CLOUD CHARGES IN THUNDERSTORMS

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PREFACE

The nature of the charges developed in thunderstorms has only been recently determined, since this is a relatively new phase in the study of atmospheric electricity. The Oklahoma Institute of Technology has initiated a research program which deals with the particular type of charged clouds that develop in the Southwest area of the United States. The present investigation describes the position and sign of the charged areas in the clouds as determined by measurements made from the earth's surface.

A number of typical storm situations have been analyzed. The findings have been compared with those of other investigators to give a broader perspective and a better comprehension of the subject. A system is proposed for the investigation of the charges and the potential gradient in tornadic situations. This should make it possible to determine any peculiar variations in these quantities during a tornado period. The knowledge thus acquired, it is believe, may help in the recognition of the tornado type clouds.

A description of the measuring instrument, its theory of operation, and its limitations are covered in this thesis. Illustrations of the equipment installation are included to give a clear picture of how the measurement process is performed. The purpose of this study is to extend the present knowledge of atmospheric electricity and tornado detection.

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CHAPTER I

POTENTIAL GRADIENT

A. Early Developments in Atmospheric Research

The study of atmospheric electricity began with the association of static electricity with the phenomena of lightning. Although thunderstorms have been known to the human race from earliest times, it is only in comparatively recent times that the nature and origin of lightning have been clearly understood. In 1708 Wall[1] was the first investigator to consider lightning and static electricity as the same type of phenomenon. On hearing crackling and observing a flash to his finger from a charged amber rod, Wall remarked that: "It seems in some degree to represent thunder and lightning." The development of static generators and the Leyden jar permitted the study of larger electrical charges and larger sparks. Next it was suggested by Franklin in 1750 that with the use of pointed conductors electricity might be obtained from thunderclouds. Franklin[2] obtained electricity from a thundercloud by his famous kite and conductor experiment. The presence of electricity in thunderclouds was proved by the sparks obtained. By the use of a kite de Romas,[3] working independently, obtained a spark three

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[1]W. Wall, Philosophical Transactions Royal Society, 26 (1708), p. 69.

[2]B. Franklin, Philosophical Transactions Royal Society, 47 (1751), p. 289.

[3]J. de Romas, Mém. à l' Acad. de Bordeaux, (1753).

meters long and three centimeters in diameter. This observation further verified the relationship between lightning and electrical discharge. The most common method used to produce sparks by the early experimenters was the point discharge method.

Lemonnier[4] first observed that even in fine weather electrical effects could be obtained. His method used a wooden pole with a pointed iron rod attached to the top. Fastened to the rod was an iron wire that entered an adjacent building without making any contact with the wall of the building. Inside the wire was held tightly by a stretched silk fibre. When the iron wire was electrified the dust particles, which were attracted to the wire, showed the presence of electrification that was too weak to produce sparks. Lemonnier also used a horizontally stretched wire in place of the pointed rod. This arrangement acted as a weak collector, slowly acquiring the potential of the surrounding space. The stretched wire method was used by Beccaria to determine the existence of a daily potential variation. The concept of positive and negative electricity was first applied by Beccaria[5] to atmospheric electricity. He demonstrated that the wire was positively charged during fine weather, and that during thunderstorms it became either positive or negatively charged. The next

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[4]L. G. Lemonnier, Mém. de l' Acad. des Sci., 2 (1752), p. 233.

[5]G. B. Beccaria, Dell' Electricità Terrestre Atmospherica a Cielo sereno, Turin, (1775).

advance in measuring electrical effects was made by de Saussure[6] who devised a form of electrometer which consisted of two small elder pith balls supported by fine silver wires in an enclosed glass vessel that had a metal casing. The pith balls would diverge when the conductor was raised. An understanding of the action occurring can be had by considering first a vertical earthed conductor in a vertical electrical field. For a given position the conductor would have a bound charge on the unearthed end of the conductor to neturalize the potential at that point. Raising the conductor higher into the air, where the potential is greater, requires a larger bound charge to neutralize the field. Next an insulated electrometer, which was initially at ground potential, was connected by a conducting wire to the vertical conductor, the vertical conductor being ungrounded. The bound charge was increased as the conductor was elevated. By the law of Gauss this increased charge must come from within the system. Moreover, this induced charge will have to be balanced by an equal and opposite charge on the opposite end of the conductor. The electrometer received this opposite charge which in turn caused the pith balls to repel each other. The balls came together again when the conductor was lowered to its original position; hence no charge was received outside the system by the conductor. With this instrument de Saussure discovered that there was an annual fair

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[6] H. B. de Saussure, Voyages dans les Alpes, Geneva, (1779).

weather variation in the potential gradient.

Another scheme using a flame collector was first utilized by Volta. He found that when a candle flame was placed in contact with the point of a rod a larger charge was required than was necessary without the flame; also the conductor arrived at the potential of the air in less time. A controlled experiment, performed in an enclosed room, proved that the observed electrical effects were not due to combustion.

Erman[7] first set forth the notion that the earth itself was charged instead of the surface air. He did not, however, develop the concept that somewhere there must be a charge of equal and opposite sign to that carried by the earth. Peltier confirmed Erman's theory and set forth the hypothesis that the earth carried a permanent negative charge. He demonstrated that an electrometer measures only the potential difference between the cage and the gold-leaves, and thus explained why a grounded electrometer will not show any charge.

B. Theory of The Potential

The concept of potential was first introduced by Lord Kelvin. Using the Faraday theory of lines of force and mathematical principles he showed that the vertical potential gradient was due to the surface charge carried on the earth. He theorized that a flame collector and his newly invented water-dropper equalized the potential of the conductor to the

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7P. Erman, Journ. de Phys., 59 (1804), p. 95.

potential of the adjacent air. The increase in bound charge acquired by raising a conductor was shown by him to be due to the increase of potential and not to an increase in potential gradient, this was demonstrated by producing these same effects in a constant electric field. This demonstration destroyed the theory of a positive or negative charge in the lower air, but raised the question of where the lines of force leaving the earth were terminated. This question has not yet been answered, but recent work has shown that these flux lines might end on conducting layers in the upper atmosphere.

Coulomb and Matteucci demonstrated that air was a conducting medium, but it was Linss[8] who realized the importance of these investigations. Linss pointed out that the charge on the earth would leak off in ten minutes due to the conductivity of the air if there were no means of replacing it. In order to maintain a negative charge on the earth there must be some means for replenishing the lost charge. At the present time the generally accepted theory is that in stormy weather a negative charge flows to earth to balance the positive charge which flows earthward during fair weather.

Recently considerable work in the realm of atmospheric electricity has dealt with the thunder-cloud, research emphasis being placed on the electrical nature of the thundercloud and the processes of charge separation. These studies

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[8]F. Linss, Met. Zeit., 4 (1887), p. 345.

lead to a controversy as to the polarity of cumulo-nimbus clouds. A cloud having a positive upper part and a negative base is considered as having positive polarity, while a cloud having a negative charge in the upper regions and a positive charge in the lower regions is said to have negative polarity. By using ballons, Simpson and Scrase[9] showed the top of a cloud to be positive, and the base to have negative regions, or positively and negatively charged regions.

Lord Kelvin introduced the concept of an electrical potential at a point. This concept is used extensively in the subject of atmospheric electricity. The potential difference between two points, by definition, is the mechanical work necessary to move a unit positive charge from one point to the other point. The potential of a point is the work done in bringing a unit charge of positive electricity from beyond the boundaries of the field in question to that point without disturbing the distribution of the field. It is impossible to find the potential of the earth's surface since nothing is known about the electrical conditions outside the conducting layers above the earth through which a unit positive charge from infinity must move to reach the earth's surface. The potential of the earth is therefore assumed to be zero. Great importance is placed on the potential difference between points while the absolute potential of points

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[9]G. Simpson and J. F. Scrase, "The Distribution of Electricity in Thunderstorms." Proceedings of the Royal Society, 161 (August, 1937), pp. 309 - 352.

is disregarded. The potential gradient[10] is the maximum rate of change of voltage with distance. The direction of the potential is in the direction that a positive unit charge would be urged in the electric field. It will be assumed that the electric field is always vertical in the atmosphere. During fair weather the field is nearly vertical, but during a thunderstorm this assumption may be erroneous because the field at a point is a resultant of the fields produced by different charged volumes in space. The positive direction of a field is usually taken as the direction in which a unit positive charge would move. In atmospheric electricity however, the field is considered positive in the direction a negative charged particle moves. In fair weather a negative charge is carried by the earth, thus producing a positive field. The electrostatic flux lines are depicted as starting on a positive charge and ending on a negative charge.

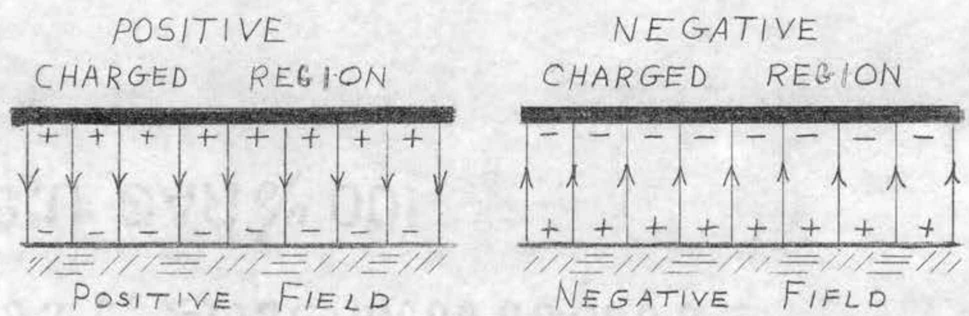

Figure 1. Polarity of Electric Fields

In Gaussin units $\oint \overline{D} \cdot d\bar{a} = 4 \pi Q$. This equation

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[10]H. H. Skilling, Fundamentals of Electric Waves, (New York, 1948), pp. 19-20.

states that the flux passing through a closed surface is equal to 4π times the electric charged contained within that surface. The flux density is $\bar{D}$, the area is $\bar{a}$, and the charge is Q. For a vertical field that has a change of potential gradient in the vertical direction, charges must be present from which the extra flux lines originate. By applying Gauss's theorem $\oint \bar{D} \cdot d\bar{a} = \int_V (\nabla \cdot \bar{D})\, dv = 4\pi Q$. If ρ is the density of electric charge per unit volume, then

$$4\pi Q = 4\pi \int_V \rho dv = \int_V (\nabla \cdot \bar{D})\, dv.$$

Both sides of this equation are volume integrals, and so

$$\nabla \cdot \bar{D} = 4\pi\rho \qquad (\nabla \cdot \varepsilon_0 \bar{E}) = 4\pi\rho.$$

and if $\varepsilon_0 = 1$

then $\bar{\nabla} \cdot \bar{E} = 4\pi\rho$. If $\bar{E} = -\nabla V$, then

$$\nabla \cdot \nabla V = \nabla^2 V = -4\pi\rho.$$

The equation of an electric field varying only in the vertical direction is $\frac{\partial V^2}{\partial X^2} = -4\pi\rho$.

The relationship between the lines of force ending on a conductor and the surface charge carried by the conductor is

$$\oint_S \bar{D} \cdot d\bar{a} = 4\pi Q = 4\pi \oint \sigma\, da.$$

The symbol σ is the charge per unit area. When the charges on a conductor are in equilibrium all lines of force must leave normal to the surface. To leave at any other angle would indicate a component of electric intensity parallel to the surface, which would result in a flow of electrons along the surface until an equilibrium with all lines of force leaving normally is reached. Let the normal flux density be $D\bar{n}$, and $da\bar{n}$ the vector normal to a small surface representing the surface in magnitude and direction. Then

$$D\bar{n} \cdot da\bar{n} = \sigma 4 \pi \, da \qquad \text{and} \quad D \, da = 4 \pi \sigma \, da.$$

Hence $D = 4 \pi \sigma$ and $e_0 E = 4 \pi \sigma$.

If $e_0 = 1$ then $E = 4 \pi \sigma$.

The symbol E is the magnitude of $\bar{E}$.

C. The Theory of Atmospherics

The atmosphere conducts an electric current which consists of negative and positive ions. The current flowing is usually proportional to the potential difference between any two points and the conductivity of a unit cross-sectional area of air. Since the ions are equivalent to conductors in parallel it is simpler to use the conductance of air, for to find the total conductance of a given area of air it is only necessary to add the conductances of every point in the area.

Ions move about in a field with a velocity which is the product of the field and the mobility. This latter factor is related to the velocity that an ion acquires when traversing a potential change of unity. It is actually the mean velocity of the ion after it has made so many impacts with other molecules that it no longer travels at its initial velocity.

A few brief facts will be given on the ionosphere to note how it contributes to the vertical field. In the atmosphere there is a good electrical conducting region about 100 kilometers above the earth. This region actually has from two to three layers and is called the ionosphere. Since it is a conductor this region acts as an equipotential surface having a higher potential than that of the earth. The potential difference between earth and the ionosphere is believed to fluctuate from time to time. Because the ionosphere has good conductivity, it acts as a shield that does not permit lines of force to enter the surface region of the earth from outer space, or flux lines starting on earth to extend out into space. This layer is believed to be the starting point for flux lines that end on the negatively charged surface of the earth.

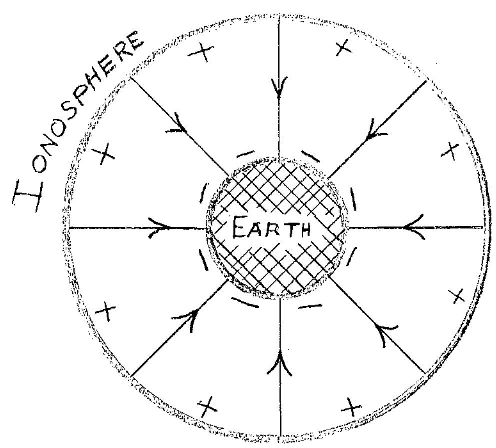

Figure 2

The Electric Field Between the Earth and the Ionosphere

The two general subdivisions in the study of atmospheric electricity are (1) the study of fair weather conditions, and (2) the study of stormy weather phenomena. The fair weather conditions are characterized by the earth carrying a negative charge and the non-existence of a charged region in the lower atmosphere. The electrical field is positive with the lines of force leaving the earth and probably terminating at the ionosphere. During fair weather the vertical current causes the ions to move up or down depending on the sign of the charge. The absence of a charged region requires that no accumulation of charge can occur. To satisfy this condition the vertical current density has to be the same at all heights. This positive vertical current arriving at the earth must be neutralized by some means. The manner by which this is done has not yet been adequately explained, but it is now thought that a negative current to the earth occurs during stormy weather. With increasing height the potential gradient decreases due to the lines of force ending on positive charged particles. These positive particles, which are formed by ionization, are more plentiful in the upper, rarefied atmosphere where the mobility is greater than in the lower, denser regions. The vertical current flowing in the direction of the lines of force is assumed to be the same at all levels. Since the conductivity is increased with height, the same vertical current will flow at higher altitudes where the voltage gradient is less. This phenomenon gives rise to a positive space charge above the earth.

The vertical current density, being proportional to the conductance of a unit cross section of air, will change if the conductivity changes. A change of conductivity near the earth will not, however, affect the vertical current density; but the change in conductivity will alter measurements made at the surface of the earth; therefor the field measurements on the earth's surface should be performed in a local that is free from ion pollution.

The ionization occurring near the earth is mainly due to cosmic rays from space and radioative radiation from the earth. Ionization produces small ions that have a mobility of one to two centimeters per second. These ions combine with the so-called Aitken nuclei, which are the nuclei responsible for the condensation of moisture in clouds. The Aitken nuclei are large ions that acquire a mobility of 10^{-2} to 10^{-4} centimeters per second. In the atmosphere the conductivity consists largely on the flow of small ions. These small ions are present in fewer amounts when an abundance of Aitken nuclei exists; therefore the varying amounts of the Aitken nuclei with time and place varies the electric field or vertical current or both.

The conditions existing during a storm are such as to make precise measurements extremely difficult. The potential gradient during turbulent weather has a polarity of either sign, magnitudes of very high values and field changes in rapid sequences. The charges in the cumulo-nimbus seldom arrange into horizontal layers; but rather into odd, strange and unusual volume forms scattered throughout the cloud which introduces into the electric field a horizontal component in addition to the vertical component. Rain, hail, snow, lightning and ions change the normal daily conduction radically. The ions are produced by lightning and point discharges from towers, buildings, poles, trees, bushes and grass.

The fair-weather-cloud and the rain-cloud have a negative base. These clouds seem to have no method for separating the charged particles. Gunn[11] in his investigations of cumuli found the electric field to be practically neutral, or less than 100 volts per meter. He determined that drops of 10 microns or larger in diameter carried +3.8 X 10^{-6} e.s.u. cm^{-3} charge, that the 10 to 10^{-2} microns drops carried +2.3 X 10^{-6} e.s.u. cm^{-3} and that the drops less than 10^{-2} microns carried -6.1 X 10^{-6} e.s.u. cm^{-3} charge. Now it appears that these clouds are made up of millions of positive and negative charged particles so close to each other that the resultant field is almost neutral. It is assumed that the vertical current density has to be the same within as without the fair-weather cloud. The number of ions within the cloud is decreased because of the large quantity of Aitkin nuclei present. The field strength must then be greater to keep the current density inside and outside the cloud equal. The field strength is increased by the accumulation of charges in the top and bottom of the cloud, and this accumulation of charges gives the cloud a positive polarity.

Cloud charges as a simplification are assumed as spherical volumes one above the other. Charge regions, one above

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[11]R. Gunn, "The Electrification of Cloud Droplets in Non-Precipitation Cumuli." Journal of Meteorology, 9 (December, 1952), pp. 397-402.

the other, are the characteristic of a bipolar cloud; moreover it is the magnitude, orientation, polarity and configuration of these charged areas that has been the subject of many investigations.

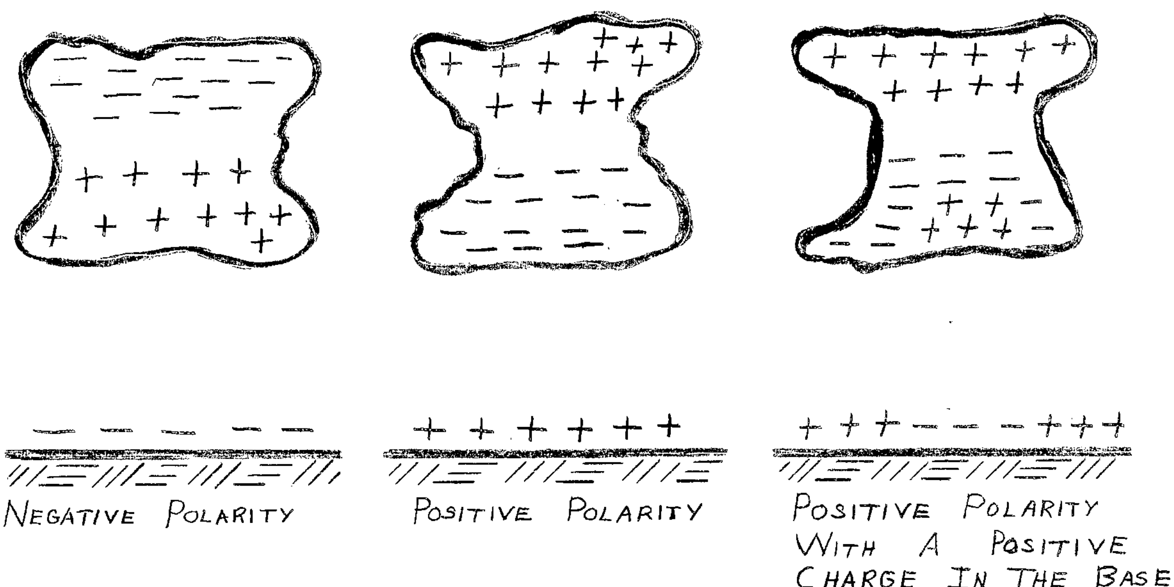

Figure 3. Cloud Polarity

Three methods to determine these cloud characteristics are: (1) to measure the potential gradient below a cloud, (2) to measure the field changes produced by lightning and (3) to send an alti-electrograph into the cloud. The use of the alti-electrograph measures the field at one point in the cloud. For the first type of measurement, assume a hypothetical cloud with a positive point charge in the top and with a negative point charge in the base.

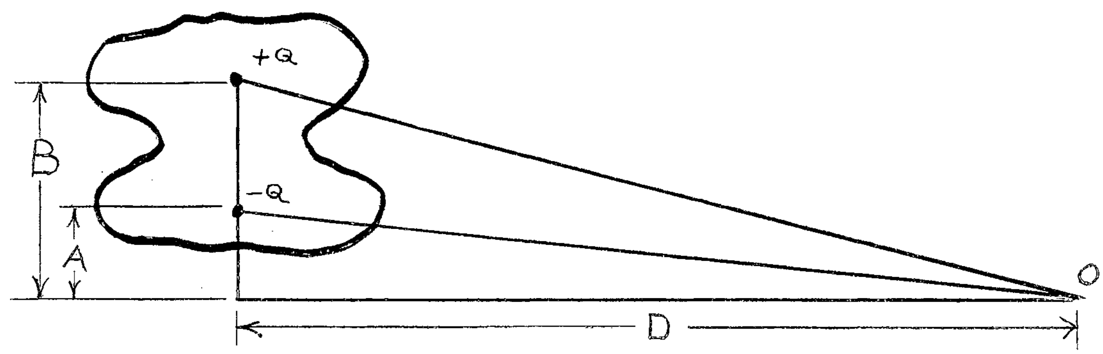

Figure 4

Point Charges in a Hypothetical Cloud

The higher cloud charge gives the sign of the vertical field when the cloud is distant, and at great distances from the observation point the fields produced by the two charges are nearly equal and very weak. As the cloud passes overhead the sign of the field is controlled by the charge in the base; also the shorter distance between cloud base and ground

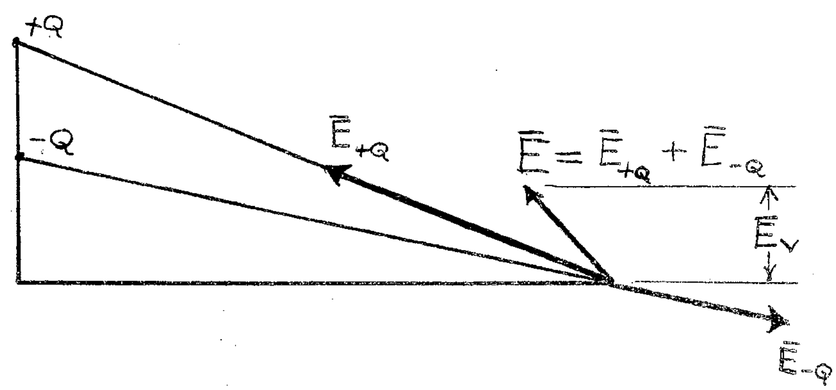

Figure 5

Electric Field Due to a Distant Cloud

causes larger field strengths to be experience. The polarity of the steady field will be changed by an approaching cloud

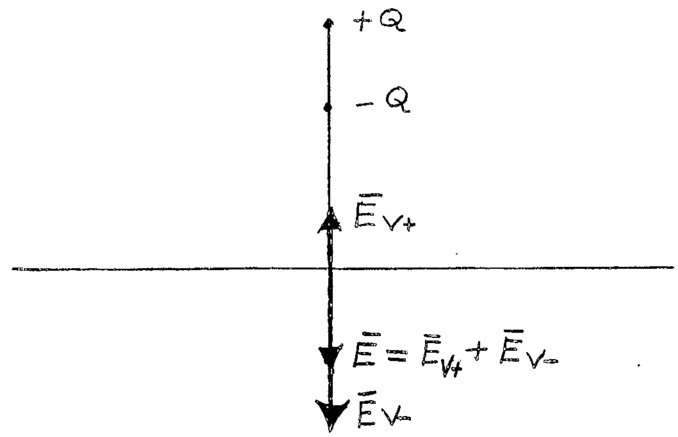

Figure 6

Electric Field Due to an Overhead Cloud

at the critical point, the field changes sign again when the critical point is reached by a receding cloud. Although in reality the charges are not point charges and do not aline into vertical regions above each other, still the behavior of the vertical fields due to clouds can be determined with some certainty by using these assumptions.

The field produced by a distant cloud is measured with the fields produced by other distant clouds; moreover it is difficult to determine the clouds affecting the field and in what amounts each cloud affects the field. The accuracy of determining the polarity of far-away clouds is not great compared to the greater degree of accuracy obtained from measuring the fields of overhead or nearby clouds, since these fields are too strong to be influenced greatly by those of other clouds. The polarity of overhead clouds can usually be determined from ground observations.

The changes in field intensity can be used to ascertain the nature of the electrical charges in clouds. These field changes are due to a transfer of charge, and the change of field potential is caused by the charges flowing in the lightning storke. The position of the charges and the type of charge in motion can be determined from a combination of electric field and visual observations. By visual observation the cloud involved in the discharge and the regions between which the discharge occurs can usually be determined. Whether the charge flow is between the base and the top of the cloud or between the base and earth is again determined by visual observation. Clouds of positive polarity passing overhead give a positive field change with an internal discharge; moreover a cloud to ground discharge from this cloud will also produce a positive field change. As the cumulo-nimbus travels farther away, a point is reached where a discharge in the cloud will manifest itself by a negative field change, yet a cloud to ground stroke by this cloud will still produce a positive field change.

CHAPTER II

INSTRUMENTS FOR MEASURING POTENTIAL GRADIENT

A. Basic Instrumentation

Many different kinds of instruments have been devised for measuring potential gradient. One early method used the water dropper,[12,13] which was developed by Lord Kelvin, as a potential equalizer. This particular instrument consisted

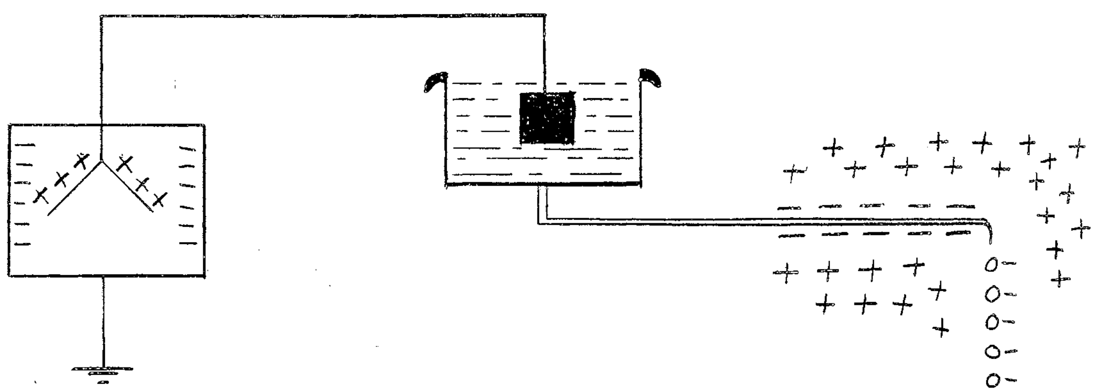

Figure 7

Water-dropper Equalizer

of an insulated water tank that had a long tube which extended to the point where the potential was measured and protruded from the base. A rod placed in the water tank was connected by an insulated wire to an electrometer which had the cage grounded.

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[12]E. N. Gilbert, Electricity and Magnetism, War Department Educational Manual EM-469, p. 90.

[13]J. A. Chalmers, Atmospheric Electricity, (Oxford, 1949), pp. 51-53.

If the air has a positive potential with respect to the tube, a negative charge will be induced on the tip of the tube. By having each droplet carrying away a proportion of the negative charge as it leaves the tube, the induced charge will be quickly carried off. The negative charge will be carried away until the tube comes to the potential of the air around it; then there will be no induced charge left on the surface. A gold leaf electroscope is used to measure the potential difference between tube and ground. The electroscope is connected to a plate or rod that is suspended in the water tank. The charge flows from the end of the tube through the water tank onto the plate and from the plate to the electroscope. In order to follow the rapid changes of gradient, the number of drops per unit time has to be increased. However there is a limit to the maximum rate that drops can fall, and this limit confines the water-dropper to the measurement of relatively slow field variations.

Another type of equalizer uses a radio active disk,[14] ball or rod.[15] These various forms are coated with a thin layer of a radio active substance. In order to keep the coating protected a lacquer, varnish or other suitable material is applied over this coating. The radio active substances used are predominantly alpha partical emmiters.

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[14] ..... "Atmospheric Electricity." Carnegie Institution of Washington Department of Terrestrial Magnetism, Vol. 3, pp. 830-2.

[15] J. A. Fleming, "Terrestrial Magnetism and Electricity." Physics of the Earth, VIII (1939), pp. 233-4.

These positive alpha particles are slow and heavy and do not move far from the emitting source. The air molecules near the equalizer are broken up into positive and negative ions by the alpha particles, and when the air has initially a negative potential with respect to the collector, a drift of negative ions will leave the air and flow onto the equalizer. This flow, due to the potential difference between the air and probe, will continue until both elements obtain the same voltage.

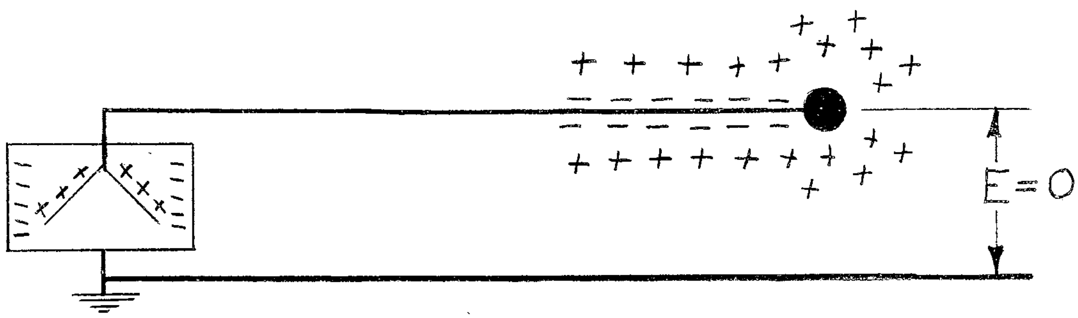

Figure 8

Induced Charge Produced by a Change in Gradient

When the initial ground is first removed from the probe it will acquire an induced charge when raised into the air; this induced charge will cancel the electric field around the probe.

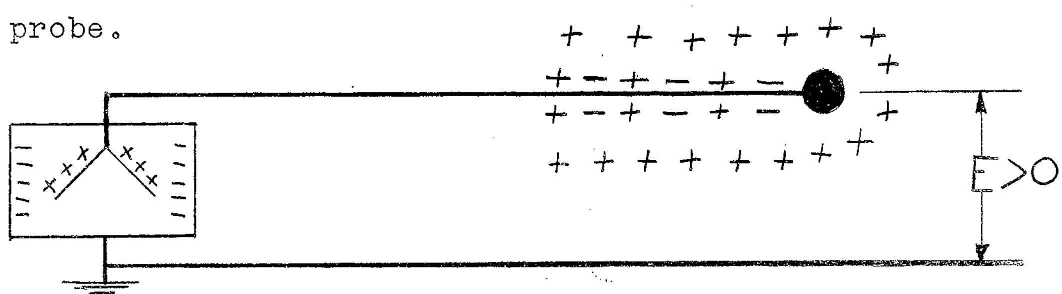

Figure 9

Equalizer Acquiring the Potential of the Air

An ion current will then flow to the collector to bring it to the potential of the air. When both potentials are the same, the ion current stops. A change of potential gradient will induce another charge on the probe, and an equal and opposite charge will be fed to the electroscope causing another change of reading. The probe is then equalized to the new potential, and is again ready for the next gradient change. A time delay occurs between the time when the gradient change occurs and when the equalizer acquires the new potential. This time delay limits the radio-active equalizer to sluggish field changes.

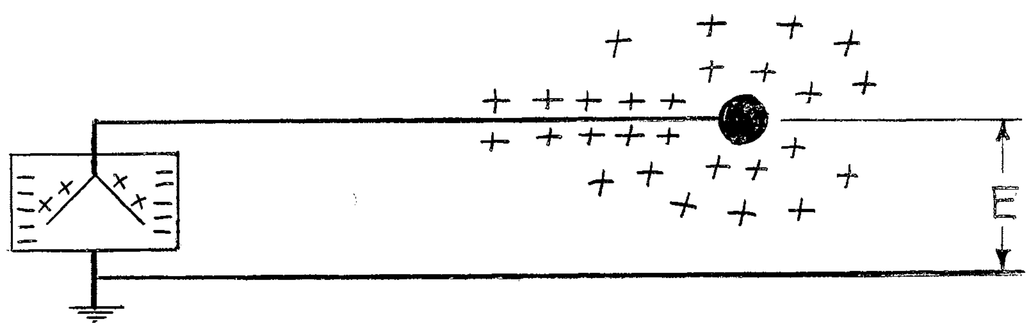

Figure 10

Equalizer at the Potential of the Air

To study the nature of the fields existing through the periods of storms C. T. R. Wilson[16] developed the elevated-sphere and the test plate apparatus. The elevated sphere apparatus is a metal ball on an insulated hinged rod which permits the sphere to be lowered into a grounded metal box.

16C. T. R. Wilson, "Investigations on Lightning Discharges and on the Electric Field of Thunderstorsm." Philosophical Transactions of Royal Society, 221-A (1921) pp. 73-115.

An insulated wire connects the sphere to a suitable electrometer. The test plate consists of a metal plate embedded in a large circular container. The container fits flush into a circular hole in the ground, and this container is insulated on the sides and bottom from the ground. From the embedded plate a lead is used to connect to a capillary electrometer.

In general these instruments are best suited for different types of measurements. For example in fair weather, when the potentials are steady and relatively small, the ionization collector is best applicable; while for mild and distant storms the point discharge or elevated sphere are best adapted; and for violent or near by thunderstorms the test-plate performs best. The raised sphere uses the principle of electrostatic induction. For measuring purposes the sphere is first grounded, then raised to a known height. Assuming that the earth has a negative charge and the air above to be at a positive potential with respect to the earth, a negatively induced charge will be induced on top of the sphere. A connection made from the sphere to a capillary electrometer allows the positive charge on the sphere to flow to ground as it is raised from earth into the air. The charge Q flowing to ground is measured by the capillary electrometer. The capacity C of the sphere can be calculated by knowing the physical dimensions of the sphere from the

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[17] C. T. R. Wilson, Proceedings Royal Society, 92-A (1916), p. 555.

formula

$$C = 4\pi\mathcal{E}a$$

where C is the capacity in farads, $\mathcal{E}$ the dielectric constant and a is the radius of the sphere in meters.

To account for the effect produced by the conduction of the nearby earth, the potential due to the image charge at point h must be accounted for. The image potential V_i at a distance h above ground is

$$-V_i = \frac{-Q}{2h(4\pi\mathcal{E})} .$$

The summation of the potentials at h, with the sphere in the raised position, must equal zero and, is given by the expression

$$V + \frac{Q}{(4\pi\mathcal{E})\ r} - \frac{Q}{(4\pi\mathcal{E})\ 2h} = 0$$

The symbols used are: V to represent the voltage at h in volts, h for the height of the sphere in meters, r for the radius of the sphere in meters and Q for the charge flowing through the electrometer. By rearranging the above equation it follows that

$$V = \frac{Q}{4\pi\mathcal{E}}\left[\frac{1}{2h} - \frac{1}{r}\right]$$

The potential gradient $\overline{E}$ is determined from the expression

$$E = \frac{V}{h} .$$

A negative charge will flow through the electrometer when the sphere is lowered back to earth; moreover this charge is equal to the positive charge that flowed when the sphere was elevated. The charge flowing, when the sphere is raised or lowered, is proportional to the field strength. Changes in gradient produce changes in the bound charge on the sphere. The field variations will produce greater changes of bound charge on the sphere than on the earth because the sphere has a greater potential to equalize. To measure the potential gradient the sphere has to be raised or lowered and thereafter the bound charge has to be released through a suitable measuring instrument. This feature does not lend itself readily to continuous recordings of the electric field. Another disadvantage is that it is difficult to differentiate between the current or charge flow due to induction and that due to corona discharge. This instrument is particularly adaptable to the measuring of potential gradient changes caused by distant thunderstorms where the change of bound charge occurs instantly with a field change.

The point discharge collector is another means of measuring electric fields. It is a needle, usually a platinum needle which does not corrode, mounted several feet in the air, and it is connected through a suitable measuring device to ground. When a negatively charged center in a thunderstorm passes over the earth, a positive charge is induced on the earth's surface, and as a result the top of the point acquires a positive charge which attracts the negative ions in the vicinity of the point. The potential gradient becomes intensified, and when the gradient has exceeded a critical value, a sudden surge of positive ions to the atmosphere occurs. Thereafter a positive space charge will surround the point which so greatly weakens the field that the discharge is stopped. The charge afterwards again builds up on the point, and the entire process is repeated again and again. The frequency of repetition of the discharges depends on the configuration of the collector, the size of the points, the strength of the field and on the type of objects surrounding the instrument. The discharges occur in the order of thousands of cycles per second which is too fast for recording instruments to follow; however the recorders do give the mean value of the discharge current. The use of corona current as a measure of electric field has three disadvantages: (1) the field intensity must be a given value before corona discharge occurs; (2) the calibration of the instrument is not linear; and (3) a current flowing into or out of the point occurs in response to lightning discharges producing changes in the electric field which in turn effects the collector. This latter phenomena is easily distinguished from corona, for the variations will be larger and of greater rapidity than that caused by corona discharge. The deflections caused by this effect may or may not have the same sign as the corona current because their magnitude is not representative of changes of field intensity.

To determine the charge distribution in a thunderstorm, a point attached to a sounding balloon was used by Simpson and Scrase[18] at Kew Observatory. As shown in Figure 11 two 20 meter wires, AB and CD, were attached below the balloon. These wires made electrical contact with each other through a piece of pole-finding paper BC. As the balloon made its way aloft adjacent to clouds of positive polarity negative ions were caused to leave from point A, and to flow to point D. The current flow through the wire from A to D passes through the disk causing a brown stain, due to electrolytic action, to appear at point B.

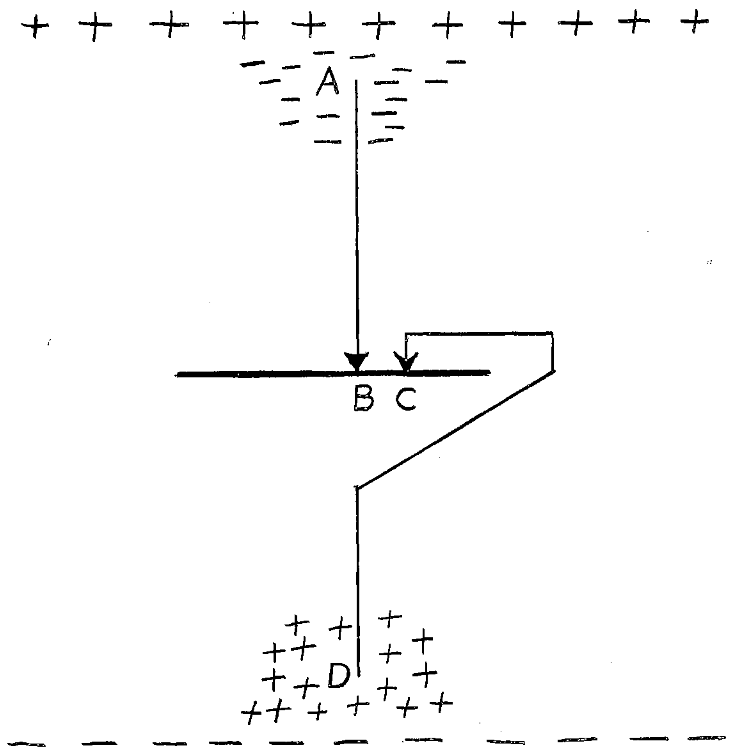

Figure 11

Point Collector with Pole-Finding Paper

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[18]G. Simpson and J. F. Scrase, "The Distribution of Electricity in Thunderstorms." pp. 309-314.

A reversed field makes the stain to appear at point C.

The point discharge is also used with the radiosonde method of measuring potential gradient in clouds. The radiosonde employed by Berlin[19] used the current flowing through the points to operate the signal frequency of the oscillator. A switching arrangement in the radiosonde made it possible to send back to the receiving station the pressure, altitude and the potential gradient.

A surface system which used the point as a collector, consisted of a needle point antenna connected to a G. E. recorder. It was calibrated for plus or minus 700 volts per centimeter; a high speed photoelectric recorder[20] was used to record the rapidly occurring fluctuations; two recording speeds, one inch per hour and one inch per second were used.

To find the current flowing through the points the empirical equation[21]

$$i = B \left[F^2 - M^2 \right]$$

is used where F is the existing potential gradient, M the minimum gradient required for a discharge and B a constant which depends upon the sharpness, number and the series

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[19] R. F. A. Berlin, "Radiosonde Potential Gradient Measurements." Electronics, 21 (January, 1948), pp. 184-190.

[20] U. S. Air Force, Navy, National Advisory Committee for Aeronautics and Weather Bureau, The Thunderstorm Report of the Thunderstorm Project, p. 265.

[21] F. J. W. Whipple and F. J. Scrase, "Point Discharge in the Electric Field of the Earth." Meteorological Office Geophysical Memior, No. 68, p. 6.

resistance of the point collector. This formula applies only when a large resistance is inserted between the points.

The theory of the insulated plate stems from the formula

$$E = -4\pi\sigma.$$

Since the earth can be regarded as a sphere, the potential gradient at the surface will be proportional to the charge carried by the earth. The bound charge on the plate, which has to be released for each reading, is released by covering the plate with an earthed cover. The test plate measures the number of lines of force that end on the plate. This method is particularly suitable for measuring the electric field and electric field changes occurring in overhead thunderstorms.

Another potential gradient instrument called the field mill was first used by Macky.[22] It consisted of a rotating plate that covers and uncovers an insulated plate. An alternating potential is produced on the insulated plate by the changing of the bound charge thereon by the rotoring plate. The alternating voltage, which is proportional to the bound charge placed on the insulated plate, is fed to an amplifier that drives a recorder. In this manner continuous recordings are obtained. The polarity of the

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[22] W. A. Macky, Terrestrial Magnetism and Atmospheric Electricity, 42 (1937), p. 77.

potential gradient cannot be determined directly. To overcome this difficulty the final output is rectified after amplification by a mechanical rectifier driven in synchronism with the rotating shielding plate. Rectification is accomplished by having the rectifier connected to the drive shaft of the motor turning the rotor plate. A synchronous motor turning at 900 rpm was used by Termain and Cheek[23] in their voltage gradient meter, which could measure gradients from 40 to 40,000 volts per meter.

The radio activity collector has been and is still commonly in use as a potential equalizer. This instrument operated to produce ionization in a small volume of air around the collector. When a potential difference exists between collector and air the ions will move in the field of force until both collector and air are at the same potential. Alpha ray emitters are used because the large, slow alpha particles do not disturb the field away from the equalizer. The emission of both beta and gamma particles will seriously distort the field around the collector by producing ionization beyond the range of the equalizer. The two radio active substances often used are polonium and ionium.[24] It

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[23]R. L. Termain and R. C. Cheek, "A Voltage Gradient Meter." Electrical Engineering, 69 (May, 1950), p. 425.

[24]S. J. Mauchy, "Control of Ionium Collectors Used in Potential-Gradient Registrations at the Observatories of the Department of Terrestrial Magnetism." Carnegie Inst. Wash. Year Book, 25 (1926) p. 227.

is better to use ionium than polonium because the half life of ionium is much longer. However ionium is difficult to put on objects as a coating. One collector employed had a lacquer coating on one side of a brass disk. Ionium was embedded into the lacquer coating. Another thin coat of lacquer was applied to keep the radioactive materials from contaminating the site. The second coat lowers the emission of alpha particles, thereby increasing the effective resistance. Two collectors are used, one as a standard and the other for actual measurements. As the protective coating is worn off by abrasion and weathering, the activity of the collector increases, and when the one in use has increased its activity by 20 or 25 per cent the collector is either replaced or a new lacquer coating is applied.[25] The observatories of the Department of Terrestrial Magnetism of Washington[26] used a collector of this type that was mounted 2.54 meters above ground level and one meter out from a wall of a building three meters high. A Dolezalek electrometer was used to measure the voltage.

Collectors of the water dropper and radioactive variety both have an effective resistance. For the water-drop type the charge Q carried away by each water drop is

$$Q = C\ V$$

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[25] *Ibid.*, p. 227.

[26] J. A. Fleming, "Terrestrial Magnetism and Electricity." p. 237-8.

for a system where C is the capacity of the drop and V is the potential difference between the air and collector. If there are N drops falling per second, the current flow from the dropper is then

$$I = N\,Q = N\,C\,V.$$

The effective resistance R of the collector is then

$$R = \frac{V}{I} = \frac{V}{NCV} = \frac{1}{NC}.$$

To reduce the effective resistance the number of drops per second or the capacity of the drop has to be increased. To decrease the effective resistance of the water dropper the number of drops N must be increased which decreases the water drop capacity. To find the effect of a leakage resistance R to ground, the collector is considered as a constant current generator. For the case with no leakage to ground the voltage V_1 between ground and collector is

$$V_1 = S_i,$$

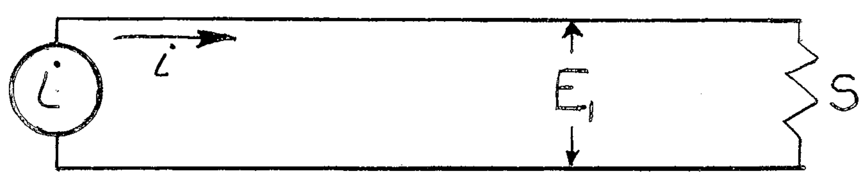

Figure 12

Equivalent Circuit for a Potential Equalizer

where S is the effective resistance of the collector and i is the constant current produced by the generator. The voltage V_2 that is developed due to the leakage resistance R to ground on the collector is $V_2 = \frac{iRS}{R+S}$.

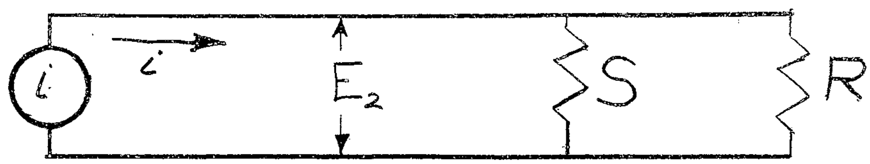

Figure 13

Equivalent Circuit Altered by Leakage Resistance

The ratio of the two voltages is then

$$\frac{V_2}{V_1} = \left[\frac{iRS}{R+S}\right]\left[\frac{1}{Si}\right] = \frac{R}{R+S} .$$

In order to have the ratio $\frac{V_2}{V_1}$ equal to unity, S much approach zero. The effective resistance S of the collector can be reduced only to a limiting value determined by the physical construction of the instrument.

The preceding discussion applies equally well to the radioactive element. The effective resistance of a ratioactive collector cannot be computed, but it can be measured by employing an ionization chamber. The effective resistance of the Kew water dropper was estimated by Scrase[27] to be about 5×10^{10} ohms and that of a polonium collector as about 2×10^{10} ohms. A leakage resistance of ten times the effective value will give a ratio for $\frac{V_2}{V_1}$ of 0.91.

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[27]G. Simpson and J. F. Scrase, "The Distribution of Electricity in Thunderstorms." Proceedings of the Royal Society, 161 (August, 1937), p. 309-352.

The leakage resistance of these instrument must therefore be in the neighborhood of 500,000 to 200,000 megohms to give reliable potential readings.

The field changes in thunderstorms have been investigated with the object of establishing the nature of radio atmospherics. Appleton and Chapman,[28] in their study of atmospherics, used an exposed conductor consisting of a Wilson phere connected to a rapid response triode electrometer. The output of the triode was applied to an amplifier which in turn applied the deflection voltage to an oscilloscope. The rate of change of the electric field could be measured by placing a high resistance in series with the conductor. To permit the electrometer tube to follow the faster field changes the time constant was made very small, and an arrangement was incorporated whereby the time constant could be varied. Pictures were taken of the oscilloscope traces which later were analyzed. Atmospherics of storms at great distances (over 100 km) could be detected and analyzed.

The installation used by Watson and Appleton[29] to study atmospherics consisted of:)a) the aerial system, (b) a triode voltage amplifier, (c) a cathode-ray oscillograph and and (d) a device for the local generatation of known type of impulses. To give faithful reproductions of the field

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[28] E. V. Appleton and F. W. Chapman, "On the Nature of Atmospherics IV." Proceeding of Royal Society of London, 185-A (January, 1937), pp. 4-5.

[29] P. A. Watson and E. V. Appleton, "On the Nature of Atmospherics I." Proceedings of the Royal Society of London, 103-A (1923), pp. 84-102.

changes a highly damped antenna with a time constant much less than that of the atmospheric was used while the methods that have been described do not include all the possible ways for measuring potential gradient and the rate of change of the electric field, they are essentially the basic methods from which are built many variations.

B. The electrometer used to measure the potentials of the various collectors operates from the 117 volt 60 cycle power lines, with a one ampere fuse in series with the power line to serve as a protective device. The switch S_1 is the on-off switch that supplies power to the power transformer T_1. This transformer T_1 supplies 6.3 volts to the filament of the 6AK6 and to a pilot lamp; a 5 volt winding supplies the filament current for the 5Y3 rectifier; the 680 volt high voltage center-tapped winding is connected to the 5Y3 rectifier for full wave rectification. A resistance-capacitance filter is used to smooth out the ripple voltage.

The power supply was designed in accordance with the design procedure described by Reich,[32] with the addition of one assumption in the procedure. Normally a value of resistance equal to the series resistance of the high voltage winding to center tap is the value used. Since the high voltage output was too high, it was necessary to lower the voltage across the input condenser C_1; moreover a large input condenser C_1 was needed to obtain the necessary filtering,

[32] H. J. Reich, Theory and Applications of Electron Tubes (New York, 1944), pp. 569-590.

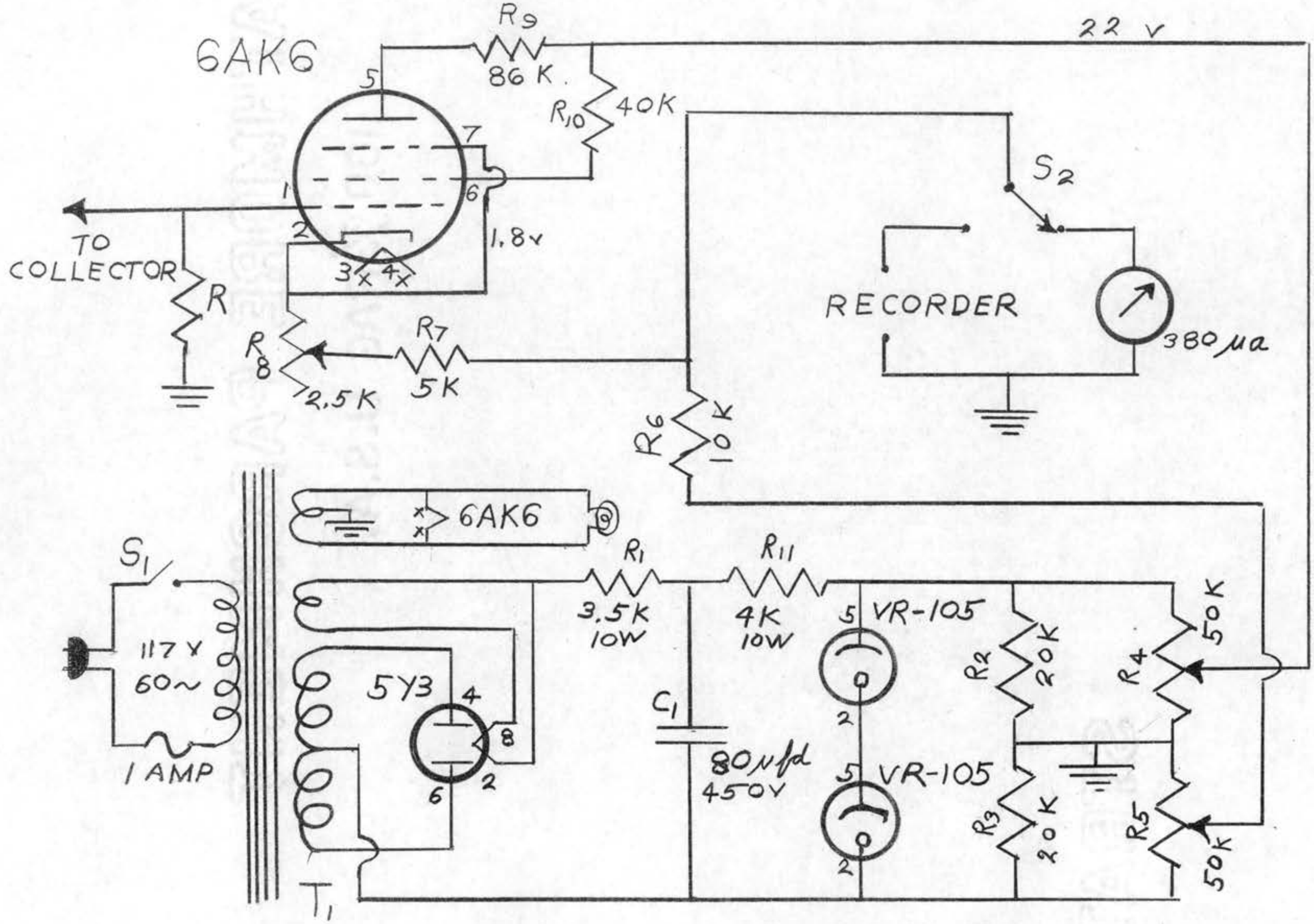

Figure 14. Diagram of Electrometer

and consequently the surge current had to be reduced. The method used to overcome these difficulties was to place a resistor R_1 between the 5Y3 rectifier and the input condenser C_1. The assumption was then made that the transformer series resistance was R_1 plus the transformer resistance. The voltages calculated in the designed procedure agreed within 10% of the voltages actually measured after the supply was built.

The resistor R_{11} is a resistance that allows the voltage regulator tubes (VR-105) to maintain a constant voltage with line voltage variations from 105 to 130 volts. The resistors R_2, R_3, R_4 and R_5 are bleeder resistors that carry a current that is five times the current drawn by the 6AK6. By using a large bleeder current, the voltage across the tapped portion of R_4, which supplies the plate and screen of the 6AK6, will not change appreciably with changes of plate current. Consequently, the screen voltage will remain constant, and as a result the plate characteristic curves remain constant with a change in grid voltage. The bucking current[32] through the meter is supplied from the tap off R_5 through a current limiting resistor R_6. The value of R_6 gives the desired bucking current with the tap on R_5 at the mid-point position. The plate resistor is R_9 and the screen resistor R_{10}. The two resistors R_8 and R_7 make up the cathode resistor assembly, where R_8 controls the bias voltage. The

[32]S. C. Hoare, Trans. Am. Inst. Elec. Eng., 46 (1927), p. 451.

use of wire wound resistors of low temperature coefficient are recommended by Victoreen.[33] The grid resistor R is the total leakage resistance of the grid circuit. In order to maintain this resistance at a high value the tube is used without a tube socket, and is held in place by a metal clamp.

The procedure for preparing the tube for use is as follows: (1) the clamp was mounted around the tube, (2) the tube and clamp were mounted on a heavy metal plate to keep the tube from falling over, (3) two six-inch twisted strands of #23 wire were soldered to each tube prong, (4) the tube was washed in absolute pure ethyl alcohol, (5) the tube was baked at 500° F. for 2 hours and (6) the mounting base was removed and the tube immediately placed in the instrument. During the process the glass of the tube was never touched with the hands, as this would give leakage paths to ground or between the electrodes.[34] With dry air the resistance remains very high, but when moisture becomes present in the air the tube surface will become moist and the resistance is reduced to a low value. This difficulty is remedied by applying a coating of silicone[35] to the tube.

One of the simplest definitions[36] of a three-element electron tube is that it is a device in which the current flowing from the cathode to the anode is controlled by the

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[34] J. A. Victoreen, op. cit., p. 438.

[35] G. A. Hay, "Receiving Valves for Electrometer Use." Electronic Engineering, 23 (1951) p. 260.

[36] J. A. Victoreen, op. cit., p. 433.

potential of a grid to which no current flows. By this definition the triode would show no change of plate current if the grid were disconnected; for no current flows to or from the grid to change its potential. Grid current was found by Elmore and Sands[37] to be caused by the cathode emitting ions which flow to the grid and by positive ions which are produced by the ionization of the residual gas in the tube. The plate or other parts of the tube also emit electrons. The impinging of electrons on the plate have enough energy to cause emission of soft X-rays that in turn can bombard the grid and release electrons. Electrons also reach the grid from the cathode by virture of the finite velocity with which they are emitted. To test for grid current the instrument was placed in a metal box where the electric field was known to be zero. The grid was then grounded and the meter zeroed at mid-scale. If the meter reading is increased after the ground is removed it can be concluded that there is a flow of grid current. The parameters of the circuit were adjusted in order that no grid current would flow. The instrument was tested for linearity. As a final check it was noted that when ± 3 volts was applied to the signal grid, a full scale deflection from mid-scale was registered on the meter.

The collector is connected by a brass rod 18 inches long to the control grid by a short wire. The rod is sup-

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[37]W. C. Elmore and M. Sands, "Electronics." National Nuclear Energy Series, Division 5, Vol. 1 (New York, 1949), pp. 180-1.

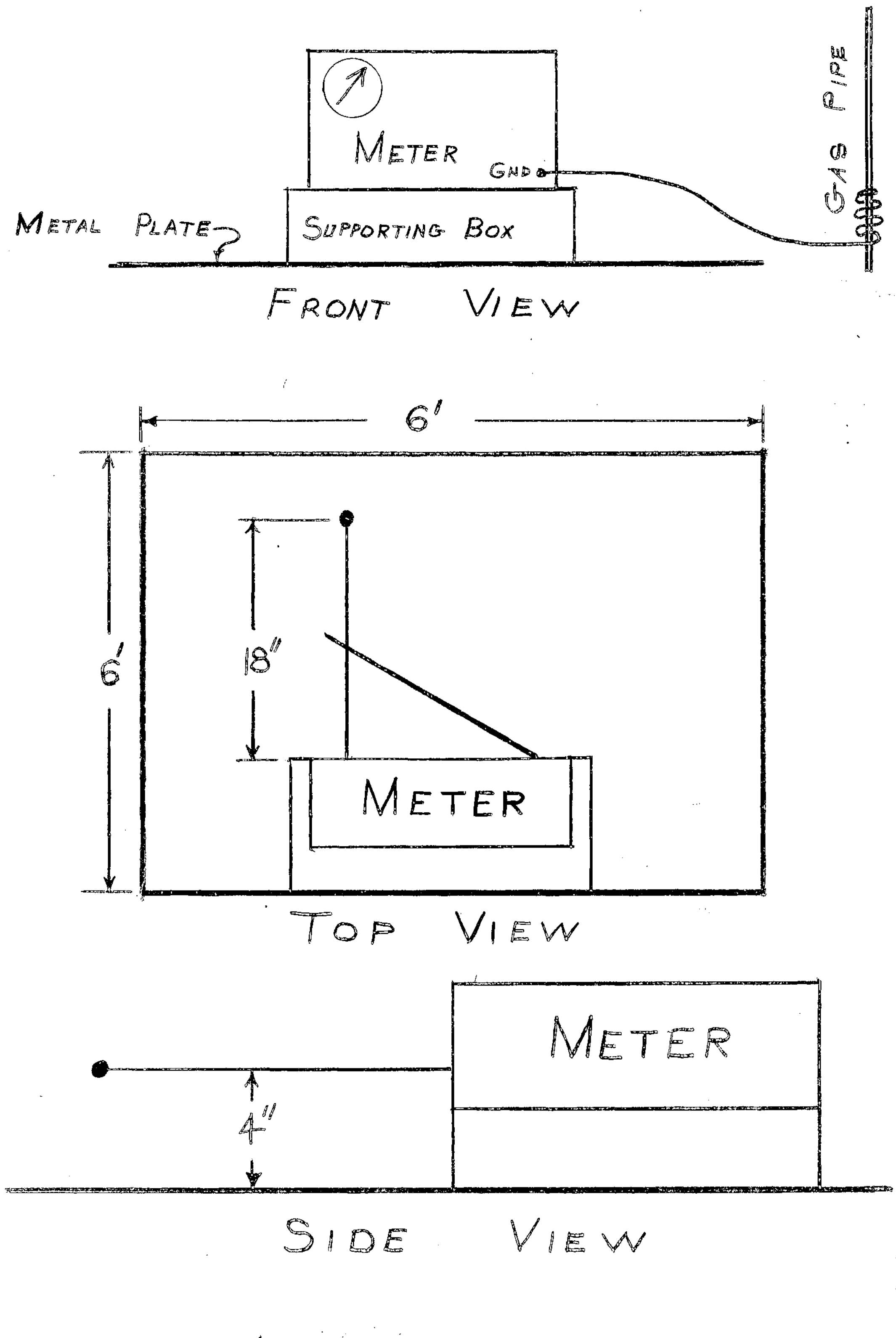

Figure 15. Instrument Installation

ported by a one-inch diameter polystryrene rod 12 inches long mounted at a 30° angle with the back of the case. The collector is horizontally mounted 4 inches above and in the middle of a six foot square metal plate. This plate is also grounded. The whole installation is placed inside the attic of a house. The field is distorted somewhat by the roof, but since the sign of the field changes are of primary importance it is believed the distortion of the field will not greatly affect the measurements.

One difficulty encountered consisted of fluctuations in the meter as a result of variations in line voltage. This was eliminated by using a constant voltage transformer. The fluctuations were due to the filament temperature of the 6AK6 being changed by the variations in input voltage. Another trouble experienced was the change of the meter reading when the line plug was turned over. The cause was that the constant voltage transformer had a small leakage current flow to ground. By mounting this transformer on insulators the effect was eliminated. Transformers used in this type instrument should have more insulation than usual in order to prevent the flow of these small but troublesome currents.

The electrometer used to measure the voltages was taken from a circuit that was developed to measure the rate of change of potential gradient. One of the objectives of the of the project was to build an instrument using a circuit designed to measure the rate of change of gradient. Another objective was to determine the possibilities of this circuit for measuring the potential gradient and in addition to make measurement of the fields produced by thunderclouds. Originally it was intended to measure the potential gradient using a potential equalizer. However experiments have shown that the electrometer would not hold a charge when applied to the grid circuit when the equalizer was removed; moreover it was determined that the instrument performed the same with as without the equalizer; in addition the response of the instrument to field changes was believed to be too fast to be accurately reproduced by equalizer action. Now it is believed that the fundamental operation is similar to that of the test plate or elevated sphere. The instrument is believed to operate on the principal of induction in the measurements of the changes of electric field and to be equivalent to the test plate in operation. A down scale reading of the meter is believed to correspond to a positive field change, and consequently the meter will show a more positive reading for a negative field change.

The suggested improvements in design that are mentioned here represent only a few of the many refinements that can be made to improve the instrument performance. The most necessary improvement is to place the electrometer tube in a dust-proof housing. Again the probe should be mounted coaxially in the polystryine tube, with the tube and rod extending at right angles into the case with at least three inches of the polystryine rod extended on either side of the case to act as insulation. In particular a site should be choosen for the instrument that gives good vision in all directions. By the addition of an amplifier the range of the instrument can be easily extended to 10 and possibly 20 miles. It would then have a range equivalent to the elevated sphere.

CHAPTER III

THE ELECTRIC PHENOMENA OF THUNDER-CLOUDS

Scientists the world over have made contributions that have made it possible to determine more exactly the precise nature of the thunderstorm. Wilson was one of the first of these scientists to begin making a quantitative study of thunderstorms.[38] His investigations led to the belief that the negative charge on the earth's surface was replenished by a negative current flowing from the base of clouds of positive polarity.[39] To test this theory, it is necessary to make numerous observations in every part of the world to ascertain whether most of the existing clouds are of positive polarity; moreover a hypothesis is adopted that a thunder-cloud is essentially bipolar to facilitate the understanding of the phenomena involved in determining the polarity. The exact positions or relative magnitudes of the charges will not be specified, but the charges in the cloud will be classified as the upper and the lower charge. Two charges in a cloud, one a positive charge at a height H and the other a negative charge at second height h, lying in a vertical plane will produce an electric field on the earth; the vertical component of this field is given by the formula

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[38] C. T. R. Wilson, Royal Society Proceedings, 92-A (1916), p. 555.

[39] J. E. McDonald, "The Earth's Electricity," Scientific American, 188 (April, 1953), pp. 32-7.

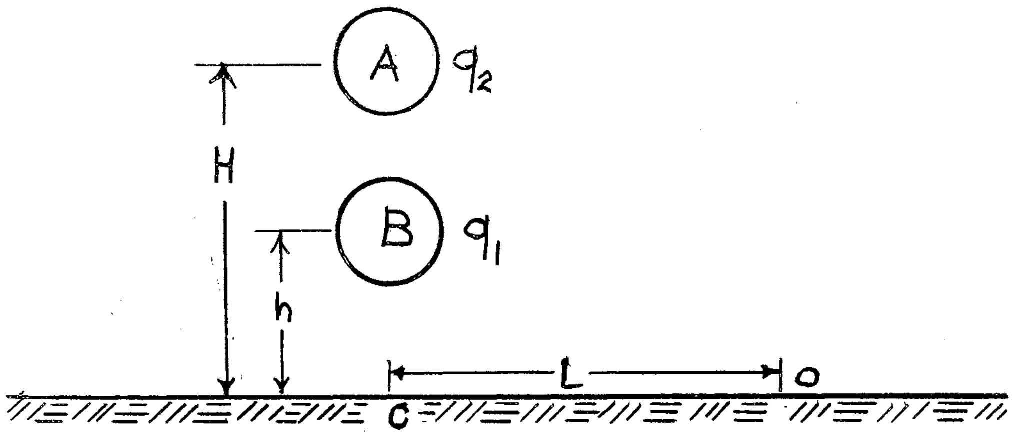

Figure 16. Positive Bipolar Cloud

$$E = \frac{2\ q_2 H}{(H^2 + L^2)^{3/2}} - \frac{2\ q_1 h}{(h^2 + L^2)^{3/2}} .$$

The two terms in the numerator of this formula account for the image of the two charges in the earth. For values of L less than a constant critical value the charge B will determine the sign of the vertical field; on the other hand for values of L greater than the critical value the charge A will control the sign of the vertical field; moreover the conditions that the sign of the field will reverse with distance are that

$$q_2 > \frac{h_1^2}{H_2} \qquad \text{and} \qquad q_1 < \frac{H_2}{h_1}\ q_2 .$$

Still another way to obtain the electrical nature of clouds and their polarity is to measure the sign and magnitude of the electric field changes caused by lightning. Another necessary assumption is that an isolated bipolar cloud will have nearly vertical discharges between the two poles, or between one of the poles and ground. By definition an AC discharge is a discharge between the upper pole and ground, and a BC discharge is one between the lower pole and ground; while an AB discharge is one within the cloud. The field changes produced by different discharges are as follows:

AC discharge

$$\Delta E = \frac{-2 Q_2 H}{(H^2 + L^2)^{3/2}}$$

BC discharge

$$\Delta E = \frac{-2 Q_1 h}{(h^2 + L^2)^{3/2}}$$

AB discharge

$$\Delta E = 2Q_2 \left[\frac{-H}{(H^2 + L^2)^{3/2}} + \frac{h}{(h^2 + L^2)^{3/2}} \right] \text{ when } Q_1 > Q_2$$

and

$$\Delta E = 2Q_1 \left[\frac{H}{(H^2 + L^2)^{3/2}} - \frac{h}{(h^2 + L^2)^{3/2}} \right]$$

when $Q_1 < Q_2$,

where Q_2 and Q_1 includes both sign and magnitude of the upper and lower charge respectively. For discharges of the AC and AB type the field change is independent of distance, but for a discharge within the cloud the polarity reverses as the distance between observer and cloud increases. It is also possible to have discharges occur between the top of the cloud and the ionosphere which will produce the same type of field change as an AC discharge. Table I and II shows the field changes produced by different type discharges in positive and negative polarity clouds.

TABLE I

Positive Polarity Cloud

Discharge	Sudden Field Change	
	Near	Distant
AB	Positive	Negative
BC	Positive	Positive
AC	Negative	Negative

TABLE II

Negative Polarity Cloud

Discharge	Sudden Field Change	
	Near	Distant
AB	Negative	Positive
BC	Negative	Negative
AC	Positive	Positive

The study of the association of positive field changes with cloud to ground discharges should be made at night when these discharges can best be seen.

Many exceptions occur that falsify the assumptions that have been made. Since the discharge within a cloud involves the disappearance of equal and opposite quantities of electricity, an exception will occur if one pole had originally a greater charge; for another discharge may occur between this pole and the earth, the upper atmosphere, or another cloud giving different types of field changes. In addition many discharges do not take place in the cloud but between the charged regions of different clouds. These changes can be of either polarity. Also clouds of posititive polarity will give a positive field change when discharged by more distant clouds, particularly when the charges are about on the same plane, or if the lower charge is closer to the observer than the upper charge. This type of discharge is called skew lightning and is manifested by the horizontal flashes that occur across the sky.

A cloud of positive polarity at a great distance will produce a large number of negative field changes, and as the cloud approaches the observer this condition will be reversed and a large number of positive field changes will occur. This pattern, however, is greatly influenced by the presence of numbers of positive and negative charged regions scattered throughout the cloud which vary the components of the electric fields. Moreover it is not possible to determine the polarity of clouds from just this reversal of field changes. Both field change measurements and visual observations are needed to determine the polarity.

The steady field of the potential gradient is defined as the field produced when neither pole of the cloud is discharging or recovering from a discharge.[40] By measuring the steady field and noting the sign of this steady field,

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[40]B. F. J. Schonland and J. Craib, "Electric Fields of South African Thunderstorms." Proceedings of Royal Society, 114-A (1927), p. 232.

the polarity of the cloud can usually be determined. Generally, however, the effect of the fields of other clouds have such an influence that these measurements cannot be used to find the polarity of any particular cloud. For seven storms studied by Schonland in 1927 the steady field exceed -5000 per meter for 300 minutes and +5000 volts per meter for 5 minutes.[41] For storms ranging in distance from 8 to 35 kilometers away, Schonland and Craib[42] found that for 798 field changes studied, 666 were negative and 132 were positive. This gave a ratio of 5.0 to 1.0; for five storms that were less than 6 kilometers distant there were 39 positive and 9 negative field changes. This resulted in a ratio of 4.3 to 1.0. For the first group of storms the changes were predominantly negative for the sudden field changes due to distant lightning discharges; while those for the second group were predominantly positive. During a two-year period Schonland[43] found that 517 negative and 6 positive field changes were caused by pole to pole discharges for storms that were more than 15 kilometers from the observing station, moreover two of these positive field changes were produced by two horizontal discharges. For a two-year period the number of positive field changes due to cloud to earth discharges from these

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[41]B. F. J. Schonland, "Ther Interchange of Electricity between Thunderstorms and Earth." Proceedings of Royal Society, 118 (1928), p. 255.

[42]B. F. Schonland and J. Craib, loc. cit., p. 236-7.

[43]B. F. J. Schonland, "Polarity of Thunderclouds," Proceedings of Royal Society, 118 (1928), p. 238.

distant storms were limited to 48. Only 6 positive field changes due to discharges within the clouds were recorded during this period; moreover 2 of these 6 positive field changes were caused by horizontal discharges.[44] On the contrary for 6 storms that were within 7 kilometers of the observing station, there were 188 positive and 9 negative field changes, giving a ratio of 21 to 1.[45] These results indicated that the clouds were of positively polarity, and it was concluded that the polarity of South African thunderstorms were essentially positive.[46]

Other scientists have also studied the thunderstorm from the ground. During the years of 1914, 1915 and 1917 Wilson[47] recorded 528 positive discharges and 336 negative discharges. These results, which were obtained by the use of the raised sphere and the test plate[48] gave a ratio of 1.56. Another observer, Wormell,[49] used a point discharge device that was raised to a height of 8.3 meters. His observations suggested that the cumulo-nimbus cloud is of positive polarity.[50] The point collector was also used by Wipple and Scrase to study

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[44] Ibid., p. 239.

[45] Ibid., pp. 243-4.

[46] B. F. J. Schonland, loc. cit., p. 247.

[47] C. T. R. Wilson, "Investigations of Lightning Discharges and the Electric Field of Thunderstorms." Proceedings of Royal Society, 221 (1921), p. 85.

[48] Ibid., pp. 74-7.

[49] T. W. Wormell, "Currents Carried by Point-Discharges beneath Thunderstorms and Showers." Proceedings of Royal Society, 115 (1927), pp. 443-4.

[50] Ibid., p. 455.

the electric field of the earth,[51] and their measurements gave a radio of 3.5.[52] Simpson states that a discharge can leave the cloud, travel towards the earth, but fail to reach the earth;[53] furthermore that the measurements of field changes alone lead to extremely ambiguous results. This ambiguity can be overcome to some extent by the use of several stations that are not too close together.[54]

The measurements described in the last paragraph were made at the earth's surface and give at best only a general indication of the electrical structure of the clouds. In order to determine the charge arrangement in thunderclouds Simpson and Scrase employed potential gradient instruments. These devices were of the point collector type, and were attached to sounding ballons. The variations of the sign of the potential gradient were measured from ground level to heights beyond the tops of the thunderclouds. These measurements showed that the types of potential gradient disruptions were too varied to be classified into a simple scheme, and emphasized the complexity of the electrical structure of thunderclouds. In addition the frequency of occurrence of positive and negative potential gradients near the ground was found to give a preponderence of negative potential gradients in the ratio of 3:1.[55] This ratio decreased with

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[51] F. J. W. Whipple and F. J. Scrase, "Point Discharge in the Electric Field of the Earth." Meteorolgical Office Geophysical Memoirs, 68, pp. 3-4.

[52] F. J. W. Whipple and F. J. Scrase, loc. cit., p. 13.

[53] G. C. Simpson, "The Mechanism of a Thunderstorm." Proceedings Royal Society, 114, (1927), p. 390.

[54] Ibid., p. 401.

[55] G. Simpson and F. J. Scrase, loc. cit., p. 320.

height and was found to be zero at a height of about 0.3 kilometers. This is usually where the cloud base begins. Moreover it was found that for heights ranging from 3 kilometers up to 9 kilometers, the positive gradients predominated; at 8 kilometers the ratio was 3:1.[56] The strongest gradients which occurred most frequently were found to be positive, and occurred between 3 and 8 kilometers. This is usually the space between two charged regions.[57] In almost every sounding there was evidence of a positive potential gradient in the upper cloud layers; but in no case did this positive gradient extend down to the ground. On the other hand a large number of the recordings showed a negative field extending from the ground to the upper positive fields. Again other readings gave a positive field at the earth, followed by a change to a negative field in the lower part of the cloud, then a change to a positive field in the upper part of the cloud. The positively charged upper regions were found to occur in all cases above the freezing level; moreover 9 of the 23 positively charged regions occurred above the -10° C. level; furthermore the negative charged regions generally occurred close to the 0° C. level.[58] When the readings were averaged it was found that the upper positive charge was somewhat higher than 4.6 kilometers or 15,000 feet, and that the region of negative charge was at 2.7 kilometers or 8,850 feet. The region of separation of the higher charges was above 3.9

[56] G. Simpson and F. J. Scrase, loc. cit., p. 320.
[57] Ibid., p. 321.
[58] Ibid., p. 323.

kilometers, or 12,450 feet, while the lower positive charges were at 1.7 kilometers, or 5,560 feet. The lower region of charge separation was placed at 2.2 kilometers.[59] These results led to the conclusion that the charge separation of the upper positive and negative charges must necessarily occur in a region that is below the freezing point; furthermore that the charge separation process in the top of the cloud must be different from that occurring in the base of the cloud where the temperature is above the freezing point.[60]

By measuring the potential gradient from the surface Workman, Holzer, and Pelsor[61] found that there were several positive and negative cellular regions of charge; furthermore as the thunderstorm developed the positive center often moved to a lower level. This action was accompanied by a shift to one side of the negative charge. Moreover the charges gave the aspect of being grouped into pairs that were separated by distances ranging from 3 to 4.5 miles.

The changes in the electric field as a function of the cell growth of a thunderstorm has been the subject of extensive research by different agencies of the United States Government.[62] These agencies found that the changes of

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[59] G. Simpson and F. J. Scrase, loc. cit., p. 323.

[60] Idem., p. 352.

[61] E. J. Workman, R. E. Holzer and G. T. Pelson, "The Electrical Structor of Thunderstorms." National Advisory Committee for Aeornautics Technical Note No. 864, (Washington, D. C., 1942), p. 26.

[62] U. S. Air Force, Navy, National Advisory Committee for Aeronautics, and Weather Bureau, The Thunderstorm, Report of the thunderstorm project, p. 83.

electric field with cell growth seem to follow a definite pattern. A fair weather cumulus type cloud would develop into a cumulo-nimbus cloud over periods as small as eight minutes. During this period a positive charge would form in the lower regions of the cloud. Following this change a strong positive gradient would develop in the rain area, with an accompanying strong negative gradient outside the rain area. The maximum gradient would occur about a half hour after the development started.

It was also found that there was no correlation between the electric field and the updrafts or downdrafts in the lower parts of the cloud. Both types of fields occurred in the updrafts and also in the downdrafts. It was also found that there was no correlation between the measurements of turbulence and those of potential gradient.

Lightning is never found in small cumulus clouds, but begins when the clouds grow into the cumulo-nimbus type. The investigations of the Thunder Storm Project[63] revealed that: (1) A temperature of the order of -20° C. was required before the lightning occurred; (2) the maximum cloud height occurred when the frequency was of the lightning greatest; (3) it appeared to require a low temperature to initiate lightning than was necessary to continue the process; (4) the maximum lightning occurrence preceded the maximum rain by 5 minutes.

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[63]U. S. Air Force, Navy, National Advisory Committee for Aeronautics, and Weather Bureau, loc. cit., p. 89.

The maximum field ever measured inside a cloud was 34,000 volts per meter at an altitude of 12,900 feet. The measurement was made by Gunn.[64] However, his potential gradient measurements made by flying through clouds that were producing steady rain obtained values that were less than 400 volts per meter. Values for non-precipitating clouds were found to be less than 100 volts per meter. The average gradient produced in thunderstorms was found to be 7,000 volts per meter; moreover for nine thunderstorms it was found that the average maximum gradient was 13,000 volts per meter. These maximum gradients were found near the freezing level. In addition the gradient decreased with height at the rate of about 5,000 volts per meter at 10,000 feet. At 5,000 feet the maximum gradient was 2,000 volts per meter. Numerous flights by Gunn through isolated clouds showed that large gradient measurements were not obtained until the airplane had actually entered the cloud; furthermore when the cloud was directly above the airplane it was found that the gradient was usually small. In conclusion these measurements indicate that the charges are confined to the cloud boundaries, and are of a close bipolar distribution, that produce electric fields that almost neutralize each other outside the cloud boundaries.

Malan and Schonland[65] estimated that the mean height

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[64] R. Gunn, "Electrical Field Intensity Inside of Natural Clouds," Journal of Applied Physics, 19 (1948), pp. 481-4.

[65] D. J. Malan and B. F. J. Schonland, "The Distribution of Electricity in Thunderclouds," Proceedings of Royal Society, 209-A (1951) pp. 174-5.

of the negative charge column of the thundercloud begins at 3 to 4 kilometers above the ground, the maximum height of the negative charged column being about 9 kilometers. This negative charged column therefore starts at about 2.7 to 3.7 kilometers above the cloud base. Since the maximum height is at 9 kilometers, the region of charge separation must be at a higher level where the temperature is between -19° C. and -40° C.

Many workers have observed that the development of the electrification necessary to initiate lightning is related to the upward movement of radar echoes reflected from the hydrometers in the cloud. Jones[66] found that frequently a temperature level of -40° C. was reached before lightning began. Workman and Reynolds[67] found that a temperature of -28° C. was required before lightning occurred.

Workman and Reynolds[68] have shown that freezing leaves a negative charge on the large ice particles and a positive charge on the smaller ice particles. This indicates that the mechanism for the generation of static electricity depends mainly on the process of development of supercooled water drops. As these water drops congeal the heavier ice particles form the negative charged region of the cloud while the smaller particles form the positive

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[66] F. F. Jones, Quart. J. R. Met. Soc., 76 (1950), p. 312.

[67] E. J. Workman and S. E. Reynolds, Bull. Amer. Met. Soc., 30 (1949), p. 142.

[68] E. J. Workman and S. E. Reynolds, Phys. Rev., 78 (1950), p. 254.

pole of the bipolar cloud. S. E. Reynolds[69] has established that, while freezing is in progress, the charge separation of the liquid water particles from the ice particles can be produced under suitable meteorological conditions. Under suitable conditions, the formation of the charges can occur in the time required.

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[69]S. E. Reynolds, "Thunderstorm-Precipitation Growth and Electrical-Charge Generation." _Bulletin of the American Meteorological Society_, 34 (March, 1953), pp. 117-23.

CHAPTER IV

FIELD VARIATIONS FOR THUNDERSTORMS IN OKLAHOMA

A. The Storm of April 14, 1953.

Many disastrous storms occur in Oklahoma. However, for the spring of 1953 very few heavy storms were in evidence. The southwestern region as a result of the small rainfall has been very dry. Consequently it was not possible to make a large number of measurements, nevertheless the few that were made gave considerable insight into the electrical nature of the Oklahoma thunderstorm.

The first storm to be observed occurred on April 14, 1953. At 1732 very dark clouds began appearing in the west. At 1742:12 the first abrupt field change was recorded as shown in Figure 17A. At 1748 the frequency of the field changes began to increase, reaching the first maximum of 7 per minute at 1753. At 1805 a second maximum of 8 charges per minute was reached as shown in Figure 17B. The last maximum of 11 changes per minute occurred at 1807, Figure 17C. This was the highest frequency rate of the storm. The highest frequency rate, it is believed, occurs when a charged area or region is directly overhead. During this storm there occurred 64 positive and 68 negative field changes, giving a ratio of 0.94:1. When it began raining the steady field changed from unity to zero between 1809 and 1811. This phenomenon always accompanies rain.

B. Storm of April 23, 1953.

On April 23, 1953 a storm approached Stillwater from the

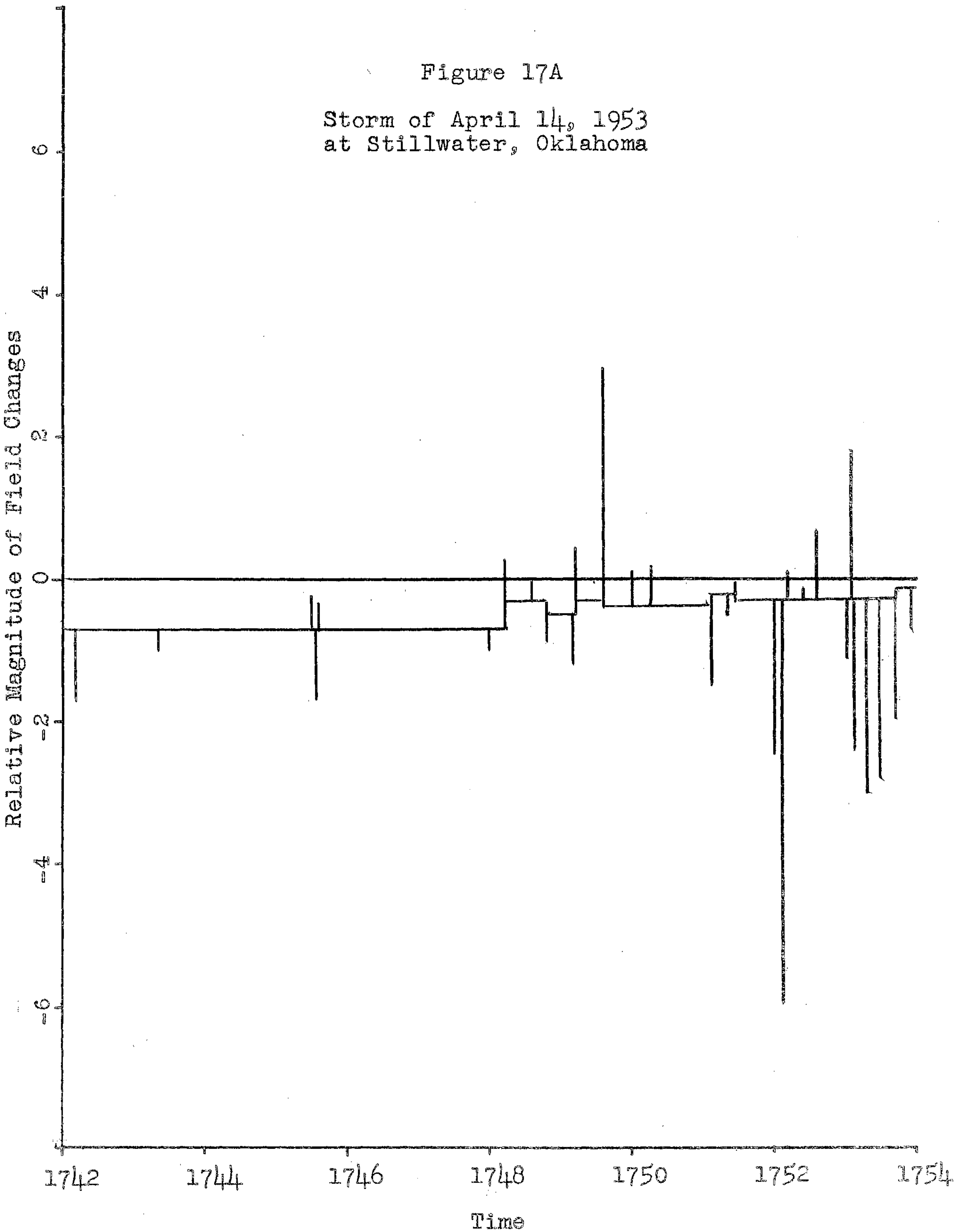


Figure 17A
Storm of April 14, 1953
at Stillwater, Oklahoma
Relative Magnitude of Field Changes
6
4
2
0
-2
-4
-6
1742
1744
1746
1748
1750
1752
1754
Time

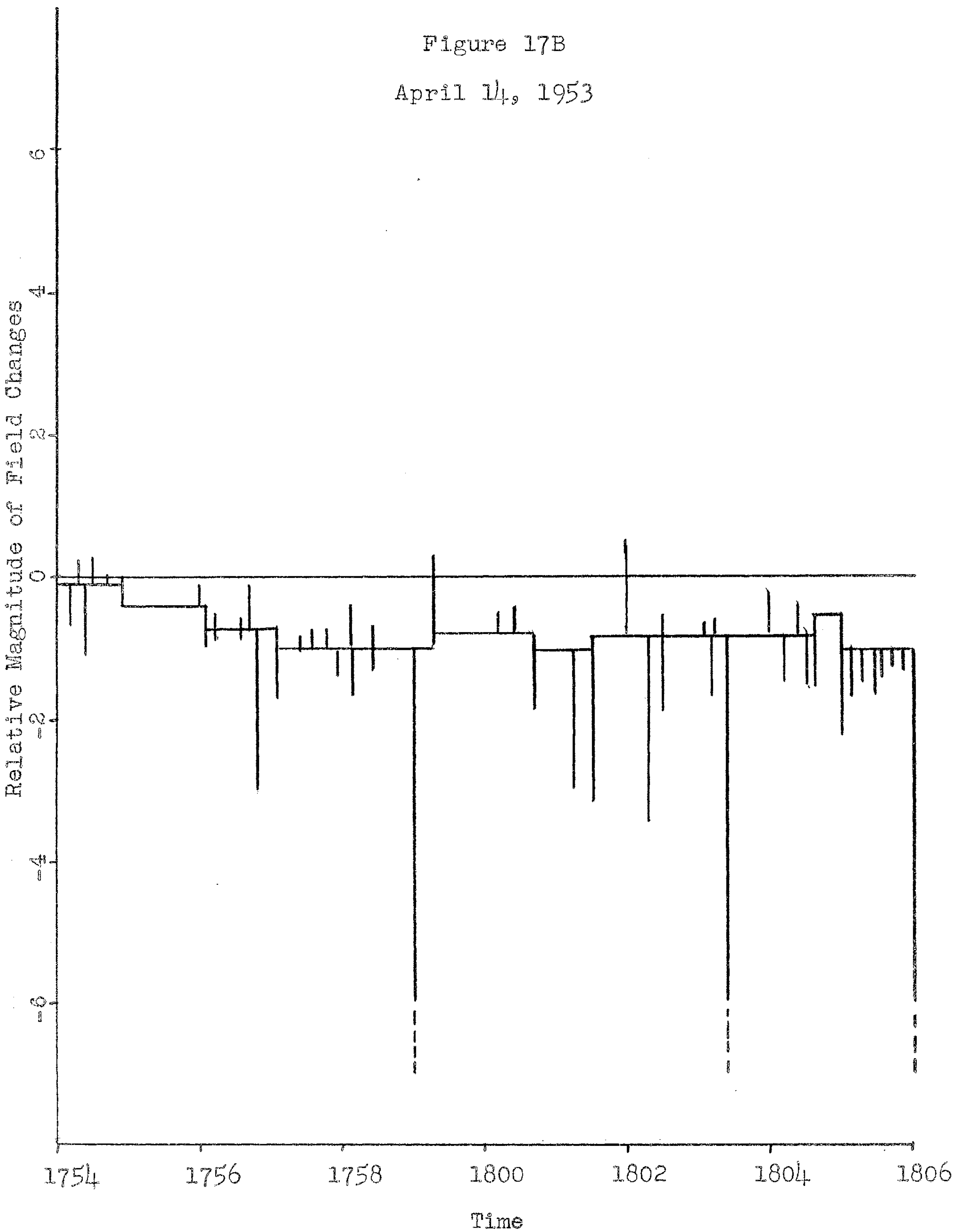


Figure 17B
April 14, 1953
Relative Magnitude of Field Changes
6
4
2
0
-2
-4
-6
1754
1756
1758
1800
1802
1804
1806
Time

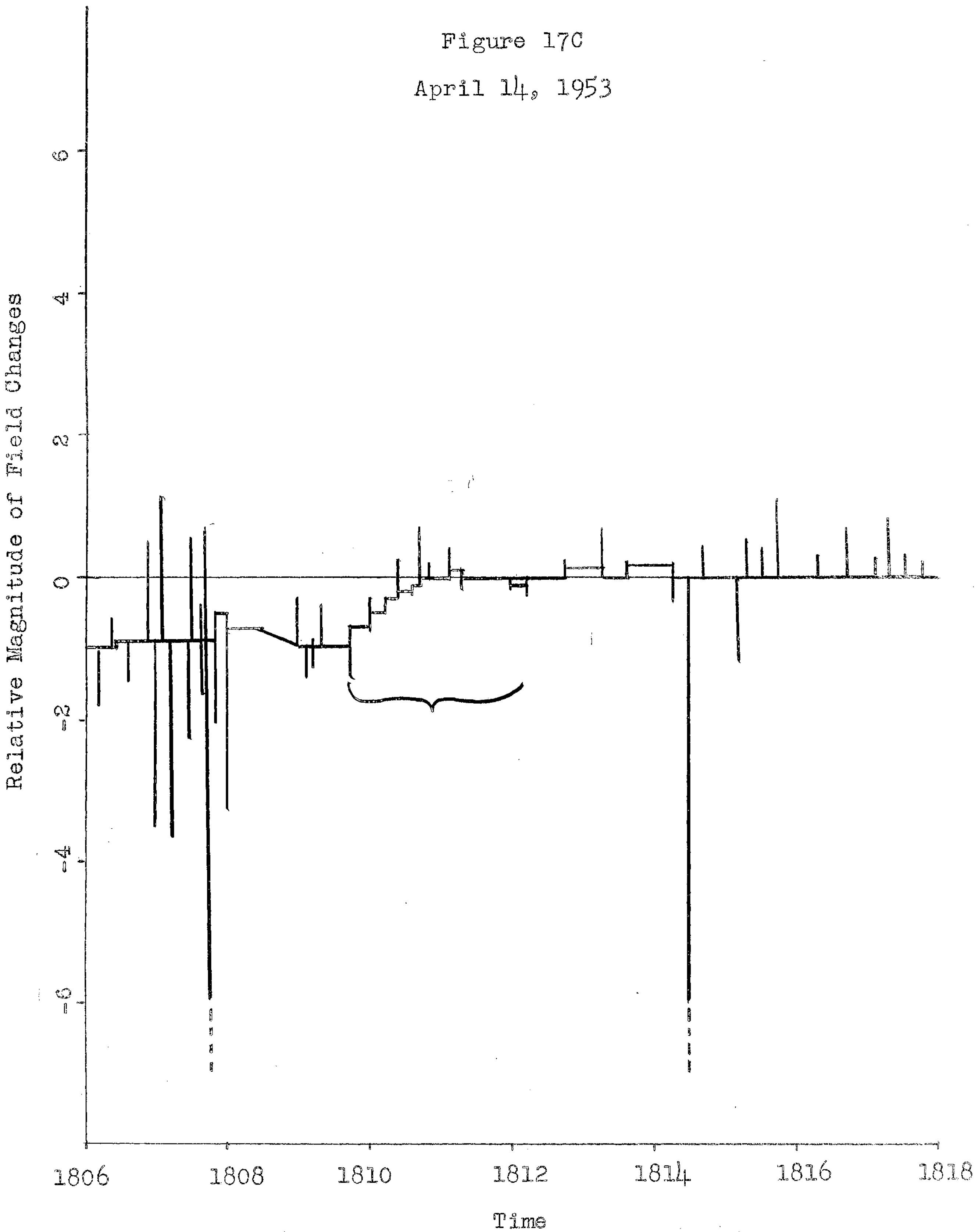


Figure 17C
April 14, 1953
Relative Magnitude of Field Changes
6
4
2
0
-2
-4
-6
1806
1808
1810
1812
1814
1816
1818
Time

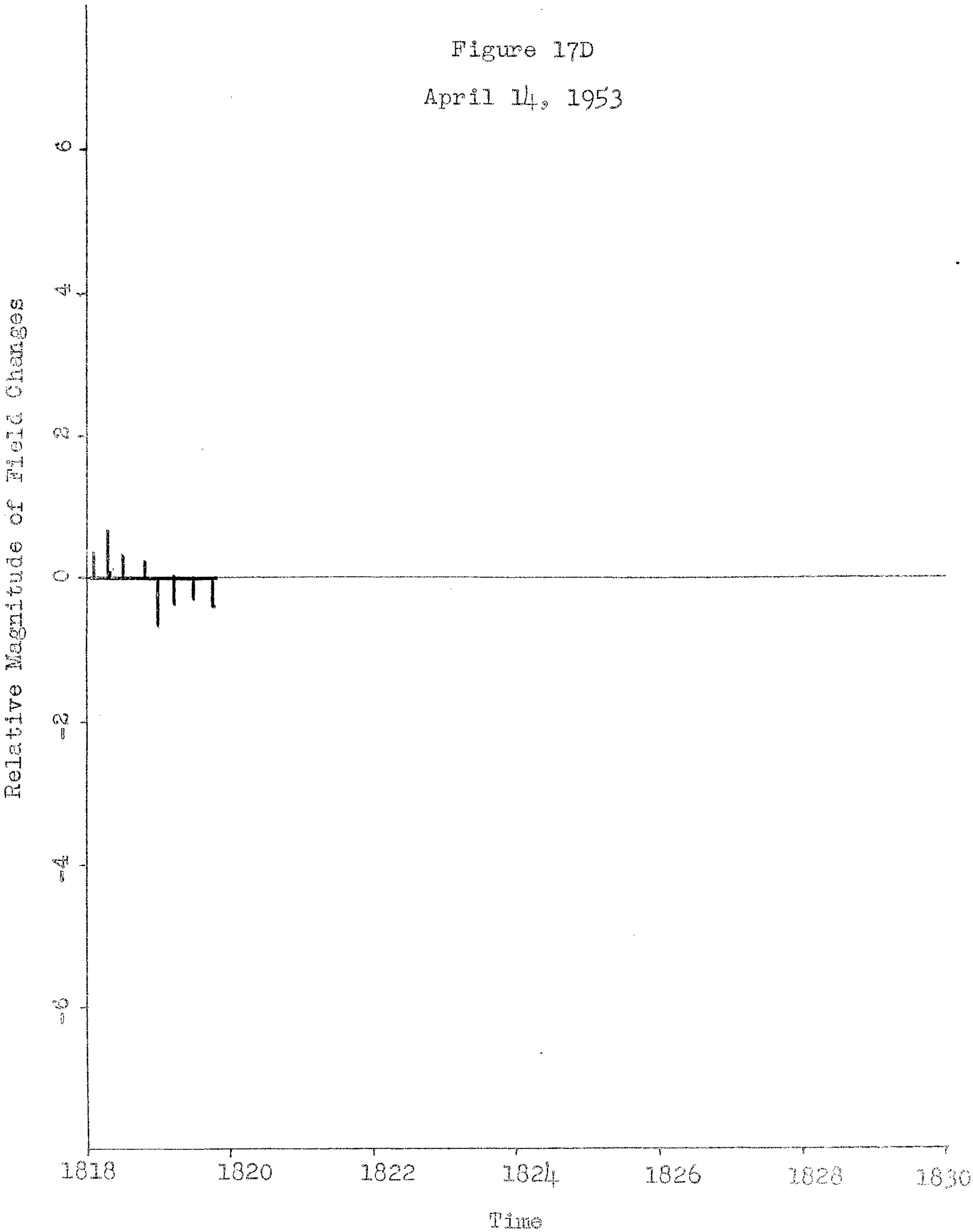


Figure 17D
April 14, 1953
Relative Magnitude of Field Changes
6
4
2
0
-2
-4
-6
1818
1820
1822
1824
1826
1828
1830
Time

southwest. This was a very weak and small storm with little or no thunder or lightning in evidence. During the period between 1140 and 1204, as shown in Figure 18A, two negative field changes were recorded 10 minutes apart. Rain begain at 1152:30, and afterwards the potential gradient changed from 0.6 to unity, as shown in Figure 18A. The next record was made between 1346 and 1400, as shown in Figure 18B. During this interval three abrupt field changes occurred. The average time between the three field changes was about 5 minutes. The last recording between 1255 and 1314 produced one negative field change as shown in Figure 18C. The outstanding characteristic of this storm was the occurrence of field changes spaced 5 to 15 minutes apart.

C. The Storm of May 10, 1953.

Another storm occurred on May 10, 1953. The recording of this storm, which began after the storm had reached Stillwater, is presented in Figure 19. The storm produced 32 negative and 3 positive sudden field changes. The ratio of negative to positive field changes was 11:1. At 0518:24 a negative field change gave an off-scale deflection for 39 seconds, Figure 19A; and one at 0526:14 gave an off-scale deflection for 34 seconds, Figure 19B. The highest rate of 9 and 8 field changes per minute occurred at 0524 and 0525, respectively, Figure 19B. This storm appeared to be the common type of thunderstorm which occurs in the spring and the summer.

D. The Storm of May 11, 1953.

The next storm occurred in the early morning of May 11,

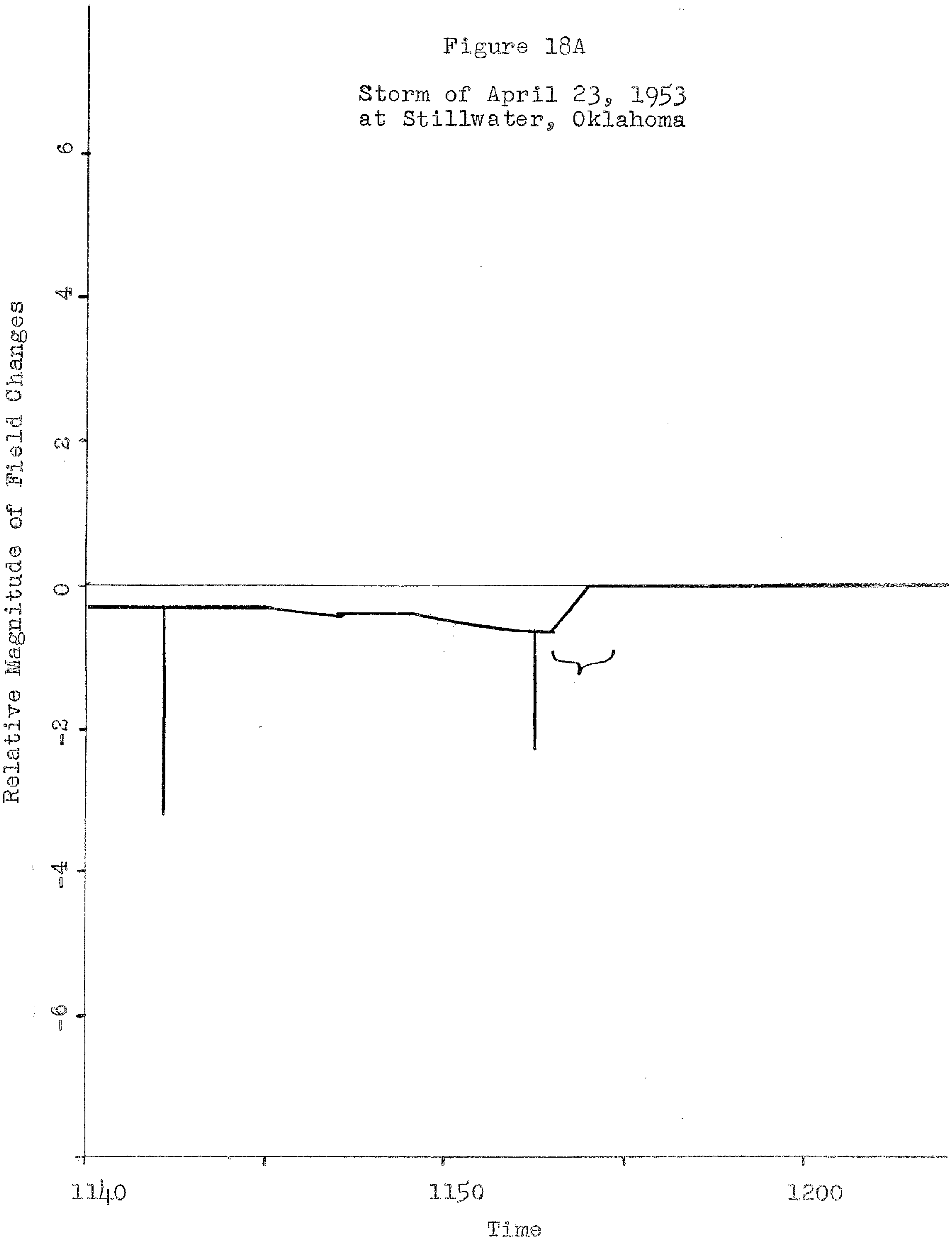


Figure 18A
Storm of April 23, 1953
at Stillwater, Oklahoma
6
4
2
0
-2
-4
-6
Relative Magnitude of Field Changes
1140
1150
1200
Time

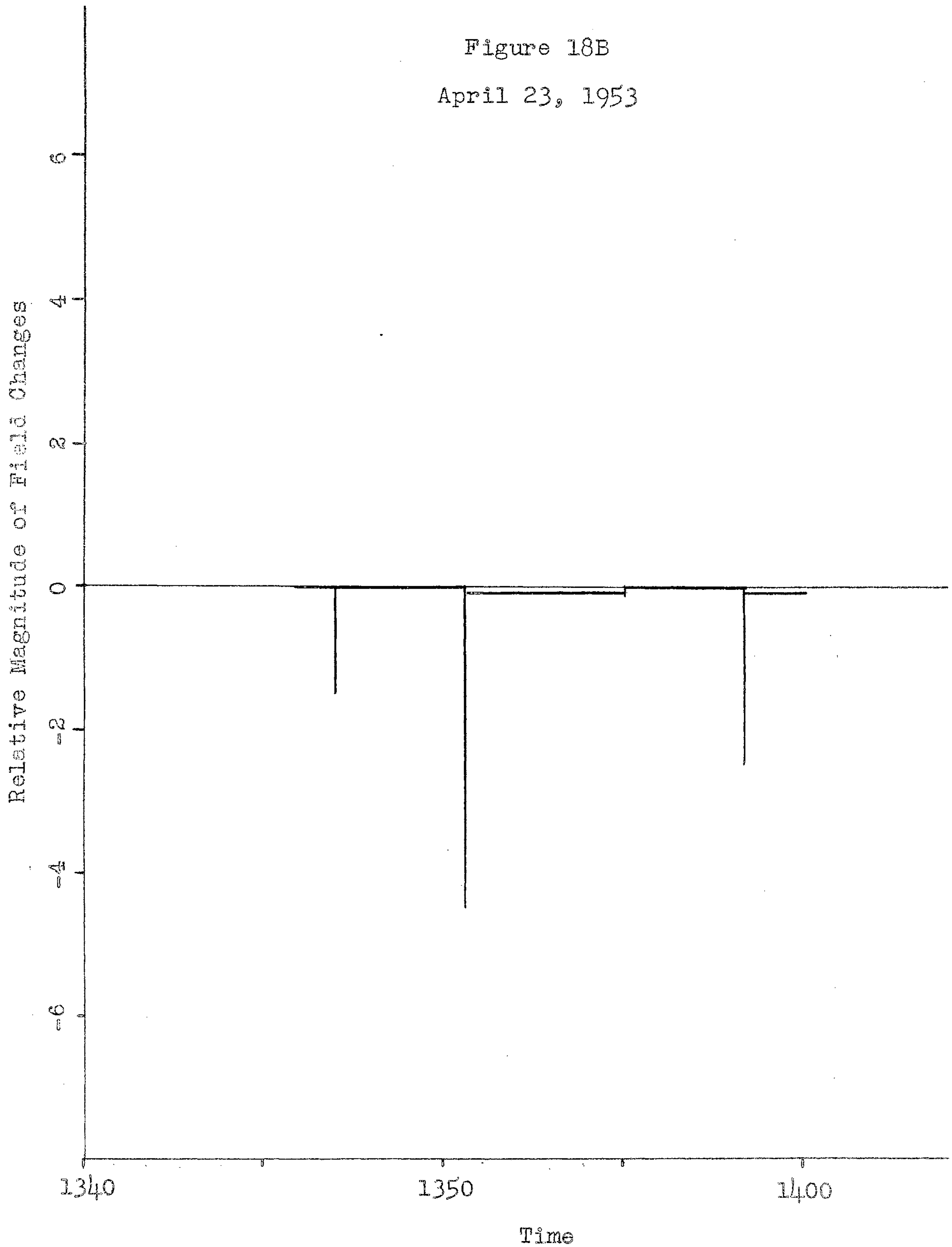


Figure 18B
April 23, 1953
Relative Magnitude of Field Changes
6
4
2
0
-2
-4
-6
1340
1350
1400
Time

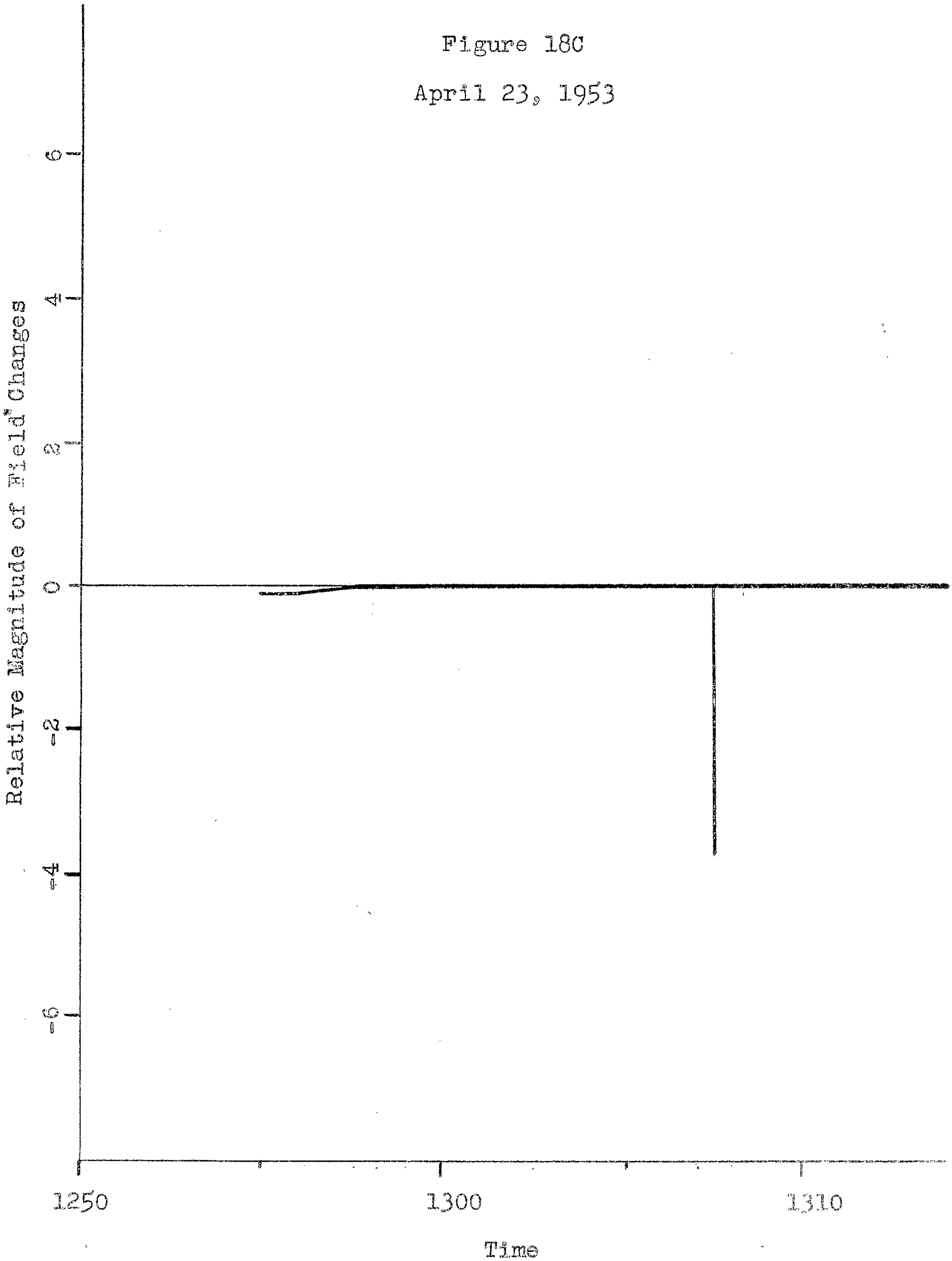


Figure 18C
April 23, 1953
Relative Magnitude of Field Changes
6
4
2
0
-2
-4
-6
1250
1300
1310
Time

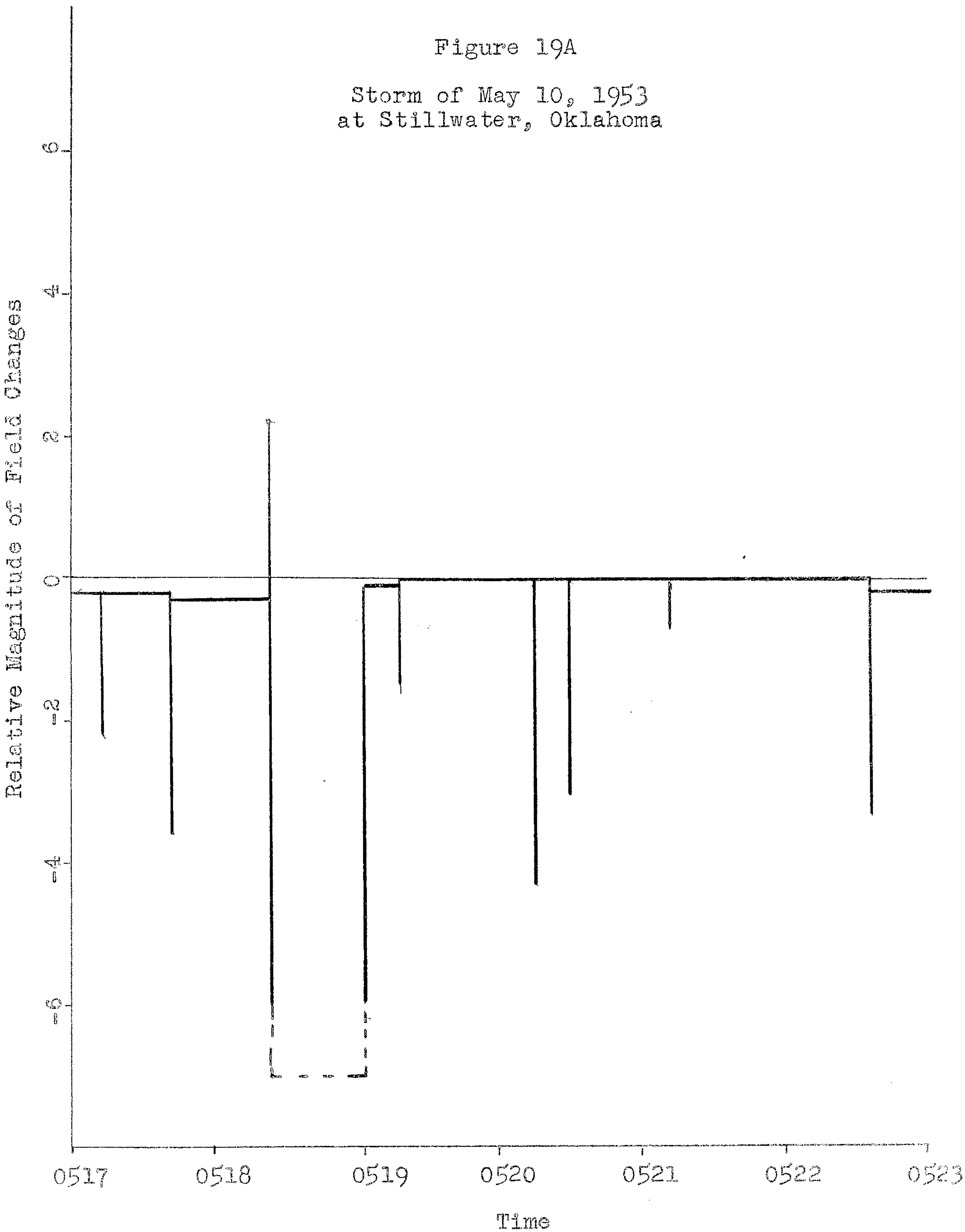


Figure 19A
Storm of May 10, 1953
at Stillwater, Oklahoma
Relative Magnitude of Field Changes
6
4
2
0
-2
-4
-6
0517
0518
0519
0520
0521
0522
0523
Time

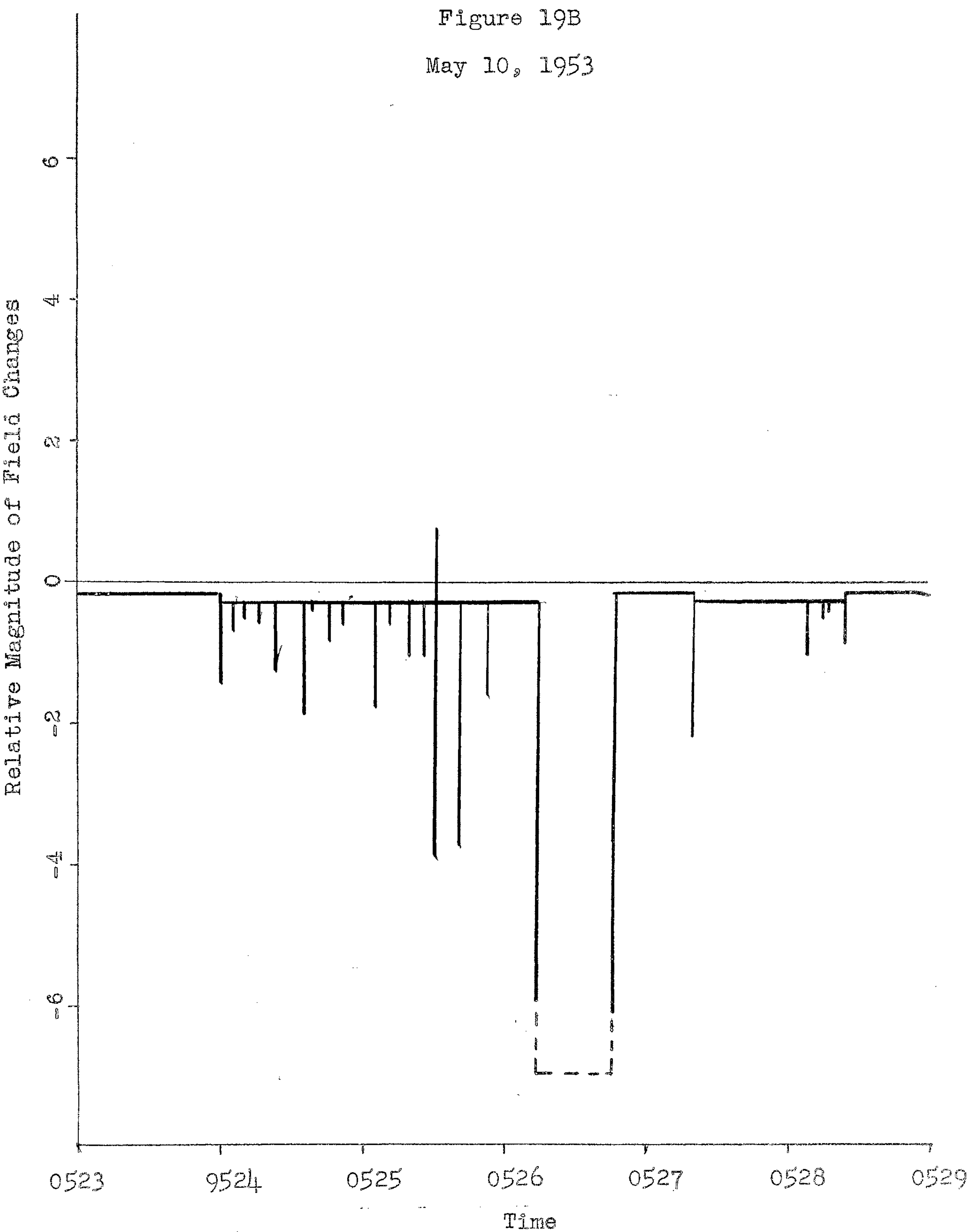


Figure 19B
May 10, 1953
Relative Magnitude of Field Changes
6
4
2
0
-2
-4
-6
0523
9524
0525
0526
0527
0528
0529
Time

1953. The field changes that occurred are shown in Figure 20. A tabulation of the sudden field changes gave 24 negative and 6 positive, or a ratio of 4:1. This ratio appears to be abnormally large. Between 2110:45 and 2110:54 the steady gradient changed from 0.8 to 0.5 and back to 0.8 for 2 abrupt negative changes. Moreover, these sharp changes occur frequently; sometimes with a sudden field change and at other times without, as at 2113 in Figure 20A. The largest change of the steady field occurred at 2124:36. At that time a change from 0.9 to 0.3 was produced by a large negative field change, Figure 20B.

E. The Storm of May 12, 1953.

In Figure 21 is shown the field changes of the storm of May 12, 1953. There were 19 negative and 7 positive sudden field changes. The ratio of the negative to the positive field changes was 2:71. The frequency rate of this storm did not exceed 3 per minute. The active center did not pass overhead, but went south of Stillwater in a path from west to east.

F. Storm of June 6, 1953.

The next storm occurred on June 6, 1953, when a coal black cloud swept down upon Stillwater late in the afternoon at 1730.

After a few recordings were made it became evident that the field changes were varying too fast to be recorded by the means employed. At times the field changes appeared to break into small steady oscillations for 10 to 20 seconds,

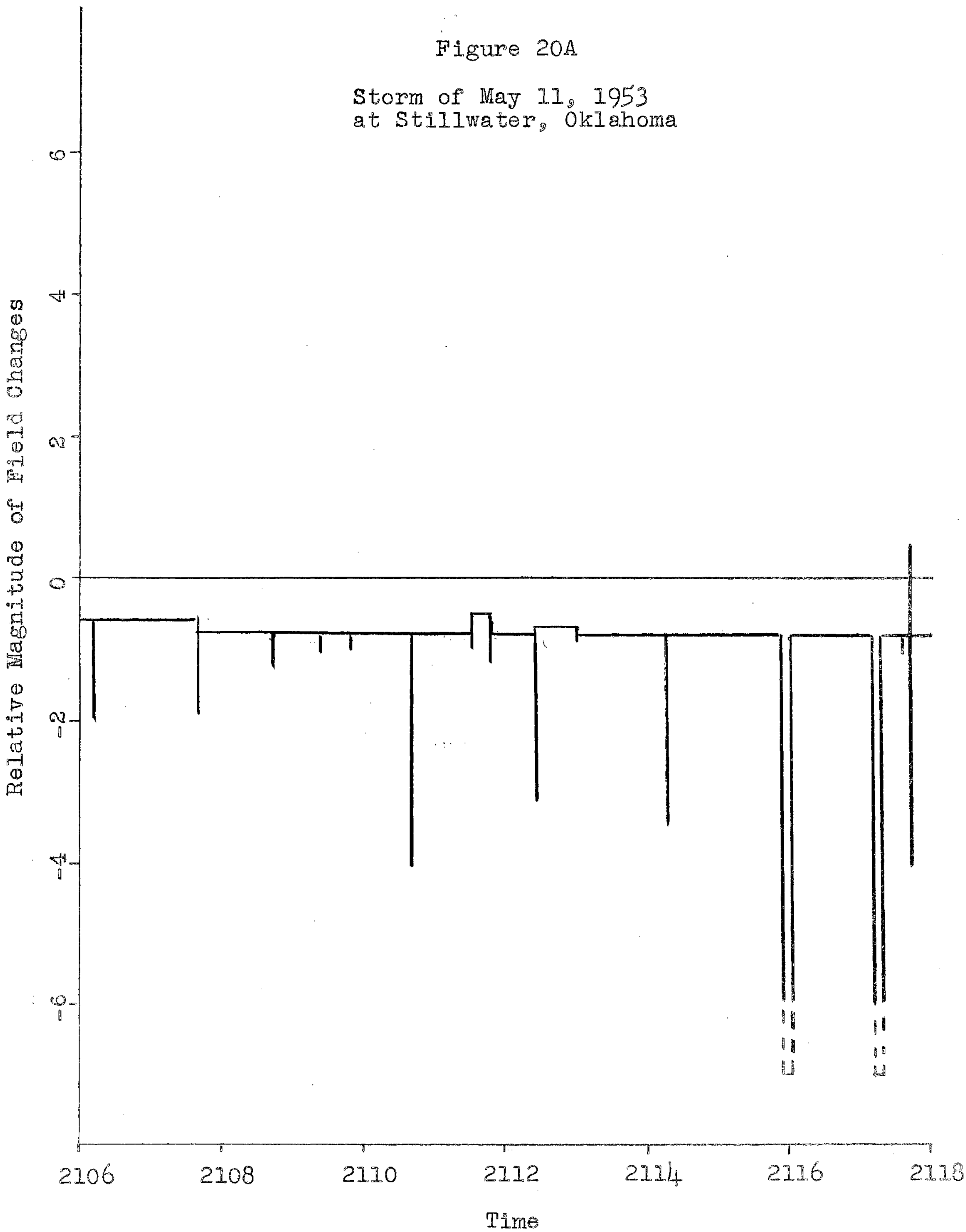


Figure 20A
Storm of May 11, 1953
at Stillwater, Oklahoma
Relative Magnitude of Field Changes
6
4
2
0
-2
-4
-6
2106
2108
2110
2112
2114
2116
2118
Time

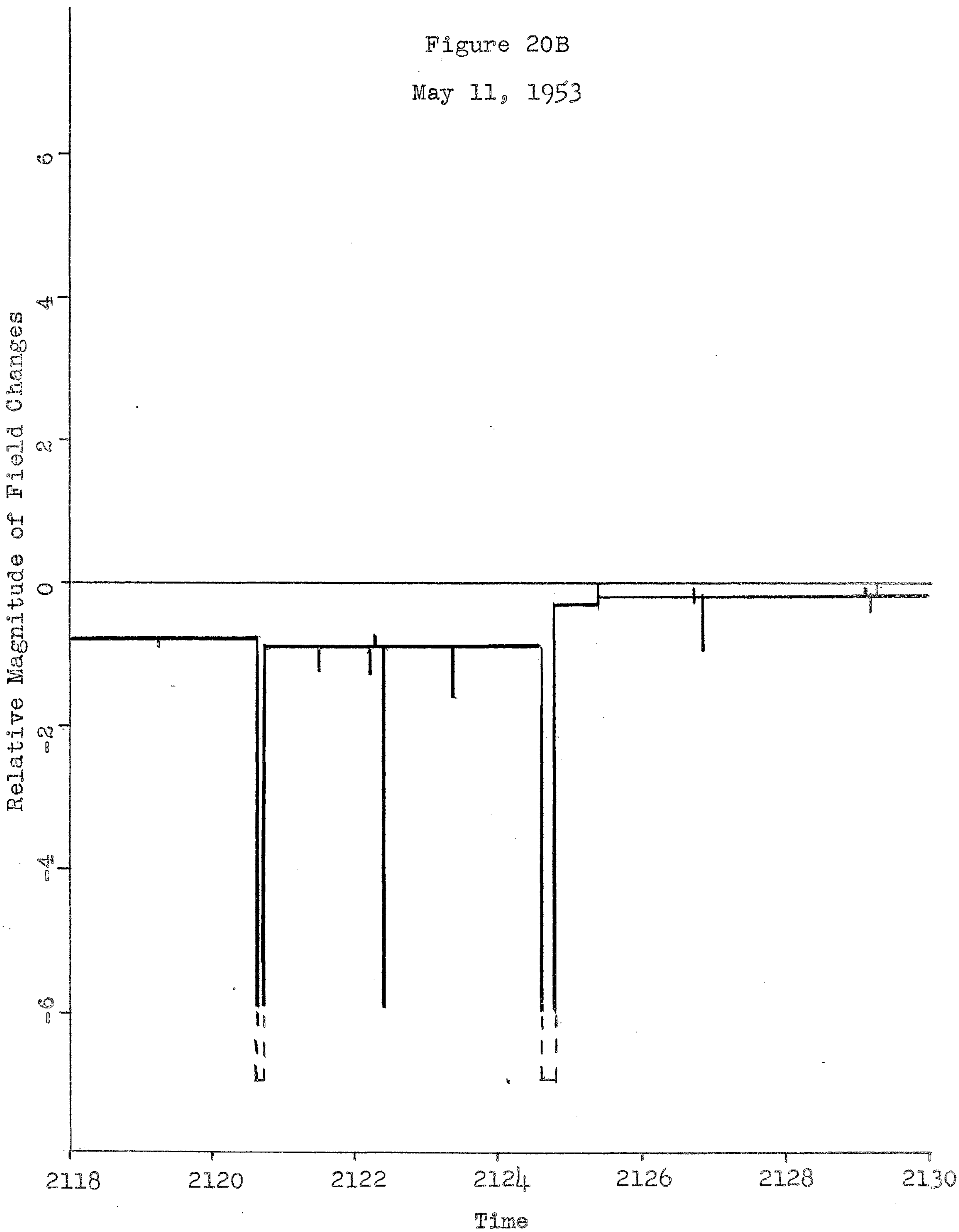


Figure 20B
May 11, 1953
Relative Magnitude of Field Changes
6
4
2
0
-2
-4
-6
2118
2120
2122
2124
2126
2128
2130
Time

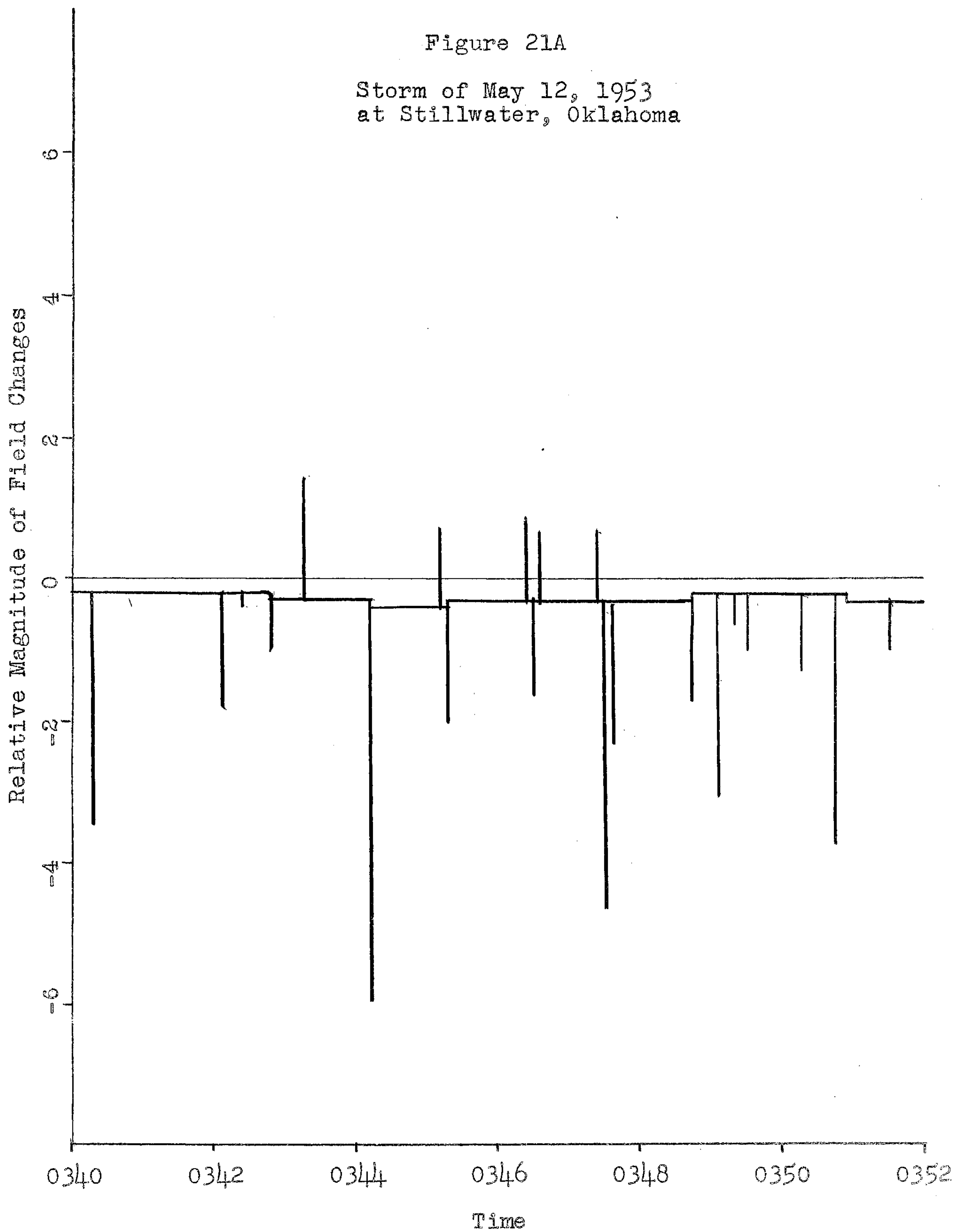


Figure 21A
Storm of May 12, 1953
at Stillwater, Oklahoma
Relative Magnitude of Field Changes
6
4
2
0
-2
-4
-6
0340
0342
0344
0346
0348
0350
0352
Time

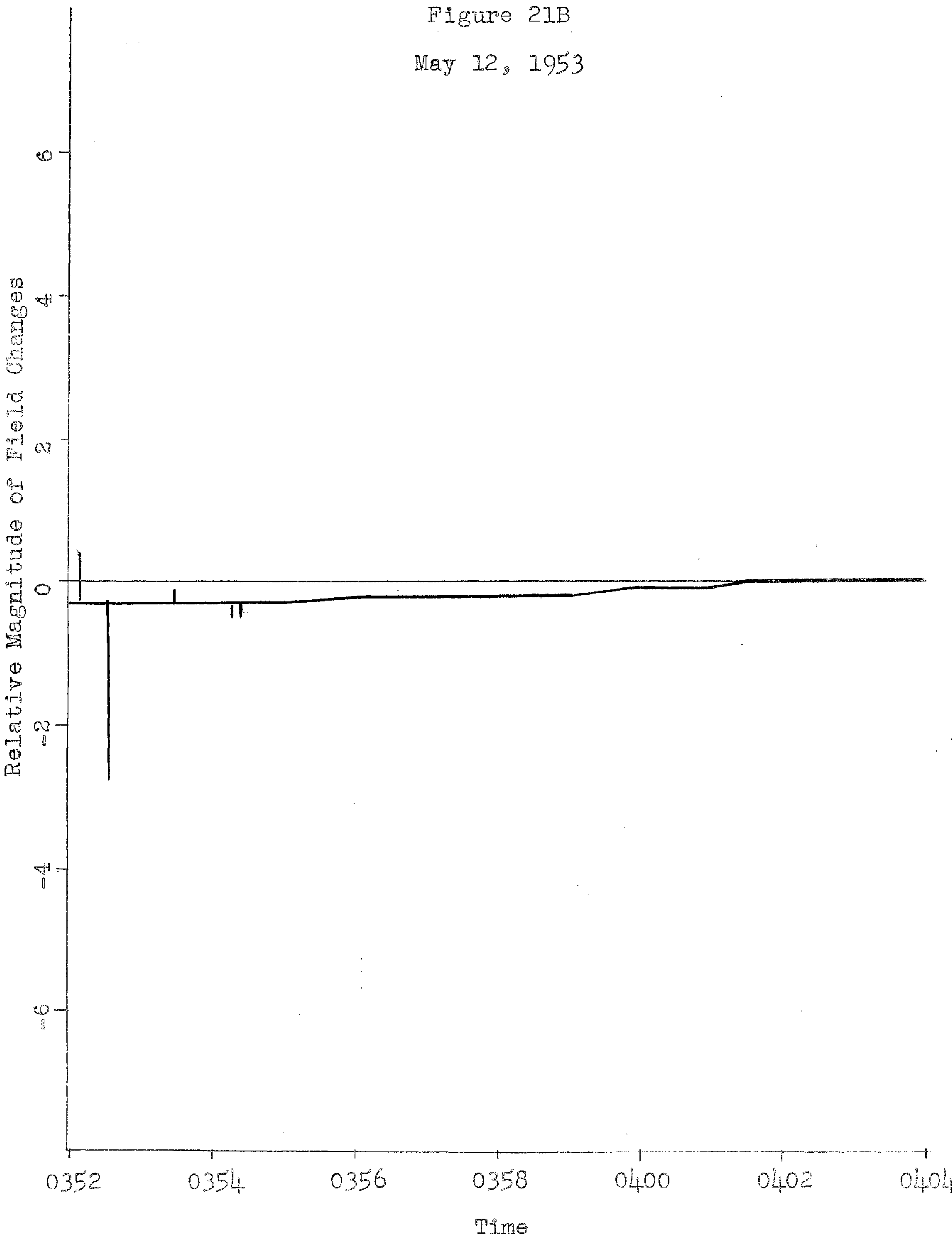


Figure 21B
May 12, 1953
Relative Magnitude of Field Changes
6
4
2
0
-2
-4
-6
0352
0354
0356
0358
0400
0402
0404
Time

at other times there were field changes produced upon field change, and at other times off-scale deflections occurred for periods of 20 to 30 seconds. The fast varying electric field appears to be a characteristic of very violent thunderstorms.

G. Storm of June 8, 1953

The last storm recorded occurred on June 8, 1953. Moreover it was the most severe storm that took place during the year. As shown in Figure 22 170 sudden field changes occurred within a period of 33 minutes. There were 113 negative and 57 positive field changes, producing a ratio of nearly 2:1. Three noteworthy characteristics were exhibited during this storm. One was that the frequency rate seemed to increase to a maximum at 0152 as detailed in Figure 23; and the gradually decreased to zero in a almost symmetric manner. The second characteristic exhibited was the gradual build up of the magnitude of the negative abrupt field changes. This build up continued until 0200:20 when a maximum off-scale deflection of 24 seconds was produced, as shown in Figure 22E. Afterwards the magnitude of the negative field changes decreased rapidly within a 5 minute interval. The third and last characteristic was the re-occurrence of the same type of field changes spaced at nearly equal time intervals. For example, in Figure 22D the three negative discharges of 0154:55, 0156:10 and 0157:05 were separated by 1 minute, 3 seconds, and 58 seconds, respectively, and each gave off-scale deflections of about 11 seconds duration. In Figure 22C at 0147:55, 0148:35 and 0149:18 occurred three

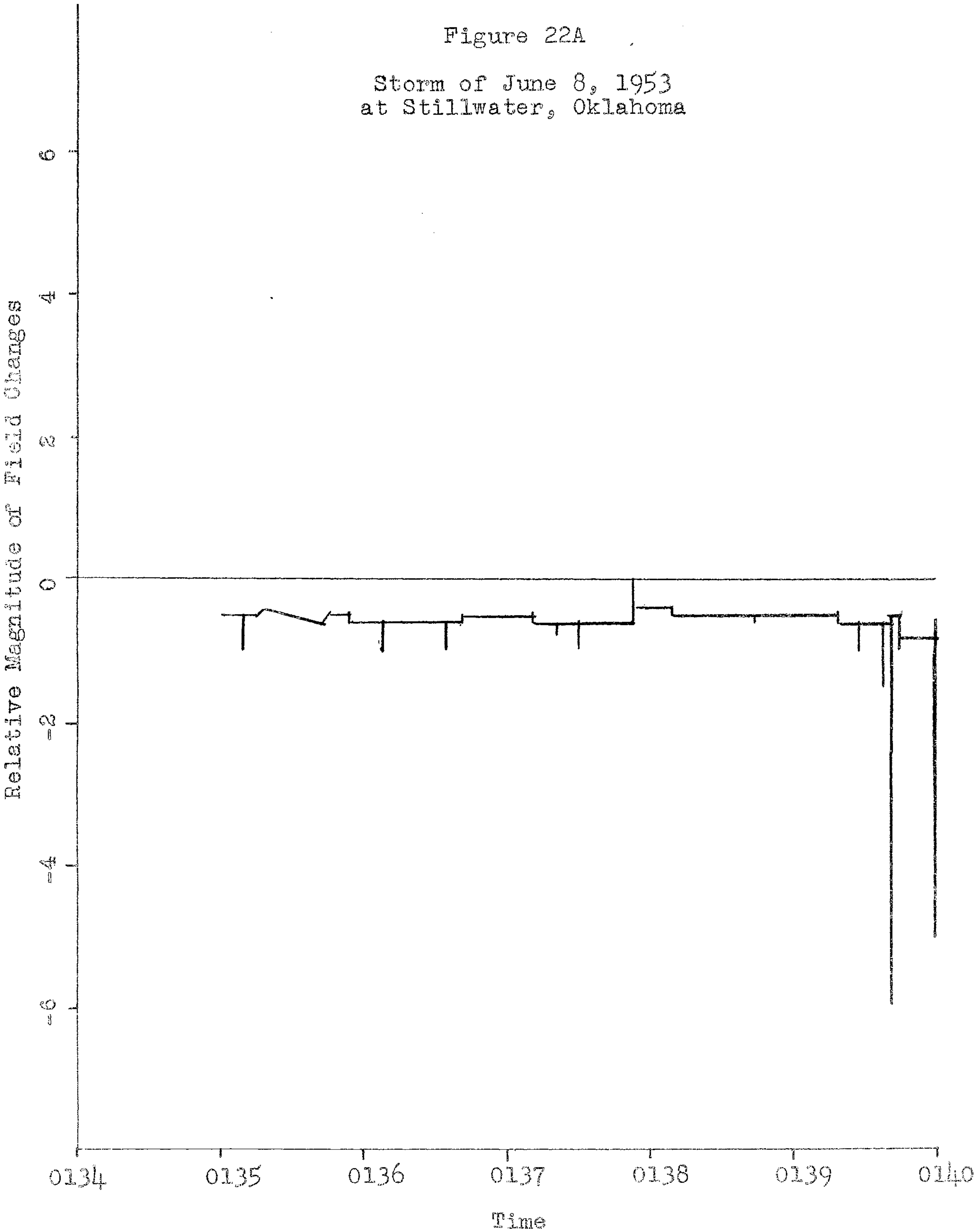


Figure 22A
Storm of June 8, 1953
at Stillwater, Oklahoma
Relative Magnitude of Field Changes
6
4
2
0
-2
-4
-6
0134
0135
0136
0137
0138
0139
0140
Time

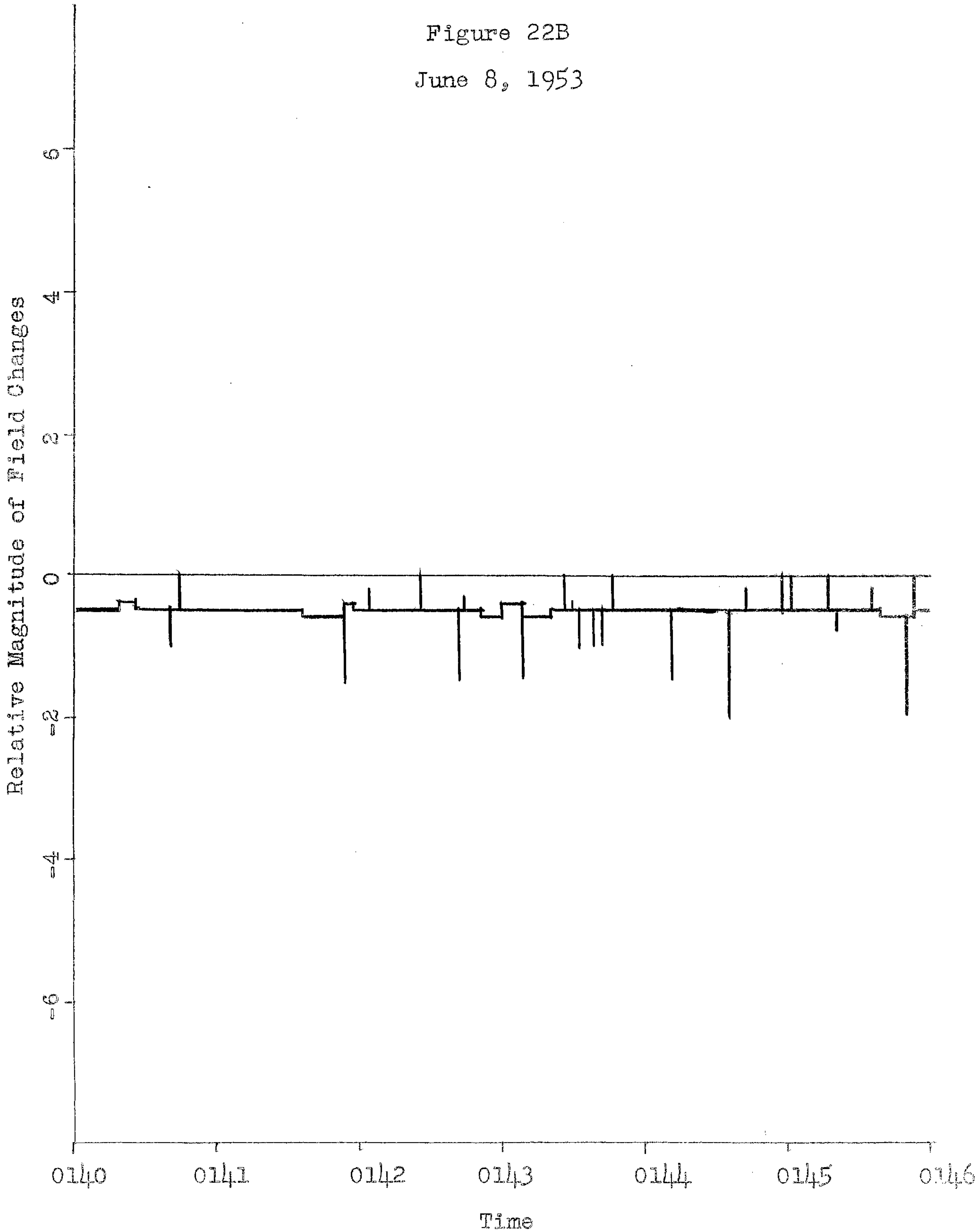


Figure 22B
June 8, 1953
Relative Magnitude of Field Changes
6
4
2
0
-2
-4
-6
0140
0141
0142
0143
0144
0145
0146
Time

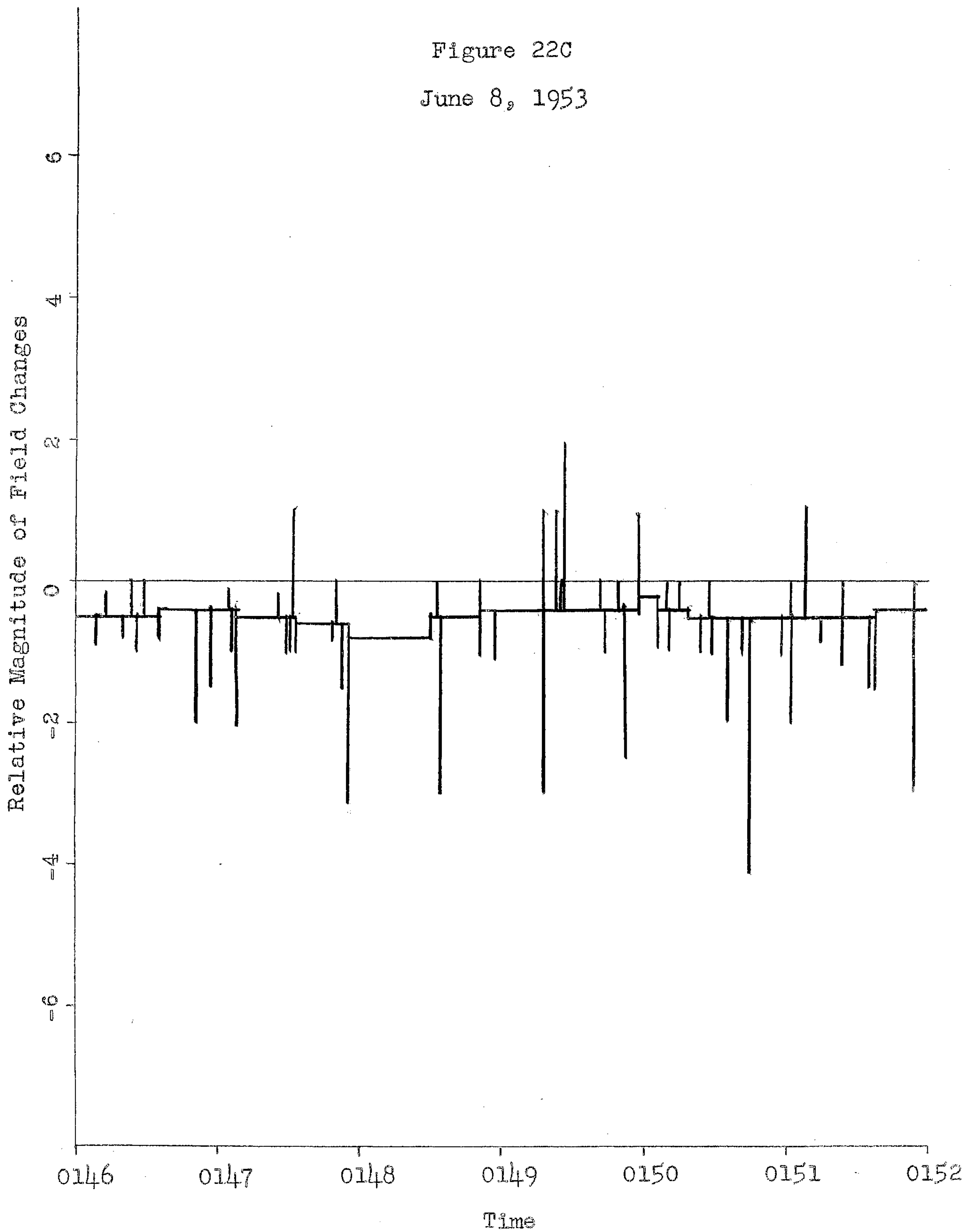


Figure 22C
June 8, 1953
Relative Magnitude of Field Changes
6
4
2
0
-2
-4
-6
0146
0147
0148
0149
0150
0151
0152
Time

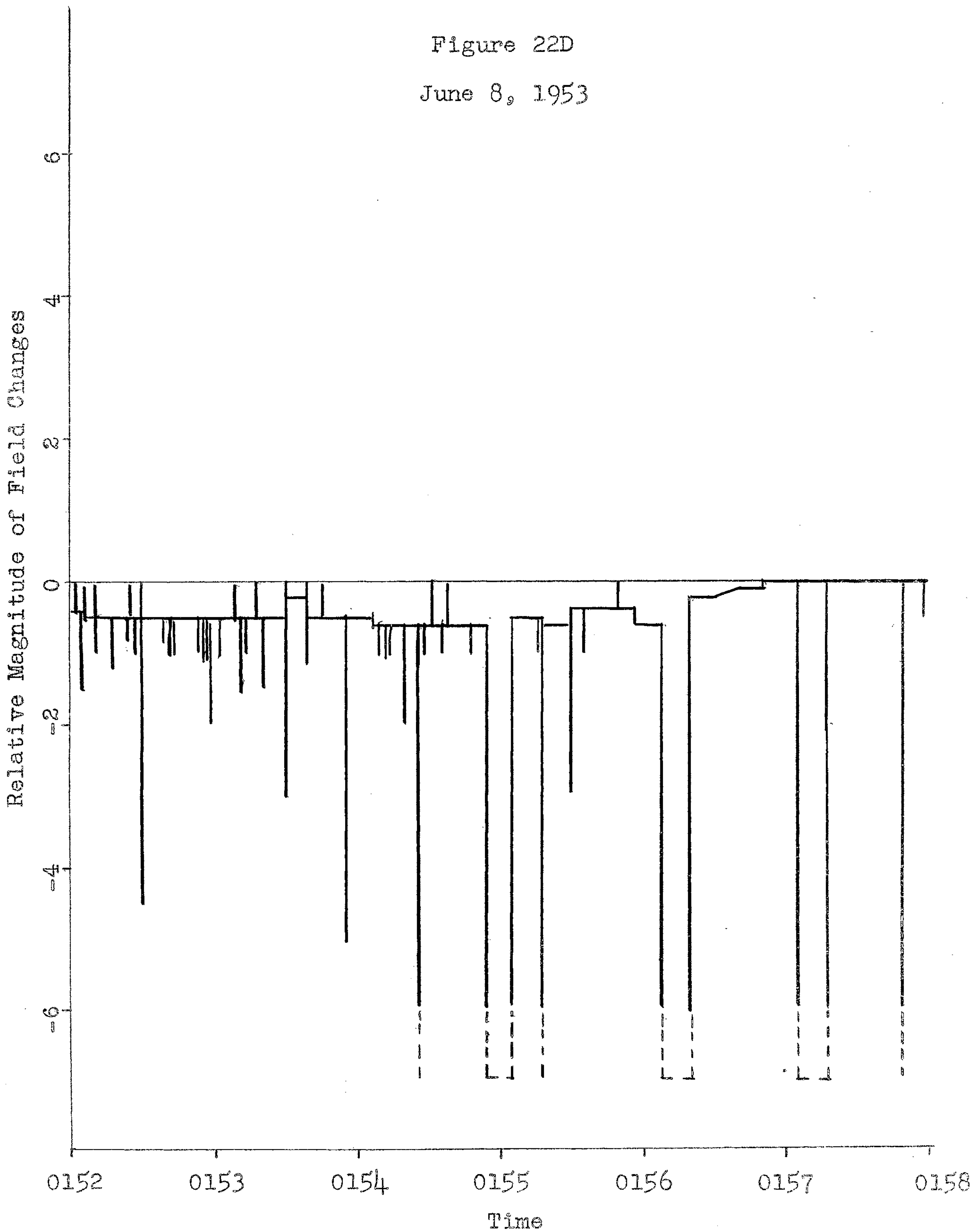


Figure 22D
June 8, 1953
Relative Magnitude of Field Changes
6
4
2
0
-2
-4
-6
0152
0153
0154
0155
0156
0157
0158
Time

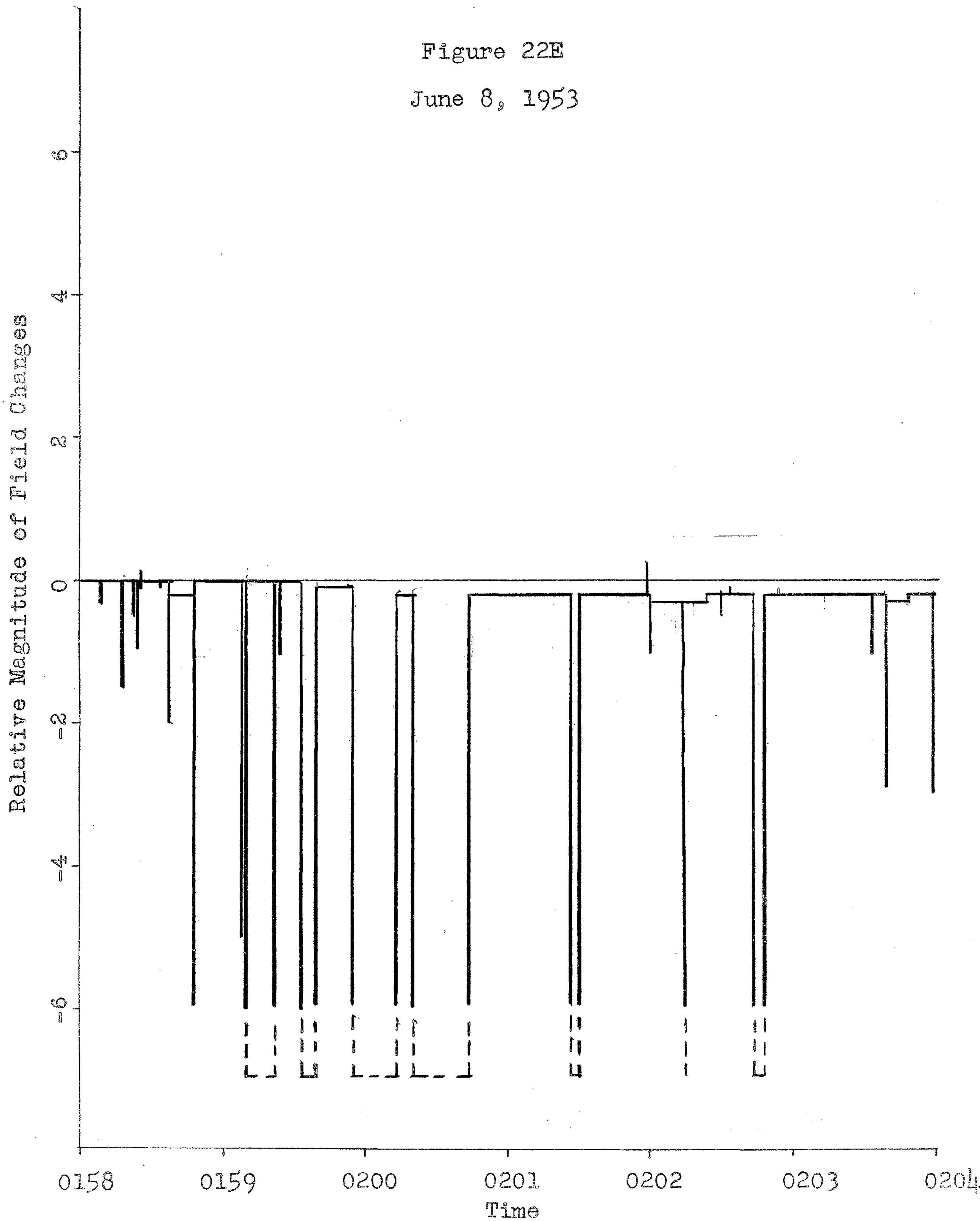


Figure 22E
June 8, 1953
Relative Magnitude of Field Changes
6
4
2
0
-2
-4
-6
0158
0159
0200
0201
0202
0203
0204
Time

Figure 22F

June 8, 1953

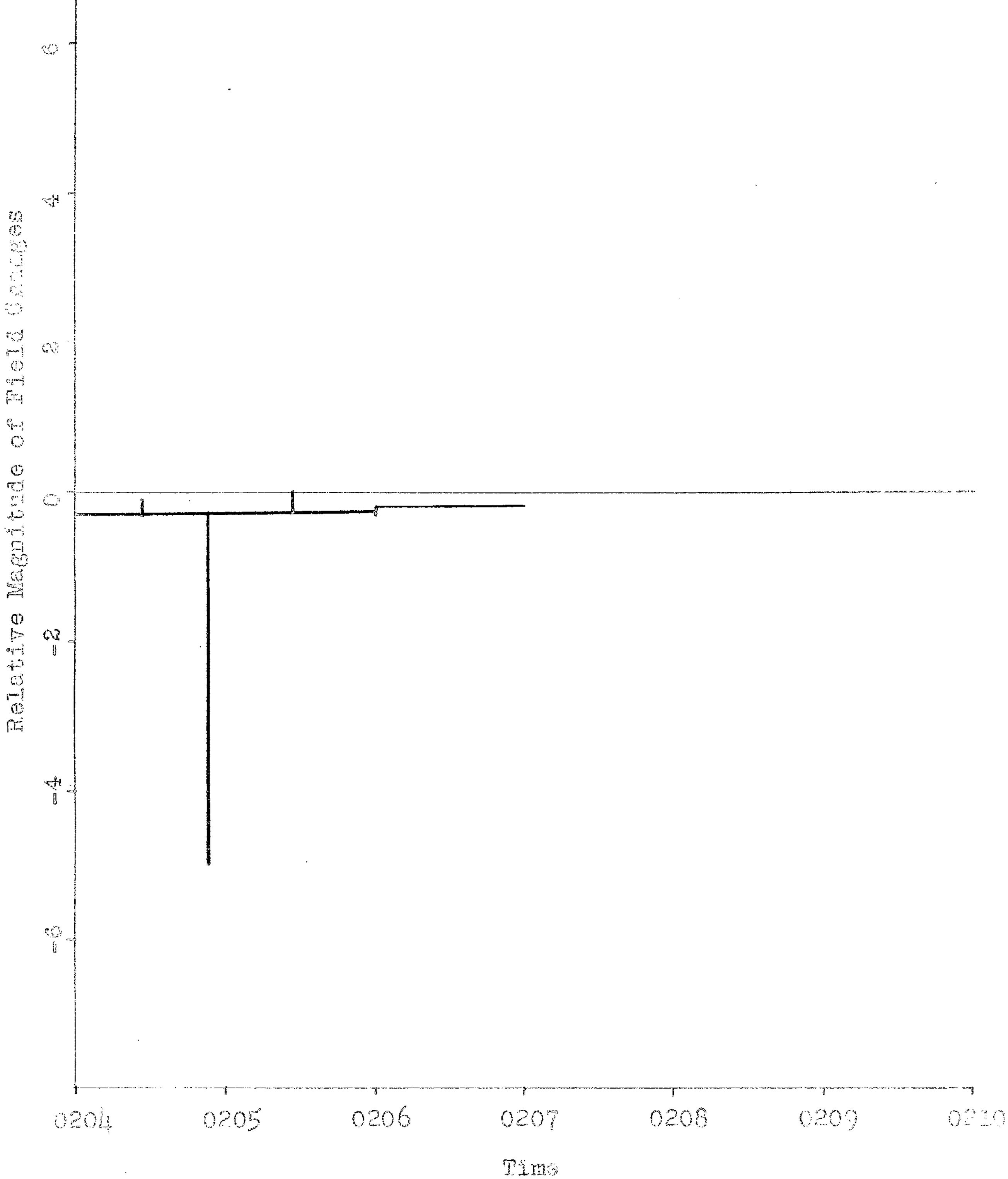
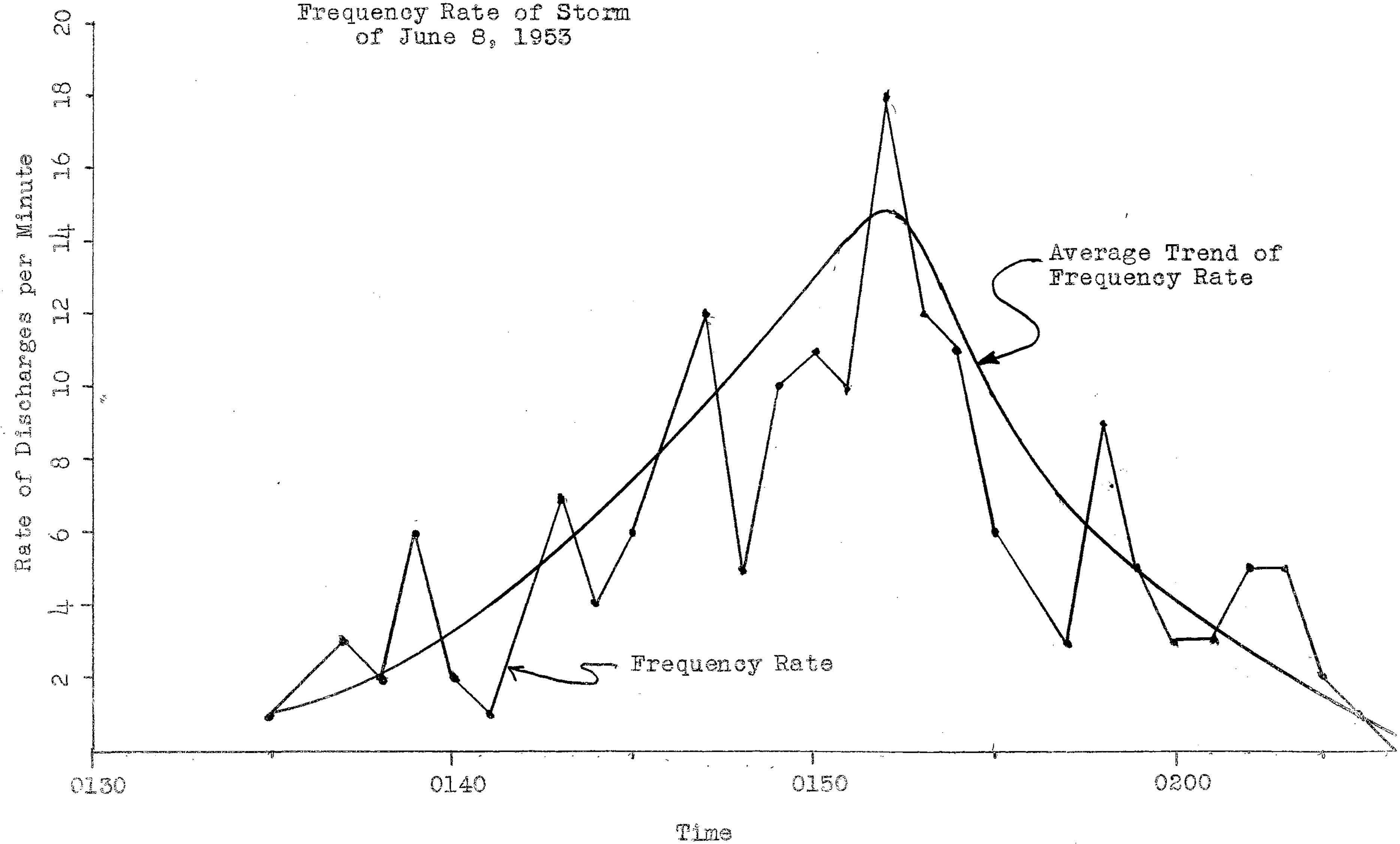


Figure 23

Frequency Rate of Storm of June 8, 1953



changes of nearly the same magnitude separated by almost equal intervals of 40 seconds. It is believed that these field changes are due to the same cloud mechanism, and that for a one or two minute period, the cloud remains essentially the same in its electrical structure. On the other hand these characteristics given are only for this particular storm and are not to be applied to storms in general.

CHAPTER V

CONCLUSIONS

The potential gradient meter was the instrument that was designed to measure changes in potential gradient, and to be calibrated in volts per meter. It was necessary to construct a test instrument for this purpose. The test apparatus consisted of a large metal box in which were placed two large horizontal metal plates. The metal plates were insulated from the box by stand-off insulators. The metal box itself was well grounded and acted as a shield. A voltage was applied to the plates to produce a vertical electrical field. Since the plates were widely separated, a large amount of fringing was expected to occur, but it was believed that a vertical field would be produced in the center of the plates. The potential gradient meter was placed in this chamber and a 300-volt power supply connected to the plates. When the connections were such that a negative field was produced, a large deflection to minus six occurred when the voltage was first applied. Afterwards the meter went back to zero. A positive field change of the same magnitude produced a very small deflection, much less than a scale division. For both instances, however, the reading of the instrument returned to zero after the initial deflection. It is evident that it was the Maxwell displacement of vertical component current of this field that produced the large negative deflection. In other words this deflection was produced by the change in induction between the parallel plates and the probe.

The explanation of this phenomenon became clear after an electroscope had been built. By bringing a known small positive charge near the probe of the instrument a positive deflection of plus two was obtained. Then a large deflection in the negative direction occurred. When a large charge was brought close to the probe a spark would occur between the object and the probe; moreover the instrument pointer would not move when this occurred. A negative charge brought near the probe would give a negative deflection. Thus it appears that the instrument was insensitive to large positive field changes. It is believed that the action at first the grid becomes less negative or more positive. Than a grid potential was reached when an avalanche of electrons flows to the grid. In the case of a small change of the electric field a small charge is induced on the grid. When the avalanche of electrons occurs the induced charge is neutralized; moreover the excess electrons hold the grid at a negative potential, giving off-scale deflection. When the large charge wasbrought near the probe the electron avalanche passed to the charged object through the spark. This left no negative charge on the grid. Consequently the limitations of the instrument made it impossible to determine the actual polarity of the thunderstorms.

The two parallel plates were also placed outside in the open. The probe of the instrument was then placed between them. The same effects were observed with the addition of a secondary effect. This effect occurred when a negative field existed between the plates. The needle of the meter would then sway back and forth. Again for a positive field between the plates the reading was zero. It was concluded that this effect was produced by the earth's electric field, and consequently the artificial electric field must be separated from the field of the earth by shielding.

The fringing effect should be eliminated in order to produce a vertical field in the metal box. To reduce the effects of fringing and to give a uniform field a large number of equipotential surfaces should be placed between the two parallel plates. This can be effectively done by placing a large number of wire loops equidistant between the plates. These loops should be the same size as the horizontal plates or slightly smaller. The loops should be placed one above the other, and should be separated by about one inch. A resistor should be connected between each wire loop. A resistor should also be connected between the metal plates and the loops nearest to them. A power supply of at least 3000 volts should then be connected across the parallel plates. By this means the effects of fringing would be greatly reduced, and the electric field would be isolated and nearly vertical.

The screen, grid, and electrods were interchanged in a later investigation of the meter. The circuit was then similar to than employed in most potential gradient instruments. This caused the bias voltage to increase, produced more plate current, and gave less amplification. A negative charge was then placed on the grid and the meter then read a minus six. It took 20 minutes for this charge to leak off. The equalizer was then placed on the probe, and the same charge again applied to the tube. This time it took 1.5 minutes for the charge to leak off, thus demonstrating the effectiveness of the equalizer. A negative 30 volts was also applied to the grid by a battery. This gave a negative deflection of one scale division. After the battery was removed this deflection remained the same for about 5 minutes. When a positive potential was applied to the grid the meter was deflected up scale, but when the battery was removed the meter immediately read zero. It is thought that if the bias were made greater the same action could be produced for positive charges as was produced by negative charges. When the probe held a negative charge a positive charge would move to the immediate vicinity and cause a positive deflection. Again this represents the measurement of a change in potential gradient.

A conventional circuit for electrometer tubes should be employed to measure the static potential gradient. A commercially designed electrometer tube, or one of the few receiving tubes that are adaptable to this purpose should also be used. Moreover the tube should be coated with a silicon coating if the instrument is to be used during rainy weather.

The following procedure is recommended in case it is desirable to investigate the effect of humid weather on the instrument. The instrument should be placed in a box similar to the one described. With very dry air in the box, a known voltage should be applied to the horizontal plates. This voltage will produce a fixed deflection of the meter of the potential gradient instrument. Next air that has passed through a water spray should be blown into the box. The air then will be extremely humid. If any decrease in the reading of the instrument occurs, it must of necessity be due to the moisture deposited on the tube and insulators. When wet the glass surfaces of the tube and insulators give low leakage paths to ground. To overcome such difficulties the insulators and the tube may be treated with silicon.

The instrument that was designed and constructed for this project is capable of measuring the sudden changes of electric field. In order to improve the performance for detecting positive field changes, it is suggested that a 50 to 100 megohm resistor be connected across the input grid and ground. Another improvement would be to increase the bias voltage. This would keep the grid from drawing current when the positive field changes occurred.

For consistent operation it is very important that the enclosure of the electrometer tube should be made dust and bug proof. Also the insulator outside the electrometer enclosure should be placed where it can easily be inspected. Thus if any cobwebs are present they can easily be seen and removed. Cobwebs are often formed between the probe and ground, and when damp, these cobwebs act as a low resistance between the probe and ground.

In order to simplify the process of recording field changes, it is suggested that a recording milliammeter be used. An instrument with a recording speed of one to two inches per minute is recommended. This will allow for the separation of the field changes that occur very rapidly.

The instrument employed on this project has provided recordings that show numerous thunderstorm characteristics. While it is reasonable to assume that the small positive field changes have been faithfully reproduced, there may be some error in values. It was observed that as the severity of the storm increased, the rate of the sudden discharges also increased; moreover there seemed to be a trend for the more violent storms to give a larger number of the negative field changes with large and abrupt characteristics. Finally the predominance of the negative field changes gives evidence that the Oklahoma thunderstorms have positive charged regions in the base. This is an unusual result and differs from the findings of investigators working in other regions.

During the 1953 tornado season no actual tornadoes occurred within range of the station. If the method of potential gradient change is to be used for the purpose of studying the tornado type of storm, the relations that should be studied are given in the following outline:

(1) The correlation of the relationship of the field changes per unit time with that of ordinary storms.

(2) The comparison of the magnitude of the potential gradient due to tornadoes with that produced by thunderstorms.

(3) The comparison of the field change patterns taken during thunderstorms with those due to tornadoes.

It would be interesting to dispatch five radio-sondes equipped with potential gradient instruments into an incipient tornado cloud to measure the electrical field changes. This might give an improved understanding of the phenomenon involved.

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