth matches the diurnal variation of potential gradient on the oceans.

A question may be raised after reading the foregoing discussion: How is it possible for the atmosphere, in view of its conductivity, to maintain a permanent electric field? This problem has been considered at great length by Gish (1950). It is generally accepted at this writing that thunderstorm activity is the device responsible for the maintaining of this air-earth electric field. The conductivity of the atmosphere carries negative electric charge from the earth upward, thus tending to discharge the condenser. The charging process, i.e., the carrying of negative electric charge back to the earth, is accomplished by lightning strokes in thunderstorms. In areas where the potential gradient in the atmosphere becomes high enough, an electrical breakdown occurs. Events leading to this condition involve processes that are still not completely understood, but will be discussed in the chapter devoted to thunderstorms.

Simplicity of the above conditions and processes is not implied. Such things as the ionosphere, polar phenomena related to the aurora borealis, etc., have not been conclusively explained.

Many of these phenomena have a first-order explanation in terms of basic electricity and magnetism. For example, the idea of magnetic momentum resulting from the spin of electrons in an atom may be applied to a simple theory of the earth's magnetic field. It is known that the surface of the earth carries a negative charge. A given charge follows a circular path about the earth's axis due to its rotation. The result is a magnetic vector parallel to the earth's axis, making the north pole that which is sought by the north pole of compass needles. There are additional theories as to terrestrial magnetism: The foregoing, whether the correct one, or whether it explains only one of the factors contributing to the magnetic field of the earth, is offered as an illustration of the application of basic ideas to some of these phenomena.

The electrical nature of thunderstorms seems to be a rather remote subject from that of the atmosphere. An attempt will be made in later chapters to answer some of the questions arising from this statement, and to seek answers to other questions related to the electromagnetic nature of thunderstorms.

CHAPTER II

THUNDERSTORMS

The thunderstorm, with its lightning strokes, has awed and impressed man strongly since his advent on earth. He remained completely ignorant of its nature and cause until the science of electricity began to develop, and Benjamin Franklin in his famous kite experiment identified a lightning stroke as an electric spark.

The origin and the heart of the thunderstorm lies in the so-named cell, which is a center of atmospheric density unbalance. The ensuing electrostatic energy within the cell makes it an electrostatic machine of enormous energy and power. In the common type of thunderstorm, damage is done by heavy lightning strokes to the ground. If one of these thunderstorms runs wild, and causes the so-named tornado, a large part of the stored electrical energy in the cell or cells is converted to mechanical energy of air motion, and the result is winds of destructive velocities.

Although considerable knowledge has been amassed relative to the common thunderstorm, very little is known about the tornado. Obvious hazards incidental to the measurements and study of the tornado have resulted in man's almost complete ignorance of the nature of the tornado.

This chapter will be devoted to a discussion of the elementary thunderstorm, using as a background knowledge which has been amassed in recent years by many researchers in this field.

The Thunderstorm Cell

The thunderstorm cell appears to be created by a local atmospheric inversion, i.e., a region where pressure and temperature gradient are the reverse of the normal. Any set of circumstances leading to the heating and humidification of air nearest the earth's surface results in a strong convective updraft unit which is called the cell. This updraft carries the moisture-laden air to upper atmospheric levels where the temperature is considerably below freezing, so that ice crystals are formed. Many circumstances can lead to these strongly convective updrafts--high ground-temperatures, unusual air-mass movements, and fires of large extent, such as those resulting from volcanic eruptions, incendiary bomb attacks, and large forest fires.

Figure 2.1 shows a schematic diagram of a thunderstorm cell at the beginning stage of its development. Moisture has been carried sufficiently high to bring about precipitation and its partial freezing into hydrometeors such as hail and snow. At this stage no electrification has so far developed. Figure 2.2 shows the same cell approximately a half-hour later. There are considerable increase of updraft, entrainment of outside air, and ice and snow aloft. Rain falls freely at this time and causes some downdraft. At this stage the thunderstorm, which is the present state of the cell, is at the height of electrical activity, and the major portion of its lightning strokes are occurring. The size of the activity in the horizontal direction should be carefully noted.

It will be noted that no electrification occurs unless there is convection that carries moisture-containing surface air well into or past the freezing isotherm. It is, at the present state of knowledge, fairly certain that cell electrification involves the presence of snow, ice, and

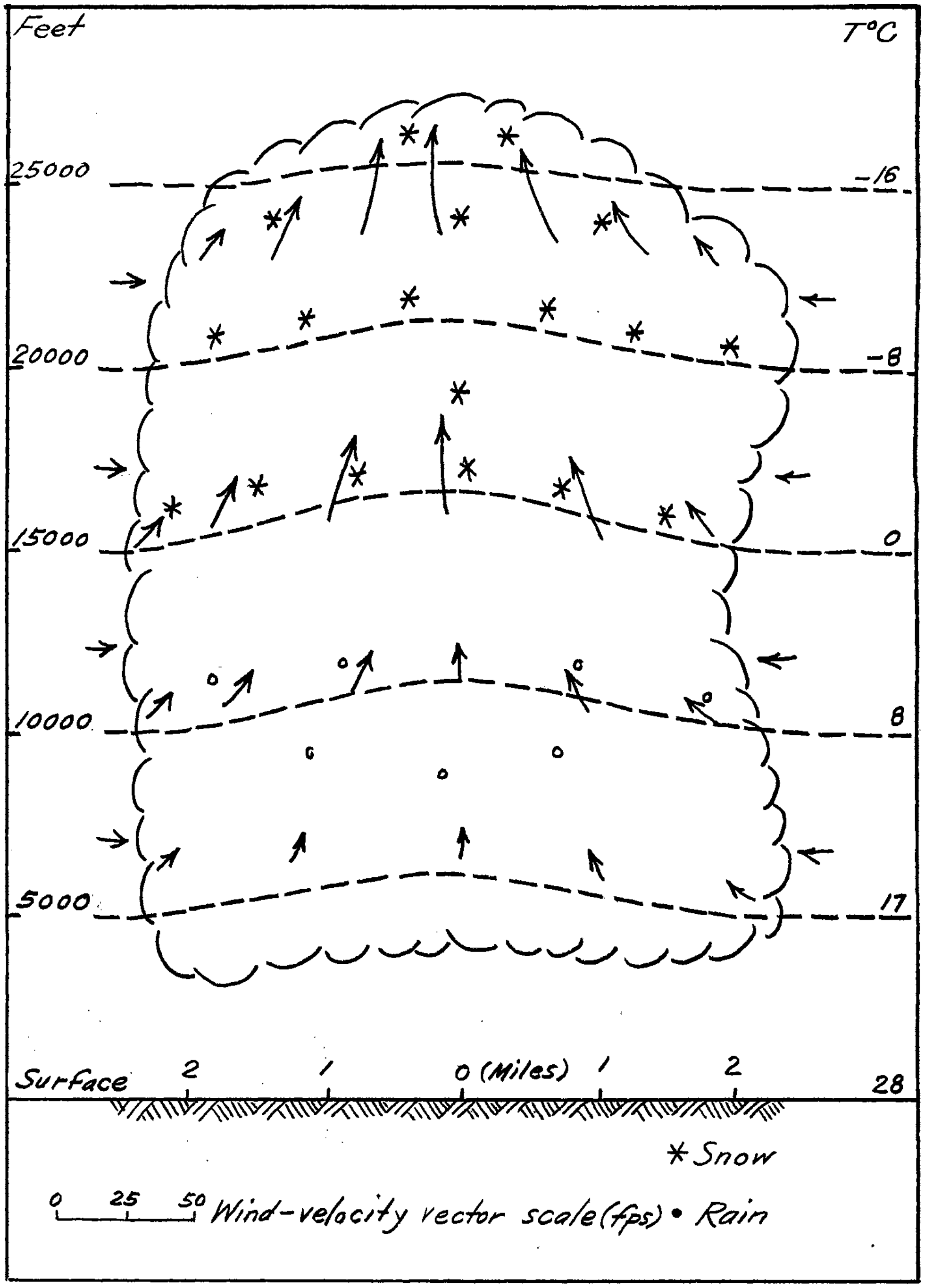


Figure 2.1. Schematic of thunderstorm cell in early stage of development.

(Adapted from Byers and Braham, "The Thunderstorm.")

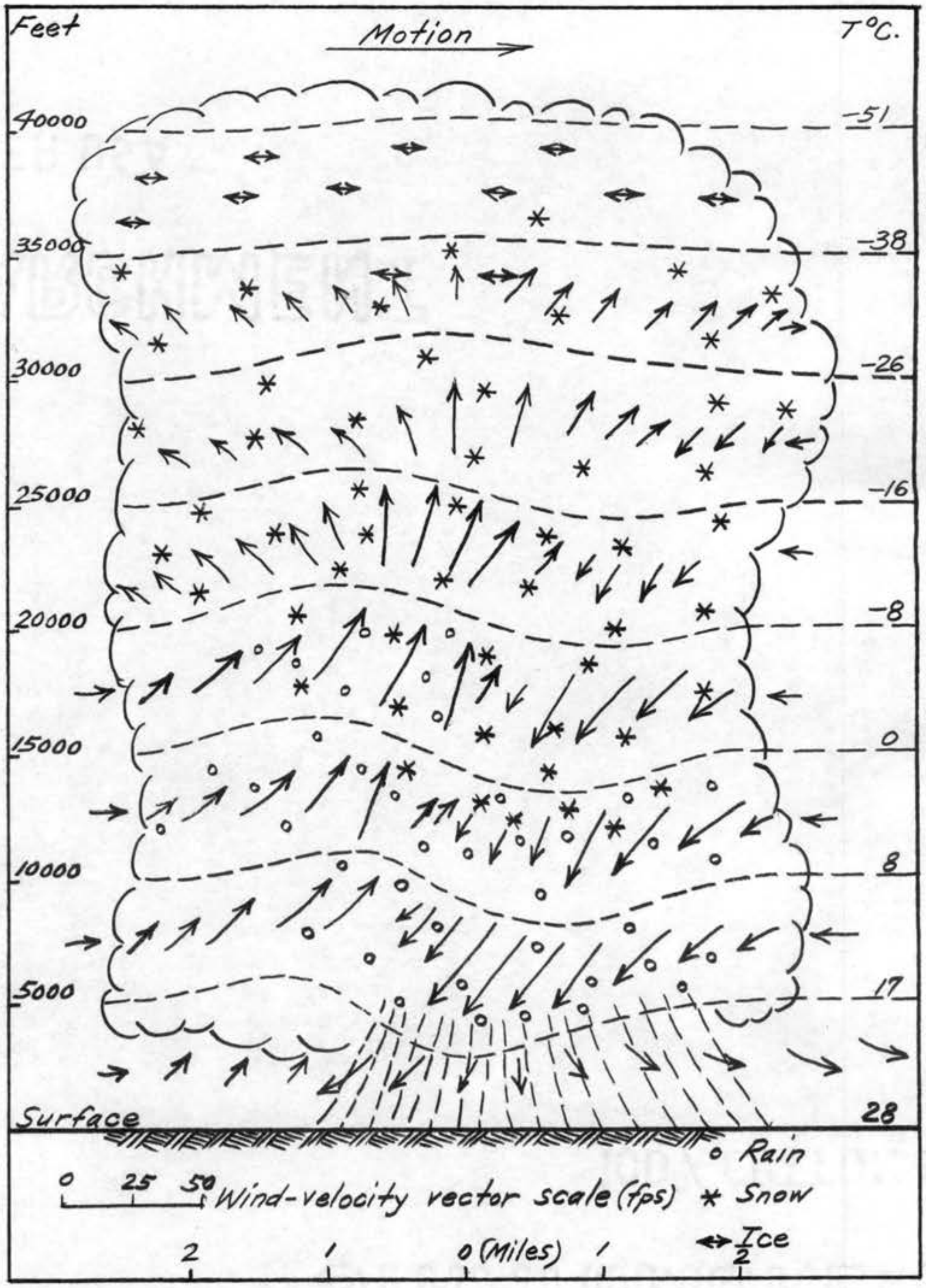


Figure 2.2. Schematic of mature thunderstorm cell at height of electrical activity.

(Adapted from Byers and Braham, loc. cit.)

hail as well as water in the upper levels of the cell. This is merely another way of stating the theory that electrification involves the change of state of the moist air by coalescence into water droplets, thence to snow, ice, and hail.

Before outlining the theories in connection with charge-separation in thunderstorm cells, one may note the third stage in the life of the thunderstorm cell. This is represented schematically in Figure 2.3. When the cell has passed through about twenty minutes of its most active elecrical stage, it gradually loses energy. In the course of approximately sixty minutes its electrical charge has completely vanished, and it takes the form of the cloud shown in Figure 2.3. Updrafts are either nonexistent or very slight, and rain falls from almost the entire lower area of the cell, although very lightly, and all electrical activity in the form of lightning strokes has ceased.

As a rule, the thunderstorm cell is not stationary. In addition to slight movement near the surface, there may be fairly high winds at high levels that will alter the convection pattern somewhat and give the cell cloud the characteristic anvil shape.

Figure 2.4 depicts the distribution of charge within the thundercloud. Many workers in this field have contributed material in this immediate phase of thunderstorm electricity. Electrification within the cells has been recorded from aircraft flying directly through and around them as well as from ground stations in areas where thunderstorms are frequent. /The next chapter deals with this subject in considerable detail./ The data from the latter, however, is open to much question, since it has been shown recently that measurements taken from without the cell present no reliable information as to electrical activity within the cell itself.

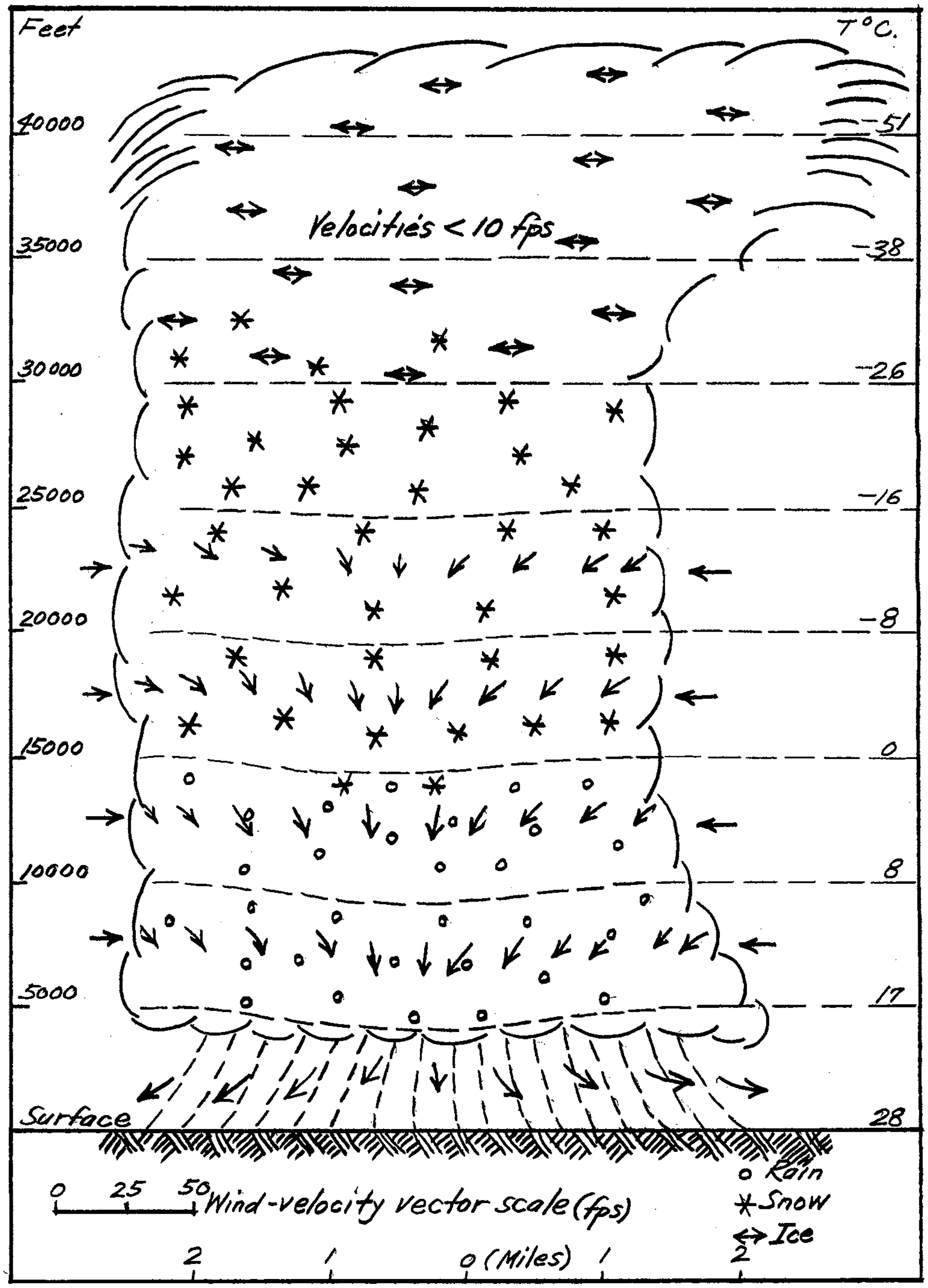


Figure 2.3. Schematic of thunderstorm cell after electrical activity has just ceased.

(Adapted from Byers and Braham, loc. cit.)

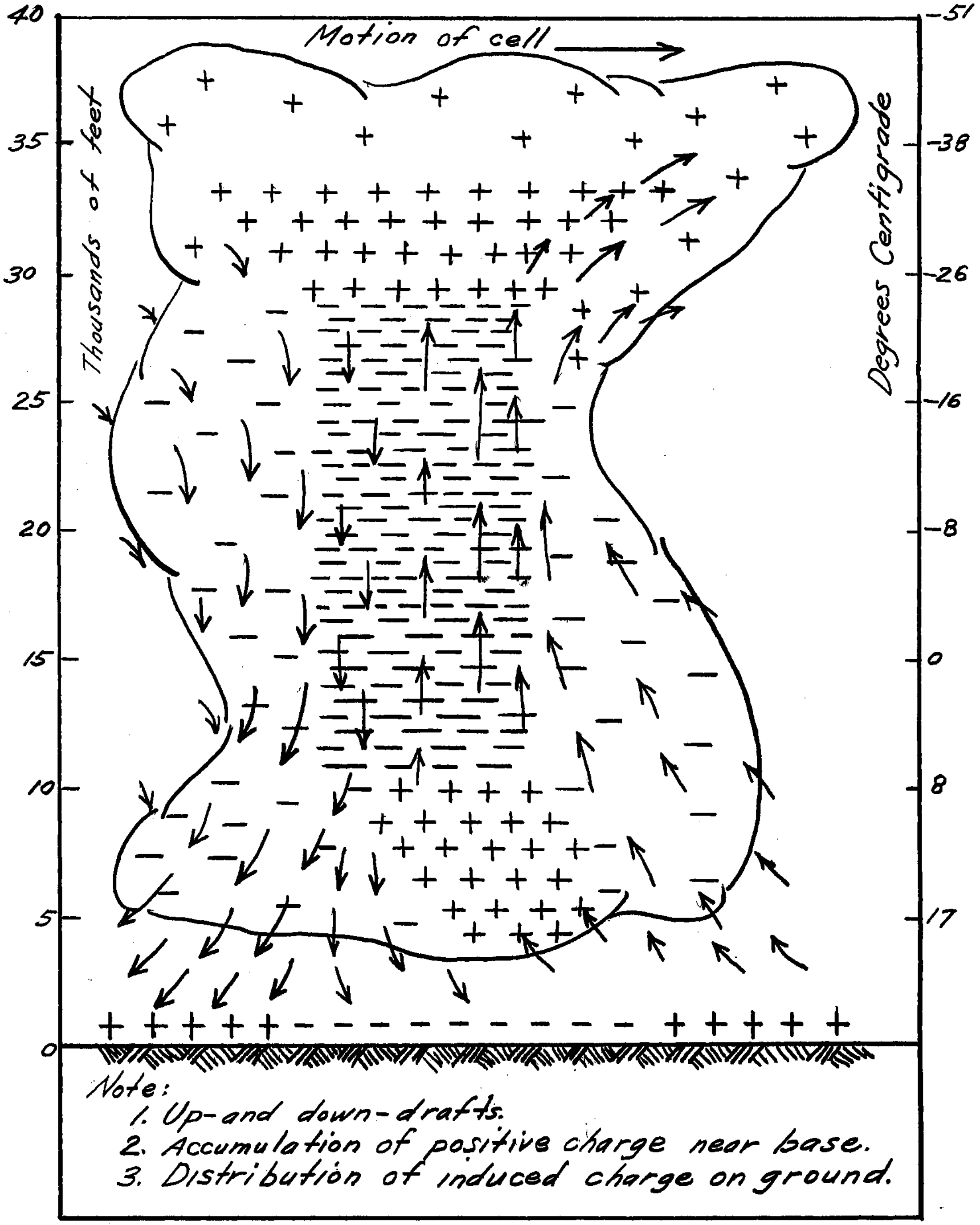


Figure 2.4. Schematic of approximate charge distribution in an active thunderstorm cell.

(Adapted from Byers and Braham, loc. cit.)

This will be discussed in more detail in a later chapter describing details of some very recent and somewhat exhaustive experiments in which the electrical and aerodynamic processes within active thunderstorm cells were studied.

It will be noted in Figure 2.4 that most of the positive charge is in the top region of the cell, where it is associated with snow or ice. The main negative charge is in that section of the cell where updrafts and downdrafts are most prominent. The negative charge is associated with most of the rain, and the majority of the rain falling from the thundercloud is negatively charged. Also, in most clouds that were studied there exists a low-lying accumulation of positive charge associated with large raindrops in the region of turbulence at the base of the cloud. It is believed, and it is logical from the electrostatic viewpoint, that this positively-charged region, plus the negative charge at the earth's surface, is largely responsible for cloud-to-ground lightning strokes.

Figure 2.4 also points up another noteworthy fact: the electrical charge in the thunderstorm cell is segregated into three cloud regions and is associated in all cases with hydrometeors, i.e., snow, ice, and water droplets. As will be discussed later, these solid and liquid hydrometeors play the major role in the creation of the charge. Regardless of how the charges are generated, however, they would rapidly be picked up by these hydrometeors.

It has been found by measurement that in thunderstorm cells there are between one and ten grams of water per cubic meter, of which an average of four grams per cubic meter is distributed among 250 to 4000 water droplets. Ross Gunn (1952) measured the charge on individual droplets in airplane flights and found that drops of various sizes carry from 0.03 to

0.15 statcoulombs of charge. The electric field at the surface of a typical drop ranges from 300 to 3000 volts per centimeter. It therefore follows that the charge density within a cell can range between 38 and 120 statcoulombs per cubic meter. The larger value of charge density corresponds to about 240 coulombs in 6 cubic kilometers of cloud mass, a figure generally accepted as the proper order of magnitude.

The foregoing was intended to be of a general descriptive nature and is based upon observation and measurement. In the next section the most generally accepted mechanism of thunderstorm electrification will be discussed in some detail.

Mechanisms of Thunderstorm Electrification

Many theories have been advanced as to the mechanism of charge generation in thunderstorm cells. Some of these have been discarded, and of those that remain, workers in this field are still uncertain as to which is correct and also as to whether more than one of these are correct, allowing more than one process to contribute to the overall electrification. Workman and Reynolds (1949) have shown conclusively that, when water of the purity found in raindrops freezes, very high electrical potential differences exist between the water and ice phases during the freezing process. Similarly, potential differences exist between the two phases when melting occurs. The sense of the potential difference appears to depend upon the impurities dissolved in the water. Because an electric potential difference exists between the liquid and the ice phases during the change of phase, it is evident that the two phases have charges of different polarity. Now, if the two phases of a given particle become separated, as when water is blown off an ice particle, then charges have become separated. Whether the process is a melting or a freezing one, the potential difference exists, and if the two phases become physically separated during the change of phase, there are two charged particles of different polarity. This theory has been verified positively in the laboratory by Workman and Reynolds and appears to account for both the polarities and magnitudes of the charges observed in thunderstorm cells.

In a thunderstorm cell, as already noted, warm, moist air is carried by updrafts into the upper levels of the cell. Here it freezes and, in starting downward, coalesces into hail or falls as snow to the freezing isotherm. The updrafts condense and freeze water-vapor found there or freeze water droplets already falling as rain and thus bring about the potential difference and ensuing charge separation. A similar process takes place if frozen particles descend below the freezing isotherm and melt. As has already been mentioned, the sense of the potential difference between the ice-liquid phases depends upon the nature of the impurity found in the water. Usually the impurities are such that the heavier solid particle is charged negatively, and the liquid is charged positively. The blowing away of liquid by updrafts carries a positively-charged vapor to higher levels in the cell, but falling ice or snow carries negative charge to the lower portion of the cell. As the ice or snow melts into rain, if there is no physical separation during the change from ice to liquid, the raindrops retain the negative charge and carry it to the earth. This process appears to be the only one that is capable of accomplishing the massive charging that exists in thunderclouds, as noted earlier in this chapter.

The above charge-separation process results in the charge-distribution illustrated in Figure 2.4. The high electrostatic fields that now exist may bring about further charging processes, that of polarization of falling raindrops by the high field and again by ion movement. It will be borne in mind, however, that these latter processes may contribute only in a small way to the charge magnitudes that have been observed. Furthermore, they depend upon the previously established electrostatic field that has been set up by the phase-change charge-separation process.

The electrification theory of thunderstorm cells has been outlined briefly above. Attention will now be directed to the electrodynamic manifestation of the thunderstorm--the lightning stroke. A great deal of effort has been put forth in obtaining measured data of these phenomena. Measurement techniques, plus the fact that these strokes are visible, make a compilation of reliable data relatively easy.

As mentioned in the first chapter, it appears that thunderstorms account for the maintaining of the atmospheric electric field, in spite of the continuous flow of atmospheric current that tends to discharge the air-earth condenser. It appears that cloud-to-ground lightning strokes are of such polarity as to neutralize negative charges in the cloud. This means either of two things, the flow of negative charge to earth or the flow of positive charge from the earth to the cloud. Either satisfies the current requirements of the stroke mentioned above. Also, this is in agreement with the theory that the air-earth condenser is being continually discharged by the flow of negative electricity from the earth into the atmosphere.

Nothing has been mentioned in the foregoing discussion about cloud-to-cloud strokes. If there are many cells in close proximity, the electric field between the upper positively charged portion of a cell and the negatively charged portion of another cell may become sufficiently high to cause an electrical breakdown between these two regions. This idea accounts for the near-horizontal strokes frequently observed. Of course, there may be a stroke within a single cell where the altitude of the lower portion is such that the breakdown field within the cell is reached before that in the region between the negatively charged lower portion and the ground.

In conclusion, thunderstorm electrification is remote from the de-electrification of our air-earth condenser. Negative electricity in fair-weather areas may be presumed to be carried all the way from the earth to the positively charged stratosphere. Therefore, the recharging process of the air-earth condenser is accomplished entirely by cloud-to-ground lightning strokes. Intra-cloud or inter-cloud strokes merely bring together charges that have been separated by the process described earlier.

Characteristics of Thunderstorms

Thunderstorms, both in the formative and discharge stages, differ in several ways. Their size, height, manner of discharge, and length of life depend upon a number of factors. It appears that the most important influence determining the character of thunderstorms is land elevation.

The diameter of the cell depends upon the area in which there is sufficient turbulence to carry air masses upward. This is usually a maximum of four kilometers. In the United States the average height of the cloud base above ground is two kilometers. The length of the lightning strokes to ground in such cells varies between 3 and 9 kilometers. The number of strokes required to discharge a cell to the extent that no further electrical activity is observed depends on the vertical distance from the base of the cloud to the top of the negatively charged portion. The number of strokes increases with this vertical distance; for a distance of

5.1 kilometers the number of strokes is two; for a distance of 9 kilometers the number of strokes is approximately eleven.

When the cell acquires a charge sufficient to bring about a discharge to the ground, a conducting channel of ionized gas gives rise to further strokes; each stroke effectively lowers the negatively charged portion of the cloud until the cell is discharged. During a storm some of these cells may recharge and give rise to new strokes. The writer feels that the condition under which a cell may discharge via several strokes and then recharge, repeating the process, may have an important bearing on the formation of tornadoes. This is merely mentioned in passing; much must be learned before these ideas can be expanded upon.

As to the sequence of events in a cell which repeatedly recharges, after reaching maturity, the average number of flashes in each ten-minute interval is 40, then 80, then 60, then 40; the maximum frequence of strokes occurs 50 minutes after the first stroke. If there are six strokes per flash, which represents a complete cell charge, there are about 37 rechargings in 40 minutes. Averaging a discharge of about 20 coulombs per stroke, a cell having a life of 50 minutes may generate a total charge in the neighborhood of 3000 coulombs. This, plus other approximate figures to be given later, gives one some idea of the enormous energy stored electrically in these cells.

The Lightning Discharge

The electrical discharge to the ground is a rather complicated process involving a pilot leader, a stepped leader, and the return stroke. These, and the processes involved with them, pave the way for an explanation of the various phenomena very commonly observed in thunderstorms.

Surprisingly enough, some of these explanations have not been made until quite recently.

The first ground stroke is initiated by the pilot leader, which is invisible except at close distances. This pilot leader feels its way downward and gives a forked effect as it progresses. Its path, including the forks, is greatly illuminated in steps when its channel is followed by the stepped leader. These individual steps vary from 10 to 200 meters in length.

There are two types of stepped leaders, the alpha and the beta types. The former represents a relatively weak discharge progressing to the ground in uniform steps at an average rate of 2 x 10^7 cm/sec. The latter, or beta-type, begins with larger steps and considerable branching, progresses to the ground at the rate of about 1.5 x 10^8 cm/sec, and gradually evolves into an alpha-type leader. The time required for a stroke to reach the ground from a cell base 4 kilometers above the ground varies between 2 and 20 milliseconds.

It might be mentioned in passing that the information above is obtained photographically by means of a rapidly rotating prismatic lens. This permits observing the various events accurately in time. From a measurement or estimation of heights involved, the velocities mentioned may be calculated. Figures 2.5(a) and 2.5(b) illustrate the chronological sequence for an alpha-type and beta-type discharge. The variation of the electric component of the radiated electromagnetic field is plotted above each event. These are due to Schonland (1953).

To return to the discharge process, when the path that has been ionized by the step-leader reaches within ten meters of the ground, the gap is closed by an upward positive streamer, which causes the characteristic

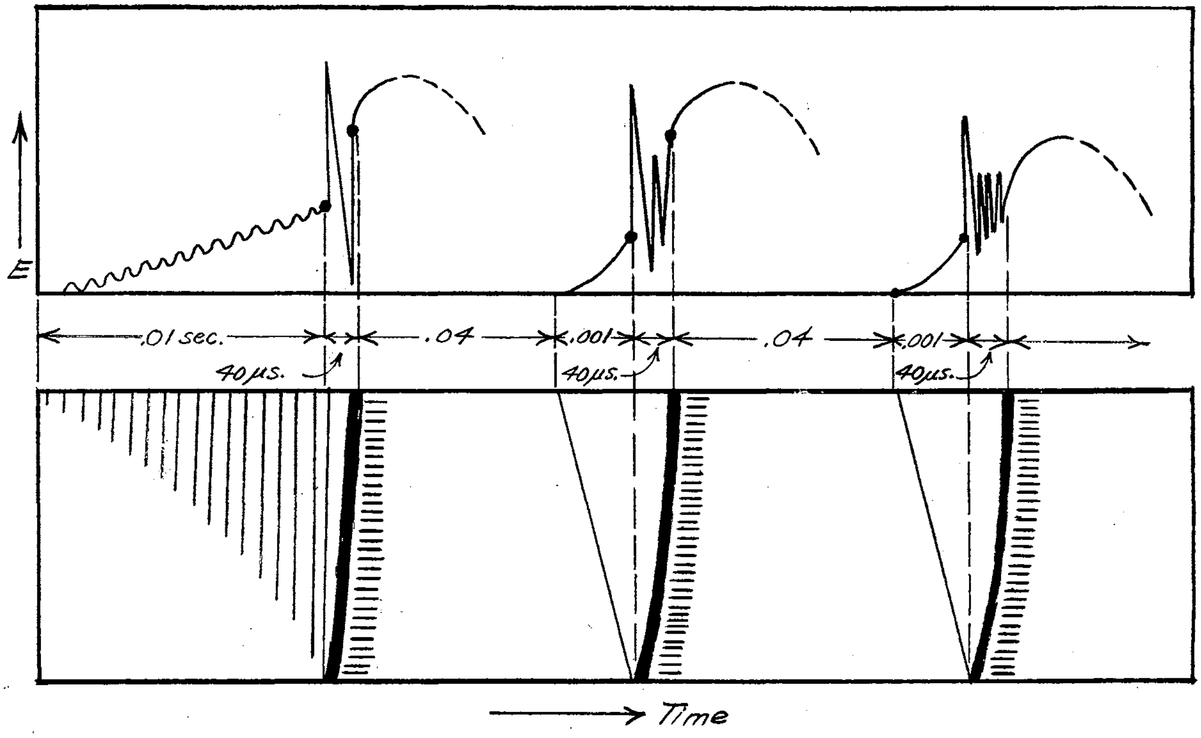


Figure 2.5(a). Sketches after Schonland showing the time relationship between alpha-type stepped leaders, return strokes and the electric component of the radiated electromagnetic field. The heavy lines show the return stroke, followed by the persistent luminosity of the heavily ionized channel. Note that in the second and subsequent discharges, the leader is not stepped, but proceeds directly down the partially decayed channel. This is the "dart leader." Note also the beginning of the oscillation of the electric field, giving way to the quasi-stationary electric field as the ionized channel partially decays.

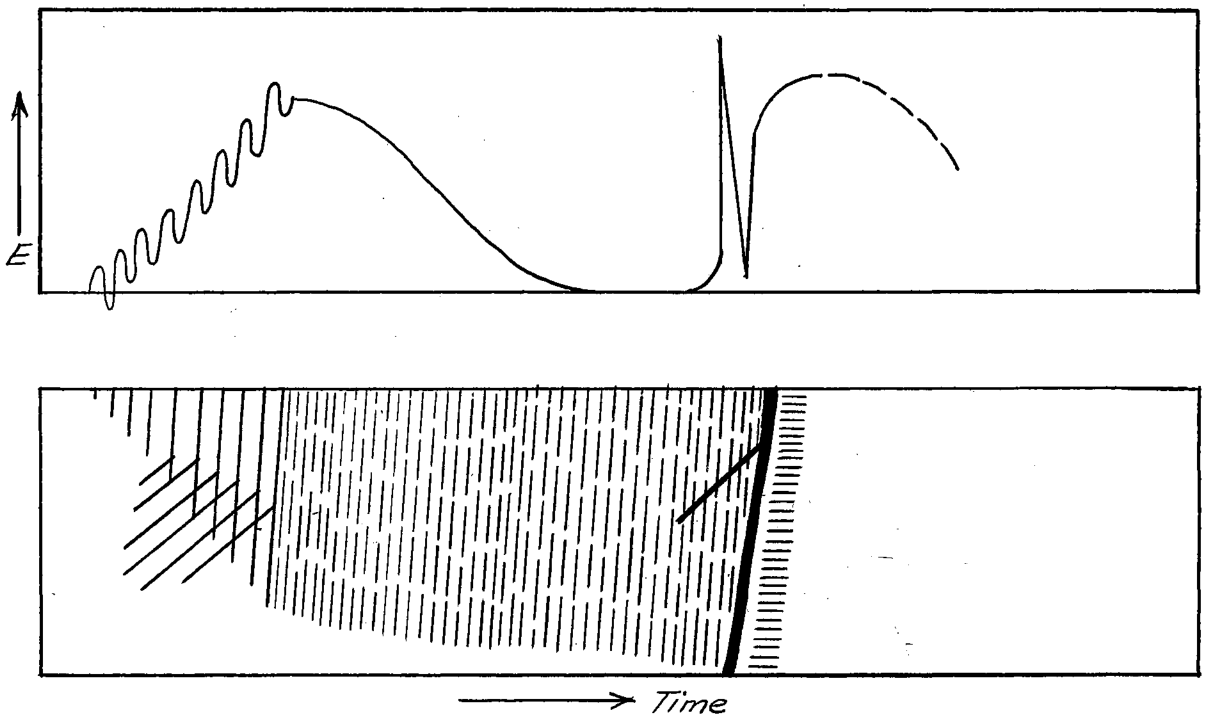


Figure 2.5(b). Sketches after Schonland similar to previous figure for a beta-type stepped leader, and its evolution into an alpha-type. Note the branching of the stepped leader, which gives rise to vigorous oscillations of the radiated electric field, which die out during the alpha-type stepping. Note also that the excessive branching of the beta leader causes a branch of the return stroke. In other respects, the overall phenomenon is the same as that brought about by an alpha-type leader.

blinding flash and leads to the return stroke, which is a very violent and fast-moving pulse of high luminosity that travels as a wave of high potential gradient up the ionized path left by the leader stroke. Its velocity is initially 10^{10} cm/sec, but it decreases to 3×10^{8} cm/sec as it approaches the cloud. This rapidly-rising potential wave causes the brilliant light and accompanying ionization that carry the heavy current flow that discharges the lower sections of the cell base. Current flow and luminosity usually persist for about a half-second, during which the discharge of the cell is completed.

If conditions warrant it, the complete process of recharging and discharging may be repeated. The ionized path of the completed discharge is rapidly decayed, with the result that the new discharging process will acquire a new pilot leader and stepped leader. The time required for a leader to reach the earth from a height of 6 kilometers is from 1 to 3 milliseconds, but separate strokes occur at intervals of an average of 30 milliseconds. These figures lead to fair estimates of current magnitudes involved: A collection of charge from 1 kilometer height proceeds earthward at about 3×10^{6} cm/sec. The charge lowered to earth may be about 5 coulombs for 6 kilometers of cell height, and strokes carry a total charge to the earth from 20 to 200 coulombs. The current involved in the pilot and stepped-leader amounts to from 50 to 600 amperes, but the return stroke carries currents as large as 500,000 amperes; the average is somewhere between 5000 and 30,000 amperes. This peak current flows for from 100 to 1000 microseconds.

It has been estimated that the diameter of both the step-leader and return-stroke channels is of the order of 20 centimeters. The constriction is likely due to the pinch-effect, caused by the magnetic field because of current flow.

As will be brought out in the next chapter, the potentials of the charged cloud masses are not known, but Schonland (1950) has estimated this to be of the order of 6 x 10^8 volts.

In the heaviest of lightning strokes the power developed is of the order of 2.4 x 10^{11} kilowatts. If the stroke lasted for one millisecond, the energy liberated would be 1.3 x 10^5 kilowatt-hours. Of this, only about 1.6 percent is expended in ionizing the gas in the column carrying the stroke. The rest is expended as heat via friction in the movement of ions through the gas. During the 50-minute life of a very active thunderstorm cell, 2.6 x 10^6 kilowatt-hours of electrical energy are generaged and are dissipated by some 200 flashes delivering 20 coulombs each. The expenditure of this amount of energy in the restricted channel will raise the temperature to something like 20,000° Kelvin in a millisecond. The heat energy thus stored in the conducting column manifests itself visually by a brilliant luminosity during and after the stroke and exists for about 0.2 second.

The acoustic manifestation of this process, namely, thunder, may be explained by means of the adiabatic expansion of the gases around the channel. The subsequent rarefication of gas in the channel causes surrounding atmospheric pressure to recompress the gases within. The original heat energy thus results in transverse oscillations, which are audible over a wide area. The low frequency and duration of the oscillations are due to the large axial dimension of the column. It might be added here that this phenomenon was not satisfactorily explained until quite recently, when atomic explosions made an accoustic study of the above phenomena possible.

The Initiation of the Lightning Stroke

As mentioned previously, the central negatively charged region is probably the major contributing factor in the electrical breakdown between the cell and the ground. Reference to Figure 2.4, however, shows that the negative region of the cell is partially shielded from the ground by the region of positive charge at the base of the cell. If there is sufficiently intense turbulence in the cell so as to bring the low-lying region of positive charge nearer the negatively charged region, a very strong electric field then exists between the two, of the order of 10,000 volts/cm. The surface-tension of raindrops in this region is overcome by electric polarization, and the droplet is stretched out into an elongated shape with fine tips at either end, the upper positively charged, and the lower negatively. Both tips break into a fine spray, the positive tip forming a corona discharge in addition. The negative tip yields no corona discharge, but the fine droplets emanating from it yield a positive corona by secondary induction at their upper ends. Thus positive ions and positively-charge mist move up into the negative region of the cloud and leave behind heavy droplets that are negatively charged. The existence of corona discharges in the strong field causes one of them to develop a very strong localized stress. This stress, progressing up toward the negative cell, leads to a spark discharge, or lightning stroke, between the region of positive charge and the base of the negative portion of the cell. Because of the above dipole formation and subsequent corona discharge an electrical breakdown can occur in a field of 10,000 volts/cm, whereas the breakdown field in dry air is 30,000 volts/cm.

In the intra-cloud spark discharge a considerable amount of negative charge is transferred from the negative region to the nether positive region. The shielding of the negative portion of the cloud from the ground is thus greatly reduced, and the electric field at the cloud base is greatly increased. The way is now clear for the advance of the negative electron streamer, which is the pilot leader, to advance toward the ground. What follows has already been discussed in some detail.

When the return stroke has drained sufficiently large quantities of negative charge from the lower portion of the cell, the potential gradient diminishes, and positive-ion carriers decay, and the heavy current of the return stroke diminishes. The top of the return-stroke channel is positively charged, however, and the field between this and the remaining negatively charged column of the cell again becomes high enough for a new leader to begin. This leader, having a partially conductive channel to follow, does not branch outward but proceeds to the ground by a rather direct path. This secondary leader is generally called the dart leader. When nearly to the ground, it is met by the return stroke, and another portion of the negatively charged portion of the cell is drained off. This process repeats until the cell is completely discharged. The return strokes have a time separation of approximately 30 milliseconds. During the life of a thunderstorm cell there will be several rechargings of the cloud at intervals of from 1 to 10 minutes. Each recharging leads to the succession of strokes described above.

CHAPTER III

THUNDERSTORM MEASUREMENTS

Introductory

For many years there has been much speculation as to the precedence of precipitation over electrification in thunderstorm cells. In recent years radar techniques have facilitated many experiments that seem to throw some light on this question.

This chapter will be devoted to a brief discussion of a series of experiments reported on by Moore, Vonnegut, and Botka (1958), which lead to some very interesting conclusions. Because the mechanism of electrification of thunderstorms has already been discussed, some of the material in this chapter will at first appear to be redundant; but some of the conclusions seem to point up the fact that little or no information may be determined about electrical activity within a thunderstorm cell from measurements made without the cell. As will be shown later, however, electric field measurements made sufficiently near a cell should provide some information as to electrical activity within.

To return to the subject of the present chapter, much can be learned about the techniques employed in making measurements, upon which the information presented in Chapter II is based.

The Mount Withington Experiments

In the experiments described below, a number of measurements were made, i.e., potential gradient below, within and above the thunderstorm cell, by means of instruments on aircraft, captive and manned balloons, and observations of precipitation within and below the cell by means of radar. Simultaneous observations of these as functions of time were made, so as to facilitate co-ordination of data and subsequent conclusions.

These data were taken above and on Mount Withington, New Mexico, in August, 1957, where during the summer, cloud-formations resulting in thunderstorms occur almost daily.

It has long been assumed that the fall of precipitation in thunderstorm cells is responsible for their electrification. Measurements made during the subject experiment, however, indicate that potential gradients of 10 or 20 volts/cm, vertical, have been measured prior to any precipitation observed by radar echo.

An experiment earlier than the subject one involved the measurement of field intensity at the same location, along with observation of precipitation by radar echo. The results were that, as the cell formed, there was a reversal of fair-weather electric field, which then increased exponentially with time until the first lightning stroke occurred. Radar observations made during the above process indicated that precipitation preceded the field variations mentioned above. From this it was concluded that precipitation is a necessary but not sufficient condition for thunderstorm electrification.

It will be carefully noted that the above conclusions were drawn relative to a time-study of the potential gradient <u>on the ground</u> beneath the thunderstorm cell. A closer study of the data in this early experiment, together with measurements made by others, indicates bases for strong arguments leading to the above conclusion. It has been found, for instance, that just prior to the lightning stroke in a cloud the electric field therein is of the order of 1500 volts/cm. At the ground the electric field at the same time was of the order of 30 volts/cm. A graphical study of measurements made as functions of time indicates that the electric field within the cloud must have been of the order of 50 volts/cm. at the time of the first radar echo, which is assumed to be the time of initial precipitation. In the light of this argument, the experiment described here was planned expressly for the prupose of determining whether organized precipitation or electrification occurred first in a cloud.

Vertical components of potential gradient were measured by means of radiosondes suspended in the cloud by means of captive balloons. Distinctively different types of apparatus were used for the measurements. These were in substantial agreement; therefore the results were logically assumed to be fairly reliable.

In addition to the above, a P-38 aircraft was used to carry instruments to measure the electric field above the cloud and to obtain time-lapse motion pictures of the cloud-tops as well as to record temperature and humidity. Also, the aircraft was flown through the cloud for purposes of repeated observations of the nature and extent of precipitation therein. The results were as follows:

(a) On no occasion was reversal of the electric field observed on the mountain beneath the cloud before the first radar echo. This was in complete agreement with earlier experiments.

(b) The potential-gradient measurements within the active cloud and directly over it show that appreciable electrification develops in apparently organized fashion before rather than after the first radar echo.

Space-Charge and Air-Conductivity Measurements

Measurement of space-charge density at the summit of the mountain was made by means of a Faraday Cage. Before and during the initial development of the clouds the air had a space-charge of several hundred relative units per cubic centimeter, positive. It might well be mentioned here that the fair-weather conductivity of the air at the mountain summit is always much greater than at sea level. The time constant for a charged body at this location is approximately 200 seconds.

Two measurements indicate the general picture of the electrostatic situation prior to the thunderstorm:

(a) Radiosondes supported on captive balloons within the cloud <u>near its base</u> show fair-weather potential gradients as much as 10 volts/cm up to 30 minutes before radar detection of precipitation.

(b) Measurements made above the top of the growing cloud show that the potential gradient there has usually decreased or has reversed from the fair-weather value some time before the radar detection of precipitation. This suggests the fact that positive charge is being accumulated in the growing cloud.

This last conclusion may be clarified by a discussion of the fair-weather potential gradient in the atmosphere.

The earth carries a negative charge at its surface, as mentioned in Chapter I, relative to the atmosphere about it, which indicates an electric intensity vector perpendicular to and into its surface, in accordance with classical convention. Thus, since potential gradient is the negative of electric intensity, the fair-weather potential gradient at the earth's surface is a vector normal to the surface and upward. Whether near the earth's surface, or at a given altitude, the fair-weather potential gradient in the atmosphere is an upward-directed vector, though of smaller magnitude than at the surface.

Now, if a positively charged body were introduced into the atmosphere between a high-altitude observer and the earth, the potential gradient observed would be made of two components, the upward component caused by the negative charge on the earth and a downward component caused by the positively charged body, such as a cloud. If the cloud assumes an increasingly positive charge, the observed potential gradient would approach zero and begin to increase in the reverse of the fair-weather direction. This reasoning, together with the observation that the potential gradient above the growing cloud decreases or reverses some time before precipitation occurs, indicates that the positive charge is accumulating in the cloud prior to precipitation. Further, since the potential gradient within the lower portion of the cloud remains near the fair-weather value during the above period, the positive charge that is accumulating in the cloud apparently is confined to its upper portions, whereas the lower portions contain the negative charge.

Further observations seem to indicate a strong correlation between cloud electrification and convection within the cloud. Relative convection velocities were obtained by measurement of tension of the lines holding the radiosonde-supporting balloons within the cloud.

The build-up of negative-charge concentration within the base of the cloud was accompanied by rapid increase of the height of the cloud top and simultaneous increase in tension of the balloon-restraining line. The logical conclusion is that increase of the positive charge in the upper region of the cloud, with simultaneous increase of negative charge in its lower portions, is always coincident with strong updrafts. It will be noted here that the above observations are in complete accord with the updraft and charge-separation theory as described in Chapter II.

Another important observation made in the above experiments indicates that large electrical activity within the cloud is virtually undetectable from without. At a distance of about four miles no variation of electric field was observed in a thunderstorm until the first lightning stroke occurred. It appears that information obtained in earlier experiments in which conclusions were drawn from observations made external to the thunderstorm would be unreliable. Reference to Figure 2.4 makes the last statement readily understood. It will be noted that the low-lying positively-charged region at the base of the cell will very likely produce a potential gradient at the ground below and about the cell of the same sign as the fair-weather value. Of course, if the negatively-charged column in the cell is large enough, the potential gradient on the ground below and about the cell will be the reverse of the fair-weather value. At a reasonable distance from the cell, however, the fair-weather potential gradient at the surface has been practically undisturbed by the presence of the thunderstorm cell.

We return at this point to further observations made in the course of the subject experiment. Two radiosondes were suspended about 800 feet apart vertically from the same captive balloon. The upper one maintained a height of about 15,000 feet, mean sea level; the lower radiosonde was about 1200 feet above the cloud base. For a typical observed thunderstorm the time sequences were as follows:

The lower radiosone invariably reported a reversed potential gradient first, usually soon after increasing tension was observed in the line mooring the supporting balloon. If convection continued, the electric field at the ground next reversed from the fair-weather polarity. /This indicates a predominance of negative charge overhead with respect to the earth./ The upper radiosonde usually reported a potential gradient of the same sign, but greater than the fair-weather polarity until the first lightning stroke occurred. Measurement of space-charge in the air at the summit level was observed to change from positive to negative when the potential gradient reversal indicated a net negative charge overhead. This appeared to mark the onset of cloud electrification. When this reversed potential gradient at the summit increased to about 10 volts/cm., corona discharges were observed at several points on the mountain, and very high positive space-charge densities were observed.

The above observations suggest that convection in the cloud brings about an accumulation in its extreme lower portion. The continuation of this convection eventually results in the reversal of the potential gradient between the cloud and the ground, the negative potential gradient reaching high values. This high potential gradient seems, by virtue of observed corona discharges, to bring about the high positive space-charge densities observed at this time.

The above sequences were observed repeatedly.

One instance, in which both radar and electrical observations were made and in which the cycle was repeated, is worthy of note:

The top of a cloud began to rise rapidly, and negative-charge accumulations began at its base. About two minutes later the radar showed signs of precipitation in the upper portion of the cell, but the radiosonde showed fair-weather polarity. Strong convections accompanied the above process. Precipitation observed by radar seemed to spread, the updraft ceased, electrification vanished, and in about five minutes heavy rain fell to the ground. In about 15 minutes the rainfall decreased, a new updraft appeared, and the entire sequence was repeated. This appears to be a case in which a cell is de-electrified without electrical discharge. The case is of no interest in this study.

Measurements were also made to determine the amount of charge, if any, that was carried to the earth by rain. These were made on days when the summit of the mountain projected into the clouds. Current measurements indicated that the current magnitude during rainfall was about the same as fair-weather air-earth current, i.e., about 2 x 10^{-14} amperes per square centimeter, which is not sufficient to classify rainfall as a mechanism that contributes to the sustaining of the electric field of the air-earth condenser. Furthermore, the charge being carried by the rain was opposite to the potential gradient at the mountain top, and the magnitude increased abruptly when the potential gradient there increased beyond 10 volts per centimeter, of either polarity. This suggests that the rain was charged upon approaching the mountaintop surface, by collecting ions caused by corona discharge at the surface. It may be concluded from the above, that the charge carried by rainfall to the earth is entirely negligible.

One significant conclusion seems obvious in the face of the above: Precipitation is not the cause of cloud electrification. Electrification accompanies updrafts, and this updraft continues until the first stroke occurs. At some time during the above process the first signs of precipitation are observed by radar. After some precipitation, with subsequent rainfall, the cloud becomes electrically neutral, and the process is repeated. Of course, if the potential gradient becomes high enough within a cloud or between a cloud and the ground, the resulting breakdown manifests itself as a lightning stroke. It seems highly likely that electrification in the cloud may result in coalescence that, upon repetition, will lead to the fall of rain or some other hydrometeor.

In conclusion, some rather important consequences borne out by the above experiments are listed:

1. No conclusions can be drawn as to the electrical activity within a cloud from external measurements.
2. Rainfall does not bring about electrification within a cloud.
3. Cloud electrification is invariably accompanied by strong updrafts in the cloud. Vertical growth of the cloud, accumulation of positive charge in the upper region, accumulation of negative charge in the lower region are all incidental to the updraft.
4. The cloud electrification in (3) above was also accompanied by a reversed potential gradient at the ground [mountain summit]. When the reversed potential gradient reached 10 volts/cm., corona discharges were observed at a number of places. It will be recalled that fair-weather potential gradient indicates the normal negative-charge distribution at the ground. The reversed gradient indicates that the negative charge is now above [in cloud base].

It should be noted that the theories of Chapter II agree very closely with the experimental findings as outlined in the present chapter. It may be well to mention that the theories of Chapter II were developed in the early nineteen-fifties, whereas the experiments described above were conducted in 1957. The two were quite remote in both time and location; hence we may assure ourselves that the presently accepted theories are accurate to a considerable degree.

We are now in a position to attempt to apply some of these theories in an effort to learn more about the giant thunderstorm, or tornado. There appears to be very little known about the tornado, except its awesome capabilities. In the next chapter we will gather some of the salient properties of this phenomenon, and the rest of this dissertation will be devoted to a chronicle of all information that can be gathered in the attempt to find the relationship between the common thunderstorm and the tornado.

CHAPTER IV

THE TORNADO

Introduction

Our attention will now be directed to what is believed to be the result of an overgrown thunderstorm, the giant thunderstorm, or tornado.

There is relatively little in the way of published material of a technical nature about the tornado. Much has been compiled from eyewitnesses of these. An excellent collection of these reports, as well as much data of a statistical nature, is contained in Flora's book (1953). This book is highly recommended for the non-technical reader.

The reports mentioned above, because of their many consistencies, lead us to the conclusion that the thunderstorm and the tornado have some properties in common. Although technical data are scarce, some of it, as described in a later chapter, leads us to further generalizations as to the formation and behavior of the tornado. This chapter will be devoted to a descriptive and technical discussion, and some novel theories will be described in an effort to obtain a better understanding of the nature of the tornado.

Properties of the Tornado

The destructive properties of the tornado are regretfully known to many. Fortunately, most tornadoes are never seen, since few descend to the ground, where they perform their destruction. Although many have seen photographs of a tornado and some have witnessed the real thing, a most excellent photograph of a very large and destructive tornado is reproduced as Figure 4.1. The visible portion of the tornado is its funnel, at the base of which maximum destruction occurs, and the cloud base, or lower region of the cell, which contains the mechanism, whose action will be described shortly.

Although the only portion of the tornado between the cloud base and the earth that is visible is the funnel, winds of very high velocities exist a mile or more around it. The powerful suction of the funnel draws air along the earth towards it; this accounts for considerable damage done when tornadoes pass a mile or more away from a given point.

In addition to almost total destruction where the funnel passes, there is considerable damage done where structures literally explode, because of the difference in pressure between the inside and the outside. As the tornado passes by, the atmospheric pressure drop because of the suction of the funnel is very large, with the obvious result. Brick structures relying on the walls to support the roof are particularly dangerous.

After a tornado has passed, reports invariably indicate a burned smell in the atmosphere. Frequently, grass shows evidence of scorching, and holes several inches in diameter and several feet deep are traceable, with little doubt because of tornadic action.

Observers also report tongues of St. Elmo's Fire several feet high along the ground in the path of the funnel. Flora gives reports from observers lucky enough to have actually looked up into a tornado funnel and survived. It appears that almost invariably the column of gases in the funnel is highly luminescent, as in a gaseous conducting tube. Fliers report a very extensive sea of fire above the lower level of clouds near

Figure 4.1. The first known photo made of a tornado on May 12, 1896, five miles north of Oklahoma City, O. T.

(Courtesy of the Cunningham Collection)

the funnel. As to the size of tornadic cells as compared with those of the common thunderstorm, Vonnegut and Moore (1958) report that the altitude of the cloud top is 20 km and above for the former, as compared with about 10 km for the latter.

Considerations of Energy

The power, or energy expended per unit time, for a tornado is enormous. One immediately wonders: Where does the energy come from? What physical process or processes start a tornado? What makes some of them descend to the ground and wreak destruction? Many of these questions have gone unanswered for many years and have occupied the minds of brilliant workers in the field of atmospheric electricity. The writer will attempt to construct a set of theories and devices which may aid in further understanding the tornado; the strength of these theories of course rests upon the validity of those presented in previous chapters.

In view of all the observed facts related to the behavior of the tornado, the writer is compelled to believe that a very strong electrical activity invariably accompanies it, especially during the destructive phase of its life. There appears to be little doubt as to the origin of the energy stored in the tornadic cell. Thermodynamic conditions of the atmosphere near the earth, if of the proper relation, may bring about updrafts leading to the formation of a thunderstorm cell. This cell may remain in a static condition for some time before any electrodynamic action takes place. Now, if one considers the Principle of Similitude, familiar to the student of electric fields and electrostatic geometries, he knows that, if all quantities and dimensions of a given electrostatic situation increase in the same ratio, the properties and field configurations are unchanged. Thus a thunderstorm cell may increase several times in size and charge magnitude, and the electric fields within it will remain unchanged, although an observer from outside is well aware of these changes. The energies involved, of course, vary as the square of the charge magnitudes; hence enlarged thunderstorm cells may contain many times more energy than the ordinary-sized ones. These remarks accompany the postulation that a tornadic cell originates in the same manner as ordinary thunderstorms, except that some condition allows them to grow much larger and thus store up huge quantities of electrical energy. The source of this energy is, of course, the sun.

A consideration of some of the figures quoted in Chapter II on the energy expended in a lightning stroke convinces one of its enormity. If one considers the great size of the tornadic cell, he realizes that, if the stored electrical energy is converted to mechanical energy of air-mass movement in a relatively short time, enormous power is developed. Anyone witnessing the after-effects of a tornado is fully convinced of the fact behind this statement.

The task at hand is to attempt an explanation of the energy transduction process. A slight digression will be made to bring forth the mental picture of a typical steam plant for the generation of electric power. Picture the energy input: trainloads of coal or oil, or a very large high-pressure gas line, carrying potential chemical energy to the plant. Picture also the huge boilers, many of them comparable in size to a sixteen-story building, whose task it is to convert the fuel's chemical energy into heat energy. Picture also this energy being fed into a turbine, minute in size compared to the boilers, whose task is to convert the heat energy into mechanical energy. Next, picture the electric generator, still smaller than the turbine, whose task is to convert the mechanical energy developed by the turbine into electrical energy. Finally, this electrical energy is carried away by the relatively puny wires of a transmission line. The whole system may be termed a sort of thermo-electric transducer of energy. Further, the conversion to electrical energy enables energy to be expended or carried away at a very high time rate and in a relatively small volume of space. One recalls that practically all the destructive action is confined to the path of the end of the funnel.

This whole digression is for the purpose of illustrating the fact that large quantities of energy may be expended at a rapid rate only by electrical means. It need hardly be mentioned, of course, that nuclear processes be excluded from this discussion. To add one more statement in an effort to clarify the above, one may mentally compare the sizes of a steam engine and an electric motor of modern design for a given amount of mechanical power output.

In the light of the above discussion, it is the writer's firm belief that the energy stored in a tornadic cell is expended by electrical action. In a common thunderstorm the energy is expended in ionizing a discharge path and in the subsequent heating of the surrounding air column. In a tornado large quantities of energy are converted to mechanical energy of air motion. In this study an attempt will be made to explain how this may happen.

Among students of this problem there is considerable difference of opinion as to the true nature of the tornado, i.e., whether it is a manifestation of purely thermodynamic or partly thermodynamic and partly electrical processes.

Gunn's (1956) article and later correspondence relative to it by

Vonnegut and Moore (1957) offer excellent examples of arguments in connection with the statements made in the last paragraph.

An Approach to Tornado Analysis

In Chapter II Schonland's oscillograms of the radiated electric field were reproduced in a time relationship with a sketch of a lightning stroke made from a Boys' camera photograph. From the accompanying deductions much is learned as to what is going on electrically. Now, in Chapter III one of the conclusions reached was that no reliable information as to electrostatic action within a cell can be obtained from measurements made from without. This is true for some distance from the cell, but, as will be shown in the next chapter, much may be learned about internal action within the cell if measurements are made sufficiently near a point directly beneath the cell.

Since one obviously cannot make measurements on a tornado, he may approach the problem by a consideration of the fields about a tornado, particularly those near it. In the next chapter will be outlined those principles of electrostatics and electromagnetic radiation that may aid us in further development of the theory of thunderstorms and tornadoes.

It will be borne in mind that meteorological theory will be minimized; the writer postulates that after the formative stage tornadic action is purely electrical; further meteorological processes are carried on by electrical means.

Sferics

Although a more detailed discussion will be given later, it is necessary to discuss briefly the electromagnetic radiation from electrical disturbances in the atmosphere. Those due to electrical storms are commonly known as sferics. For many years workers in the field of atmospheric electricity have been able to localize electrical storms by the use of radio direction-finders. It has long been known that the radiation from a lightning stroke has a high energy-content at 10 kilocycles; carefully-designed direction-finders operating at this frequency have been most useful in the study of electrical storms as to intensity, locality, and frequency of occurrence.

More recently, however, it has been found[1] that tornadoes possess a radiation characteristic such that a high energy is radiated at a frequency of 150 kilocycles. It should be pointed out, however, that sferic radiation at this frequency is not restricted to tornadoes; cloud-to-cloud discharges, for example, radiate prominently at this frequency. The reference given describes in some detail the work of Dr. Herbert L. Jones and associates at Oklahoma State University, who have perfected highly successful methods of tornado tracking by direction-finders in the 150-kilocycle portion of the spectrum.

This group discovered two distinguishing properties of sferics radiated from tornadoes: (a) strong radiation at 150 kilocycles, and (b) this radiation is in pulses recurring at the rate of about 30 per second and higher. This latter property has led the writer to the concept of another mechanism that may explain tornadic action.

A Possible Mechanism of Tornadic Action

As has been mentioned previously, a cloud-to-cloud discharge has

---

[1] H. L. Jones, Report in Proceedings of the Second Conference on Atmospheric Electricity, New Hampshire, 1958, Recent Advancements in Atmospheric Electricity (New York, 1958), pp. 543-556.

been many times observed to radiate energy at 150 kilocycles. This is, of course, pulsed, but the recurrence rate is low. The distinguishing feature of tornadic sferics is a sustained train of 150-kilocycle pulses at the recurrence rate of 30 or more per second. This obviously suggests that a tornado may be a repetitive phenomenon; more explicitly, that a rapid succession of electrical discharges are involved. This idea has prompted the writer to organize a theory of tornadic action based on oscillator theory. An oscillating electric circuit, for example, consists of a device which is capable of storing energy of one type, such as a coil storing magnetic energy, and another device capable of storing energy of another type, such as a condenser storing electric energy. If these are connected so that energy may be transferred from one to the other by means of the flow of electric current, this electric current may be said to be oscillating. A similar phenomenon is possible in mechanical systems, such as the vertical motion of a mass suspended by a spring, an inertial wheel oscillating about an axis, as in a watch or clock, and countless others. It is also well known that if energy is continually supplied to an oscillating system, and the physical properties of the system meet certain requirements, that the oscillations may build up in amplitude to the extent that the system will run away, resulting in its self-destruction.

The writer will attempt to show here a possible means by which a tornado may be described as an electromagnetic oscillator.

Figure 4.2 is a schematic diagram of a thunderstorm cell in which a discharge is taking place within it. We assume here that the discharge consists in the flow of negative charge and proceeds from the negative column to the positive layer below. The conventional current is upward, and the magnetic flux lines are clockwise, /looking upward from the

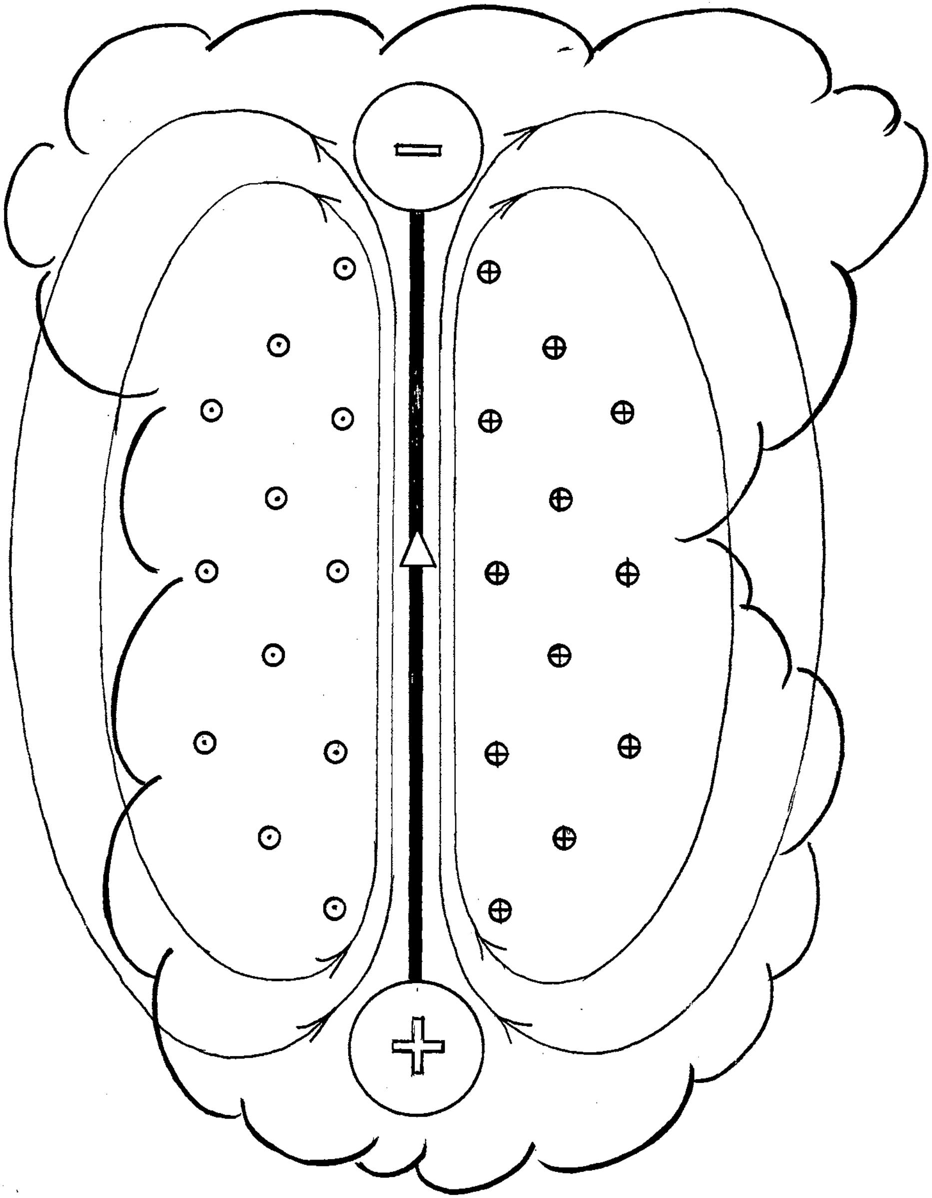


Figure 4.2. An electromagnetic model of the tornado oscillator. The crossed and dotted circles represent the sense of magnetic flux lines, and the loops show the orientation of electric lines of force when the discharge current is decreasing.

ground[7]. When the discharge current is increasing or decreasing, lines of electric force surround these magnetic flux lines. Clearly, when the discharge current is decreasing, the lines of electric force near the center of the discharge path are such as to force positive charges upward. Now, since the discharge follows a heavily ionized path, the decreasing discharge current brings about an updraft of these positive ions creating a partial vacuum near the base of the cell. This results in the drawing upward of air near the base of the cell, which may recharge the cell by the charge-separation process described in Chapter II. We note here that the electrostatic energy is converted to magnetic energy by virtue of the discharge. This magnetic energy is converted to electrical energy, part of which is converted to mechanical energy of vertically-upward air motion. If the above process takes place where there is plenty of cool, moist air below the cell, the above charging and discharging process may become repetitive at a rapid rate, with updrafts below the cell becoming increasingly stronger. If the suction near the base is strong enough and the air below sufficiently cool, moist, and dense, the cell may pull itself down to the ground where the suction may have destructive effects at the earth's surface.

The writer is well aware that the above is a simple explanation of a doubtlessly highly complex phenomenon when one considers the many factors involved such as terrain, temperature, humidity, and so on; but it is a highly plausible one in the light of energy transduction considerations made earlier in the chapter. Further, the above explanation may be seen to agree with all of the associated phenomena that have been observed in connection with tornadoes.

One further question may be raised: How are the funnel and twisting effects accounted for? It is highly likely that these are merely incident to tornadic action. As shown in hydrodynamics, a localized flow within a homogeneous fluid results in the familiar whirlpool; the resulting constriction of the updraft will cause an increased density or concentration of debris, thus resulting in the visible funnel.

The above is meant to be a departure from other theories that put tornadic action on a purely meteorological basis and exclude all notions of an electrical theory. It is hoped that further investigation will bear fruit in supporting the above electromagnetic theory of the tornado. Work in connection with the remainder of this investigation will be directed to this end.

CHAPTER V

SOME FIELD CONSIDERATIONS

Introductory

Up to this point an attempt has been made to organize a coherent sequence of theories that agree a little more than reasonably well. The rather dry descriptive material is necessary if one is to have a logical foundation upon which he may build further theories. The reader must certainly agree that the usual trend in progress is to use ideas and theories borrowed from earlier workers and either to disprove them or put them to use in the advancement of new applications or further development.

The object of this chapter is to use these previously developed ideas and to apply mathematical methods that will perhaps lead to a better understanding of the electrical nature of thunderstorms.

The Electrostatic Dipole

It will be assumed here that the reader is somewhat familiar with electrostatics. Anyway, he may refer to any of the many texts published in recent years, whose clarity brings this subject within easy reach of anyone reasonably well trained in mathematics at the undergraduate level.

The potential at the point P in Figure 5.1 is easily shown to be[1]

---

[1] J. A. Stratton, Electromagnetic Theory (New York, 1941), p. 175.

$$V = \frac{Ql\cos\theta}{r^2} \qquad (5.1)$$

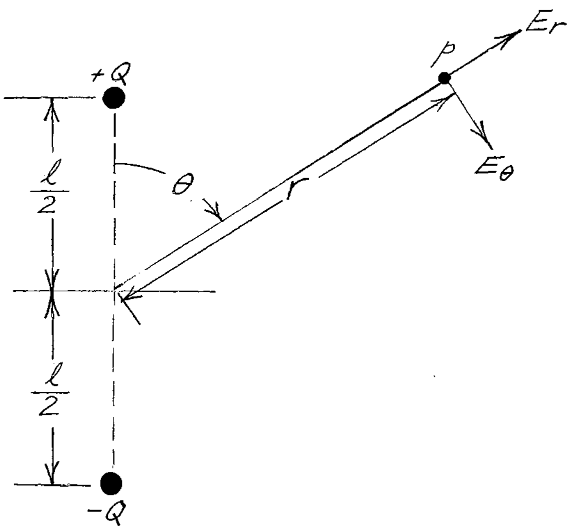


Figure 5.1

Now, recalling that the electric intensity is the negative space derivative of the potential gradient, one may write, using spherical coördinates,

$$E_r = \frac{Ql\cos\theta}{2\pi\epsilon r^3} \quad ; \quad E_\theta = \frac{Ql\sin\theta}{4\pi\epsilon r^3} \qquad (5.2)$$

One notes here that, if he is interested in the component of electric intensity in a plane normal to and bisecting the axis of the dipole, he sees that the r-component vanishes, and the component normal to this plane, E_θ, becomes

$$E_\theta = \frac{Ql}{4\pi\epsilon r^3} \qquad (5.3)$$

Now, applying the image method, one may pass a conducting plane where the hypothetical plane considered above is, and the negative Q may be removed without disturbing the field above the plane.

Thus if one has a charge Q above a conducting surface such as the earth, he may compute the normal component of electric intensity at the earth's surface by the expression just obtained. Note that r is the distance measured from a point on the earth directly below the charge. Note also that, if the charge Q above the earth is negative, then the electric intensity is upward.

Recall now the theory of the air-earth condenser as described briefly in Chapter I. In fair weather condition the electric intensity at the surface of the earth is vertically downward. In Chapter II it was pointed out that in a thunderstorm cell there is a large negatively charged region near the center of the cell, with a small positively charged region near the base. Far above, the rapidly rising top of the cell contains a positively charged region. The experiments described in Chapter III verify this. One may, then, postulate with reasonable accuracy that the electric field caused by the thunderstorm cell [before it reaches the active stage] is due mainly to the negatively charged core of the cell.

One is now in a position to describe the behavior of the electric field below a thundercloud as it is being formed. First, the electric field has the fair-weather or negative value. The opposite field caused by the formation of the cell soon brings this to zero. Further increase in the magnitude of the negative core results in the electric field at the earth becoming reversed. It appears certain, then, that no lightning strokes will occur until after the field at the surface is large and is the reverse of the fair-weather value.

As to the behavior of the electric field at points away from beneath the thundercloud, one recalls that the field caused by the cell is inversely proportional to the cube of the distance. It may be expected, then, that the fair-weather value of the field will vary slightly, if at all, unless one is fairly near a point below the cell. It would appear, then, that electric-field measurements, unless made very near a point beneath the cloud, can reveal little or nothing in the way of knowledge as to the electrical processes within the cell. It will be recalled that this is one of the conclusions reached experimentally as described in Chapter III.

Quasi-static Fields

If a charged body lies in the atmosphere, it will soon discharge because of the conductivity, as described in Chapter I. The situation is analogous to a capacitor discharging through its own leakage resistance. Here one speaks of time constant as that time required for the condenser to lose 63 percent of its charge. For charged bodies in the atmosphere the term relaxation time is used. This time varies considerably with altitude, being longest at the earth's surface.

One now defines the quasi-static state as that in which changes take place very slowly in comparison with the relaxation time. One may state more simply that the quasi-static field is that governed by the laws of electrostatics. This will become clearer when one studies the fields caused by the non-quasi-static state, i.e., for more rapidly-changing dipoles.

The Non-quasi-static State; Induction and Radiation Fields

One may easily see the relation between a current element or current dipole and the static dipole of Figure 5.1 by noting that, if some of the charge Q can combine with -Q, then the dipole strength Ql is reduced by the amount of the displaced charge. This displaced charge, of course, represents an electric current. It follows, then, that the current dipole is equal to the time rate of change of the dipole moment:

$$\frac{d}{dt}(Q\ell) = \ell\left(\frac{dQ}{dt}\right) = \ell I \qquad (5.4)$$

where lI, or more appropriately Idl, is called the current dipole.

In the thunderstorm, quasi-static fields exist around the cell during the buildup, but at the time of the intra-cloud and cloud-to-ground discharges there are time-varying magnetic fields caused by the time-varying current.

It is clear that the variation of current with time for a lightning discharge would be a very complicated one, but for the purposes of this discussion one recalls that an arbitrary function of time may be converted to a function of frequency by the Fourier-Integral Transformation:

$$I(\omega) = \frac{1}{2\pi}\int_{-\infty}^{+\infty} I(t)e^{-j\omega t}dt \qquad (5.5)$$

There is, of course, an inverse transformation, but for purposes of this discussion the mere fact that such a transformation is possible suffices. This means that for a given I(t), one may think of a continuous spectrum of sinusoidally-varying currents acting simultaneously and producing the same field as the original time-varying current of arbitrary shape. These remarks go a long way toward simplifying this discussion, for one may reason in terms of a simple current dipole of the form $I_0 \sin \omega t \, dl$, and then the overall phenomenon is made up of the contributions of all of the current-dipoles obtained from equation 5.5.

One now considers the magnetic field about a short current dipole, as illustrated in Figure 5.2 below:

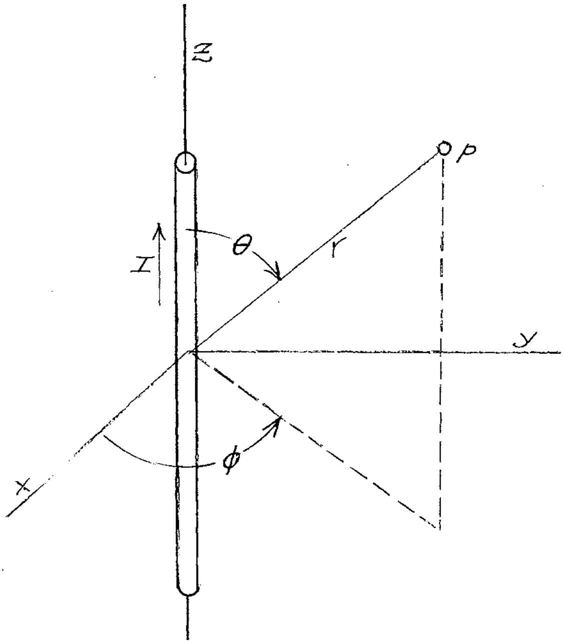


Figure 5.2. Current-carrying element or current dipole.

It is not the object of this discussion to develop electromagnetic relations, so that only a brief outline will be given here. For the details the reader may consult the references given.

It has already been shown that a current-dipole may be expressed as the time derivative of an electric dipole. If this time derivative is a constant, of course, there is a steady current, which sets up a steady magnetic field about the dipole. If the current changes, however, the effect of the change is not immediately manifest at a distance r from the wire, but the effect is delayed by an amount r/c where c is the velocity of propagation, shown by Maxwell to be equal to the velocity of light in free space.

For the field away from the dipole, then, instead of using the current $I = I_0 \sin\omega t$, one uses the retarded current $[I] = I_0 \sin\omega[t - r/c]$, which may also be written $[I] = I_o \exp j[\omega t - \beta r]$, recalling that $\beta = \omega/c$.

Referring to Figure 5.2 above, one is interested in obtaining a general expression for E_θ, i.e., the electric field normal to the radius vector drawn from the center of the dipole to the point P. Further, since one is interested only in this electric field at the surface of the earth, he may take the angle θ as 90°.

Since one knows the relationship between the current and the electric dipole, he can easily obtain the scalar potential V at any desired point. Further, he may set up the retarded vector potential A[1] at this point, after which he employs the relation

$$E = -\nabla V - \frac{\partial A}{\partial t} \qquad (5.6)$$

which is the general expression for the electric field in terms of the scalar and vector potentials.

The steps[2] from here to the final result are rather cumbersome, but the details are straightforward. The interested reader, unfamiliar with these steps, should consult the indicated reference.

The result is the general expression

$$E_\theta = \frac{I_o l \exp j(\omega t - \beta r)}{4\pi\epsilon_0} \times \left(\frac{j\omega}{c^2 r} + \frac{1}{c r^2} + \frac{1}{j\omega r^3}\right) \qquad (5.7)$$

for the electric field at the earth's surface $[\theta = 90^\circ]$.

The three terms of this equation are highly significant and may be

---

[1] J. D. Kraus, Electromagnetics (New York, 1953), pp. 195, 486.

[2] Ibid., pp. 492-499.

written thus:

$$E_\theta = \frac{j\omega I_0 \ell \exp j(\omega t - \beta r)}{4\pi \epsilon_0 C^2} \cdot \frac{1}{r} \qquad (5.8)$$

$$E_\theta = \frac{I_0 \ell \exp j(\omega t - \beta r)}{4\pi \epsilon_0 C} \cdot \frac{1}{r^2} \qquad (5.9)$$

$$E_\theta = \frac{q_0 \ell}{4\pi \epsilon_0 r^2} \qquad (5.10)$$

Equation 5.10 is recognized as Equation 5.2, which is that of the quasi-static electric field, i.e., the field for the case when $\omega = 0$.

Equation 5.9 is an expression recognizable as the familiar Amperes' Rule for the current dipole. As r increases, this member of the general expression for E_O diminishes less rapidly than the quasi-static member. Also, this member has an amplitude which is independent of frequency. This is the familiar induction field, the energy of which is alternately propagated away from and back to the current dipole but the average energy of which is zero. This is analogous to reactive power in alternating-current circuit in the steady state.

Equation 5.8 is the term which commands great interest if one is concerned with radiated energy. If one calculates the energy in a thin sphereical shell of radius r about the dipole, he finds it to be independent of r, which means that energy is radiated outward, never to return. He notes further that this member, being inversely proportional to the first power of r, is the greatest of the three for a given distance. He sees further that its magnitude is directly proportional to the angular frequency ω. These are the important properties of this member, which we call the radiation field and to which we shall frequently refer as we progress in this investigation.

It must be borne in mind that these three equations are for a short current element--the total field for a given current configuration is the sum of the fields at a given point because of each current element considered. As is well known to workers in the fields of antennas, if the distribution of current in an antenna is known, the field at a point is the integral of the fields because of an infinite number of very short current dipoles. This, of course, applies for a single frequency under consideration.

One still has another sum idea involved: As was shown above, the current as a function of time was converted into an infinite number of sinusoidal currents, each of different magnitude and frequency.

For each frequency component, then, there is an electric field radiated that is the overall result of the time-varying current for that frequency. Now, at that point, there is an electric field that is equal to the sum of the electric fields of all of the many frequency components that existed in the original time-varying current.

Just as one used the Fourier-Integral transformation to convert a current from a time-function to a frequency function, he may perform the inverse operation of transforming the frequency components of the electric field at a given point into an electric field which is a function of time.

One may now compare the electric fields at two distinct points on the earth's surface for a given source, i.e., for a given lightning discharge, for example. The shape of the wave form of the electric field is determined by the magnitude and distribution of its frequency components. We have shown above that the radiation component is directly proportional.

to frequency and inversely proportional to distance. Thus, at two distinct points one may expect each frequency component to be different because of the inverse-distance relationship. Then, the waveform for a constant distance from the source will not change but will change with distance.

This radiation from atmospheric electrical phenomena is given the name sferics, an abbreviation for the expression atmospheric disturbances. These have, for many years, commanded the attention of workers in this field. Since it is generally known that ground waves encounter small attenuation in the process of propagation when the frequency is low, the lower-frequency components of spherics are detectable at great distances. Furthermore, since the radiation from a lightning stroke is propagated in all directions, one may expect considerable sky-wave propagation at some of the higher-frequency components. Of course, the sky-wave spheric and the ground-wave spheric will not arrive at the observer's location at the same time, a fact further complicating the process of analysis or of finding a common-denominator of these sferics which will aid in determining their direction and possibly the distance of their point of origin.

These last considerations actually lie outside the domain of this writing, since the objective is to study the near-fields of tornadoes and thunderstorms and to try to learn more of their electrical origin and behavior.

CHAPTER VI

MEASUREMENT OF THE QUASI-STATIC ELECTRIC FIELD

Introductory

In the foregoing chapters, the writer has attempted to stress the importance of knowing the behavior of the quasi-static electric fields about thunderstorms, if one seeks to find out about the electrical behavior of the cells themselves. In this chapter, methods of electric-field measurement will be considered in detail.

This problem of measurement has many solutions, i.e., many methods[1] have been used to measure atmospheric electric fields. For our purpose we need to know magnitude, polarity, and variations that require from about 0.1 second to 10 seconds or more to take place. We find from the literature that there is no single instrument yet designed that is capable of indicating both extremely slow, and fairly rapid variations. Thus, a decision was made to employ two instruments; one for slowly-varying fields, and one for rapidly varying fields, and whose ranges overlapped. In this way it is expected that complete information as to the variation of the atmospheric electric field due to a given thunderstorm cell could be recorded and studied. For the sake of continuity, a brief digression on electrostatic principles will be made so that the operation of the equipment described herein will be most readily understood.

---

[1] J. A. Chalmers, Atmospheric Electricity (New York, 1957), pp. 81-127.

Electrostatic Induction

In Figure 6.1 (a) below, a uniform electric field above a conducting plane, such as the earth's surface, is depicted. In Figure 6.1 (b), a conducting sphere is introduced, and the new configuration of the electric field in its neighborhood is sketched.

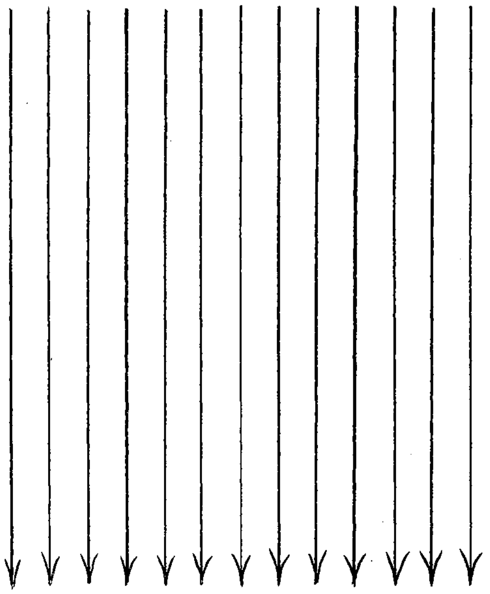


Figure 6.1 (a)

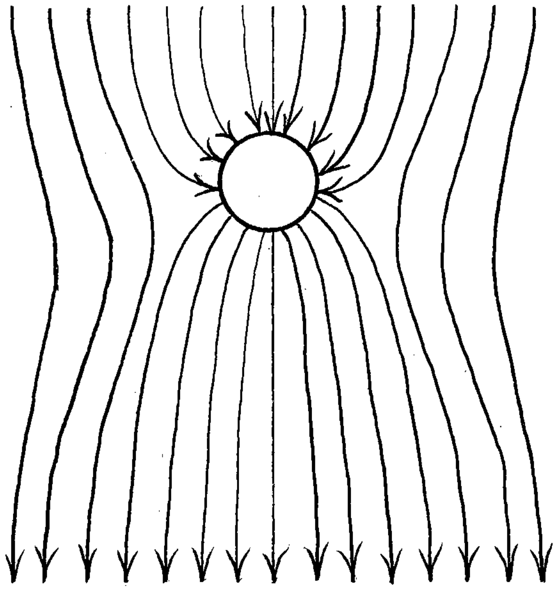


Figure 6.1 (b)

In the case of Figure 6.1 (b), the sphere is said to have a charge induced upon it by the electric field. If one knows the capacitance of the sphere relative to the earth, the electric intensity of the ambient field, and the height of the center of the sphere above the ground plane, the potential to which the sphere has been charged may be easily calculated. If one were to connect the sphere to ground, then we would have a completely different electrostatic situation, and a different charge on the sphere. The changed charge is brought about by the flow of charge in the conductor connecting the sphere to the ground. If the sphere were moved up and down, its potential would change; this situation would be permitted by the flow of a varying electric current in the conductor between the sphere and the ground. On the other hand, if the grounded sphere did not move, but the ambient electric field were to vary, the potential of the sphere would vary; this would again be permitted by the flow of an electric current between the sphere and the ground via the grounding conductor.

The above principle will be employed in both instruments described below, i.e., the electric fluxmeter and the electric probe.

The Electric Fluxmeter

The design and construction of this instrument, while for the most part novel, employs some of the features of one[1] developed some years ago.

The heart of this instrument is a rotating probe as illustrated in Figure 6.2. The probe is a length of straight conductor attached to an insulated hub, which is driven by a motor:

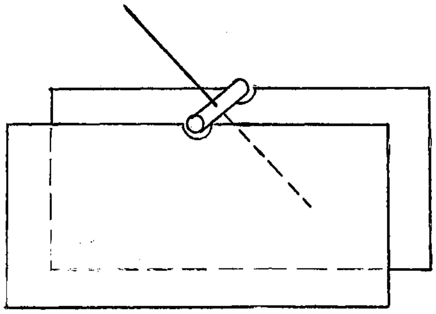


Figure 6.2

---

[1] Ross Gunn, U. S. Patent No. 1919215, Issued June 25, 1933.

The two spokes of the probe rotate alternately in and out of the space between two parallel metal plates that are grounded, so that there is zero electric field in between. As a spoke emerges from this field, it is uncharged, and its charge is increasing as it approaches a vertical attitude. As it continues to rotate, its charge decreases as it again approaches the zero field region between the plates. If a vertical electric field exists above the plates, then, and if the probe and hub are connected to the ground, then two cycles of an alternating current per revolution of the hub will flow through the grounding conductor, since each spoke is active in generating one cycle per revolution. Now if a resistance is inserted in the grounding lead, there will be an alternating voltage developed across it whose amplitude will be proportional to the strength of the ambient electric field. This voltage, of course, will be very small so that amplification is necessary if we are to use meters or indicators of reasonable sensitivities.

If the output voltage of the probe is amplified sufficiently, it may then be rectified and filtered, and the resulting voltage will be directly proportional to the ambient electric field, if the amplifier is assumed to be linear.

It is necessary, however, that we know the polarity of the electric field as well as its magnitude. The scheme described above obviously cannot produce both answers. It may be noted, however, that if the electric field should be reversed, the alternating output of the probe will be shifted 180 degrees in phase. Thus, if we have a reference voltage of the same frequency as the probe output voltage and independent of the electric field, the two may be fed into a synchronous rectifier circuit, whose output will be a direct voltage whose polarity depends upon that of the ambient electric field. The above, in essence, is a brief description of the electric fluxmeter, which will be described here in considerable detail.

The complete circuit is shown in Figure 6.3. The rotating probe and hub assembly are on the same shaft as the induction generator and drive motor. The induction generator, whose function is to provide the reference voltage mentioned earlier, will be discussed in detail in a later paragraph.

The probe is grounded through the R_1C_1 combination, whose time constant is 0.1 second, so that the input to V_1 may follow fairly rapid variations of the probe output without distortion. The tube V_1 and its associated components constitute a conventional cathode-follower circuit. This was intended to preclude any overdriving as would be encountered in a conventional voltage amplifier. Since the fluxmeter must of necessity be operated outdoors, while the recording equipment must be indoors, the mechanical parts plus the cathode-follower circuit are contained in a weatherproof box. The output of the cathode-follower is fed via C_2 to a coaxial cable which leads to the input of the rest of the circuit which is located in a nearby shelter convenient to the operator and recording apparatus.

The switch S_1 across the input to V_2 simulates a zero field condition for purposes of initial adjustment of the recording apparatus.

The output of the interconnecting coaxial cable is connected directly across the attenuator network consisting of R_3, R_4, and R_5. The output of the attenuator is fed to the grid of the high-gain pentode V_2, which in turn, drives the grid of the power amplifier V_3. In the V_2 stage, two feedback paths are used: one is the unbypassed cathode resistor, and the other is an adjustable regenerative feedback loop consisting of R_7 and C_3.

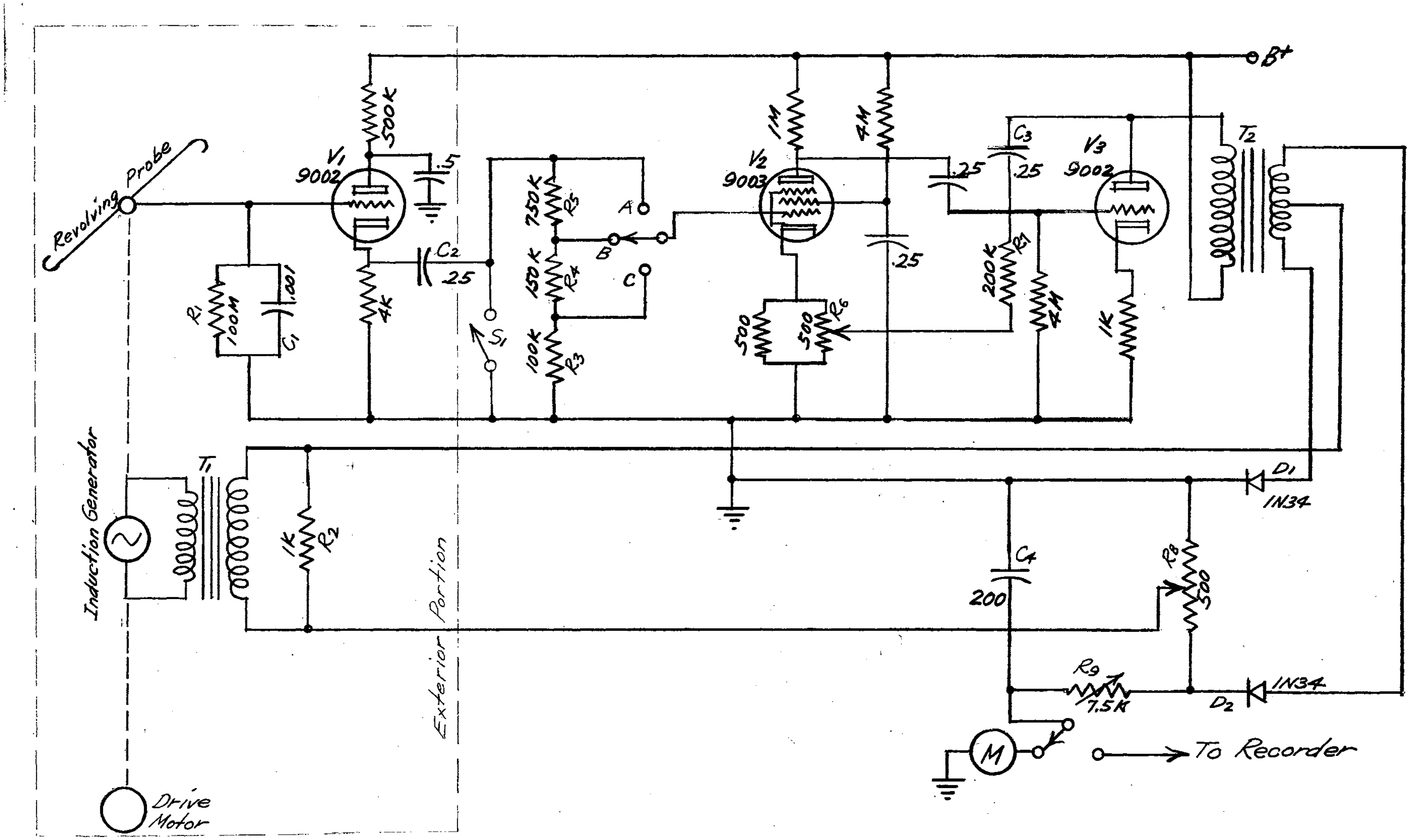


Figure 6.3. Overall Schematic of the Electric Fluxmeter

This provides for an adjustable phase shift so that the output of the amplifier is exactly in phase or 180 degrees out of phase with the reference voltage of the induction generator.

The drive motor turns at about 1500 r.p.m., so that the amplifier is required to amplify a 50-cycle signal. This accounts for the rather large by-pass capacitors used in the circuit. This also requires that the power amplifier output transformer be of good quality, i.e., have a good low-frequency response to give good results. Such a transformer having a center-tapped secondary is rather difficult to find. In this circuit, with the tubes used, a Western Electric type 150 A output transformer was used with excellent results.

The synchronous rectifier circuit consists of the secondaries of T_1 and T_2, the diodes D_1 and D_2, and the potentiometer R_8. The center point of R_8 is to adjust for possible mismatch of the diodes.

The operation of this circuit is as follows: If the ambient electric field is zero, the output of T_2 is zero, and the reference voltage alone is applied to the center-tap of the secondary and the assumed midpoint of R_8. Equal currents will flow in the opposite directions in the two halves of R_8, and the voltage between the ground and the output selector switch input terminal is zero.

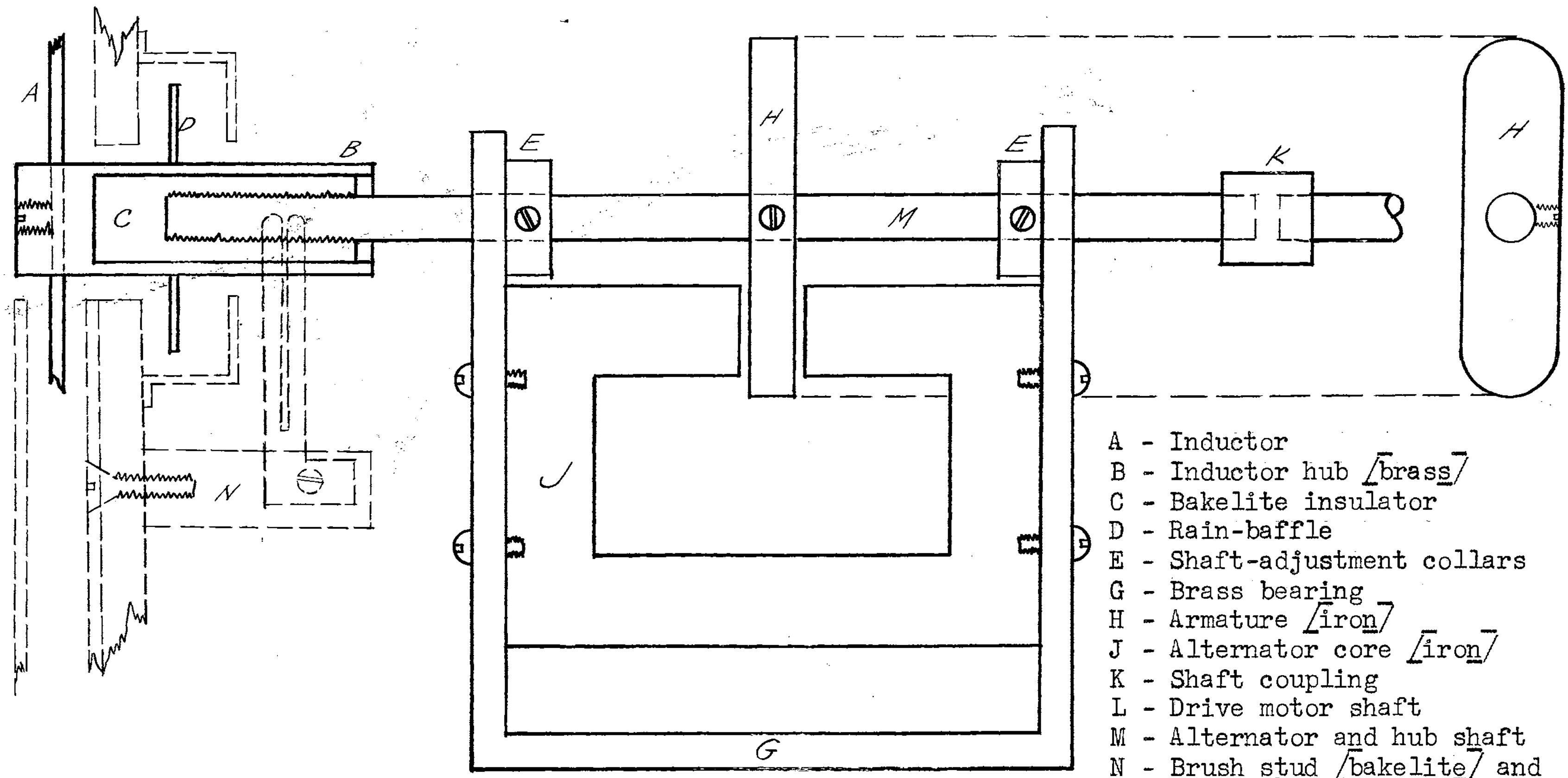
Now, if the ambient electric field is not zero, there will be a voltage across the T_2 secondary which will result in a larger voltage applied to D_1 than to D_2. The result will be a direct voltage at the input to the selector switch. If the ambient electric field should reverse, the opposite of the above statement will be true, with the result that the polarity of the direct voltage at the selector switch will likewise be reversed. The filter for the output consists of R_9 and C_4. R_9 is adjusted for minimum ripple output and minimum time constant, so that as rapid a variation of the electric field as possible may be recorded.

In the design of the fluxmeter, the generator of the reference voltage presented a difficult problem. It necessarily had to be of the four-pole type since the frequency must be the same as that of the amplifier output. It appears that no such generator is available on the market, so one had to be designed and built.

Figure 6.4 is an actual size working drawing from which this generator was built. It is essentially of the variable reluctance type. A C-shaped core was cut from ½ inch soft iron flat stock and 1000 turns of No. 26 cotton-covered wire wound on it. To obtain the necessary two volt output, an inexpensive universal output audio transformer was used. A battery capable of delivering 4 volts at its terminals when connected in series with the magnetizing coil and the low impedance winding of the transformer [T_1] was employed. At the operating speed the output voltage had poor waveform, but initially loading the high impedance side of T_1 with a 1000 ohm resistor restricted harmonic voltages to the high reactance of the transformer winding, with the result that a good sinusoidal waveform existed across the 1000 ohm resistor. If the airgap is kept small, the output of this generator is about two volts crest.

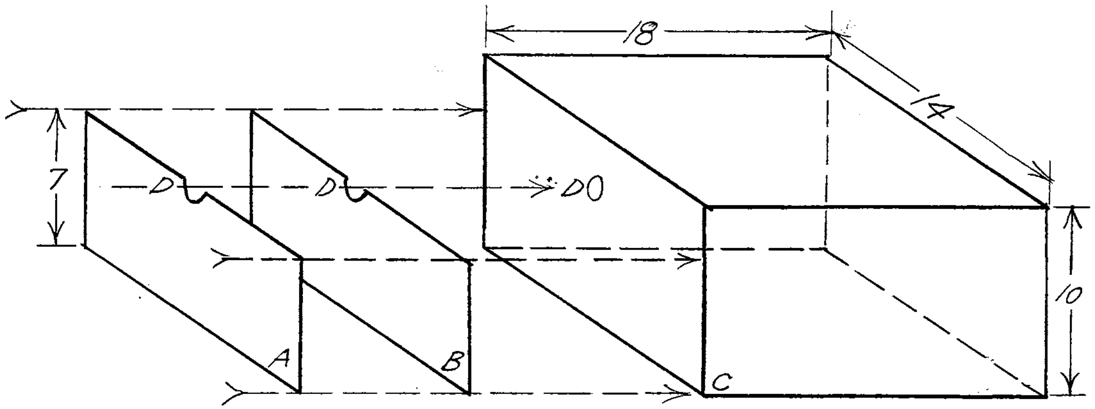
The drawings of Figures 6.4 and 6.5 and the photographs of Figures 6.6 and 6.7 give complete details of the construction of the fluxmeter. A few noteworthy features, however, may be pointed out here:

Referring to Figure 6.4, note the rain-baffle D. This is a brass washer soldered to the hub and enclosed in a hat-shaped housing. If water enters the space between the hub and its clearance, it strikes the rotating baffle, which throws the water against the sides of the baffle



A - Inductor
B - Inductor hub [brass]
C - Bakelite insulator
D - Rain-baffle
E - Shaft-adjustment collars
G - Brass bearing
H - Armature [iron]
J - Alternator core [iron]
K - Shaft coupling
L - Drive motor shaft
M - Alternator and hub shaft
N - Brush stud [bakelite] and brush [phosphor-bronze]

Figure 6.4. ELECTRIC FLUXMETER
Induction Generator, Inductor, Hub
and Rain-Baffle Assembly
[Actual Size]



A - Outer shield, 1/16 inch brass or aluminum
B - Inner shield, 1/16 inch brass or aluminum
C - Box; top and sides 1/4 inch marine plywood, bottom sheet aluminum
D - 7/8 inch hub-clearance holes [must be carefully aligned]

Note: Inner shield to be screwed to box; outer shield separated from inner by 3/8 inch studs soldered to inner. Bases for induction-generator and motor must be secured to metal housing base such that hub is properly aligned with holes.

Figure 6.5. ELECTRIC FLUXMETER
Shield and Housing Assembly

Figure 6.6. Exterior Portion of the Electric Fluxmeter

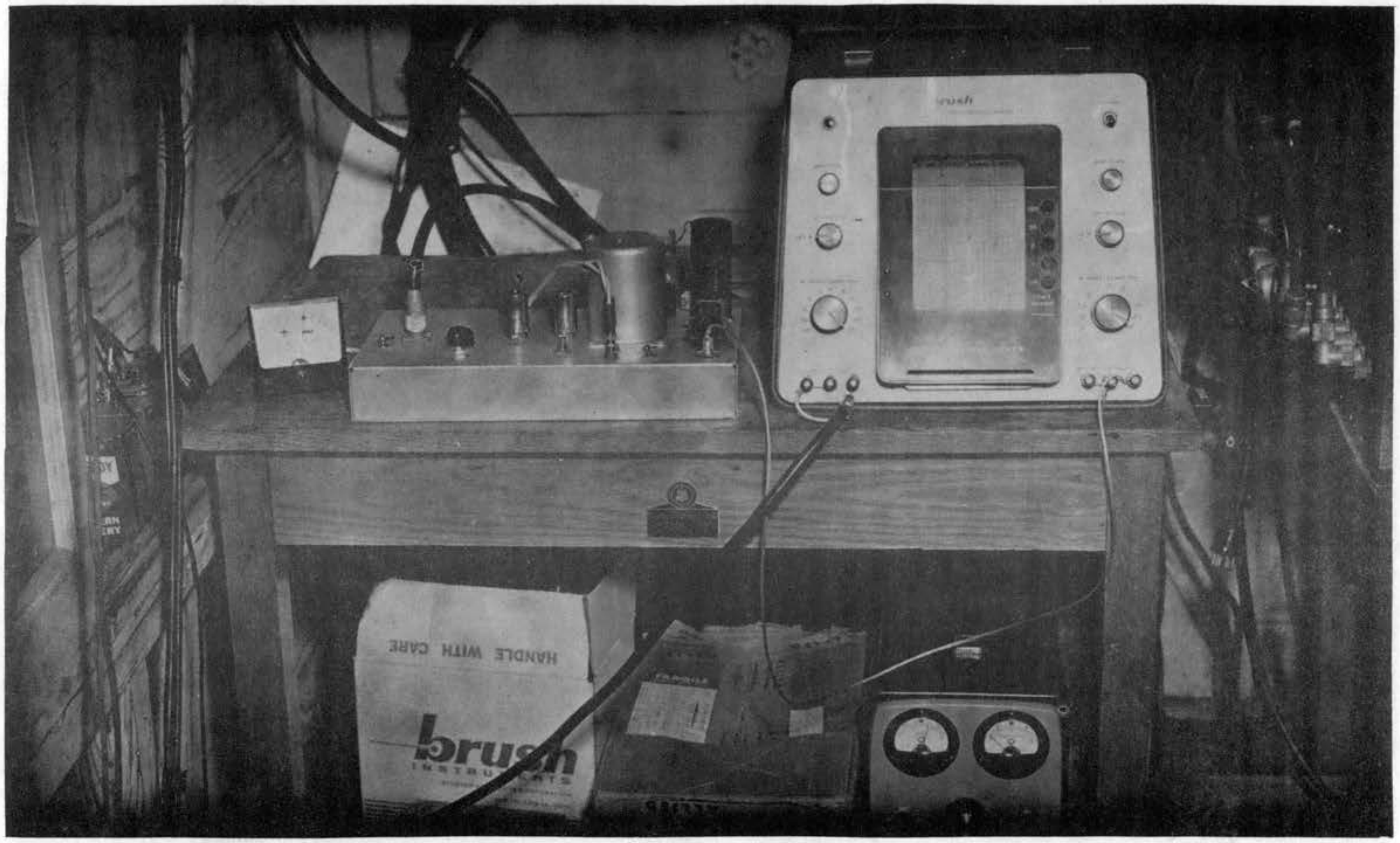


Figure 6.7. Electric Fluxmeter Amplifier and Brush Recorder Setup

housing by centrifugal action. The water then drains off into the space between the shields via a small hole drilled through the inner shield into the lower portion of the baffle housing. Because of this feature the fluxmeter may operate outside in a driving rain without interruption of recording.

With the tubes used, 6.3 volts at .45 amperes are required for the filaments, and 300 volts at 15 milliamperes for the B supply. As previously mentioned, 4 volts at the terminal of the generator circuit are required for the necessary output.

The polarity indication of the fluxmeter may be reversed by changing the polarity of the magnetic circuit supply battery or by changing the position of the armature of the induction generator by 90 degrees. In fair weather we know that the potential gradient is positive. The above factors must be established so that the fluxmeter gives an established positive reading during fair weather.

Operating Procedure

The output of the fluxmeter is recorded in this setup on one channel of a Brush Mark II Recorder. The following procedure is suggested for placing these instruments into operation when construction is completed:

1. Start motor, close battery switch. Place output switch on amplifier in AMMETER position and adjust R_8 for zero deflection of microammeter. This step is done either with amplifier turned off or with S_1 in shorted position.
2. When Brush Recorder has warmed up for 15 minutes, place S_1 in shorted position, output selector in RECORD position and adjust PEN BIAS for zero deflection.

3. The amplifier power supply is now turned on, S_1 placed in open position, and the electric field is now being recorded. If desired, the strength of the electric field may be determined from the calibration curves of Figure 6.8, due attention being paid to the position of the amplifier input attenuator.

Fluxmeter Calibration

The fluxmeter calibration curves of Figure 6.8 were obtained by placing the probe unit in a simulated uniform electric field. This uniform electric field was simulated by use of a parallel plate condenser consisting of two bronze screen plates 4 feet square and 15 inches apart. The fluxmeter was placed so that the probe and hub were at the center of the plates, with the fluxmeter ground securely grounded to the lower plate. The electric field between the plates in volts per meter is thus equal to 3.8 times the difference of potential between the plates. Figure 6.9 shows the calibration setup for the fluxmeter.

It will be noted that contrary to expectation, the calibration curves are not quite linear. It is not known at this writing whether this nonlinearity is due to the fluxmeter amplifier or that of the Brush amplifier. This situation is not serious, since the calibration curves were carefully executed. Also, magnitudes are of small consequence as compared to polarity and variations of the ambient field.

The Electric Probe

The electric fluxmeter described in the preceding sections is capable of measuring and recording field variations of the order of about one-half second, and of slowly-varying as well as constant or non-varying

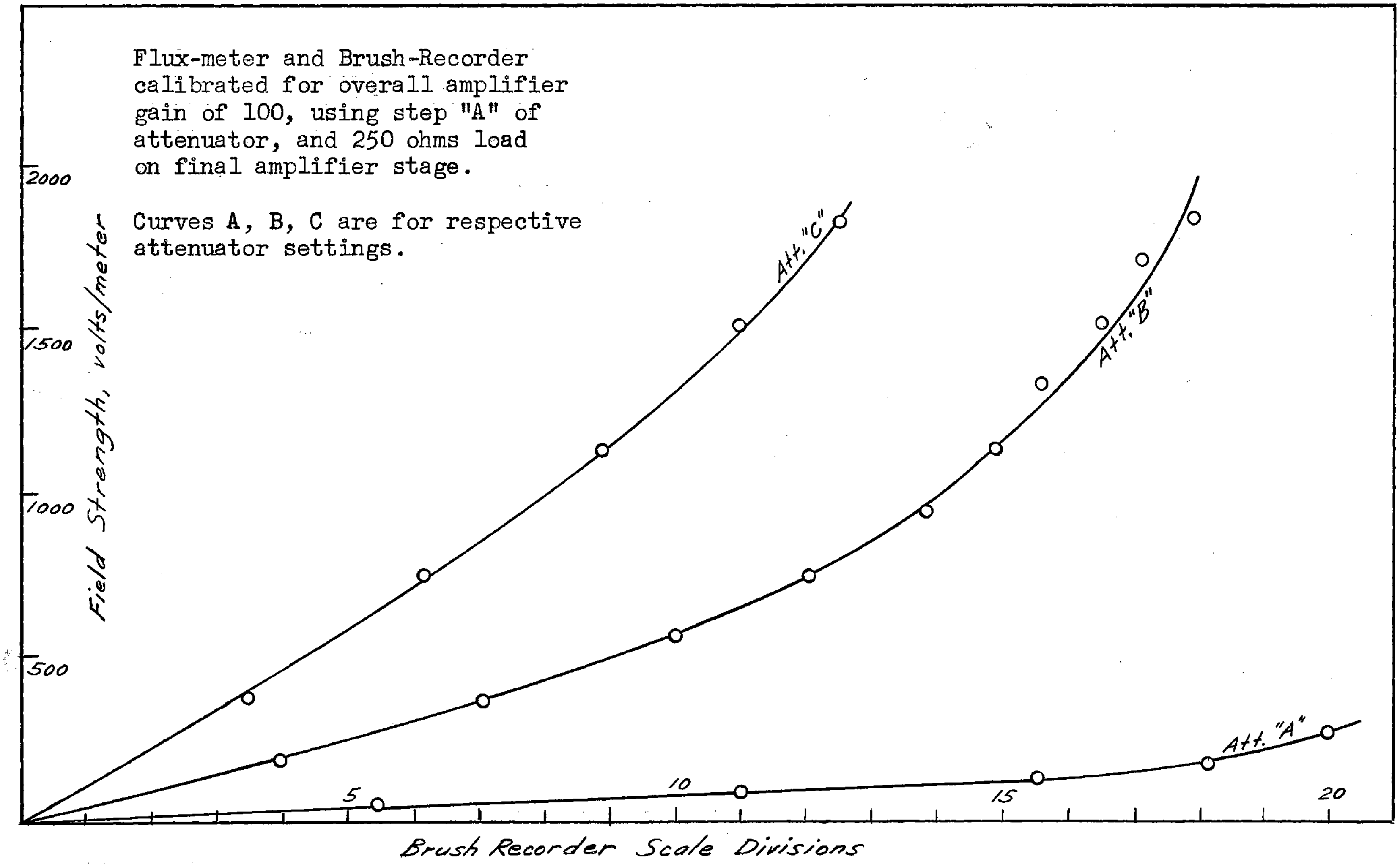


Figure 6.8. Overall Fluxmeter and Recorder Calibration Curves

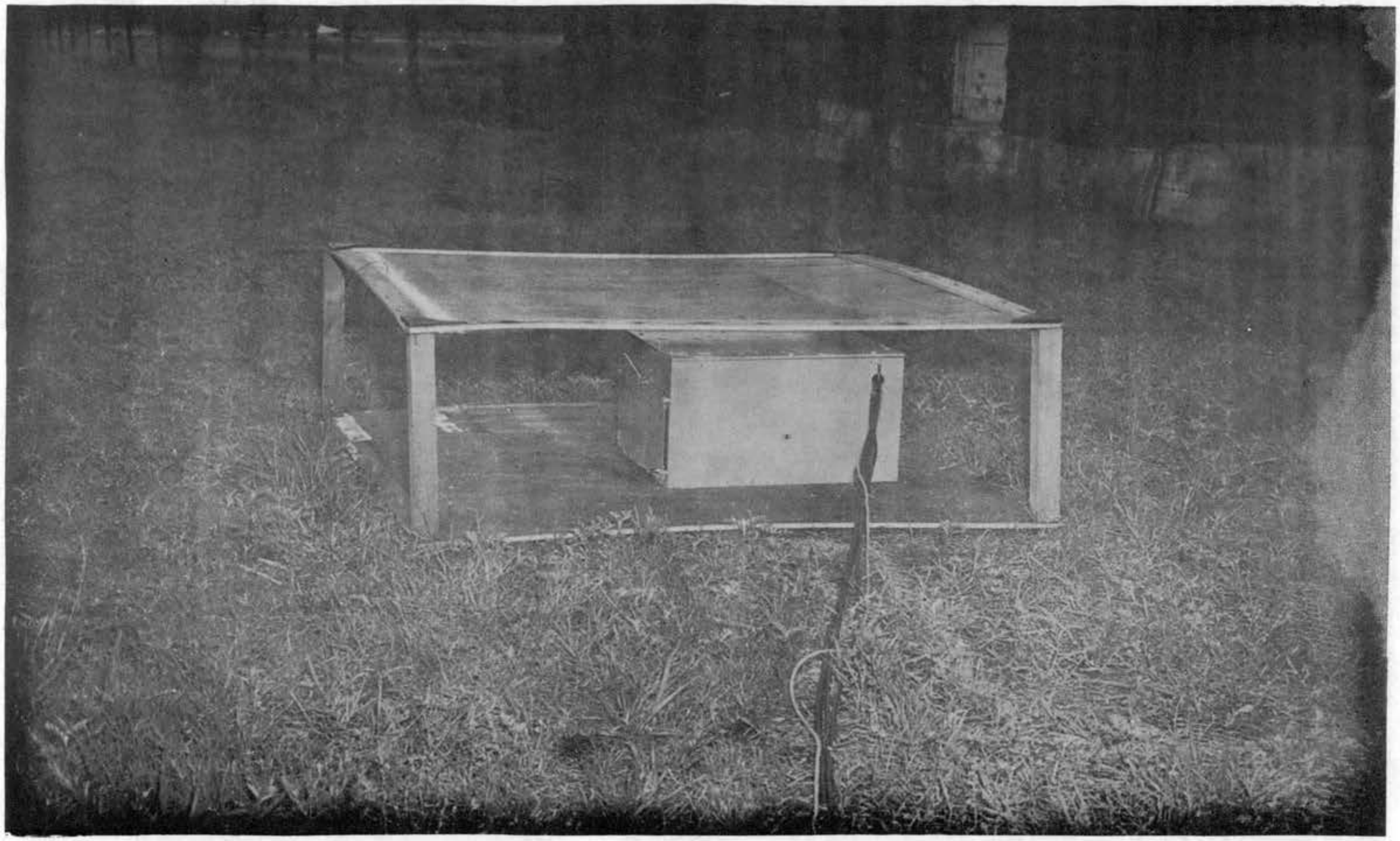


Figure 6.9. Electric Fluxmeter Calibration Setup

fields. This is much too sluggish, however, if one wishes to observe the field changes about a thunderstorm cell that is being discharged by lightning strokes. For this reason, we seek an electrostatic antenna which is capable of recording these rather rapid variations, yet so designed that the electric component of spheric radiations will have negligible effect on the output of the device.

To begin, some of the electrostatic principles discussed at the beginning of this chapter will be recalled. If a metallic body is immersed in a uniform electric field above a conducting plane, and if the body is connected to the plane [ground] by a conductor, then the body will be charged to a potential determined by the capacitance of the body relative to the ground and the strength of the ambient electric field. If this electric field should vary, the potential of the body charged by the field will vary resulting in a flow of current through the grounding conductor.

Suppose that the charged body is grounded via an impedance Z_1, the voltage across which is to vary with time in exactly the same manner as does the electric field. As is well known in alternating current circuit theory, if a sinusoidal voltage is applied to two impedances Z_1 and Z_2 in series, the voltage across the two impedances will always be of the same ratio, regardless of frequency, if these two impedances have phase angles of the same magnitude and sign. Now, the electric field which we desire to observe will be nonsinusoidal and aperiodic, but the Fourier-Integral transform of this field variation contains sinusoidal spectra, each of which will be divided between Z_1 and Z_2 in the same ratio if they meet the conditions specified above. This is the same as saying that the voltage across Z_1 will be a true timewise reproduction of the varying ambient electric field.

To solve our problem we must learn the equivalent circuit of our electric probe, which we will call Z_2, then choose Z_1 so that the required conditions are met. This probe will, of course, have a capacitance to ground. If it becomes charged, it will discharge to the ground because of air conductivity, thus the equivalent circuit of the probe is a capacitance C_2 in parallel with a resistance R_2. The electric field is the generator charging the capacitance; these three elements may be represented as in Figure 6.11(a), the Thevenin Equivalent of which is Figure 6.11(b).

It is now apparent that if the probe is connected to ground via an R_1C_1 parallel combination, and if R_1 and R_2 have the same ratio as the reactances of C_1 and C_2 respectively, then the required condition is met if $R_1C_1 = R_2C_2$, i.e., the voltage across Z_1 will vary in exactly the same manner as the Thevenin Generator of Figure 6.9(b). Further, if pR_2C_2 is large compared to unity, the Thevenin Generator reduces to E, which means that the true variation of the electric field is produced across the impedance Z_1. The whole equivalent circuit is given by Figure 6.11(c).

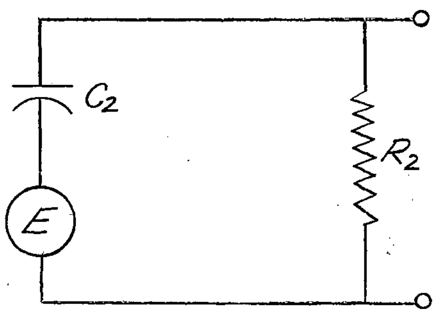
It is now clear that a probe must be chosen such that its capacitance may be easily calculated; further, a good estimate must be made of the resistance of the air between the probe and the ground.

A copper sphere 12 inches in diameter was chosen and placed at a height of 1.5 meters above the ground. The capacitance was calculated[1] to be 17.6 micromicrofarads. The air resistance to the ground has been estimated[2] to be of the order of 5 megamegohms. Thus the time constant

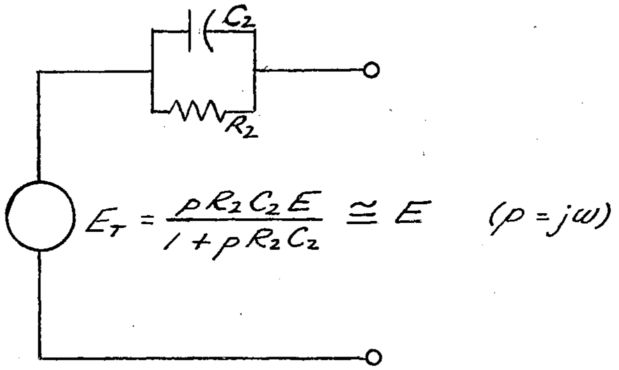
---

[1] N. I. Adams and L. Page, <u>Principles of Electricity</u> (3rd ed., New York, 1958), pp. 87-89.

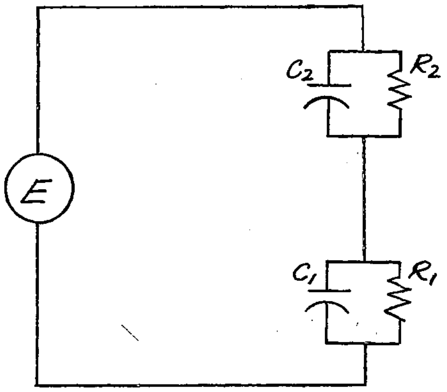
[2] J. C. Johnson, <u>Physical Meteorology</u> (M.I.T., 1954), p. 294.



(a) Equivalent Circuit of Probe Alone



(b) Thevenin Equivalent of Probe



(c) Equivalent Circuit of Probe
and Recorder Input

Figure 6.11

Figure 6.10. The Electric Probe

of the R_2C_2 combination is about 88 seconds.

The output of the probe circuit is connected directly to the input of one channel of the Brush Recorder, the amplifier of which has a DC input impedance of 5 megohms. This input resistance is R_1 of the probe circuit. Thus C_1 must have a value of 17.6 microfarads so that Z_1 will also have a time constant of 88 seconds.

From the above it is clear that we have an attenuation of one million so that the probe will not be a sensitive device. This is not a deterrent, however, since we are interested in the fields of nearby thunderstorm cells, which will be very strong.

A photograph of the electric probe is shown in Figure 6.10.

The output of the electric fluxmeter and that of the electric probe is recorded on the same paper strip of the Brush Recorder so that if variations are too slow for one device they will be shown by the other and vice versa.

The next chapter will contain recordings from the above system, and analyses and discussions appertaining thereto will be given.

CHAPTER VII

MEASUREMENTS AND OBSERVATIONS

On April 27 recordings were begun for a long line squall starting 10 miles southeast of Stillwater and extending southward for about ninety miles. The field strength was at all times negative and did not vary greatly except that strong gusts of wind caused rather sharp increases of field strength in the negative direction. A tracing of the recording for a typical interval is reproduced as Figure 7.1.

Since only fluxmeter recordings are reproduced in the first several illustrations, only the appropriate half of the Brush recording strip is reproduced. Both halves of the strip will be reproduced in later cases where recordings of both the electric probe and fluxmeter are of interest.

No lightning strokes were observed during the time that the line squall was in the area. Incidentally, the skies were clear except for the line squall area.

On the Brush Recorder reproductions, the heavy line along the middle of the strip represents zero field intensity, and near each tracing is the letter A, B, or C, indicating the appropriate attenuator setting. Unless otherwise indicated, one centimeter of length along the strip represents 10 seconds of time.

Figures 7.2 and 7.3 show fluxmeter recordings for a line squall about 12 miles away in which lightning strokes were observed. It will be noted that the field is strongly negative; the fluxmeter attenuator is set on

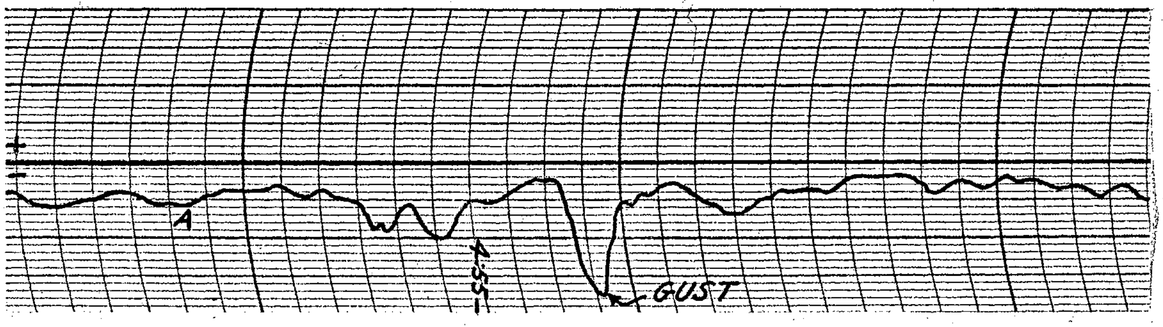


Figure 7.1. Line squall 10 miles away [nearest point]. No lightning strokes observed. Strong negative dips are synchronous with strong gusts of wind.

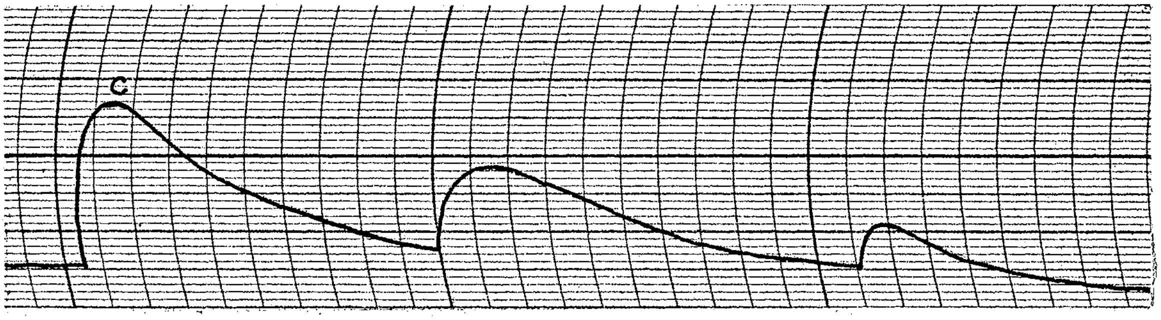


Figure 7.2. Line squall about same distance as in Figure 7.1, except that strokes are observed. This type of stroke is called positive.

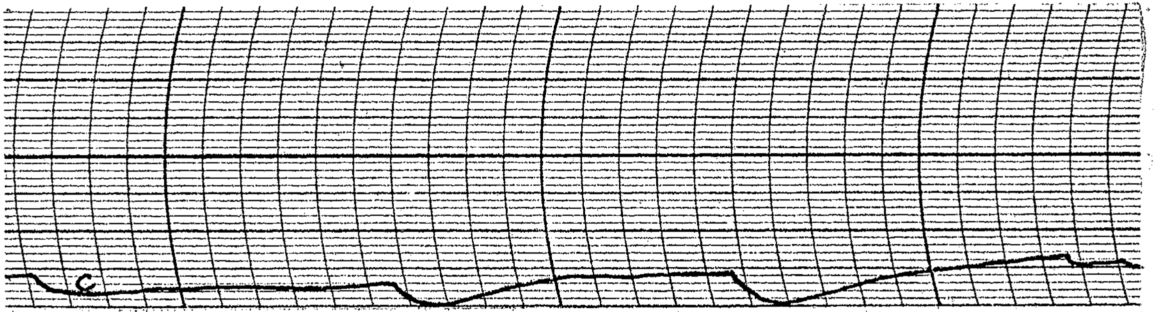


Figure 7.3. Recording a few minutes after that of Figure 7.2. The small dips are negative strokes.

C, and the recorder deflection is almost full-scale. In Figure 7.2 three strokes are shown. The negative field is presumably due to the dipole of the large negative column in a cell, and a stroke [or series of strokes in rapid succession] discharges the negative column partially. In between these the cell recharges, and the process repeats. This type of stroke will be called a positive one, since this is apparently the most common. At any rate, large negative columns in thunderstorm cells seem to account for most cloud-to-ground strokes.

Figure 7.3 is a recording of the same activity a few minutes after the recording of Figure 7.2. Static heard over the laboratory radio indicates strokes at the small dips shown in this recording. No visible strokes were observed. If these are strokes, they are evidently intra-cloud, since they apparently recharge the cell, or act so as to increase the negative dipole strength. For this reason, these will be called negative strokes.

Figure 7.4 is a fluxmeter recording for a clear day, only partly cloudy. This is definitely a fair-weather condition, since the field is positive with a strength of between 1 and 10 recorder scale divisions. It may be noted that even on a clear day strong gusts of wind will cause an indication of a negative field, or at least a sharp decrease of the positive field. This is very likely due to a change of atmospheric charge density near the surface by air mass movement.

An interesting set of recordings of the electrical activity in a squall line were made in which the fair-weather intensity slowly reached zero and started to become negative as the squall approached Stillwater. The fluxmeter reading reached a high value after which several positive strokes were recorded and several small negative strokes shortly thereafter,

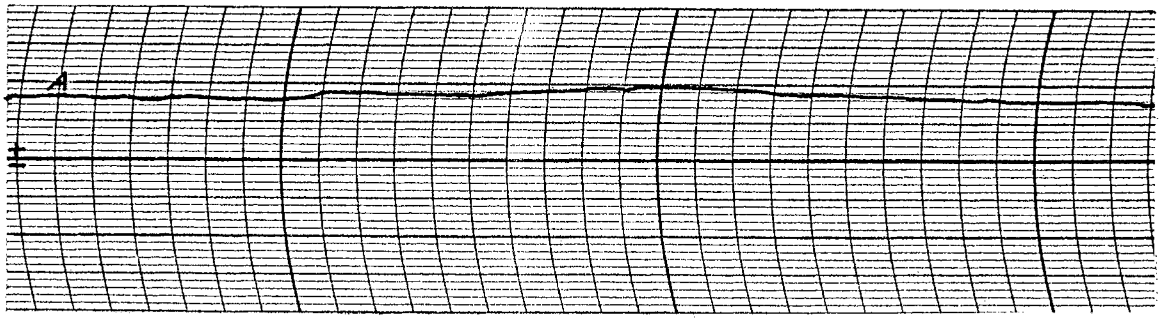


Figure 7.4. Fluxmeter recording for clear day, partly cloudy. No wind.

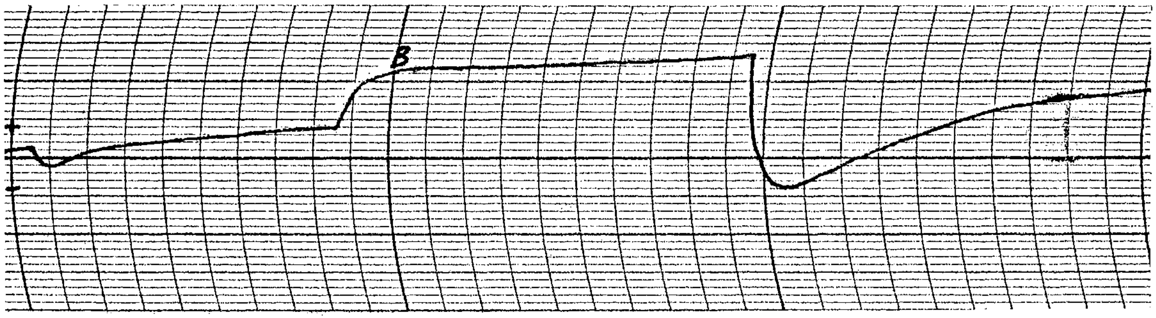


Figure 7.5. Fluxmeter recording showing the case of a small negative stroke followed by a larger positive stroke, and again by a still larger negative stroke; all taking place during a period of high positive potential gradient.

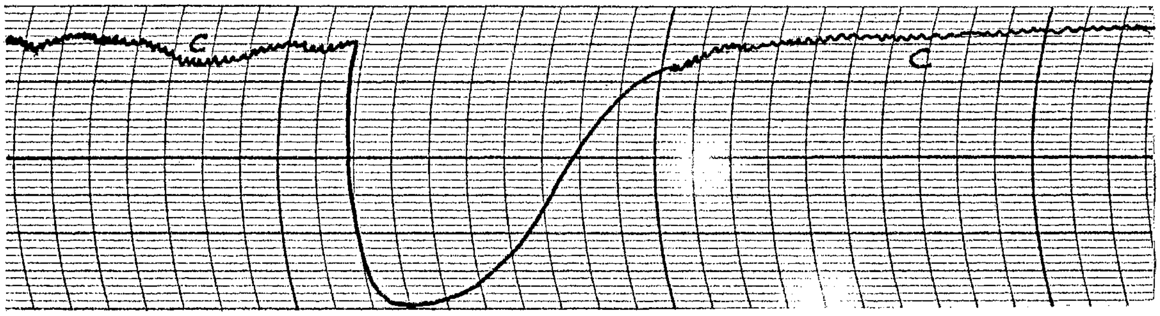


Figure 7.6. High positive field condition accompanied by a large negative stroke. St. Elmo's Fire was observed on antenna nearby during this period.

during which time the electric field went through zero, and positive strokes were recorded while the field was positive! Also, very shortly afterward, a large negative stroke was recorded, also while the field was strongly positive. This would appear to be confusing at the outset; however, if one is aware of the fact that there were no doubt several cells in action at the same time and that in all probability there were both intra-cloud and cloud-to-ground strokes in progress alternately and/or simultaneously, these processes are not confusing. The recording for the instance described above is reproduced in Figure 7.5.

One consistency has been noted about the behavior of the electric field as a line-squall approaches. When the squall is still some distance away, say 60 to 90 miles, the fluxmeter indicates fair-weather polarity and magnitude. The magnitude gradually decreases and goes through zero as the squall approaches, becoming more and more negative until the deflection is 15-20 scale divisions with the C position of the amplifier attenuator in use. Under these conditions, strokes as previously mentioned are noted.

In the recorder reproductions thus far given, no results from the electric probe are shown. As has been already pointed out, the attenuation of the probe is about 120 db, so that no worthwhile information will be given unless the strokes take place very near the laboratory.

It may be well to note here that one may feel the illusion of inconsistency with theory of some of the above observations, but if one recalls that while one tends to think of a cell's activity almost entirely in terms of the negative column within, one must not fail to recall that there is a considerable collection of positive charge near the cell base, which may be large enough to cause a fair-weather electrical condition at the ground while a fairly large cell may pass overhead. Intra-cloud strokes, however, usually reduce this lower positive charge to such a value that the cell behaves as though its only charge is the large negative column inside.

On May 3 about 8:30 p.m., a squall line was observed on the radar about 90 miles west of Stillwater. The electric fluxmeter indicated normal fair-weather electric field. The field gradually diminished and went through zero at 9:05. At this time the radar range was about 85 miles. The electric field continued to increase in the negative direction, then began to decrease, reversing again at 9:15 p.m. After a slight increase in the positive direction, the field reversed again 3 minutes later, remaining negative for about 10 minutes. At 9:39 the field slowly reversed again at which time the radar indicated a range of 75 miles. These slow reversals repeated at intervals of about 15 minutes. At 10:04 radar showed that the line squall had broken up into 3 parts. At this time the field was positive, indicating 8 scale divisions with attenuator on A. The field varied slowly, remaining positive, finally settling down to a normal fair-weather value at about 10:20. Meanwhile, radar echoes from the line squall had completely vanished. No evidence of lightning strokes was observed.

This curious behavior was observed on another occasion. The electric field reversed slowly several times never reaching a very high value. After about six reversals the field settled to fair-weather value. Radar simultaneously indicated complete dispersal of the line squall. It may well be that the above will provide a method of determining whether a given line squall will develop into an active thunderstorm or not. We already know that for an approaching line squall if the field intensity continues to increase in the negative direction, lightning strokes will soon be observed.

For another thunderstorm during which fluxmeter recordings were made, an unusual situation arose, a sample of which is reproduced in Figure 7.6. During the course of the storm, the electric field rose to a high value in the positive direction at which time St. Elmo's fire was observed at the top of a nearby whip antenna. A receiver tuned to the lower end of the broadcast band was being monitored during this period. A sustained static was heard during the period of the St. Elmo's fire. Suddenly a loud crash of static was heard followed by a loud whistle which died down slowly. The electric fluxmeter indicated a very strong negative stroke. The high field was evidently diminished by either a cloud-to-cloud or an intra-cloud discharge.

Figures 7.1 through 7.6 are samples of typical recordings made with the fluxmeter during the first several weeks of operation. Since little or no information was obtained from electric probe recordings because of its low sensitivity, the upper halves of the Brush-Recorder tape were omitted in these figures. It will be noted that none of the thunderstorms recorded were overhead, nor, in fact, nearer the laboratory than several miles.

In subsequent illustrations recordings of both the electric probe and the electric fluxmeter will be reproduced and their results discussed.

On the evening of May 17 a thunderstorm approached Stillwater which indicated considerable activity. Since the night was a dark one, all strokes could be clearly seen and their type associated with field changes as recorded by the fluxmeter and electric probe. Figure 7.7 shows a specimen of recording of both instruments. Heretofore, strokes have been classified as positive and negative. Upon this occasion it was learned that a positive stroke is a cloud-to-ground type and a negative stroke is either an intra-cloud or cloud-to-cloud type. These observations were verified

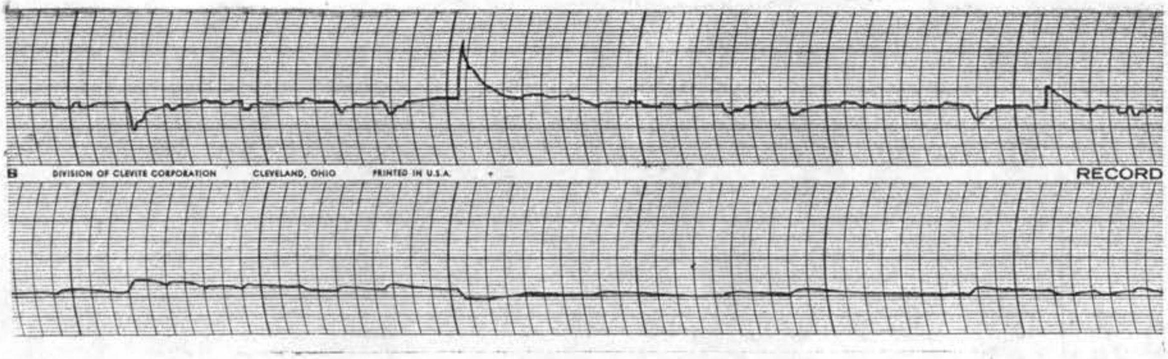


Figure 7.7. Rapid successions of varied strokes at a distance of 10-12 miles.

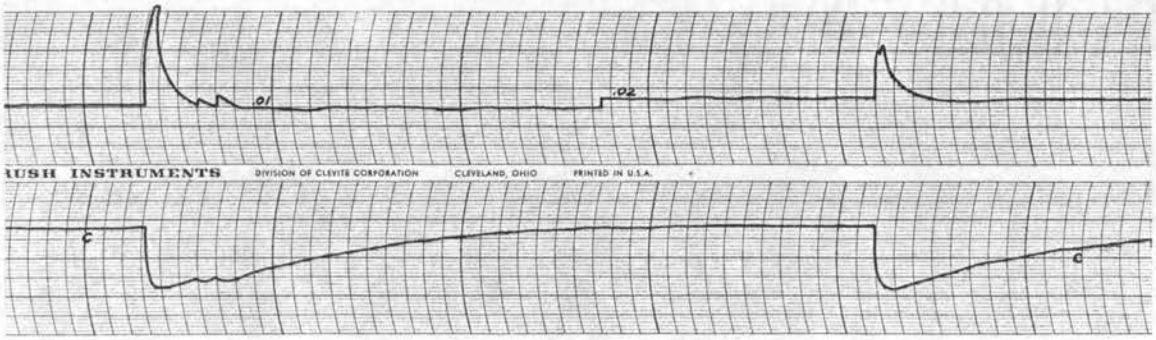


Figure 7.8. Two large intra-cloud strokes.

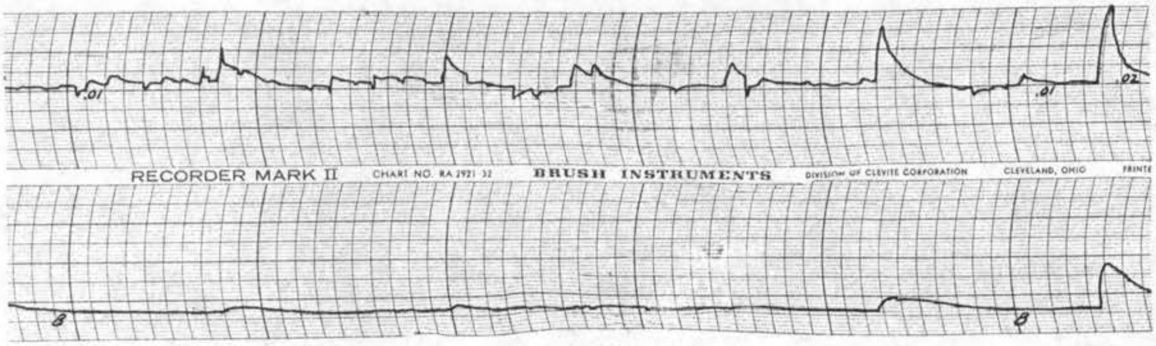


Figure 7.9. Two large cloud-to-ground strokes at the right.

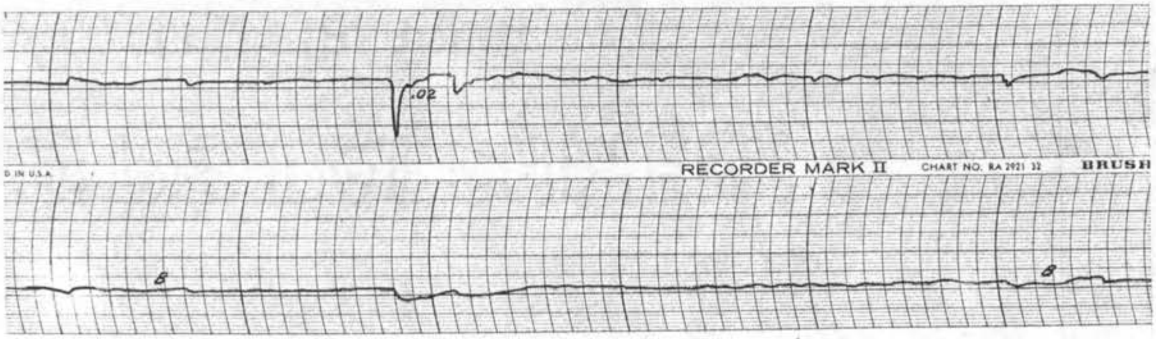


Figure 7.10. An intra-cloud stroke. Excellent contrast of probe and fluxmeter capabilities.

many times, and there appears to be an absolute certainty that the instruments can identify these strokes as they occur. It will be noted in Figure 7.7 that at the time of recording there were frequent strokes of both types. In the lower channel, a sudden increase of field intensity indicates a positive stroke and vice versa. The input to the recorder from the electric probe is such that corresponding events are symmetrical about the center line of the Brush tape. Most of these recordings were made when the thunderstorm was some distance away--about 10 miles, according to the laboratory radar.

Figure 7.8 is a tracing of the recording of two large intra-cloud strokes. Special care was taken in tracing these from the original recording. At the left is shown a heavy intra-cloud stroke, immediately followed by two small cloud-to-cloud strokes. It has been noted that cloud-to-cloud strokes have a smaller effect on the surface electric field than cloud-to-ground or intra-cloud strokes. The electrostatic significance will be discussed later in connection with recordings of a later thunderstorm. Returning to Figure 7.8, the Figures .01 and .02 represent the amplifier sensitivity for the electric probe channel. These give volts per scale division. A scale change is indicated at the middle of the recording. As in the lower half, the middle line represents zero. At the right of the recording is shown another intra-cloud stroke. A close examination of the electric-probe channel shows that actually there were two of the strokes almost simultaneously. This is a good illustration of the fact that the electric probe indicates rapid variations of the field, *and that its steady-state indications are meaningless*. On the other hand, the electric fluxmeter, while it clearly cannot indicate very rapid field changes, shows the net effect upon the ambient electric field of the various types of lightning strokes. Again this will be discussed further in a later paragraph.

The reader is reminded that the tape speed is such that 1 cm. length corresponds to 10 seconds. While the Brush Mark II Recorder is capable of paper tape speeds up to 12.5 cm. per second, these speeds will be reserved for large strokes with the hope that for a given flash the individual strokes may be observed. Since only small periods of time can be reproduced on these pages, a minimum of high-speed recordings will be given.

In the case of the May 17 thunderstorm, the cell dissipated as it passed overhead with the result that no near cloud-to-ground strokes were recorded. The good results from the other types of strokes that were observed directly above the laboratory, however, made the above recording and observations worthwhile.

In Figures 7.7 and 7.8 the deflections for the electric probe and electric fluxmeter were opposite with respect to the middle of the paper tape. It was deemed advisable to reverse the galvanometer connections on the probe channel so that the deflections on both channels would be in the same direction. Interpretation of results appears to be much more tangible for this type of presentation so that this situation will be maintained for all subsequent recordings.

On May 23, recordings were made for a rather unusual situation. A line squall formed southeast of Stillwater and remained almost stationary for a period of about six hours. Radar records show that the squall first consisted of a number of small isolated formations, which later converged then again broke up into smaller formations, converged again then slowly broke up again, finally vanishing completely as far as radar observations indicated.

During the early stages the portion of the line squall which was very near Stillwater indicated all three types of discharges. The electric fluxmeter indicated that the average field was moderately negative.

A tracing of recordings for an early period as described above is reproduced in Figure 7.9. This offers an excellent illustration of the capabilities of the two instruments in recording the behavior of the electric field. Since the deflections for a given event are in the same direction, it is much easier to observe the effects of the rapidly varying fields of the strokes upon the average value of the field at the earth's surface. For instance, near the right side of Figure 7.9 are seen two rather large cloud-to-ground strokes. These clearly make the field at the ground less negative, but this field gradually returns to the value prior to the stroke. Recalling the discussions in Chapter II, this would indicate partial discharge of the negative column by the cloud-to-ground stroke with subsequent recharging of the negative column.

Shortly after the period of activity as indicated in Figure 7.9, radar showed partial dispersal of the line squall. Electrical activity almost completely ceased, according to the electric probe channel and the average field as indicated by the fluxmeter channel decreased to a very small value, i.e., fair-weather magnitude and polarity.

About 45 minutes after the dispersal, the line squall began to reconsolidate with indications of increased electrical activity in the form of intra-cloud strokes of increasing magnitude. The average value of the field was moderately negative and these strokes increased the average negative value slightly. This behavior of the field at the ground may again be justified in the light of the discussions of Chapter II. The normal picture of a thunderstorm cell is a large central negatively-charged column with a layer of positive charge below, which tends to partially mask the electric field of the central column at the earth's surface. An intra-cloud stroke will partially neutralize this lower positive charged volumn with the result that the electric field at the surface will be increased. This phenomenon has been repeatedly observed electrically and visually. Figure 7.10 illustrates two typical intra-cloud strokes at a distance of approximately five miles.

On the morning of May 22, a roll cloud formation was observed approaching the Stillwater area at a rapid rate. This is a low-lying, thin cloud with a peculiar rolled front, very dark and undetectable on radar. There was no electrical activity whatever indicated, except that the fluxmeter indicated a slowly reversing field as the cloud front passed overhead. Before and after the electric field was of fair-weather polarity and magnitude. It is evident that these clouds carry negative charge but of fairly low density. Because of the absence of radar echoes, there is little or no precipitation within the cloud; its low altitude would make this fact apparent at the outset.

Figure 7.11 shows two brush-recorder strips, which show the variation of the field as the cloud passed overhead. The top strip is for the earlier portion of the period, and the bottom strip is a continuation of the top. This illustrates the superiority of the fluxmeter for indication of slow field variations, since the electric probe showed no variation whatever during the entire period. The time scale is 10 seconds per centimeter.

On May 26 the Stillwater area was heavily clouded and moderate rain was falling. Recordings were begun at about 10:30 a.m. after several lightning strokes had been observed.

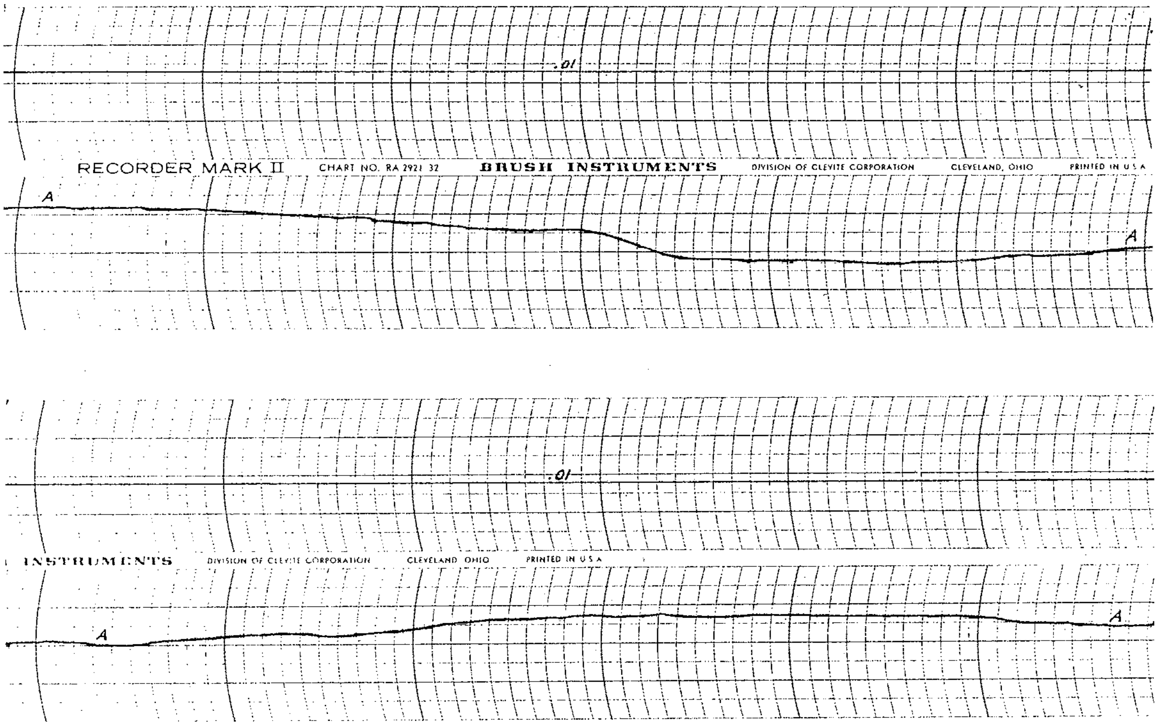


Figure 7.11. Recording of the electric field as a "Roll Cloud" passed over the laboratory. The top strip is the earlier. Time scale is 10 seconds per centimeter. Note that the electric probe showed no variations whatever during the run.

Figure 7.12 shows excerpts from the recorder during several instances of the thunderstorm. The first strip at the top represents a recording after several cloud-to-cloud strokes had been observed, the last of which is shown at the left of the strip. Right after this stroke the electric field reversed rather slowly as shown. A few seconds later the field reversed again slowly; and when it reached a maximum, corona-discharge static was heard over the radio. A heavy cloud-to-cloud stroke, which was followed by a loud clap of thunder, occurred. These events are shown in the second strip from the top in Figure 7.12.

In the third strip a cloud-to-ground stroke is immediately followed by a cloud-to-cloud stroke. A few seconds later the field slowly decreases and reverses, requiring about 70 seconds for the complete reversal to take place.

In the fourth strip of Figure 7.12 a cloud-to-cloud stroke is followed by a cloud-to-ground stroke about 15 seconds later. Shortly thereafter, the field again reverses slowly, after which there are two cloud-to-cloud strokes in very rapid succession. The probe shows these clearly, whereas the fluxmeter appears to indicate a single stroke.

Figure 7.12 is a continuation of Figure 7.11. In the first strip a slow field reversal is followed by two cloud-to-cloud strokes. In the second strip two very large cloud-to-cloud strokes that were followed by thunderclaps are shown. In the third strip a large cloud-to-ground stroke is followed by a slow field reversal.

Activity similar to the above continued for several minutes. It appears to be more and more evident that the slow field reversals herald a dispersal and dying out of a thunderstorm whether the cell is nearby or some distance away.

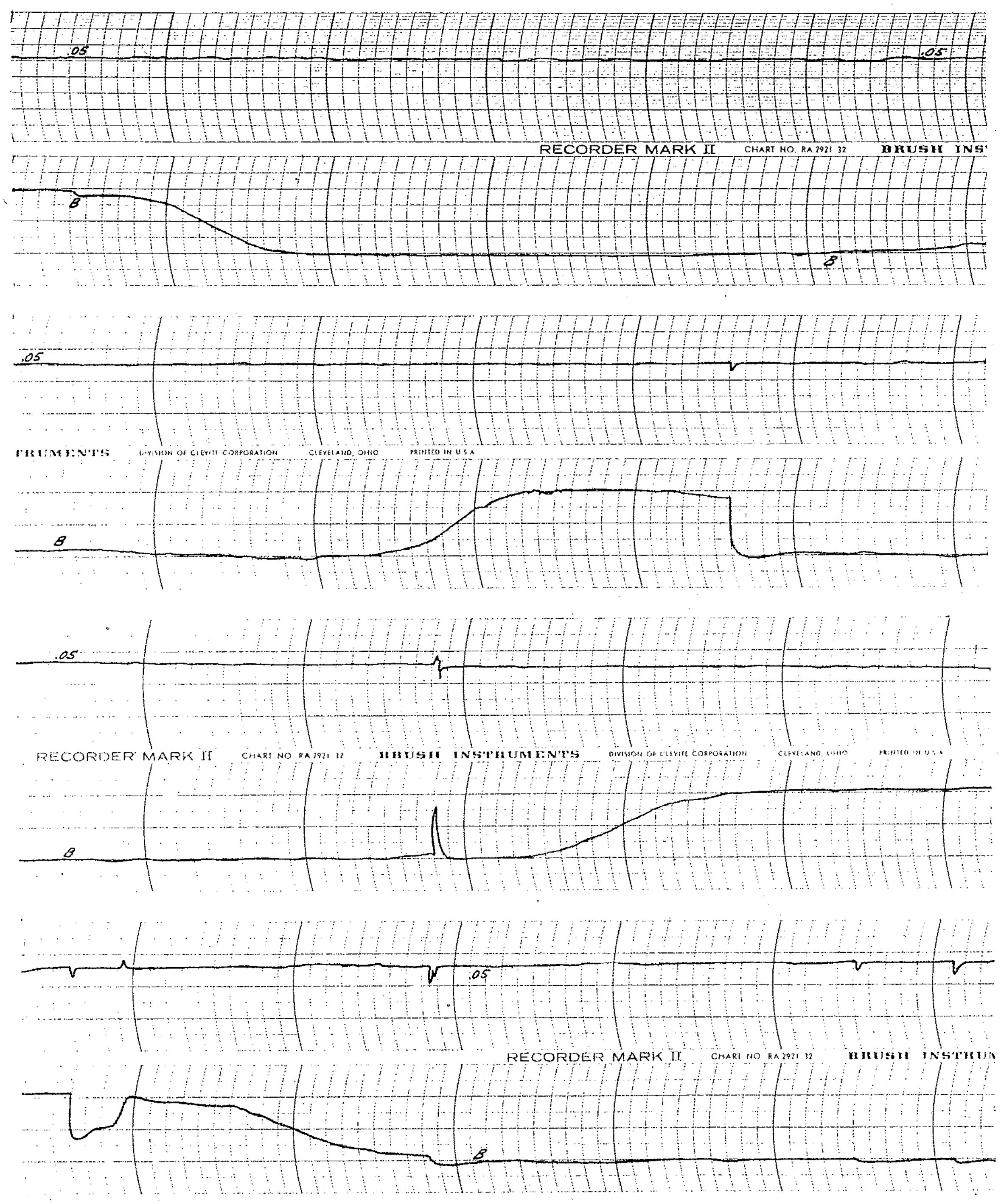


Figure 7.12. Continuous recordings for a mild thunderstorm accompanied by rain. /Continued in Figure 7.13./

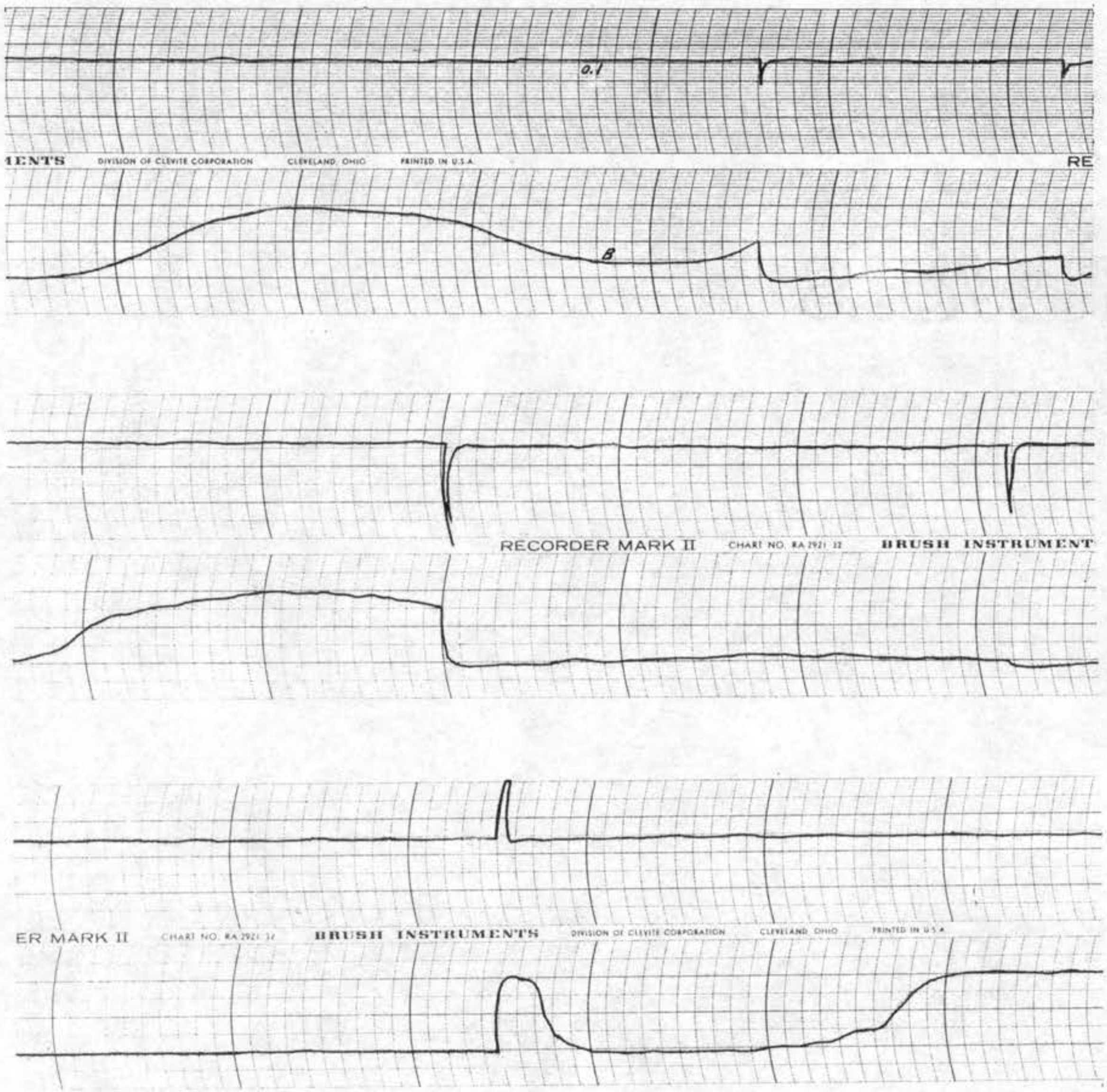


Figure 7.13. Continuation of Figure 7.12.

The writer made several attempts to obtain probe recordings of strokes with the Brush Recorder tape moving at its highest speed, but without success. Such a recording for a stroke like those in the third strip of Figure 7.12 should show the multiplicity of strokes that actually exist in what is normally termed a single stroke.

High-Speed Recordings of a Severe Thunderstorm

On June 11 an opportunity was finally had to exploit the full capabilities of the equipment developed and described herein.

A line squall was observed on the laboratory radar at a distance of 30 miles, the central and nearest portion bearing about 070°. The fluxmeter showed all types of strokes faintly; and, of course, the probe gave no indications because of its low sensitivity. Observations were begun at about 9:00 p.m.

Observations were continued until about 9:30 p.m., at which time the fluxmeter recording was indicating definitely the types of strokes that were occurring. The top strip of Figure 7.14 is a tracing of both channels at 9:30 p.m.

At 10:05 p.m. the range of the nearest point of the line squall was 14 miles. The fluxmeter channel showed more pronounced field variations, and the probe channel was beginning to indicate very slight variations. A tracing of the recording is the second strip of Figure 7.14. It will be noted that the mean value of the electric field is progressing toward the negative direction.

One unusual property of this storm was noted: Whereas the elevation of the radar antenna is about zero for optimum echo pattern for all previously observed line squalls, the radar antenna elevation was about 4°

Figure 7.14. Recordings as the electrical storm of June 11 approached the Stillwater area.

for this one, indicating that the precipitation within the cells involved was considerably higher in altitude than usual.

At 10:42 p.m. electrical activity increased to the point where several scale changes had to be made on both channels. The third strip of Figure 7.14 is a tracing of the recording at this time. The squall line was over the station and rain had begun to fall.

Immediately after the time of the third strip of Figure 7.14, the speed of the recorder was advanced to 125 m.m./sec., so that 1 m.m. corresponds to 8 milliseconds of time. On the first strip of Figure 7.15 the probe indicates three cloud-to-ground strokes, while the fluxmeter shows the resultant effect on the average electric field. Note that the first two strokes are about 80 milliseconds apart, while the third follows the second by about 120 milliseconds. These strokes partially discharge the cell so that the average electric field at the surface becomes less negative. The very sudden variations of the field as indicated by the probe are the sudden changes due to the strokes themselves. The comparatively slow return of the field toward the negative between strokes indicates that the cell becomes partially recharged in these intervals. The fluxmeter, of course, has too low a response to indicate these rapid variations. The reader will again note the highly informative value of using both instruments simultaneously. It will be noted that at the beginning and end of each cloud-to-ground stroke there is a small reverse pip. This is doubtlessly due to the induction field set up by the stroke. Incidentally, all strokes as recorded herein took place within a mile of the laboratory.

In the second strip of Figure 7.15, two milder cloud-to-ground strokes are shown. Since the field is increasing positively between strokes, there is apparently no recharging. It might be pointed out here that the action

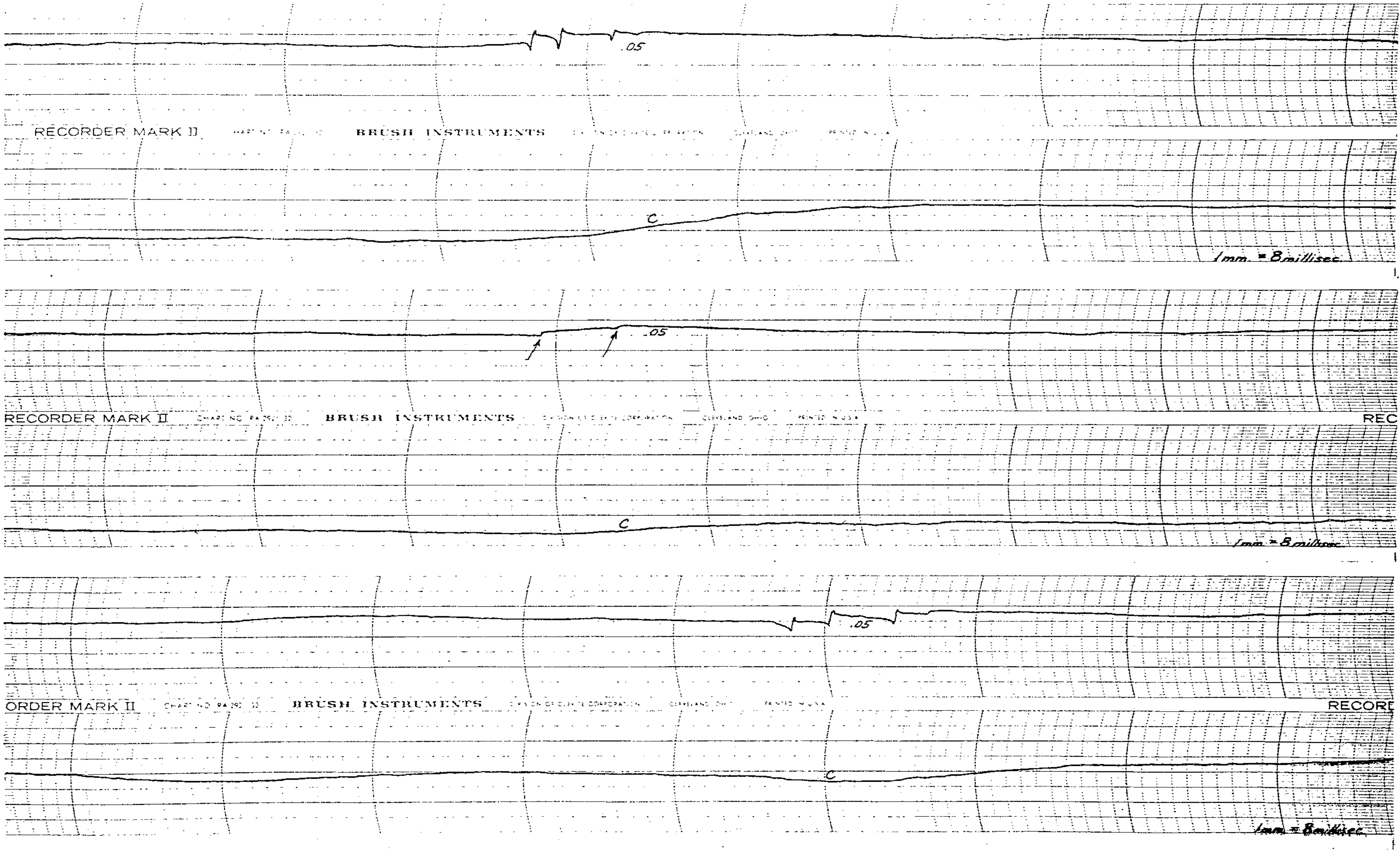


Figure 7.15. /Top to Bottom/ Three large strokes resulting in a large change of field; two mild strokes resulting in a slight change of field; three large strokes resulting in a complete reversal of field.

of a single cell is assumed for a given group of strokes. The action of several cells simultaneously may yield results that are too difficult to interpret at this stage of this analysis.

In the third strip of Figure 7.15 an instance is shown in which a series of three [or more] cloud-to-ground strokes brings about complete reversal of the mean electric field. Again it should be pointed out that this is due to the action of more than one cell. It may also be remarked that these three strokes may have discharged a particular cell almost completely. This would account for the complete field reversal, in contrast with the case where a series of strokes only partially discharge the cell, leaving a net negative field at the surface.

In Figure 7.16 is shown a series of about 10 strokes. It will be noted that each stroke makes the field less negative, the entire series finally resulting in a rather strongly positive field. When the strokes cease, the field slowly returns to the negative value as the particular cell recharges, possibly along with others.

Heretofore, field changes by cloud-to-ground strokes have been shown. In the second strip of Figure 7.16 are shown two intra-cloud strokes. These, according to the theories of Chapter II, diminish the positive charge layers below the negative columns of the cells, thus increasing the negative field at the ground. The essential difference between cloud-to-cloud or intra-cloud strokes and cloud-to-ground strokes will be noted. The former dip toward the negative and occur more slowly than the latter.

In the third strip of Figure 7.16 are shown about eight cloud-to-ground strokes down the same channel. At this stage the electric field was so high that, since the attenuator of the fluxmeter amplifier was in position C, the Brush amplifier gain had to be reduced by a factor of five to keep

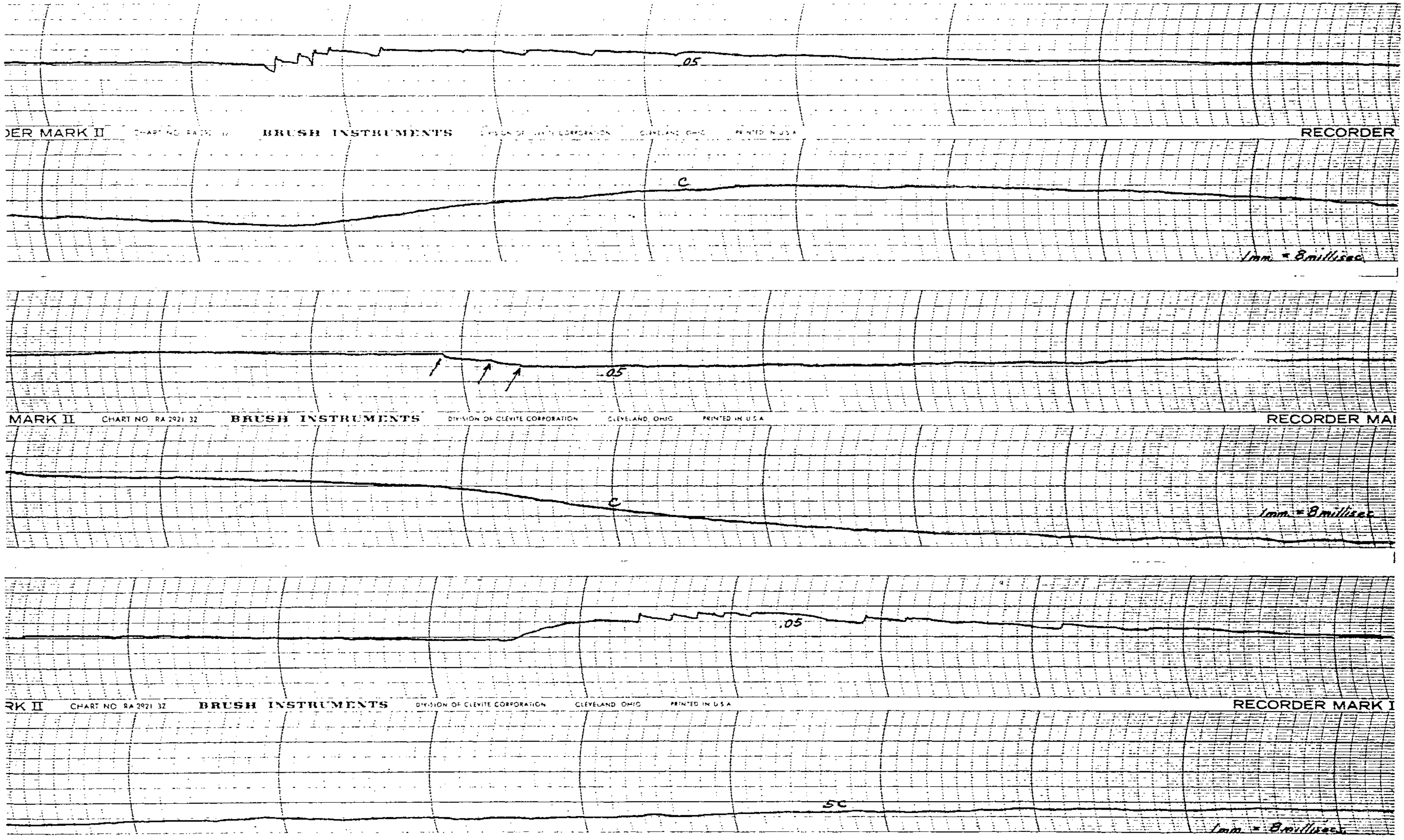


Figure 7.16. [Top to Bottom] Multiple strokes bringing about field reversal. Three intra-cloud strokes and their effect on the field; series of cloud-to-ground strokes with very high mean field. [8 kilovolts/meter]

the pen within the range of the strip. The electric field, using the calibration curves, is approximately eight kilovolts per meter, which is the highest yet recorded in this investigation.

The recordings in Figures 14, 15 and 16 are, needless to say, the barest of samplings of the nine hundred feet of paper tape recording obtained during the subject thunderstorm. Many hundreds of strokes were recorded, all consistent with samples discussed.

Since further discussion would in the main be a repetition of the foregoing, it was decided to conclude this dissertation at this point, realizing that herein lies only the foundation of further work that can be carried on in this field.

Since field intensity study is a new phase of research here at Oklahoma State University, the writer feels that the equipment developed, plus the agreement with theory of the results obtained from this equipment provides adequate facility when incorporated with other equipment at the Tornado Laboratory to carry on extensive investigations, which will doubtlessly yield fruitful results in the field of thunderstorm electricity.

CHAPTER VIII

SUMMARY AND CONCLUSIONS

Chapter I was devoted to a brief discussion of atmospheric electricity directed to an electrostatic explanation of the fair-weather electric field at the earth's surface. Since this study is directed toward the simplification of the general thunderstorm problem, the above discussion was deemed necessary.

Chapter II is devoted to a discussion of thunderstorm cells and lightning discharges. The most reasonable theory of charge-separation in these cells is adopted and their effect upon the electric field at the earth's surface is discussed. The lightning discharge is discussed in some detail along with an outline of Schonland's theory of alpha- and beta-type stepped leaders. The effect of these discharges on the earth's mean electric field is also discussed.

Chapter III is a brief description of the Mt. Withington experiments conducted by Vonnegut and Moore. These experiments, with the aid of radar and radiosondes, provide a verification of many of the theories discussed in Chapters I and II. In the main, the first three chapters integrate a wide range of electrostatic theories with highly plausible verifications. The integration of this material is claimed by the writer as a minor contribution in this field.

Chapter IV is devoted to a brief description of tornadoes. Energy considerations from a philosophic viewpoint are set down in an effort to convince the reader that a tornado is an electrical machine, in that the stored energy in a tornadic cell is converted to mechanical energy of air motion by an electromechanical energy-transduction process. Proceeding on the assumption that the tornadic cell is electrostatically similar to a common thunderstorm cell, the writer's concept of the tornado as an electromagnetic oscillator is described and the energy-conversion process in terms of basic electromagnetic laws is included. This theory, which is original with the writer, agrees with many of the electrical actions of tornadoes as reported by observers. The writer claims this as another minor contribution to the field in the sense that it adds to the list of proposals of mechanisms of tornadic action.

Chapter V is an outline of the theory of quasi-static, radiation, and induction fields about thunderstorm cells in terms of quasi-static and time-varying dipoles. While lightning strokes account for the latter two types of fields, the cells themselves account for the quasi-static field; this idea led the writer to the concept that the electric behavior of the cells may be described in terms of the electric field at the ground nearby. Also, since lightning strokes discharge these cells in steps, the quasi-static fields about the cells will be altered by these strokes.

Chapter VI describes equipment developed by the writer for the detection of slowly- and rapidly-varying quasi-static electric fields. This required two independent devices, since no device has been developed as yet which can detect both types of field variations. While the electric fluxmeter is not original with the writer, his simple and dependable design is deemed noteworthy. The electric probe design is original with the writer, and its capability of producing an output voltage which is a close copy of the varying electric field is considered by the writer as a contribution to the field. Recording of the outputs of both devices time-synchronously is deemed an important and original contribution to the field of atmospheric electricity measurement, since this recording is in entire agreement with the theories as outlined in the first three chapters of this dissertation.

Chapter VII is a series of reproductions of recordings made with the above equipment at the Tornado Laboratory, accompanied by an explanation of each, showing their agreement with theory.

It is unfortunate that the 1959 thunderstorm season yielded a minimum of opportunity to use this equipment, since only one extensive electrical storm passed over the Stillwater area, and no tornadoes passed sufficiently near to be detected. However, enough data was collected to convince the writer of the capability of the equipment and to enable him to foresee the possibility of much that may be accomplished in future seasons.

Figure 7.16, for example, shows clearly multiple cloud-to-ground and intra-cloud strokes. In a recent paper, Dr. H. L. Jones[1] of the Tornado Laboratory includes several of his photographs of lightning strokes, illustrating approximately the same time intervals between strokes. The time-correlation of fluxmeter and probe recordings with photographic and/or visual observation will doubtlessly lead to many further contributions from the Tornado Laboratory. Since these recordings clearly indicate lightning strokes both as to type and magnitude, it is entirely

---

[1] L. G. Smith, Recent Advances in Atmospheric Electricity, Proceedings of the Second Conference on Atmospheric Electricity held in Portsmouth, N. H., May 20-23, 1958, (New York, 1958) pp. 543-556.

possible that differentiation between strokes preceded by alpha- and beta-type stepped leaders may be accomplished. Further, time-correlation between these recordings and film recordings of sferic waveforms may yield much information in propagation studies.

Suggestions for Further Researches

In summation, the writer hopes that the initiation of field intensity studies at the Tornado Laboratory, combined with the other research facilities there, will lead to fruitful avenues of further researches.

For example, if the electric field of a nearby tornado could be recorded, much hitherto unknown knowledge as to its electric activity would be revealed.

Further, correlation of sferic waveforms, visual and/or photographic observations, and qausi-static field intensity recordings will doubtlessly lead to a much more elegant understanding of atmospheric electric phenomena.

Conclusion

The writer finds excellent agreement between theory and observation of the results of the equipment developed during the course of this study. While, like most investigations, this one is far from complete, much progress has been made which, it is hoped, will pave the way for further progress in this most fascinating field of atmospheric electricity.

SELECTED BIBLIOGRAPHY

Appleton, E. V., R. A. Watson-Watt, and J. F. Herd. Proceedings of the Royal Society, III (April, 1926), p. 654.

Brooks, C. E. P. "The Distribution of Thunderstorms over the Globe." Geophysical Memoirs, III (1925) pp. 145-164.

Byers, H. R. Thunderstorm Electricity. Chicago: The University of Chicago Press, 1953.

Byers, R. B., and R. R. Braham. The Thunderstorm. (Report of the Thunderstorm Project, 1949) U. S. Government Printing Office.

Chalmers, J. A. Atmospheric Electricity. London: Pergamon Press, 1957. (Contains a most excellent bibliography for the entire field.)

Flora, S. D. Tornadoes of the United States. Norman: University of Oklahoma, 1953.

Gish, O. H., and G. R. Wait. "Thunderstorms and the Earth's General Electrification." Journal of Geophysical Research, LV (1950), pp. 473-484.

Gish, O. H. "Universal Aspects of Atmospheric Electricity." Compendium of Meteorology, American Meteorological Society, (1951), pp. 101-119.

Gunn, Ross. "Precipitation Electricity." Compendium of Meteorology, American Meteorological Society, (1952), pp. 128-135.

Gunn, Ross. "Electricity Field Intensity at the Ground Under Active Thunderstorms and Tornadoes." Journal of the Meteorological Society, (June, 1956), pp. 269-273.

Linss, F. "Ueber einege die Wolken und Luftelectricitat Betreffende Probleme." Meteorological Zeitschrift, IV (1887), pp. 345-362.

Moore, C. B., B. Vonnegut, and A. T. Botka. Results of an Experiment to Determine Initial Procedence of Organized Electrification and Precipitation in Thunderstorms. Cambridge: Arthur D. Little, Inc., The Air Force Cambridge Research Center.

Ridenour, L. N. Modern Physics for the Engineer. New York: McGraw-Hill, 1954, pp. 330-357.

Schonland, B. F. J. Atmospheric Electricity. London: Methuen and Company, Second Edition, 1953.

Schonland, B. F. J. The Flight of Thunderbolts. Oxford: Oxford Clarendon Press, 1950.

Smith, L. G. Recent Advances in Atmospheric Electricity. New York: Pergamon Press, 1958.

Vonnegut, B., and C. B. Moore. "Correspondence." Journal of Meteorological Society, (June, 1957), pp. 284-286.

Vonnegut, B., and C. B. Moore. Giant Electrical Storms. Contract Number 1684(00), Office of Naval Research, Cambridge: Arthur D. Little, Inc., (March 15, 1958).

Whipple, F. J. W., and F. J. Scrase. "Point Discharges in the Electric Field of the Earth." Geophysical Memoirs, VIII, No. 68 (1936).

Workman, E. J., and S. E. Reynolds. "Electrical Activity as Related to Thunderstorms Growth." American Meteorological Society, XXX, No. 4 (1949), pp. 141-144.

VITA

Felix Joseph Boudreaux

Candidate for the Degree of

Doctor of Philosophy

Thesis: A STUDY OF THE QUASI-STATIC ELECTRIC FIELDS OF SEVERE THUNDERSTORMS

Major Field: Electrical Engineering

Biographical:

Personal Data: Born in Washington, St. Landry Parish, Louisiana, December 15, 1916, the son of Raphael and Elodie St. Cyr Boudreaux.

Education: Attended grade school in Opelousas, Louisiana; graduated from State High School, Opelousas, Louisiana in 1937; received the Bachelor of Science degree from the Southwestern Louisiana Institute, with a major in Electrical Engineering, in June, 1941; received the Master of Science degree from the University of Illinois, with a major in Electrical Engineering, in February, 1947; completed requirements for the Doctor of Philosophy degree in August, 1959.

Professional Experience: United States Navy, Radio-Radar Officer on aircraft carrier in Pacific Fleet, 1943-1946, and is now a Commander in the United States Naval Reserve; Associate Professor of Electrical Engineering, Southwestern Louisiana Institute, 1947 to present; Field Engineer for RCA Manufacturing Company, Camden, New Jersey, 1941-1943.

Organizations: Member of IRE, Sigma Xi, Louisiana Engineering Society, Registered Professional Engineer, State of Louisiana.