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METEOROLOGICAL OFFICE

Geophysical Memoirs No. 84

(FOURTH NUMBER, VOLUME X)

ATMOSPHERIC ELECTRICITY DURING DISTURBED WEATHER

BY

SIR GEORGE SIMPSON, K.C.B., F.R.S.

LONDON: HIS MAJESTY'S STATIONERY OFFICE

1949

Decimal Index
551.508.94
551.594.2

London, Geophys. Mem.
10, No. 84, 1949

TABLE OF CONTENTS

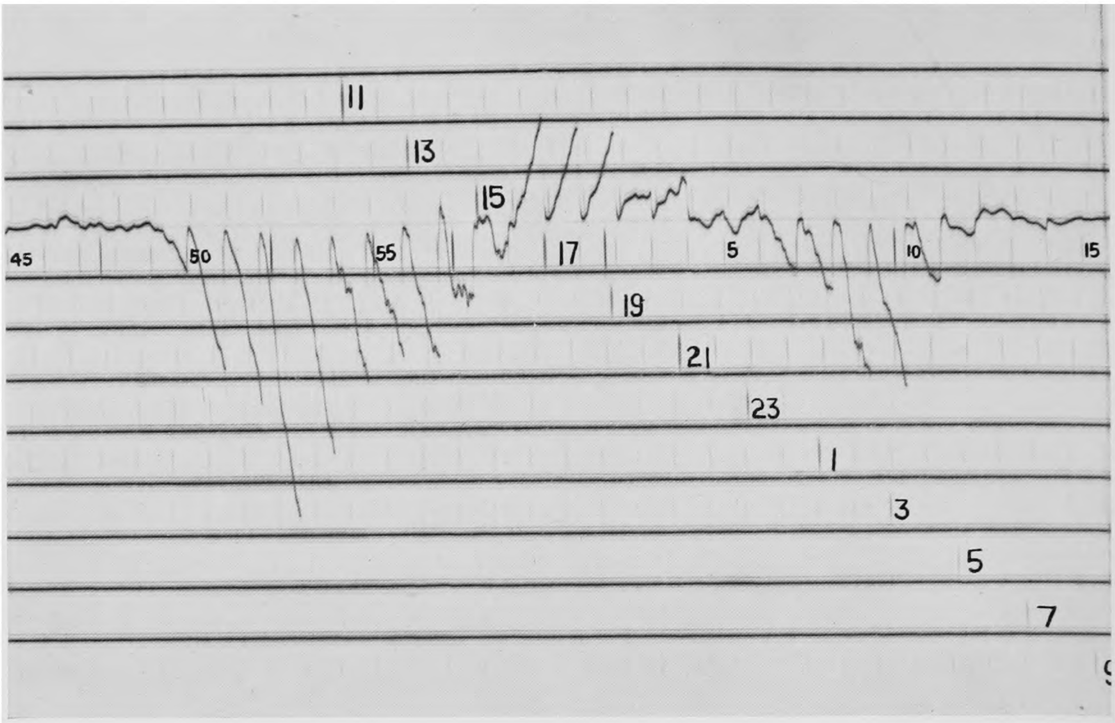

FIG. A.—PORTION OF A RAIN-ELECTROGRAPH RECORD (NATURAL SIZE)

FIG. B.—PORTION OF THE POINT-DISCHARGE RECORD CORRESPONDING TO FIG. A (NATURAL SIZE)

ATMOSPHERIC ELECTRICITY DURING DISTURBED WEATHER

INTRODUCTION

In 1934, Dr. F. J. W. Whipple, then Superintendent of Kew Observatory, adopted a scheme for obtaining continuous records of all the more important factors of atmospheric electricity. The scheme included the measurement of the electricity carried down by rain, and in 1938 F. J. Scrase published a valuable *Geophysical Memoir*[1]* analysing the results of the observations of the rain electricity made during the two years 1935–6. The observations had by then become part of the routine of the Observatory, and the results for 1937–8 were worked up by G. D. Robinson but not published when war broke out.

On the outbreak of war the routine work of the Observatory was reduced to a minimum in order that special war work might be undertaken, and although the rain-electricity apparatus was not dismantled all the work on the records came to an end. In 1942 the special war work was running smoothly so that it became possible to give more attention to the normal work of the Observatory and work on the records of rain electricity was resumed.

It had become clear in the interval that the old method of treating the observations in bulk, obtaining mere statistical relationships between the various factors, was not likely to give much more useful information. A closer study of the simultaneous values of the rain electricity, the potential gradient, the rainfall and other physical factors was required, and this could only be done by taking observations at short intervals of time, a minute at the most, and plotting them together on the same base so that their simultaneous variations could be followed. Further, recent discussions of the problems of rain electricity had shown the desirability of obtaining more information regarding non-thunderstorm rain ; this necessitated measuring smaller charges on the rain than had previously been done.

In order to meet these needs a number of changes were made in the apparatus then in use and a new series of observations commenced in October 1942. The reduction and study of the records proceeded as the observations were made and the preparation of this report was taken in hand early in 1946. The observations used in the report extend from October 1942 to June 1946, so comprising 45 months of continuous observations ; but the records before and after this period have been used in some sections of the report.

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* The index numbers refer to the bibliography on p. 50.

PART I—INSTRUMENTS AND METHODS

§ 1—INSTRUMENTS

The following instruments were used in the investigation :

(i) the rain-electrograph for measuring the electricity carried by the rain,

(ii) the rain-gauge for measuring the quantity of water carrying the measured quantity of electricity and at the same time the rate of rainfall,

(iii) the point-discharge galvanometer for measuring the current of electricity discharged into the atmosphere through a freely exposed point and indirectly providing a measure of potential gradients greater than $|20|$ v./cm., and

(iv) the potential-gradient electrometer (Benndorf) for recording potential gradients less than $|20|$ v./cm.

A description of these instruments follows :

Rain-electrograph and rain-gauge.—The instruments in use at Kew up to 1942 were described by Scrase in his memoir[1] from which the following extract and Fig. 1 have been taken :

A scale drawing of the rain-receiver is shown in Fig. 1. An insulated funnel, F, of diameter 23 cm., is covered by a conical shield C having an opening above the funnel of 16 cm. diameter. The outer cylindrical shield S has a diameter of 44 cm. and a height above the top of the conical shield of 39 cm. The dimensions of the outer shield were selected so as to reduce the induction effect of the earth's electrical field on the edge of the cone to a negligible amount and the efficiency of the screen was tested by measuring the decrease of field with depth inside the cylinder with a portable Wilson electrometer. It was found that the field at the depth of the opening of the cone was about one per cent. of the field at the top of the cylinder, or three per cent. of the field over level ground ; the field extending inside the cone to the funnel would, of course, be smaller still. The funnel is supported by a stand A which is insulated by embedding its base in a sulphur block ; this stand also carries a rod which connects the funnel to the electrometer. The base of the receiver is a teak cabinet which houses the gauge for measuring the volume of rain ; the receiver stands in a shallow concrete trench at the side of the underground laboratory in which the electrometer and recording drum are installed ; the top of the cylindrical screen is 45 cm. above the top of the trench which is level with the roof of the laboratory and a surrounding asphalt apron. A photograph showing the site of the apparatus with the cylindrical screen in position is reproduced in Fig. 2 [not reproduced here].......

A Dolezalck electrometer is used for measuring the charge caught by the insulated funnel. . . The electrometer deflections are recorded photographically on a drum which turns once in two hours and traverses about 8 mm. every revolution ; the time scale is 5 mm./min. and time marks are recorded every hour by means of a light spot switched on by a relay in the circuit of a contact clock.

For measuring the amount of rain caught by the funnel a gauge of the tilting-bucket type is used (B, Fig. 1). ......The gauge carries an enclosed mercury switch which, at each tilt, turns on the same light spot which registers the time marks ; the latter are easily distinguished on the records by their regularity. The mercury switch is also arranged to work a relay which earths the electrometer at every tilt of the bucket ; thus the electrometer record shows continuously the change in voltage produced when charged rain is falling into the funnel and it returns to zero for two seconds every time 3 $cm.^3$ of rain has been caught.

Precautions have been taken to minimise the errors to which measurements of the charge on rain are liable.... The most serious drawback to the apparatus is the fact that in moderate or strong winds rain is partially, or even completely, prevented from entering the funnel and so better samples are obtained of rain associated with light winds than of rain associated with strong winds. It is difficult to avoid this without introducing errors due to inefficient screening from induction effects.

The instrument described by Scrase in the above quotation was still in use in 1942; but for the new investigation a number of changes were made. In the first place the sensitivity of the electrometer was increased ten fold from 4 v./mm. to 4 v./cm. so that the electricity of non-thunderstorm rain could be measured.

The tall cylinder around the funnel of the rain-gauge, as stated by Scrase, prevented a large proportion of the rain from entering the funnel especially if there was any appreciable wind. This was objectionable for two reasons ; (*a*) it reduced the amount of water entering the funnel, which is equivalent to reducing the effective sensitivity of the instrument, and (*b*) it destroyed every relationship between the amount of water reaching the funnel and the rate of rainfall. The cylinder was therefore cut down until its rim was 7 cm. above the mouth of the cone C when the angle between the rim and the mouth of the cone was 26°, which is the permissible angle between the mouth of a standard rain-gauge and surrounding objects. The rain-receiver could now be used as its own rain-gauge, and direct comparisons showed that there was little difference between the rain recorded by the rain-electrograph and that caught in the observatory gauge, even in high winds.

One had to pay for this improvement ; for cutting down the cylinder removed the protection against the earth's field, which was the purpose for which it was originally installed. After the cylinder had been cut down deflections due to induction could be recognized, especially those due to the large changes of field which accompany lightning discharges. The induced deflections were, however, usually small compared with the deflections due to charged rain, and as they are

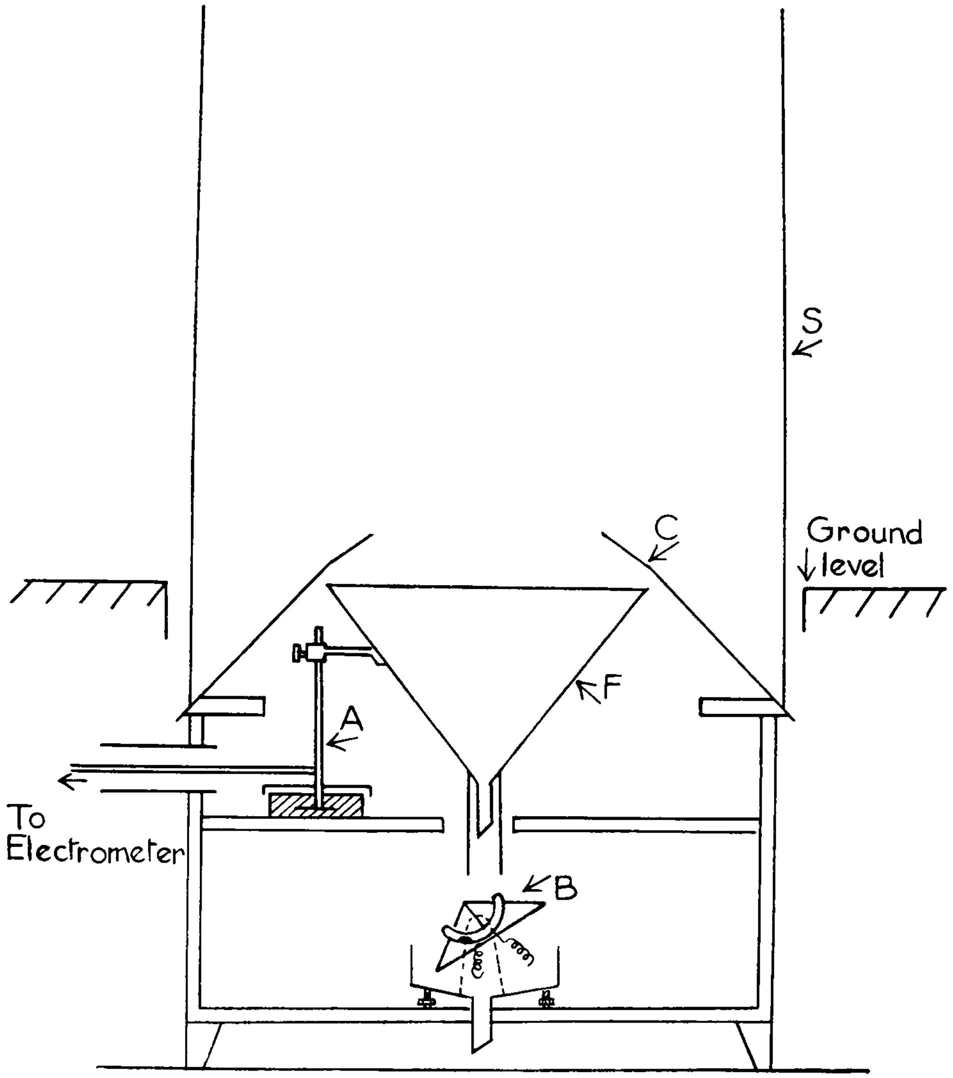

FIG. 1—RAIN RECEIVER AND TILTING BUCKET

A, insulated stand supporting funnel
B, tilting bucket rain-gauge.
C, conical shield.
F, insulated funnel.
S, outer cylindrical shield.

irregular in sign and magnitude they can be treated as accidental errors which cancel out. In actual practice there was no difficulty in recognizing deflections due to induction, they could practically always be detected by comparing the curve for the rain electricity with the curve for the potential gradient, taking note at the same time whether there was any rainfall.

There was, however, one possible source of error the magnitude of which could not be calculated or tested by inspection of the curves. The rim of the cone, with the cut-down cylinder, is exposed to the full field at ground level. With high fields the induced charge on the rim must be appreciable. If in these circumstances drops of rain fall on the rim portions would splash into the funnel carrying some of the induced charge with them. This source of error became of vital importance when it was found that the sign of the rain electricity is frequently opposite to that of the field ; for, as the charge on the rim is of opposite sign to that of the potential gradient, if sufficient drops splashed on the rim and entered the funnel they might lead to the observed relationship. To make quite certain on this important point the high cylinder as used in Scrase's work was put back and kept in use for four months, February to May, 1945. The relationships between the potential gradient and charge on the rain during this period were found to be indistinguishable from those with the short cylinder, although as stated by Scrase the field at the rim of the cone is reduced by the high cylinder to three per cent. of the field over level ground. Thus the possibility of the observed relationship being due to induced charges, either directly or by splashing on the rim of the cone, was shown to be non-existent.

Another change in the apparatus was also introduced : arrangements were made for the rain-electrometer to be earthed at minute intervals instead of each time the rain-gauge bucket tipped. This was easily arranged for the standard Observatory clock is fitted to give electrical impulses every minute. Leads were taken from the clock to the various instruments, and these impulses were used to put minute time marks on the records and to earth the rain-electrometer simultaneously. The electrical contact on the tipping bucket was retained, and each time the bucket tipped a special mark was made between the time marks on the rain-electrograph trace; in this way the time interval between tips could be measured and the rate of rainfall determined.

The following are the constants of the rain-electrograph as used throughout this investigation :

Area of the mouth of the cone receiving the rain	200 cm.^{2}
Volume of water required to tip the bucket	3·5 cm.^{3}
Electrical capacity of rain receiver with electrometer	110 cm.
Sensitivity of electrometer	4 v./cm.

Fig. A, Plate I (*frontispiece*), is a full-size reproduction of a portion of the record of the rain-electrograph.

Point discharge.—Since 1932 a record has been maintained at Kew Observatory of the discharge from a needle point at a height of 8·4 m. above the ground (Whipple and Scrase[2]). The record is a photographic trace of the movement of the spot of light from the mirror of a galvanometer through which the discharge current passes from the ground to the point. As the deflection of the trace from the zero line is directly proportional to the current through the point the latter can be read off directly from the trace. A portion of a point-discharge record is reproduced full size as Fig. B, Plate I.

The point-discharge current is a function of the potential gradient and therefore can be used for determining the gradient if that function is known. Whipple and Scrase determined the function for the point in use at Kew in 1934 by making simultaneous observations during six thunderstorms of the discharge from the point and of the potential gradient as measured in the usual way, but using a specially powerful polonium collector. They found the following relationship :—

$$I = a\,(P^2 - M^2)$$

in which I = the discharge from the point in e.s.u./sec.
P = the potential gradient in v./cm.
M = the minimum potential gradient at which the discharge commences.
a = a constant.

Different values for a and M were found for positive and negative gradients.

Between the observations made by Scrase and those made for this investigation the mast carrying the point had been moved to a new site ; but otherwise everything remained the same. As it was impracticable to make a redetermination of the relationship it was decided to adopt Scrase's values ; this appeared justified as there was no reason to believe that the exposure of the needle was appreciably different at the two sites. At the same time there appeared no need to retain the small difference Scrase had found between the constants for positive and negative discharges. The mean values of these constants were therefore used, giving the relationship between the point-discharge current and the potential gradient :—

$$I = 2{\cdot}7\,(P^2 - 8{\cdot}2^2) \text{ e.s.u./sec.}$$

Values of I and P for various deflections (D) on the point-discharge record are given in the following table.

TABLE I

D	I	P	D	I	P	D	I	P
mm.	e.s.u./sec.	v./cm.	mm.	e.s.u./sec.	v./cm.	mm.	e.s.u./sec.	v./cm.
	$\times 10^3$			$\times 10^3$			$\times 10^3$	
0·5	0·7	18	7	10·1	62	20	28·8	103
1·0	1·4	23	8	11·5	66	25	36·0	115
1·5	2·2	29	9	12·9	70	30	43·2	127
2	2·9	34	10	14·4	73	35	50·2	137
3	4·3	41	12	17·2	80	40	57·6	146
	5·8	48	14	20·1	87	45	64·8	155
	7·2	53	16	23·0	92	50	72·0	164
6	8·6	58	18	25·9	98	55	79·2	171

In practice it was found that a deflection of half a millimetre can just be recognized on the trace ; but it cannot be accurately measured owing to the thickness of the line. Also there is considerable variation from time to time in the value of the potential gradient at which the discharge commences, due to a number of unknown causes. As a deflection of half a millimetre corresponds according to the above table to 18 v./cm. it is clear that the point-discharge record cannot be used for measuring potential gradients below 20 v./cm.

Potential gradient.—For recording potential gradients below the range of the point-discharge instrument a Benndorf self-recording electrometer was used. This instrument is a quadrant electrometer, to the needle of which is attached a long arm swinging freely over a band of paper which is moved forward by a built-in clock. Between the paper band and the swinging arm is a typewriter ribbon. The clock closes a circuit every two minutes the current from which, passing through a magnet, causes a bar to press the swinging arm down on to the typewriter ribbon, so leaving a dot on the paper band. The current from the standard clock was used to make the hour marks, so that the Benndorf record was synchronised with the other instrument at hourly intervals. The range of the electrometer was adjusted to be from −25 v./cm. to +25 v./cm., thus giving a small useful overlap with the point-discharge instrument when used for measuring the potential gradient. A polonium collector was used which was powerful enough to attain the full potential over the whole scale in about half a minute; thus, except for very rapid changes of the field, the record could be relied on to give a true measure of the potential gradient.

§ 2—REDUCTION OF THE RECORDS

The records for all periods with precipitation were investigated; but each period was extended to include the disturbed potential gradient before and after the precipitation. Numerical values of the required quantities were then derived for each minute during these periods by the following methods.

Point discharge (I).—The mean displacement of the point-discharge trace was measured for each minute and tabulated. As the displacement is linearly proportional to the current, the mean current is given by the relationship:

$$I = 1 \cdot 44 \times 10^3 D \text{ e.s.u./sec.}$$

in which I is the point-discharge current in electrostatic units and D is the deflection in millimetres. The sign of I is taken to be positive when positive electricity flows into the point from the air; thus the sign of I is the same as the sign of the potential gradient.

Potential gradient (P).—Potential gradients above $|20|$ v./cm. were obtained from the deflections of the point-discharge record, D mm., by using Table I (expanded to give the value of P for each half-millimetre deflection).

For potential gradients less than $|20|$ v./cm. each dot on the record of the Benndorf electrometer was measured on a scale graduated in volts per centimetre, and entered to the nearest minute by reference to the hour marks made by the standard clock.

The sign of P in fine weather is taken to be positive, and therefore the sign of the gradient is the same as the sign of the charge in the upper atmosphere which would produce the observed field.

Rate of rainfall (R and R').—From the marks made on the rain-electrograph record each time the rain-gauge bucket tipped, the time of each tip can be read off to one-tenth of one minute. These times were tabulated and the intervals in minutes between successive tips obtained by subtraction.

Let N = number of minutes between two tips,
R = rate of rainfall in cm./sec.,
R' = rate of rainfall in mm./hr., and
r = rainfall in mm. equivalent to one tip;

then as the area of the mouth of the rain-gauge was 200 cm.^{2} and $3 \cdot 5$ cm.^{3} of water were required to tip the bucket we have

$$R = 2 \cdot 9 \times 10^{-4}/N \text{ cm./sec.}$$
$$R' = 10 \cdot 5/N \text{ mm./hr.}$$
$$r = 0 \cdot 175 \text{ mm.}$$

It is useful to note that $R = 2 \cdot 77 \times 10^{-5} R'$, and $R' = 3 \cdot 6 \times 10^4 R$.

Rain current (i).—This is a convenient expression for the vertical electrical current due to the transport of the electricity on the rain. It is equivalent to the total charge which falls on a square centimetre of the ground in one second.

Let d = the deflection of the rain-electrograph in mm. at the end of a minute interval,
K = the sensitivity of the electrograph = $0 \cdot 4$ v. ($0 \cdot 4/300$ e.s.u.) per mm. deflection,
C = the electrical capacity of the receiver = 110 cm., and
A = the area of the mouth of the cone = 200 cm.^{2}

$$\text{Then } i = \frac{KCd}{60A}$$

$$= 1 \cdot 22 \times 10^{-5} d \text{ e.s.u./cm.}^2 \text{ sec.}$$

Thus to obtain the rain current in electrostatic units (i) the deflections on the rain-electrograph record was measured in millimetres at the end of each minute and multiplied by $1 \cdot 22 \times 10^{-5}$.

The sign of i is taken to be the same as that of the charge on the rain.

Charge per cubic centimetre of rain (q).—The amounts of electricity and rain received on each square centimetre of the surface each second are i e.s.u. and R cm.^{3} respectively.

Hence for the charge per cubic centimetre carried by the rain we have

$$q = \frac{i}{R} = \frac{1 \cdot 22 \times 10^{-5} Nd}{2 \cdot 9 \times 10^{-4}} = 0 \cdot 042 Nd \text{ e.s.u./cm.}^3$$

As minute values of N and d have already been tabulated, as described above, the minute values of q are obtained by simple multiplication.

Snow.—As it was found impossible to devise any satisfactory method of melting the snow immediately on falling into the receiver there was no record of the rate of snowfall ; but as the receiver remained insulated the rain-electrograph gave a record of the amount of electricity carried down by the snow each minute. Thus during snowfall there are no values of R or q, but minute values of P, I and i are generally available.

§ 3—PLOTS OF THE OBSERVATIONS (WORKING SHEETS)

Having obtained and tabulated, in the way just described, minute values of the potential gradient (P), the point-discharge current (I), the rain current (i), the charge per cubic centimetre (q) and the time of each tip of the rain-gauge bucket, it was found that they could best be studied by plotting them on a common base using a time scale sufficiently open to allow of each minute value being shown.

Large sheets of section paper, 22 in. by 17 in., divided into inch squares (sub-divided into tenths of an inch) were obtained. Each sheet was divided by horizontal lines into four strips each 4 in. deep. The central horizontal line in each strip was taken as the common zero or base for plots of P, I, i and q. Each inch horizontally was taken to represent ten minutes so that the tenth divisions represent the individual minutes. Each of the four curves was plotted in a characteristic way so that it could be easily distinguished from the other three, and the rainfall was represented by a series of short vertical lines each marking the time at which the rain-gauge bucket tipped.

Eighty-four sheets (which will be referred to as " working sheets ") were used for the period from October 1942, when the observations commenced, to May 1946 when further analysis was suspended in order to prepare this report. These 84 working sheets comprise in effect one long strip of record nearly 600 ft. long showing the variations from minute to minute of P, I, i, q and R' for more than 1,000 hours of disturbed weather, and provide a powerful means for studying the electrical phenomena connected with precipitation.

§ 4—TYPES OF PRECIPITATION

To facilitate discussion the periods of precipitation have been classified in four main types (*a*) steady rain ; (*b*) showers ; (*c*) thunderstorms ; and (*d*) snow and sleet.

Steady rain.—Three arbitrary conditions were chosen for a period of rainfall to be classed as " steady rain " :

(i) the rainfall must continue for at least one hour,
(ii) there must be no large variations in the rate of the rainfall, and
(iii) the rate of rainfall must not fall below 1 mm./hr. (one tip of the bucket in 10 minutes).

The third condition is necessary because with very light rainfall highly charged rain does not produce a measurable deflection on the rain-electrograph and the rain appears uncharged. It was therefore necessary to have a lower limit to the rate of rainfall and a calculation showed that the limit must be 1 mm./hr. if rain charges which are significant were to be recorded.

Showers.—All periods of rainfall which are not automatically included in " steady rain " are grouped together as " showers ". The majority of these periods would be classified as " showers " in the strict meteorological sense,* but others would have been classified as " steady rain " if they had continued for an hour. Thus the word " shower " is not to be interpreted too literally ; it is rather to be considered as a convenient term to cover all periods of rainfall which are intermittent or of irregular intensity.

Thunderstorms.—Thunderstorms are accompanied by such large and rapid changes of the electrical conditions that mean values of field and charge can seldom be determined for minute intervals. Thunderstorms could not therefore be investigated quantitatively ; but whenever possible the records obtained during thunderstorms were plotted on the working sheets and useful lessons can be learnt from a study of the resulting curves ; reference to these will be made as occasion arises in the discussion.

Snow and sleet.—There were only a few periods of snow and sleet during the three winters covered by the investigation. These are dealt with separately from the periods of rainfall.

PART II—POTENTIAL GRADIENT

§ 5—POTENTIAL GRADIENT AND THE WEATHER

While there are many general statements in the literature about the potential gradient during disturbed weather, e.g., the potential gradient during rainfall is mainly negative and very variable and that during thunderstorms it oscillates rapidly between high positive and high negative values, yet no detailed study of the potential gradient during precipitation appears to have been made. This is a remarkable fact which can only be accounted for by the practice in observatories of adjusting the self-recording instruments to register only the fine-weather potential gradient, so that all records during disturbed periods are " off the trace " and therefore lost. The continuous records of the Benndorf electrometer and of the point-discharge galvanometer at Kew when plotted together give a record of the potential gradient in all kinds of weather, the study of which will now be described.

It will be most convenient to discuss the characteristics of the potential gradient for each of the four types of precipitation described above ; but before doing so the diagrams used to

* See " Meteorological Glossary ", 3rd edn., London, p.170.

illustrate this section (Plates II–VI) will be described. These diagrams are all traces from the working sheets on which the minute values for P, I, i, q and R are plotted to the same base lines, as described above (p. 9). The inch squares of the working sheets have been reproduced so that the intervals between the vertical lines represent ten minutes. The thin continuous curve gives the potential gradient as recorded by the Benndorf electrometer for which the scale is given on the left of each diagram. The thick curve gives the point-discharge current which is an indirect measure of the potential gradient, and a scale of potential gradient has been added on the right of the diagram for use with this curve. The short vertical lines mark the tipping of the rain-gauge bucket, each tip representing 0·175 mm. of rain (1 tip in 10 min. = 1 mm./hr.). The small dots and circles refer to the rain electricity and are not used in this section. The horizontal lines between crosses shown above some of the curves will be explained later.

Steady rain.—There were 44 periods of steady rain between October 15, 1942 and May 16, 1946, comprising altogether 79 hours during 83 per cent. of which the potential gradient was negative. The periods, however, differ very much from one another in that while some have negative gradient throughout others have more or less positive potential gradient. In an endeavour to find the cause of this difference the periods were divided into three classes :—

(A) periods in which the potential gradient was negative throughout ;

(B) periods in which there was some positive potential gradient without the positive gradient exceeding | 20 | v./cm., and

(C) periods in which the positive gradient reached or exceeded +20 v./cm.

Typical examples of each of these three classes are reproduced as Figs. A, B and C on Plate II. There proved to be 17 periods, representing 30 hours, in Class A ; 14 periods, representing 25 hours, in Class B and 13 periods, representing 24 hours in Class C. The synoptic charts were then studied to see if the different classes were associated with distinctive types of weather. The result was quite definite ; of the 17 periods of steady rain in Class A, 10 were due to rain falling in advance of a warm front or of an occlusion, 2 occurred in warm sectors and the other 5 were associated with no recognizable fronts ; all these are signs of a quiet atmosphere in which the vertical currents necessary to produce the rain are of small velocity and uniform over large areas. Turning now to the class at the other end of the series it was found that of the 13 periods in Class C, 9 were associated with the passage of a cold front : that is in conditions which are usually associated with instability and turbulent vertical currents. The 14 periods in Class B were not sufficiently different from those of Class A to show any special characteristics. The conclusions to be drawn from this survey would appear to be that when steady rain falls from a quiet atmosphere the potential gradient is negative ; while when the rain is associated with active instability in the atmosphere the potential gradient undergoes rapid changes from large positive to large negative values.

It is interesting to notice that the intensity of the rainfall was practically the same during the periods represented by Figs. A and C on Plate II yet the potential-gradient curves are entirely different in the two cases. This leads to the conclusion that the intensity of steady rainfall is not an important factor in determining the character of the potential gradient.

Showers.—The four diagrams of Plate III illustrate various aspects of the potential gradient during showers.

Fig. A, Plate III is typical of periods of rainfall in which there are large variations in the intensity of the rainfall, indicating the showery nature of the rain. In this diagram the potential gradient is represented by the curve for the point-discharge current, and if it is compared with the corresponding (thick) curve on Fig. C, Plate II it will be seen that while the two curves agree in showing alternations of positive and negative gradient the variations are greater and more rapid in the period of showers than in the period of steady rain. This is the characteristic difference between showers and steady rain.

Figs. B, C and D, Plate III are records of real showers in which the rainfall is of short duration and not preceded or followed by continuing rain. Such showers are always accompanied by disturbed potential gradient, but the records show no relationship between the quantity of rain or its intensity in the shower and the sign or magnitude of the potential-gradient disturbance. Fig. B, Plate III reproduces the record of the rain period which gave the greatest positive gradient recorded during rainfall in this investigation, the potential gradient reaching the peak value of +170 v./cm. Fig. D, Plate III gives the record of another shower in which practically the same amount of rain fell, and at a comparable rate, with the same type of potential-gradient disturbance, yet in this case the peak value of the potential gradient was only +15 v./cm.

Fig. C, Plate III shows the record of the period with the largest negative disturbance during rain. The shower was not particularly heavy but the potential gradient was depressed to −140 v./cm. (estimated as the curve went off the photographic paper). On Plate XVIII there are reproductions of several much heavier showers which produced negative gradients, but only to about −10 v./cm.

Thus the characteristics of the potential gradient during showers are rapid, positive and negative variations which are often large, but independent of the quantity or intensity of the rain in the shower.

Thunderstorms.—It is impossible to draw a hard and fast line between " showers " and " thunderstorms ". The point-discharge record frequently shows discontinuities, which can only have been caused by an electrical discharge in the cloud, without lightning being seen or thunder heard. It would obviously be wrong to classify periods in which one or two such discharges occurred as thunderstorms. There is a slow gradation from showers without any discharges to true thunderstorms which may have as many as twenty or thirty visible discharges in a minute. The following discussion of the potential gradient during thunderstorms will be based on examples about which there can be no doubt as to their nature.

The electrical conditions during the more severe thunderstorms are so disturbed that it is impossible to measure and plot the records. A few of the less severe storms can however be dealt with and the records for three thunderstorms are reproduced on Plate IV. These three records are typical and illustrate all the conclusions which it has been possible to draw from the whole mass of data.

The discontinuities in the potential gradient due to the lightning flashes are clearly seen on each diagram. The nature of the changes in the field which accompany a lightning flash have been studied by Wilson, Wormell, Schonland and others and will not be considered here; for our purpose it is sufficient to notice that the disturbances due to the lightning discharges are superimposed on a slowly changing general field and that this field is similar both in magnitude and time variation to the field during showers. Except for the momentary fields due to lightning discharges the electrical field at the ground during thunderstorms is no greater than during many showers which are not accompanied by lightning discharges. Further, during thunderstorms, as during showers, the field at the ground bears no relationship to the intensity of the rainfall. In Fig. A, Plate IV there are periods in which the rainfall reached a rate of 30 mm./hr., in Fig. B it did not exceed 10 mm./hr. and in Fig. C it was too small to be measured; yet the general field was practically the same in all three periods.

Thus the potential gradient during thunderstorms is little different from that during showers without thunder or lightning except for the large momentary disturbances which are associated with near lightning discharges.

Snow and sleet.—During the three winters over which this investigation extended records were obtained during 16 periods of snow or sleet. With snow as with rain the fields are different according as to whether the snowfall is steady or in the form of showers. We will commence the discussion with a case of steady snowfall and pass on to heavy sleet showers associated with the passage of cold fronts.

Fig. A, Plate V, is part of a long record extending over four hours during which there was continuous light snowfall, the intensity probably varying from 0·1 to 1·0 mm./hr. The temperature was just below the freezing point. The record for the 70 minutes reproduced is typical of the whole period. Compared with a similar period of light rainfall, *e.g.* Fig. A, Plate II, there is one similarity and one difference : they are similar in that the potential gradient is steady without large variations either in the positive or negative direction ; but they are different in that light steady rain is almost invariably accompanied by negative potential gradient, while in this long period of light snowfall the potential gradient was positive throughout. There were other short periods of snowfall with positive gradient ; but these alone are not sufficient to justify a generalization that light snowfall is different from light rainfall in that the former is accompanied by positive potential gradient and the latter by negative. There are only a few observations of potential gradient during snowfall available in the literature but what there are confirm the few observations at Kew. P. A. Sheppard[3] in his report on the potential gradient observations made at Fort Rae, Canada, by the British Polar Year Expedition, 1932–3, says, p. 318, " the occasions of light snowfall were many, and eliminating those attended by drift snow, the records show that on the majority of occasions the field was only slightly disturbed. Sometimes the field alternated between low positive and negative values, or else normal values of the gradient were recorded." At Cape Evans in the Antarctic there were many periods of light snow without drift but negative potential gradient was never recorded in them (Simpson[4]), and Sverdrup[5] (p. 439) on the *Maud* expedition to the Arctic in 1918–25 only observed negative potential gradient once during 13 months' continuous observations.

We may therefore conclude that Fig. A, Plate V, is representative of periods with light steady snowfall, and that in such conditions the normal positive potential gradient is little affected.

This conclusion, however, only applies to the light steady snow which falls from a stable atmosphere. If the snowfall is due to the passage of discontinuities in the atmosphere it is not always accompanied by positive potential gradient. On January 30, 1945 an occlusion passed Kew which gave four hours of snowfall of varying intensity and much heavier than the snowfalls just discussed, rising in some periods to 3 or 4 mm./hr. Fig. B, Plate V is part of the record of this period ; the part reproduced was near the beginning of the period and the negative potential gradient with which the extract ends continued for two hours, after which it became high positive and remained positive until the precipitation ceased. Here, as with rainfall, the potential gradients made excursions both positive and negative, obviously connected with the instability which accompanied the passage of the occlusion.

The remaining two curves on Plate V (note that these are point-discharge records) carry the series to greater instability, for each represents a short shower of snow evidently the result of local instability in the atmosphere. In neither case was the snowfall heavy, probably of approximately 1 or 2 mm./hr. Thus with snow as with rain the intensity of the precipitation is not a prime factor in determining the potential gradient which in these two cases ranged from −103 to +80 v./cm. compared with −20 to +30 in the period of which Fig. B, Plate V is a part, although the snowfall was heavier in the latter period.

The three periods represented by Figs. A, B and C, Plate VI were all periods of snow or sleet with temperatures above the freezing point. Compared with all the other records these show both more rapid changes and higher values of the potential gradient. They each occurred at the passage of a cold front, and in the case of Fig. B and Fig. C the snowfall was quite heavy in the squall. In Fig. B the range of potential gradient was from −170 to +170 v./cm. while in Fig. C the gradient exceeded −200 and +200 v./cm. These are the highest values of the potential gradient measured during the investigation (other than the momentary fields immediately following a lightning discharge).

Summary.—From this survey of the potential gradient at Kew in different types of weather the conclusion which seems to stand out is that the potential gradient during periods of disturbed weather depends more on the conditions in the upper atmosphere than on the amount and intensity of the precipitation.

When the atmosphere is free from fronts and occlusions so that the rainfall is steady the field is negative and undergoes only minor variations of long period. On the other hand when the atmosphere is affected by discontinuities the variations of the field become larger in amplitude and generally shorter in period. Occlusions appear to cause larger disturbances than warm fronts and the largest disturbances are associated with the passage of cold fronts.

As showers are generally associated with atmospheric discontinuities they are usually (but not always) accompanied by high fields both positive and negative, and the greatest fields recorded during rain (+170 and −140 v./cm.) were associated with showers ; but the magnitude of the field is not closely related to either the amount or the intensity of the rain in the shower.

The field at the ground is not essentially different in thunderstorms from that associated with showers, except that in thunderstorms very high momentary fields accompany the lightning discharges. It is a remarkable fact that the general field at the ground, on which the momentary fields due to the discharges are superimposed, is not greater in thunderstorms than in showers which show little or no lightning activity.

The field during snowfall shows the same general characteristics as during rainfall ; the field is steady when the atmosphere is free from discontinuities, and the disturbances of the field are associated with fronts and reach their greatest magnitude in squalls associated with the passage of cold fronts. The fields during snowfall, however, differ from those during rainfall in two important particulars : first, during light steady snowfall the normal fine weather field is only slightly affected and therefore the potential gradient remains positive, while light steady rain is almost invariably accompanied by negative potential gradient ; and secondly, the field at the ground when the passage of a cold front is accompanied by snow or sleet undergoes much greater and more rapid variations and the maximum field is greater than when the passage is accompanied by rainfall—the highest fields recorded at Kew both positive (+200 v./cm.) and negative (−200 v./cm.) occurred with these conditions.

§ 6—POTENTIAL-GRADIENT PATTERNS

So far we have been concerned only with the general characteristics of the potential gradient according to the kind of precipitation—steady rain, showers, etc., we have now to turn to quite different characteristics of the potential-gradient record.

One cannot turn over the sheets on which the curves of the potential gradient are plotted without noticing the recurrence of certain regularities in the curves. For the greater part, the curves consist of irregular ups and downs, sometimes on one side of the zero and sometimes on the other ; but over and over again there is a regularity in the run of the curve which can only be described as a pattern ; and it is these patterns which we have now to study.

In order to describe the patterns it is necessary to reproduce the original records from the Benndorf electrometer and the point-discharge galvanometer. As these records are entirely different the following short description of each is given to help the reader in his study of the diagrams. Fig. A, Plate VII is typical of the Benndorf records. On the original record the potential gradient is registered by dots made every two minutes ; these dots were connected by a curve passing through each one and the diagram is a tracing of this curve. The zero of the potential gradient is the thick line near the middle of the trace and horizontal lines are drawn for each 10 v./cm. ; as the scale is linear these lines are equally spaced. Vertical lines are drawn for each hour (G.M.T.) and it will be noticed that the time scale is very contracted compared with the time scale of the working sheets used in previous diagrams. The diagrams of the point discharge are very different. The original record is a continuous photographic trace showing every movement of the galvanometer mirror. These movements are sometimes so rapid that it is not possible to show them all on a tracing; but the curves on the diagrams, of which Fig. A, Plate XI is typical, are for all practical purposes accurate reproductions of the originals. The time scale is 14 times greater than in the case of the Benndorf records and is indicated on the diagrams by the short vertical lines drawn across the zero line at minute intervals. The deflections from the zero are linearly proportioned to the point-discharge current, therefore the curve is a much distorted representation of the potential gradient. The curve does not depart recognizably from the zero before the potential gradient reaches 20 v./cm., and then increases as the square of the gradient. Horizontal lines on the diagrams are drawn at intervals of 50 v./cm.: it should be noted that the full scale of the Benndorf record, approximately ± 20 v./cm., is represented on the point-discharge record only by a slight thickening of the zero line. The rate of rainfall is indicated on these point-discharge diagrams by short vertical lines in the lower half of the diagram, each recording a tip of the rain-gauge bucket.

In addition to the direct tracings just described, there are three diagrams in this section drawn to other scales for special reasons; these will be described as occasion arises in the course of the discussion.

The patterns which we are about to describe have been classed under two types:

(*a*) wave patterns, and
(*b*) symmetrical patterns.

Wave patterns

Fig. A, Plate VII reproduces the Benndorf curve from 21h. on July 26, 1945 to 2h. on the following morning: there was rain from 22h. 25m. onwards. Five large irregular waves are clearly visible. The range (maximum-minimum) of the waves is approximately 35 v./cm. and the period about 30 minutes. The two following diagrams, Figs. B and C, show waves superimposed on the swing of the potential gradient to the negative which generally accompanies light rainfall; in the former of these two cases there was continuous, but very light (less than 1 mm./hr.) rain throughout, and in the latter case only a few drops were reported. In none of the cases can any relationship be found between the variations in the intensity of the rainfall and the variations of the potential gradient. The next diagram Fig. D shows much more highly developed waves which obviously approximate to simple harmonic waves; in this case no rain was recorded and as it occurred during the night there were no visual observations; but it is known that there was low cloud throughout the night.

The most remarkable case is that illustrated in Fig. A, Plate VIII. Here there will be seen between 11h. and 17h. five waves increasing in range from 10 v./cm. to 40 v./cm. with a mean period of a little over an hour. This diagram is a tracing of the original curve of the Benndorf electrometer; in it, however, the vertical scale is too large compared with the horizontal scale to bring out clearly the nature of the oscillations. The original record was therefore carefully measured up and replotted with the same vertical scale but with the horizontal scale increased nearly three times; the result is reproduced in Fig. B on which the position of each dot on the original record is shown and a smooth curve has been drawn freehand through them. The harmonic nature of this curve stands out clearly; the majority of the dots lie on or close to the curve, although there is some irregularity which is most marked at the maxima and minima. It is interesting to notice that the amplitudes of successive waves increase as though they also were subject to a harmonic control, for the two curves connecting the crests and the troughs (shown by dotted lines in the diagram) appear to be parts of sine curves. Both these characteristics can be clearly seen in the train of waves reproduced in Fig. D, Plate VII, for the waves themselves are closely harmonic in form and their amplitudes decrease in a regular way reminiscent of a sine curve.

Returning to Fig. A, Plate VIII we see that just after 17h. when the curve is about to reach its sixth maximum the sequence of waves comes to a sudden end and the curve takes on a new pattern, reference to which will be made in a later section (p. 18).

The weather during this remarkable train of waves may be shortly described. Throughout the day a small almost stationary depression was centred near Brest at the mouth of the English Channel, which gave rise to a steady NE. wind of 7 m./sec. at Kew from 9h. to 24h. (the period covered by Fig. A, Plate VIII). At 9h. the temperature was 37° F. and there was light rain ; during the day the temperature fell slowly and the rain changed first to sleet and then at about 13h. 30m. it became snow which lay as it fell. From 12h. to 18h. the intensity of the precipitation was very steady, at the rate of 1 mm./hr. ; it then slowly decreased, ceasing at midnight. Thus during the period of the harmonic waves there was a steady fall of snow at the rate of 1 mm./hr. ; the temperature was a degree or two above the freezing point and the wind was steady from the NE. with a velocity of 7 m./sec.

The examples of waves discussed so far have been taken from the records of the Benndorf electrometer and therefore deal only with potential gradients between +20 and −20 v./cm. Similar waves, however, occur with higher potential gradients and can be recognized on the point-discharge records; but they are relatively few. An example will be found in Fig. A, Plate XVII, which is a tracing from the working sheet with the point-discharge current plotted as a thick curve. Although the waves on this curve are clear, the real shape of the waves of potential gradient is not apparent owing to the non-linear relationship between the point-discharge current and the potential gradient. The point-discharge curve has therefore been converted into a potential-gradient curve and reproduced in Fig. A, Plate IX. In this diagram the same time scale has been used as for Fig. B, Plate VII ; but the scale of the potential gradient has been reduced in the ratio of 4 to 1. The curve of Fig. A, Plate IX is clearly of the same nature as the curve of Fig. B, Plate VIII, with waves of approximately the same period but with amplitudes three to four times greater. It should be noted, as possibly of physical significance, that these two curves are representative of potential-gradient waves with and without point-discharge currents.

Indications of waves of this nature can be seen throughout the long record of potential gradient and point-discharge current, but the waves are frequently distorted by irregularities which tend to obscure them. The following table contains particulars of the eleven cases in which the waves are most clearly marked.

TABLE II

Date	No. of waves	Maximum range	Mean period	Instrument	Reproduced in
		v./cm.	min.		
7.12.41	4	230	6	Point discharge	—
30. 1.43	3	180	4	Point discharge	—
13. 5 44	4	133	45	Point discharge	Plate IX A
20. 8.44	3	106	35	Point discharge	—
26. 2.46	5	41	67	Benndorf	Plate VIII A
26. 7.45	5	39	34	Benndorf	Plate VII A
26. 5.46	5	26	25	Benndorf	Plate VII D
26. 4.45	2	25	106	Benndorf	—
19. 6.46	3	22	81	Benndorf	Plate VII B
7. 9.44	4	21	80	Benndorf	—
14. 8.46	2	7	34	Benndorf	Plate VII C

In Table II maximum range means the largest difference between the peak of a wave and the trough on either side, and the cases have been arranged in order of decreasing values of this range. It will be seen that there is no obvious relationship between the range and period of the waves, unless the short period and large range of the first two cases is significant. It should, however, be pointed out that while waves of a few minutes can be detected on the point-discharge record with its open time scale and continuous trace, they cannot be recognised on the Benndorf record which consists of points at two-minute intervals. Thus the absence of short waves with small ranges does not necessarily mean that they do not exist.

The wave patterns which we have discussed in this section are always accompanied by thick cloud from which rain or snow is usually falling. They are not to be confused with waves which sometimes appear on the potential-gradient record during fog, two examples of which are reproduced in Figs. B and C, Plate IX. The waves of the true wave pattern swing about the zero, with positive and negative amplitudes of approximately the same amount ; but the fog waves are only increases and decreases of an existing large positive field. The origin of such fog waves is well known. The upper layers of a fog accumulate positive electricity from the normal downward current in the clear air above. The charge thus accumulated produces an enhanced positive field at the ground. The upper boundary of a fog layer is often in wave-like motion and it is this motion which, acting on the charged layers, produces the wave-like variations in the positive field at the ground.

Symmetrical patterns

Besides the harmonic waves which we have just discussed, the curves of potential gradient frequently show patterns which are more or less symmetrical about their mid points, and it is these which are now to be considered. Any irregular curve, such as that of the potential gradient during disturbed weather, may be expected by mere chance to show periods in which the irregularities appear to form a symmetrical pattern. When, however, the same or a similar pattern is repeated several times one cannot help concluding that the pattern is due to some condition of the atmosphere which itself is symmetrical in time or space. In the following discussion only those patterns will be considered which are repeated sufficiently often to point to some underlying physical cause. There are five patterns which for convenience will be referred to as the V, UU, W, N and S patterns as these letters reproduce to some extent the form of the

The V Pattern.—It frequently happens during periods in which the potential gradient is fairly steady that the curve suddenly makes a rapid move in the negative direction and then equally rapidly regains its original value, after which the curve continues as though the disturbance had not occurred. Such a disturbance forms a pattern like a V on the potential-gradient curve. Three such cases are shown in Figs. A, B and C, Plate X, of which Fig. C shows a good example of the V pattern being superimposed upon a more general trend of the potential-gradient curve. All cases of the V pattern occur with low cloud and in the majority of cases there is a sharp shower which only lasts for a minute or two. The shower may, however, be very heavy (Fig. A with 2 mm. rain in five minutes) or it may be so light that only a few drops reach the surface (Fig. B with 0·03 mm. rain in five minutes) or even no rain may reach the surface (Fig. C with no rain recorded) ; but the disturbance produced does not appear to bear any relationship either to the intensity or to the amount of rain which falls in the shower.

Less often than in the cases just described the disturbance increases the potential gradient, giving an inverted V pattern, Figs. D and E, Plate X. In one case, Fig. F, Plate X, a positive and a negative V pattern occurred within an hour and a half of one another in a period when otherwise the potential gradient was practically steady. The disturbance generally lasts between five and twenty minutes, and in none of the cases has the potential been changed by more than 20 v./cm. It may be significant that in every case so far recorded the V pattern has commenced when the potential gradient has been positive. During the 46 months (October 1942–July 1946 inclusive) there were 14 cases of the negative V pattern and five of the positive V pattern.

The following appear to be the chief characteristics of V patterns : a V pattern is probably always associated with an isolated shower of rain (or snow ?) although the precipitation may not reach the ground ; it may be either positive or negative, but negative Vs predominate ; and so far as the records go the V disturbance is always superimposed on positive potential gradient.

The UU pattern.—A typical case of the UU pattern is reproduced as Fig. G, Plate X, from the point-discharge record. It will be seen that the pattern commences and ends with a U-shaped depression with an inverted U connecting them, or in other words a positive disturbance of the curve is preceded and followed by a negative disturbance, the whole forming a symmetrical pattern. Fig. H, Plate X, is another example taken this time from the record of the Benndorf electrometer ; it should however be noted when comparing Figs. G and H that the scales in the two cases are entirely different : the range of disturbance was 100 v./cm. in the former and only 20 v./cm. in the latter ; while the duration of the disturbance was only 10 minutes in the former and nearly one-and-a-half hours in the latter.

It will be remembered that the train of waves which occurred on February 26, 1946, Fig. A, Plate VIII, suddenly came to an end at 17h. 30m. and was succeeded by another pattern. This new pattern is now seen to be two UU patterns joined together. That two such well-marked patterns as the train of five waves and the two repetitions of the UU pattern should follow one another, occupying a total period of 11 hours, shows that on that day the atmosphere must have been in a very favourable condition for the establishment of patterns whatever those conditions may be.

Another example of the UU pattern will be seen in Fig. B, Plate III ; in this case the range of the pattern was from −66 v./cm. to +170 v./cm. and the duration 36 minutes.

Fig. J, Plate X, is a UU pattern but with the signs reversed. Thus we may have both positive and negative UU patterns according to whether the potential gradient in the central deflection is positive or negative.

There were seven good examples of UU patterns in the 46 months investigated, five associated with showers and the other two with light snowfall. The UU patterns, like the V patterns, appear to be associated with isolated showers.

The W pattern.—The most remarkable of all the symmetrical patterns is the W pattern, the best example of which is reproduced in Fig. A, Plate XI. To bring out the symmetry the peaks and depressions have been marked with letters : the centre of the pattern is a peak marked A ; on either side there is a broad depression containing a number of peaks which appear to be of a secondary nature and have therefore been bracketed in the depressions which have been marked B and B′ ; these depressions are flanked by two peaks marked C and C′ and the whole pattern is completed by two depressions marked D and D′. The duration of the pattern was 30 minutes and the range a little over 200 v./cm.

The symmetry is so striking that it needs no description, but the following points are worth noting : (*a*) the similarity in shape of the peaks C, C′ and of the depressions B, B′ ; (*b*) the equality in height of corresponding peaks and in depth of corresponding depressions, and (*c*) the equal times of the characteristic points measured from the peak at A. It was the great regularity of this example which first drew attention to this particular pattern and a search was made of all the records available at Kew to find if it was unique. Six examples in the point-discharge record extending over ten years and one in the Benndorf record extending over four years were found ; all seven are reproduced here on Plates XI and XII.

(i) Fig. A, Plate XI.—This example has already been described ; it is by far the most perfect in timing and in the correspondence of the details.

(ii) Fig. B, Plate XI.—This is a good example : the sharp points of the peaks C and C′ and the broad depressions B and B′ reproduce characteristics similar to those of Fig. A, the equal timing of the features is good, but corresponding peaks and depressions are not equal.

(iii) Fig. C, Plate XI.—This is not such a good example : corresponding peaks and depressions are not equal and the time from the beginning to the centre is more than twice as long as the time from the centre to the end. The whole effect is as though the tempo of the process quickened as it proceeded. This example is of interest chiefly because of the short time required to go through the whole pattern—less than 9 minutes.

(iv) Fig. A, Plate XII.—This is another good example, although not so perfect as Fig. A, Plate XI, and without so much detail ; but the latter difference may be due to the short duration which was only 18 minutes as compared with 30 minutes.

(v) Fig. B, Plate XII.—This example can be interpreted in two ways : at first sight it looks like a normal W pattern but with the central peak divided into two by a deep depression which extends below the zero line ; on the other hand if we consider the central depression to correspond to the central peak of the normal W pattern then the whole becomes a normal W pattern but with the signs reversed, as will be seen from the lettering which has been added on this assumption.

(vi) Fig. C, Plate XII.—This example exhibits a remarkable feature not shown in any of the other examples ; namely, the sub-division of each of the three main peaks into three sub-peaks. It is extremely difficult to believe that this sub-division is merely fortuitous ; it is much more reasonable to believe that it is due to a higher degree of the same physical action which produces the symmetry of the usual W pattern.

(vii) Fig. D, Plate XII.—This is the only example of a W pattern recorded on the Benndorf electrometer. It is interesting for several reasons : (*a*) the range is relatively very small, being only 30 v./cm. as compared with ranges of the order of 200 v./cm. in all the other cases ; (*b*) the total duration is $3\frac{1}{2}$ hours instead of 30 minutes or less ; (*c*) there are two more peaks E and G outside the D–D′ depressions. With regard to the small range and long period, it will be remembered that a similar relationship was found for the UU pattern.

The type of weather in which these highly complicated but amazingly symmetrical patterns occur is obviously of prime importance. A short description of the weather on each occasion will therefore be given.

(i) January 1, 1945, Fig. A, Plate XI.—The disturbance of the potential gradient on January 1, 1945, was associated with the passage of a well marked cold front. So far as it is possible to determine from the instrumental records the passage of the front, as marked by the sudden change of wind direction and the drop in temperature, coincided exactly with the central peak A shown on the point-discharge record. For several hours before the arrival of the cold front the direction of the wind had been steady from SW. with the velocity very slowly increasing. On the arrival of the front the wind veered within one or two minutes from SW. (220°) to W. (270°) and the velocity fell from 15 m./sec. to 10 m./sec. The temperature had been 47° F. before the arrival of the front and fell to 43° F. with the arrival of the new air current. There had been slight rain for some time before the front reached Kew, which increased to a sharp shower immediately following the change in wind direction, but the shower only lasted for about 10 minutes.

(ii) February 4, 1944, Fig. B, Plate XI.—The central peak was coincident with the passage of a squall in a NW. wind of 8 m./sec. In the squall the wind rose to 26 m./sec. and temporarily backed to N. On the passage of the squall the temperature fell from 40° F. to 36° F. There was a little light snow at the time.

(iii) January 20, 1945, Fig. C, Plate XI.—There was no front and the weather showed little change. The temperature remained constant at 32° F. and the wind velocity at 4 m./sec. ; but the wind backed 10°, from WSW. (240°) to SW. (230°) at 7h. when the central peak occurred. There was some light snow which did not melt on falling.

(iv) December 14, 1936, Fig. A, Plate XII.—The central peak of the pattern was associated with the passage of a slight squall in which the wind rose from 7 to 18 m./sec. ; but there was no change in wind direction, SSW., or temperature, 46° F. There was light rain.

(v) January 1, 1943, Fig. B, Plate XII.—A cold front passed at 15h. 0m. approx., *i.e.* after the pattern had commenced but five minutes before the centre. Before the passage the wind was SW. (240°), 7 m./sec. and the temperature 48·5° F., and after the passage WNW. (280°), 7 m./sec. and 46° F., respectively. Moderate rain commenced at 14h. 56m.

(vi) January 30, 1946, Fig. C, Plate XII.—There was a squall near the time of the centre of the pattern. Before and after the squall the wind was from W. (270°) with a velocity of 5–7 m./sec. During the squall the wind rose to 21·5 m./sec. in a gust at 14h. 20m. ; the wind veered to NW. (310°) and then returned to W. (270°). Before the squall the temperature was 43·5° F., it fell in the squall to 39·5° F. and then recovered to 42·5° F. at 15h. 30m. The squall was accompanied by a little rain.

(vii) September 11, 1943, Fig. D, Plate XII.—The pattern extends from 1h. to 4h. 30m. ; during these three-and-a-half hours an occlusion passed the Observatory ; but there is nothing in the wind record which correlates with the peaks and depressions of the pattern and the temperature remained constant throughout at 62° F. At 2h. 10m. there was a lull in the wind from 4 m./sec. to 1 m./sec. and a temporary veering from E. (90°) to ESE. (120°), this no doubt coincided with the passage of the occlusion at the surface and was probably the cause of the secondary peak marked X in Fig. D which is obviously superimposed on the main pattern. There were three light showers at 2h. 10m., 2h. 43m. and 3h. 6m.

It will be seen that in each of the seven cases a discontinuity in the atmosphere (two cold fronts, three squalls, one occlusion and one slight shift in the wind direction) passed during the period of the pattern. In five cases the passage of the disturbance coincided exactly with the centre of the pattern ; in the other two cases the coincidence is not exact—the discontinuity arriving somewhat before the centre but still well within the period of the pattern. In each case there was some slight precipitation, and it is important to notice that in two cases the precipitation was in the form of snow. It should, however, be remarked that the rain or snow was in each case slight and without correlation with the variations of the pattern ; it would therefore appear that any causative relationship between the precipitation and the pattern is extremely unlikely.

One of the most surprising things about these patterns is that when the discontinuity passes the station coincident with the centre of the pattern the first half of the pattern must be within one air mass and the second half in a different air mass. It is difficult to see what kind of physical connexion can exist between the potential-gradient depression D of Fig. A, Plate XI and the corresponding depression at D′ twenty-five minutes later, considering that a high wind of 15 or 10 m./sec. was blowing the whole time and they are on opposite sides of a cold front.

The N pattern.—The seven diagrams on Plate XIII represent examples of the N pattern. The characteristics of an N pattern may be described as follows : let the mid point of the pattern be O ; then from the initial point, some time previous to O, the curve rises to a maximum, M ; from this maximum the curve falls to the mid point and continues falling until it reaches a minimum, N, as far below O as M was above ; from this minimum the curve rises again ; the whole forming a pattern symmetrical about axes through O, something like the letter N.

In the first three examples (from the point-discharge record) the mid point of the pattern falls on the zero line and the pattern is therefore symmetrical about the zero of the potential gradient ; this appears to be generally the case with fields above 20 v./cm. It will be noticed however, that while examples A and B agree with the description given above, example C varies in that the potential gradient first reaches a minimum and the change through the zero goes from negative to positive instead of from positive to negative. A similar reversal of the sign of a pattern has been found in all the previous patterns we have discussed. To distinguish between the two types the former will be called the −N pattern and the latter the +N pattern, the sign indicating the direction in which the change through the mid point takes place.

The three following examples, Figs. D, E and F, Plate XIII, are taken from the Benndorf record and the potential gradient during the pattern does not exceed |10|v./cm. At first sight these examples do not appear so symmetrical as the point-discharge records, A, B and C, this is because one expects them to be symmetrical about the zero axis ; but if a horizontal axis is drawn through the mid point of the pattern (see dotted line), both patterns are seen to be symmetrical about this axis. Example D is a −N pattern and example E is a +N pattern. Example F shows both a +N and a −N pattern occurring within a few minutes of one another, but the symmetry in these two examples is not so good as in the others ; this is no doubt due to the two patterns distorting one another.

The most interesting portion of the N pattern is the middle period during which the curve passes through the mid point of the pattern. To study this period of change most effectively the dots on the original trace of the Benndorf electrometer have been reproduced in Figs. D, E and F. These dots record the potential gradient at intervals of two minutes and it will be seen that during the period of change the dots are equally spaced along a straight line. This means that during this period the potential gradient is changing at a constant rate. To examine whether this is also the case when the N pattern is made up of changes too large to be recorded by the Benndorf electrometer we must turn to the point-discharge records. It is however to be remembered that a constant rate of change is only represented on a diagram by a straight line when both ordinates and abscissa have a linear scale. In the point-discharge records this is not the case, for the ordinates are proportional to the point-discharge current which is not a linear function of the potential gradient, and unfortunately it is not possible to convert point-discharge records into potential-gradient values with sufficient accuracy for our present purpose. There is, however, one small piece of evidence which throws some light on this question.

Some years ago there was in use at Kew Observatory an instrument for recording high potential gradients in which an ordinary collector was used so that the deflections on the record were directly proportional to the potential gradient. The instrument is described by Whipple and Scrase[2] (p. 5) ; it was not used very much and only a few records are available ; but amongst them a record, part of which is reproduced in Fig. G, Plate XIII, was found. Here we see an almost perfect +N pattern. The period of change started at the point marked A with a potential gradient of −63 v./cm. and ended at B with a potential gradient of +80 v./cm., the duration of the change was one minute. So far as can be determined by the use of a straight-edge on the original record the trace from A to B is a straight line. It is true that all the examples of N pattern do not show a linear change of the potential gradient during the period of reversal ; but there are sufficient in which this relationship holds to make it certain that the change which gives the N pattern its characteristic shape takes place normally at a constant rate. The duration of this steady change varies from 1 minute as in Fig. G to 24 minutes as in Fig. F, and the total change may vary from a few volts per centimetre as in Figs. D, E and F to 200 v./cm. as in Figs. B and G. It will be noted that here again, as with the UU and W patterns, the duration of the whole pattern and the period of oscillation are much longer when the fields are small (Benndorf records) than when the fields are large (point-discharge records). This may be significant.

During the 46 months from October 1942 to June 1946 there were 25 good N patterns, of which 16 were −N and 9 +N, thus changes in the negative direction during the period of change were nearly twice as frequent as changes in the positive direction. The N pattern is by far the most frequent of the patterns so far discovered.

Little can be said about the relationship between the weather and the occurrence of N patterns. In one or two cases showers coincided with the pattern, and in most cases there were showers either before or after ; but as all disturbances of the potential gradient are associated with unsettled weather conditions this is to be expected. No direct association with any type of weather, such as the association of the W pattern with discontinuities or the V pattern with showers, can be found. Of all the patterns discussed here the N pattern seems the least dependent on the wind and rain at the surface round about the time of its occurrence.

The S pattern.—Fig. A, Plate XIV is a tracing of part of the Benndorf record for April 9, 1944. It shows two disturbances in an otherwise normal period of potential gradient. The two disturbances are almost identical in shape and each was associated with a short sharp shower. This cannot have been a coincidence and therefore they must be considered to form a definite pattern associated, like the other patterns, with some particular motion of the atmosphere. The S pattern is not common and only two other examples exactly comparable with those shown on Fig. A have been found ; but if the three records on Plate VI are examined it will be seen that, shorn of their short-period irregularities they closely resemble the pattern on Fig. A, Plate XIV. It will be remembered that the fields in the disturbances shown on Plate VI are the highest fields observed in this investigation, the range being 400 v./cm. compared with 25 v./cm. for the case represented on Fig. A, Plate XIV

Origin of the patterns

All variations of the potential gradient must ultimately originate in the displacement of volume charges of electricity in some part of the atmosphere. These displacements may be of two kinds: (*a*) separation of positive and negative electricity from an uncharged region, resulting in the formation of two charged regions of opposite signs; and (*b*) the displacement of volume charges relative to other volume charges. Observations with the alti-electrograph have shown that during thunderstorms and showers there is always a region of positive charge at the top of the cloud and a region of negative electricity in the lower part of the cloud ; the lower boundary of the region of negative electricity may be above, but only rarely below the level in the cloud where the temperature is at the freezing point. This distribution of charge results in the field being always positive immediately above the region of negative electricity and usually negative below. On occasions, however, the field near the ground is positive and the alti-electrograph records show that in every such case there is a region of positive charge below the main negative charge, and in practically every case this positive charge is below the freezing level or only just above. In the absence of other evidence it is reasonable to assume that the charges giving rise to the patterns are of the same nature and occur in the same region.

In discussing the cause of these local concentrations of positive electricity, Simpson and Scrase[6] (p. 348) suggested that they might be due to the disruption of rain drops in the violent ascending currents of thunderstorms, and this suggestion was supported on the grounds that the positive charges are only found below the freezing level, where alone the precipitation is in the liquid state. If, however, these charges also give rise to the patterns they cannot be due to the breaking of rain drops for many of the patterns are not associated with appreciable rain and those which are show no variations in the rainfall which can be associated with the regular variations of the potential gradient. Also many of the patterns were associated with snow and not with rain.

Consideration has been given to the possibility of patterns being connected with the point-discharge current from the earth's surface. These currents will be discussed in detail in a later section; here it is sufficient to say that when the potential gradient exceeds 10 v./cm. there is a discharge of electricity from elevated points, such as twigs on high trees or thorns on bushes, which may reach very high values. This discharge starts as small ions which are rapidly absorbed by nuclei chiefly within 200 metres of the ground. Nuclei which have absorbed small ions become themselves large ions ; but with such a small mobility that they are little affected by even the strong fields of a thunderstorm ; on the contrary they travel, like smoke particles, with every motion of the air. All showers are associated with rising currents of air which are highly localised and in these currents the charged nuclei are carried up into the clouds. Such air currents are known to be associated with a cell-like structure of the atmosphere with a pattern of ascending and descending air. It is tempting to associate this cell-like structure, "picked out" as it were with the electricity from the point discharge, with the potential-gradient patterns. Unfortunately this solution does not appear to be tenable, for while many of the patterns occur with high potential gradients and copious point discharge there are others of the same pattern in which the peak potential gradient is little more than 10 v./cm. and therefore with little or no point discharge (compare Figs. A, Plate IX with D, Plate VII; G with H, Plate X; A with D, Plate XII, etc.).

Although it is clear that point discharge plays no essential part in the production of patterns, the ascending and descending currents associated with the cell structure (which in certain conditions becomes a wave structure) of an unstable atmosphere appear to be the most likely characteristic of the atmosphere to be associated with the pattern; but the method by which the electrical separation is effected is quite obscure. Thus, unfortunately, no physical explanation of the potential-gradient patterns can be given.

Summary

When curves are constructed by plotting potential gradient against time during periods of disturbed weather they are found in general to be irregular; but from time to time there are periods during which the curve shows a regularity which can only be described as a pattern. Two main types of pattern have been distinguished which are designated wave patterns and symmetrical patterns.

Wave patterns.—As the name implies these patterns are composed of a succession of more or less regular waves. These vary from waves which are irregular in amplitude and period, to waves which are so regular that they closely resemble a series of harmonic waves with a constant period and regularly varying amplitude. Examples are found with ranges (maximum to minimum) varying from 7 v./cm. to 230 v./cm. and with periods ranging from 4 minutes to $1\frac{1}{2}$ hours. During periods with wave patterns the weather is generally quiet with light winds without fronts or occlusions; the sky is always overcast with low cloud; precipitation may occur as either rain or snow, but occasionally no precipitation reaches the ground; precipitation when it occurs is very steady.

Symmetrical patterns.—In addition to the waves, the curves of potential gradient show regularities consisting of a succession of ups and downs which generally start small and increase to a maximum after which they decrease in the reverse order, the whole forming a symmetrical pattern. The patterns vary from a simple deflection and return, forming a V-shaped pattern, to a complicated pattern consisting of four or more peaks separated by corresponding depressions, the pattern being symmetrical about its centre.

Five symmetrical patterns have been recognized which are referred to as the V, UU, W, N and S patterns, as these letters reproduce to some extent the shape of the patterns. The V, UU and S patterns are accompanied by showers, the W pattern is associated with the passage of a cold front, while no definite type of weather can be associated with the N pattern.

In the 46 months (October 1942 to July 1946) the number of occurrences of the five patterns was V 19, UU 8, W 6, N 25 and S 4. Examples of all patterns are found on the Benndorf record ($P < |20|$ v./cm.) and on the point-discharge record ($P > |20|$ v./cm.) except the V pattern which is found only on the Benndorf record.

There can be little doubt that each pattern is connected with some process in the cloud which causes differential displacement of positive and negative electricity; but as to what that process may be the observations give no indication.

PART III—RAIN ELECTRICITY (GENERAL)

§ 7—INTRODUCTION

In any discussion of the electricity carried by precipitation there are a number of ways of specifying the relationship between the precipitation and the electricity; for some problems the actual charge on individual drops is the chief factor, for others the charge carried by unit volume of water, and for still others the amount of electricity deposited by the rain on unit area of the ground in unit time.

In this investigation no attempt was made to measure the charge on individual drops. We have, however, data for the charge per cubic centimetre (q) of practically all falls of rain but not of snow, and data for both rain and snow of the amount of electricity deposited on unit area of the ground in unit time, the "rain current" (i). These two quantities are not independent for $i = qR$; hence if the rainfall is constant q and i vary together; while if q remains constant i varies as R. But q itself may vary with the rainfall (R), the potential gradient (P) and the point-discharge current (I). It is the object of the following sections to investigate the relationships existing between all the factors P, I, q and i. To do this we shall have to proceed by steps taking pairs of factors, choosing the factors according to the aspect of the problems under discussion. We shall commence by considering the general relationship between the rain electricity and the field at ground level.

§ 8—MIRROR-IMAGE EFFECT

When the four curves for P, I, q and i, plotted against time on the working sheets, were compared it was seen that the sign of the rain electricity (q or i) was practically always opposite to that of the field (P or I). This was particularly striking in the case of the more highly disturbed periods; for then the curve for the charge on the rain (q) was almost a mirror image of the curve for the field (I). The expression "mirror image" is used here in a broad sense and is meant to imply only that the changes in one curve are accompanied by similar change, but of opposite sign, in the other.

Examples of seven outstanding cases of the mirror-image effect for rainfall are reproduced on the diagrams of Plates XV, XVI and XVII which are tracings from the working sheets. In these figures the point-discharge curve is shown as usual by a thick line; but for greater clarity the dots, by which q is shown on the working sheets, have been connected by a thin line, which should not be confused with the thin curve for P on previous diagrams.

The effect is even more pronounced for snowfall. Fig. B, Plate XVII reproduces the curves for a period of snowfall of a little over an hour's duration on January 9, 1945. In this diagram the thick curve is again the point-discharge current, but the thin curve represents i, values of q not being available for snowfall.

These eight examples have been chosen as being particularly clear cases of the mirror-image effect; but the tendency for the sign of the rain electricity to be opposite to that of the field is clear on all the working sheets.

Before proceeding further it should be pointed out that a similar effect between P and i was described by Elster and Geitel[7] in their paper reporting the first observations ever made on the electricity of rain. In that paper they published several diagrams, especially Fig. 11, which show the mirror-image effect as clearly as it can be seen in the Kew records. Although Elster and Geitel satisfied themselves that the effect was real they felt bound to point out the possibility of spurious effects due to splashing on the rim of the protecting cone over their receiver or even to splashing from the ground. Subsequent observers have not entirely cleared up the matter, for while I found no similar relationship between the potential gradient and the rain electricity in my observations at Simla, Gerdien, Kähler and Schindelhauer observed many cases of changes in the sign of the rain electricity accompanying changes of the opposite sign in the potential gradient, but they also found many cases in which no such relationship was present. Thus, the whole question has been left very much in the air.

Returning to the Kew observations, the curves reproduced on the three plates mentioned leave no doubt that the mirror-image effect is real at Kew ; but as already stated these examples have been chosen because they are good examples of the effect. Are they typical of the average conditions at Kew ? To answer this question it is necessary to consider the periods of rainfall in two groups (*a*) with point discharge ; (*b*) without point discharge.

Rainfall with point discharge.—There are 42 separate periods of rainfall with point discharge and for which q is available ; 23 of these periods show the mirror-image effect as well as in the examples reproduced on Plates XV, XVI and XVII ; another 13 show it less well but still quite clearly ; while only 6 show the effect poorly or not at all. Expressed in another way : of the total time of these 42 periods, 1,414 minutes, 59 per cent., 34 per cent. and 7 per cent. fall in these three classes respectively ; that is, the mirror-image effect is more or less apparent in 93 per cent. of the time, while in only 7 per cent. is it absent.

Rainfall without point discharge.—The potential gradient is nearly always negative and the rain electricity positive in periods of rainfall without point discharge, which is in accordance with the mirror-image effect ; but in the few cases in which the gradient became positive for short periods the rain electricity did not change sign with the field. It will be seen later that this is because the relationship between the rain electricity and the potential gradient is quite different with and without point discharge.

§ 9—SELECTED PERIODS

We have now to reduce the relationships described in a general way in the last section to some more definite form and express them, if possible, in mathematical formulae. There are three main factors to be related: (*a*) the electricity carried by the rain ; (*b*) the electrical field, and (*c*) the rainfall. The total data cover something like 60,000 minutes of disturbed weather, for each of which one at least of the three factors mentioned is available. It soon became clear as the observations accumulated that it would be impossible to handle all the individual minutes in any statistical investigation. It was therefore decided to select, from the working sheets, periods during which all three elements were relatively steady (in the sense that they were not undergoing a progressive change) and to use the mean values of P, q, i, etc., for each of these " selected periods " as the data for the statistical investigation.

Each selected period was made as long as possible, and in a few cases during steady rain the period could be extended to an hour or so ; but in the general case, especially during showers, the variations were so rapid that suitable periods of more than a few minutes could seldom be found.

Each selected period was marked on the working sheets by putting crosses connected by a horizontal line above the curves, the crosses marking the beginning and ending of the period. These lines have been reproduced on all the diagrams in this paper which are traced from the working sheets, and it would be as well if the reader would at this point examine a number of diagrams marked in this way to familiarise himself with the kind of data provided by the selected periods.

In all, 210 selected periods were chosen varying in length from 1 to 64 minutes and totalling together 2,447 minutes. Of these 109 refer to showers, 80 to steady rain and 21 to snow or sleet, totalling 725, 1,542 and 180 minutes, respectively. For each of the selected periods the mean value of the point-discharge current (I), the potential gradient (P), the rain current (i), the charge per cubic centimetre (q) and the rate of rainfall (R') were computed from the minute values and tabulated. These mean values together with other relevant data are given for each selected period in Tables III and IV.

In view of the natural suspicion which is always associated with the use of selected data it may be as well to state here that the selected periods were chosen as soon as the observations had been reduced and plotted, long before any ideas had been formed as to the results which would ultimately emerge. The object in view when the periods were selected was to obtain reliable values well distributed over the whole range of the various factors to provide sufficient

TABLE III—SELECTED PERIODS WITH $P > |20|$ V./CM.

Date	Time	Period	R'	i	q	I	P	i/I
	h. m.	min.	mm./hr.	e.s.u./cm.^{2}sec.	e.s.u./cm.^{3}	e.s.u./sec.	v./cm.	
				SHOWERS				
				$\times 10^{-5}$		$\times 10^{-3}$		$\times 10^{-8}$
20.10.42	14 38	4	6·6	+ 6·8	+ 0·37	− 2·7	−34	2·5
20.10.42	14 45	4	5·0	− 5·3	− 0·39	+ 3·0	+34	1·8
20.10.42	14 53	2	14	+110	+ 2·8	− 2·2	−29	50
20.10.42	14 56	2	11	+ 83	+ 2·7	− 5·0	−44	17
20.10.42	15 06	3	20	+ 46	+ 0·85	− 2·6	−32	18
25.10.42	16 22	3	5·0	+ 12	+ 0·90	− 2·2	−29	5·7
25.10.42	16 25	3	10	− 26	+ 0·88	+ 3·5	+37	7·6
25.10.42	16 32	3	3·2	+ 7·7	+ 0·87	− 2·4	−32	3·2
26.10.42	15 53	1	32	+244	+ 2·8	−17	−80	14
30.10.42	2 59	1	21	+ 82	+ 1·4	−11	−66	7·1
8. 5.43	4 16	2	23	+ 27	+ 0·42	− 3·3	−36	8·2
10. 5.43	21 22	1	42	−109	− 0·92	+ 6·5	+50	17
10. 5.43	21 24	1	42	+ 49	+ 0·42	− 2·9	−34	17
10. 5.43	21 31	1	3·4	− 6·0	− 0·65	+ 2·9	+34	1·8
24. 5.43	11 05	4	5·8	+ 68	+ 4·2	− 4·9	−44	14
25. 5.43	15 57	3	7·5	− 65	− 3·1	+11	+64	6·0
2. 6.43	9 02	2	21	+286	+ 4·9	−17	−80	17
14. 6.43	17 25	3	—	− 84	—	+10	+62	8·4
15. 6.43	11 20	4	2·7	+ 39	+ 5·2	−14	−71	2·8
6. 7.43	12 11	2	29	− 28	− 0·35	+ 1·9	+26	15
6. 7.43	12 15	4	9·5	+ 22	+ 0·83	− 1·4	−23	16
6. 7.43	12 35	6	2·1	− 23	− 3·9	+ 9·8	+61	2·3
21. 7.43	0 16	3	17	+ 62	+ 1·3	− 4·8	−43	13
21. 7.43	1 23	6	6·2	− 95	− 5·6	+11	+66	9·5
19.10.43	19 55	2	46	+ 21	+ 0·14	− 1·2	−20	18
3. 4.44	18 34	8	4·4	+ 2·3	+ 0·19	− 1·4	−23	1·7
5. 5.44	10 44	1	21	− 90	− 1·6	+10	+62	9·0
16. 5.44	13 10	3	3·9	+ 77	+ 7·1	−10	−62	7·6
16. 5.44	15 15	4	2·6	−137	−19	+17	+80	8·0
17. 5.44	16 55	1	42	−510	− 4·4	+53	+141	9·6
17. 5.44	16 56	1	21	−510	− 8·8	+55	+142	9·5
17. 5.44	16 57	1	14	−260	− 6·8	+65	+155	4·0
17. 5.44	16 58	1	13	−510	−15	+63	+153	8·1
17. 5.44	16 59	1	8·4	−170	− 7·3	+48	+133	3·9
17. 5.44	17 00	1	4·2	−170	−15	+39	+120	4·4
17. 5.44	17 01	1	4·2	−260	−22	+56	+144	4·6
17. 5.44	17 02	3	3·4	−180	−19	+46	+131	3·9
17. 5.44	17 05	3	3·1	−138	−16	+36	+115	3·8
9. 6.44	15 44	9	8·2	+ 41	+ 1·8	− 3·2	−35	13
26. 6.44	15 33	3	6·8	− 47	− 2·6	+11	+64	4·3
				SHOWERS—*continued.*				
				$\times 10^{-5}$		$\times 10^{-3}$		$\times 10^{-8}$
20. 8.44	10 00	7	7·5	− 16	− 0·76	+ 6·0	+48	2·7
2. 9.44	12 45	4	20	− 43	− 0·78	+ 2·6	+32	16
16.10.44	14 27	4	20	+ 40	+ 0·71	− 5·8	−48	6·9
6.11.44	23 22	3	42	+ 37	+ 0·32	− 3·3	−35	11
6.11.44	23 25	4	28	+ 57	+ 0·74	− 5·8	−48	9·8
1. 6.45	8 54	5	13	+227	+ 6·5	−39	−120	5·8
1. 7.45	11 57	4	18	− 86	− 1·7	+11	+69	7·9
8. 8.45	21 10	4	5·2	+ 45	+ 3·1	− 8·6	−58	5·2
9. 8.45	0 05	16	2·1	+ 16	+ 2·8	− 2·3	−30	7·0
25.12.45	9 21	4	4·7	− 7·9	− 0·60	+ 3·5	+36	2·3
9. 1.46	20 09	20	2·6	+ 3·8	+ 0·53	− 1·9	−26	2·0
22. 3.46	18 52	2	7·5	+122	+ 5·9	−16	−77	7·7
				STEADY RAIN				
26.10.42	10 18	3	4·4	− 5·5	− 0·45	+ 1·9	+26	2·9
26.10.42	10 23	10	4·1	+ 7·7	+ 0·69	− 2·2	−29	3·5
26.10.42	11 00	11	2·9	+ 1·6	+ 0·19	—	−23	—
26.10.42	11 26	9	4·3	+ 3·5	+ 0·29	—	−22	—
7. 1.43	4 01	13	3·0	+ 1·9	+ 0·23	—	−20	—
14. 1.43	0 38	15	3·0	+ 3·5	+ 0·40	—	−22	—
14. 1.43	2 06	19	1·8	+ 2·6	+ 0·57	—	−20	—
14. 1.43	4 49	29	1·1	+ 1·9	+ 0·62	—	−21	—
13. 5.44	17 15	9	3·5	+ 82	+ 8·2	− 8·4	−56	9·8
13. 5.44	17 45	8	1·7	− 34	− 7·1	+ 7·3	+53	4·7
13. 5.44	18 04	6	3·4	+ 33	+ 3·4	− 4·5	−41	7·3
13. 5.44	18 30	10	2·1	− 14	− 2·3	+ 5·8	+48	2·4
				SNOW OR SLEET				
4. 2.44	7 53	2	slight	+ 80	—	−20	−82	4·0
18. 2.44	14 46	2	slight	+107	—	−29	−98	3·7
18. 2.44	14 48	2	slight	+ 78	—	−14	−69	5·6
18. 2.44	17 02	3	slight	−204	—	+23	+98	8·9
9. 1.45	13 01	5	slight	− 23	—	+ 4·5	+43	5·1
9. 1.45	13 12	2	slight	−116	—	+14	+75	8·3
9. 1.45	13 17	2	slight	+ 83	—	−14	−69	5·9
9. 1.45	13 24	4	slight	+ 64	—	−17	−77	3·8
9. 1.45	13 57	3	slight	− 43	—	+ 7·5	+58	5·7
22. 1.45	5 45	2	slight	+ 13	—	−10	−58	1·3
23. 1.45	5 50	3	slight	− 68	—	+14	+77	4·9
23. 1.45	1 24	2	slight	+193	—	−18	−78	11
23. 1.45	1 29	3	slight	− 73	—	+14	+77	5·2

TABLE IV—SELECTED PERIODS WITH $P < |20|$ V./CM.

Date	Time	Period	R'	i	q	P
	h. m.	min.	mm./hr.	e.s.u./cm.²sec.	e.s.u./cm.³	v./cm.
			SHOWERS	×10⁻⁵		
23.10.42	23 19	7	6·2	+ 0·12	+ ·01	+ 0·5
23.10.42	23 27	14	6·2	+ 0·10	+ ·01	− 0·6
24.10.42	0 56	8	2·6	− 0·10	+ ·01	+ 1·5
7.11.42	7 25	10	4·0	0	0	+ 4·0
22.12.42	1 55	13	2·3	+ 0·79	+ ·12	− 1·4
28.12.42	20 07	10	3·0	− 0·22	− ·03	+ 5·7
11. 1.43	6 02	10	1·9	+ 2·5	+ ·47	−17
13. 1.43	23 15	11	2·7	+ 1·7	+ ·22	−14
31. 1.43	6 39	24	2·2	+ 2·0	+ ·32	− 8·2
23. 4.43	20 54	18	2·2	+ 2·8	+ ·46	−14
30. 4.43	6 30	13	2·3	− 0·19	− ·03	+ 3·4
30. 4.43	13 39	12	2·5	+ 1·9	+ ·27	−13
18. 6.43	16 12	3	7·8	+ 0·82	+ ·04	+ 1·0
26. 8.43	3 08	5	4·1	+ 0·98	+ ·09	+ 1·0
24. 9.43	23 46	2	12	+ 1·5	+ ·05	0
28. 9.43	5 28	8	3·9	+ 1·2	+ ·01	+ 0·5
6.11.43	5 41	3	7·5	+ 1·0	+ ·05	0
13.11.43	5 09	8	4·2	+ 2·0	+ ·17	− 3·2
16. 2.44	12 37	12	2·6	− 0·10	− ·01	+ 5·6
9. 6.44	12 23	7	29	+ 7·9	+ ·10	− 5·6
9. 6.44	13 24	4	11	− 0·91	− ·03	+ 3·0
13. 7.44	13 40	7	5·8	− 0·08	− ·01	+ 1·9
13. 7.44	13 58	9	3·4	+ 2·0	+ ·21	− 6·0
15. 7.44	17 58	2	42	+16	+ ·14	− 3·0
29. 7.44	8 32	5	4·4	+ 0·39	+ ·03	+ 2·0
29. 7.44	8 47	4	4·4	+ 0·98	+ ·08	− 5·8
29. 8.44	22 09	11	2·8	− 0·18	− ·02	+ 2·2
30. 8.44	6 42	13	5·8	− 0·14	− ·01	+ 3·5
2. 9.44	0 05	12	2·8	+ 0·86	+ ·11	− 0·8
2. 9.44	2 51	10	5·2	+ 0·90	+ ·06	− 0·6
2. 9.44	8 26	5	6·2	+ 3·8	+ ·22	− 6·5
2. 9.44	10 06	8	6·2	+ 7·9	+ ·46	−13
2. 9.44	14 06	2	26	+21	+ ·28	− 6·0
4. 9.44	14 27	6	4·8	+ 1·4	+ ·11	− 4·0
4. 9.44	14 39	5	6·6	+ 2·3	+ ·13	− 7·2
4. 9.44	14 57	11	2·9	+ 1·7	+ ·21	− 5·2
26. 9.44	3 49	3	32	+14	+ ·16	− 4·5
30. 9.44	21 52	5	2·4	− 0·56	+ ·08	+ 7·0
30. 9.44	23 01	8	4·2	+ 3·3	+ ·28	−11
2.10.44	13 18	20	2·7	+ 1·4	+ ·19	− 7·6
3.10.44	17 44	12	2·6	+ 3·5	+ ·50	− 4·3
13.10.44	18 08	7	4·2	+ 3·3	+ ·29	− 4·3
16.10.44	8 03	7	17	+ 7·4	+ ·16	− 5·9
23.10.44	12 37	9	2·2	+ 1·0	+ ·17	+ 8·0
27.10.44	3 22	13	2·3	− 0·22	− ·04	+ 2·0
5.11.44	15 06	8	9·0	+ 7·7	+ ·30	−10
5.11.44	15 14	15	3·5	+ 2·2	+ ·23	−11
7.11.44	3 29	27	2·3	+ 2·1	+ ·32	− 5·3
23.11.44	3 40	19	3·9	+ 2·3	+ ·22	− 8·1
29. 6.45	19 29	4	42	+34	+ ·29	− 8·0
10. 7.45	6 06	8	5·4	+ 1·5	+ ·10	−10
19. 7.45	22 59	5	5·2	+ 1·8	− ·13	+ 0·5
13. 9.45	5 50	7	8·1	− 0·70	− ·03	+11
13. 9.45	19 31	4	32	+ 6·0	+ ·07	− 8·0
23.10.45	23 33	9	5·0	+ 2·2	+ ·16	− 4·0
28.10.45	15 10	19	1·6	+ 0·29	+ ·07	− 2·0
30. 1.46	11 46	16	1·2	+ 1·8	+ ·52	−13

Date	Time	Period	R'	i	q	P
	h. m.	min.	mm./hr.	e.s.u./cm.²sec.	e.s.u./cm.³	v./cm.
			STEADY RAIN	×10⁻⁵		
26.10.42	9 37	9	4·6	+ 3·9	+ ·31	− 9·0
3.11.42	4 23	36	1·7	+ 0·63	+ ·14	− 9·0
5.11.42	8 28	24	1·8	+ 0·37	+ ·07	− 6·0
5.11.42	9 07	21	1·5	+ 0·76	+ ·19	− 6·0
5.11.42	20 11	6	7·0	− 0·28	− ·01	+ 6·0
6.11.42	1 08	20	3·7	+ 2·3	+ ·22	− 8·0
6.11.42	1 41	10	3·9	+ 1·1	+ ·10	− 7·0
7.11.42	5 14	11	3·6	+ 0·51	+ ·05	− 3·0
18.12.42	18 24	29	1·1	+ 0·71	+ ·14	− 6·0
18.12.42	18 53	30	1·4	+ 0·40	+ ·10	− 9·0
6. 1.43	17 47	21	1·4	+ 1·1	+ ·29	−15
6. 1.43	18 08	21	1·6	+ 1·6	+ ·37	−14
7. 1.43	3 28	20	2·1	+ 1·4	+ ·23	−17
10. 1.43	2 55	16	3·3	+ 0·87	+ ·10	− 9·0
10. 1.43	3 27	15	2·9	+ 0·87	+ ·11	− 3·0
14. 1.43	1 02	17	5·1	+ 6·3	+ ·44	−17
14. 1.43	2 29	22	2·8	+ 5·2	+ ·67	−19
14. 1.43	4 24	25	1·2	+ 1·4	+ ·40	−16
14. 1.43	5 32	23	1·4	+ 1·8	+ ·46	−15
25. 3.43	3 09	22	1·5	+ 0·34	+ ·08	− 1·0
25. 3.43	3 53	17	1·8	+ 0·72	+ ·14	− 8·0
25. 3.43	5 11	21	1·5	+ 0·73	+ ·18	− 4·0
26. 8.43	6 27	30	1·4	+ 0·45	+ ·12	− 6·0
26. 8.43	6 57	23	2·3	+ 0·77	+ ·12	− 5·0
26. 8.43	7 20	23	1·3	+ 0·25	+ ·07	− 5·0
19.12.43	2 19	64	2·1	+ 0·38	+ ·06	− 4·0
19.12.43	4 00	29	3·2	+ 0·49	+ ·06	− 9·0
19.12.43	8 52	52	3·2	+ 0·17	+ ·02	− 5·0
11. 1.44	10 43	15	5·7	− 3·3	− ·21	+ 9·0
11. 1.44	11 10	12	7·0	+ 7·3	+ ·38	−17
11. 1.44	11 32	20	2·5	+ 0·39	+ ·05	− 7·0
16. 2.44	7 34	20	1·9	+ 0·06	+ ·01	+ 1·0
16. 2.44	8 26	15	2·8	+ 0·39	+ ·05	− 3·0
16. 2.44	8 45	18	1·9	+ 0·22	+ ·04	− 2·0
26. 6.44	22 40	20	3·1	+ 0·34	+ ·04	− 4·0
26. 6.44	23 03	18	1·8	+ 0·04	+ ·01	− 1·0
26. 6.44	23 39	16	4·4	+ 0·63	+ ·05	− 4·0
3. 7.44	9 40	26	3·1	+ 0·94	+ ·11	− 6·0
3. 7.44	10 20	11	3·9	− 1·1	− ·10	+12
22. 7.44	0 11	10	3·3	+ 0·21	+ ·02	+ 2·0
22. 7.44	0 33	8	5·2	− 0·13	− ·01	+ 2·0
19. 8.44	14 57	21	1·6	+ 2·2	+ ·51	−15
20. 8.44	6 52	17	5·5	− 0·87	− ·06	+10
30. 9.44	20 40	6	5·0	+ 0·82	+ ·06	− 6·0
30. 9.44	21 02	14	2·2	+ 1·1	+ ·19	+ 2·0
30. 9.44	21 20	9	2·4	+ 2·7	+ ·41	−11
11.10.44	14 18	8	3·5	+ 3·0	+ ·30	− 2·0
11.10.44	14 32	19	2·7	+ 2·9	+ ·39	− 4·0
11.10.44	15 02	13	3·2	+ 4·2	+ ·47	− 7·0
17.10.44	11 39	11	2·8	+ 1·7	+ ·44	− 2·5
17.10.44	12 02	17	4·2	+ 4·3	+ ·37	− 7·0
17.10.44	12 31	9	3·6	+ 0·70	+ ·07	− 3·0
17.10.44	12 46	16	4·0	+ 2·2	+ ·19	− 7·6
20.10.44	3 30	22	2·0	+ 0·66	+ ·12	− 4·0
20.10.44	4 00	17	2·4	+ 0·23	+ ·04	− 0·5
17.11.44	5 08	20	2·6	+ 2·0	+ ·27	+ 4·0
17.11.44	5 53	19	5·0	+ 5·4	+ ·39	−14

TABLE IV—*continued*

Date	Time	Period	R'	i	q	P
	h. m.	min.	mm./hr.	e.s.u./cm.^{2}sec.	e.s.u./cm.^{3}	v./cm.
		STEADY RAIN—*continued.*				
				$\times 10^{-5}$		
17.11.44	6 14	18	4·0	+ 3·7	+ ·33	−10
17 11.44	9 52	14	3·0	+ 1·6	+ ·20	− 2·6
17.11.44	10 12	28	1·9	+ 0·72	+ ·14	− 5·0
17.11.44	11 21	24	1·8	+ 0·30	+ ·06	− 2·0
17.11.44	15 53	16	3·3	+ 1·2	+ ·13	− 2·6
17.11.44	16 09	25	1·6	+ 0·55	+ ·12	− 4·0
17.12.44	3 40	34	1·5	+ 2·9	+ ·69	− 4·0
28. 6.45	11 14	46	1·6	+ 0·31	+ ·08	− 5·7
28. 6.45	12 11	22	1·8	+ 0·61	+ ·16	−10
9. 8 45	21 28	45	2·5	+ 0·52	+ ·07	− 4·2
29 10.45	7 26	24	3·0	+ 2·0	+ ·24	−12

Date	Time	Period	R'	i	q	P
	h. m.	min.	mm./hr.	e.s.u./cm.^{2}sec.	e.s.u./cm.^{3}	v./cm.
			SNOW OR SLEET			
				$\times 10^{-5}$		
31.12.42	0 58	10	1·0	− 1·6	− ·60	+ 9·0
31.12.42	1 15	26	1·6	+ 2·4	+ ·55	−11
31.12.42	1 52	8	1·4	− 2·1	− ·56	+11
31.12 42	3 39	8	2·6	+ 0·71	+ ·10	− 7·0
23. 1.45	13 17	23	slight	− 0·08	—	+ 2·0
23. 1.45	14 17	33	slight	− 0·92	—	+ 5·0
18. 1.46	18 31	24	slight	− 0·54	—	+ 7·0
18. 1.46	19 29	13	slight	− 0·48	—	+ 7·0

data for the statistical investigations. No period when chosen was rejected because it did not fit in with the other observations. Compared with the large number of original minute observations the number of minutes used in the selected periods may appear small; but in parts of the range where observations are few every suitable period has been used; to have increased the number in other regions would not have resulted in greater accuracy.

§10—EMPIRICAL RELATIONSHIP BETWEEN q, i AND P

Our problem is to investigate the relationship between the electrical field and the electricity on the rain. As already stated there are two aspects of the latter, namely the charge per cubic centimetre (q) and the rain current (i). It will therefore be necessary to investigate each separately. The first step in establishing a relationship between two quantities is to plot the one against the other. Fig. 2 is a plot of q against P and Fig. 3 a plot of i against P.

Consider first Fig. 2: each dot represents one " selected period ", the mean q for the period being plotted against the mean P. The small scale of the diagram has necessitated omitting a large number of the selected periods with potential gradients between +20 and −20 v./cm.; but sufficient have been plotted to show the distribution. For potential gradients greater than $|20|$ v./cm. all the selected periods are plotted. It will be seen that there is a very large scatter especially with the higher potential gradients; but it is clear that there is some relationship, for with both positive and negative gradients the magnitude of q tends to increase with that of P, but the increase, at least for the larger values, is by no means linear.

Turning now to Fig. 3, the plot of i against P, it will be seen that it is similar to Fig. 2: i like q increases non-linearly with P but the scatter is much less so that a tendency for the points to follow a definite curve is clearly visible. It has been possible to add to Fig. 3 a few selected periods for snowfall which are absent from Fig. 2; because values of i, but not of q, are available for snow. These observations during snow are represented by stars instead of dots, and it will be seen that the stars follow the same general curve as the dots.

Figs. 2 and 3 having shown quite clearly that there are relationships between P and both q and i which are not linear we must now proceed to examine whether q and i can be expressed by powers of P greater than one. This can best be done by plotting the logarithms of the variables. Figs. 4 and 5 have therefore been prepared by plotting log q and log i respectively against log P. In these diagrams the observations have been plotted irrespective of sign ; but the sign of the gradient of each observation (selected period) has been shown by using + and − signs instead of dots to indicate the positions of the points ; in every case the sign of the rain electricity is opposite to that of the gradient. In Fig. 5 observations referring to snow are marked by a star.

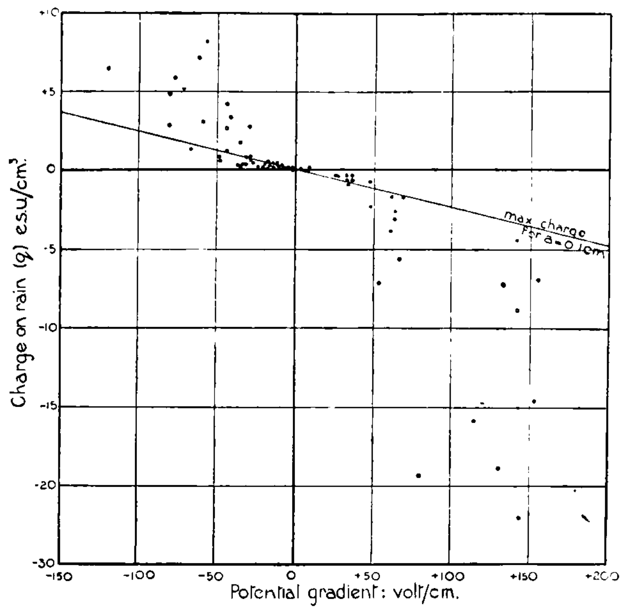

FIG. 2

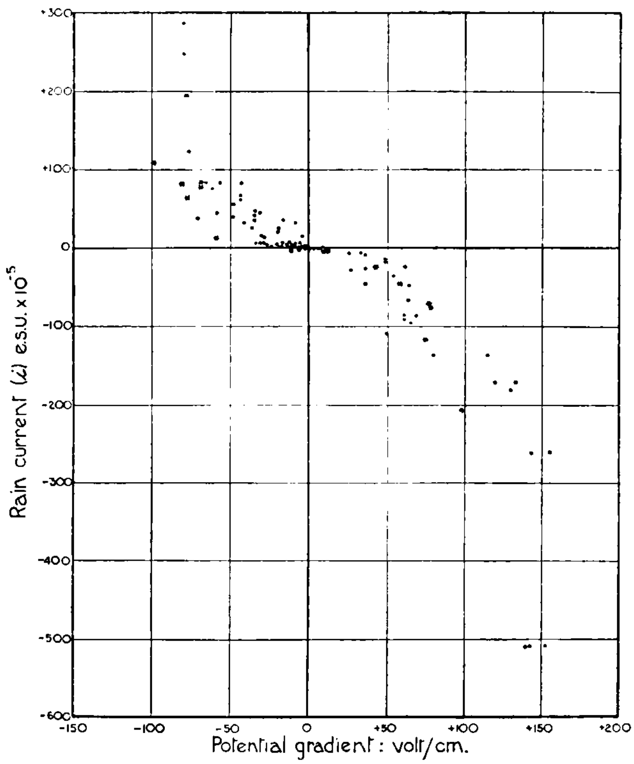

FIG. 3

There can be little doubt that in both Fig. 4 and Fig. 5 the points for the higher potential gradients are distributed about straight lines. If now the reader will take a sheet of paper and lay it on each diagram in turn with its edge along the ordinate for 20 v./cm. so that the points on the left are hidden, it will be seen that the points on the right are well represented by the straight line which has been drawn through them. Also it will be noticed that there is no consistent tendency for the positive and negative signs to group themselves on either side of the line, thus any conclusions drawn will apply equally to positive and negative gradients.

When the paper is moved to cover the diagrams to the right of the 10 v./cm. ordinate it will be seen that the points to the left of this ordinate show no tendency to a linear arrangement, and that the prolongations of the lines which represent the points with $P > 20$ v./cm. in no way represent the points with $P < 10$ v./cm. Thus we are faced with the fact that the relationship between the rain electricity and the potential gradient is different when P is greater than 20 v./cm. from what it is when P is less than 10 v./cm.

We have therefore two problems to solve and each will need a separate investigation. The first problem will be investigated in Part IV and the second in Part V.

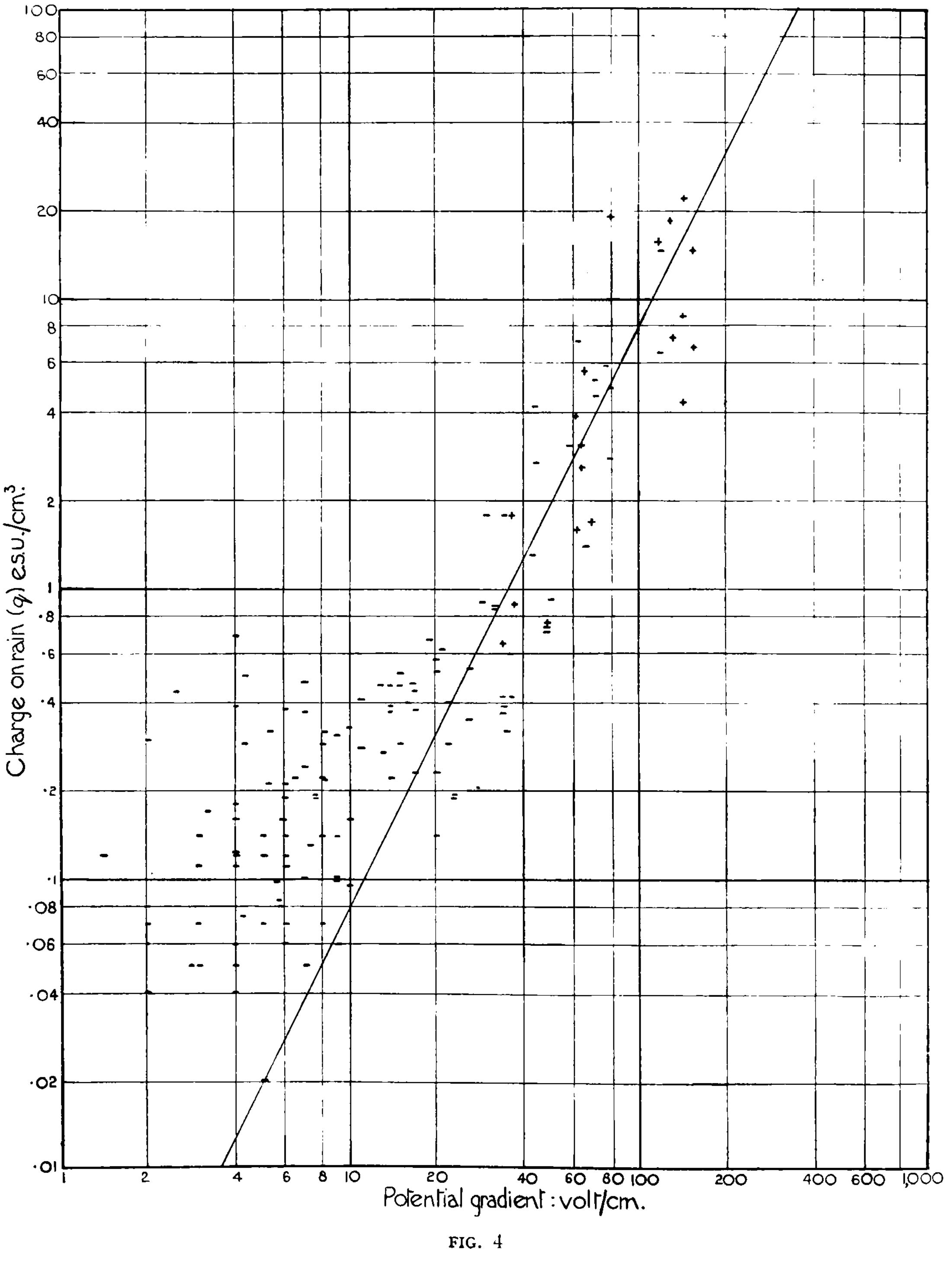
100
80
60
40
20
10
8
6
4
2
1
·8
·6
·4
·2
·1
·08
·06
·04
·02
·01
1
2
4
6
8
10
20
40
60
80
100
200
400
600
1,000
Charge on rain (q) e.s.u./cm.³
Potential gradient : volt/cm.

FIG. 4

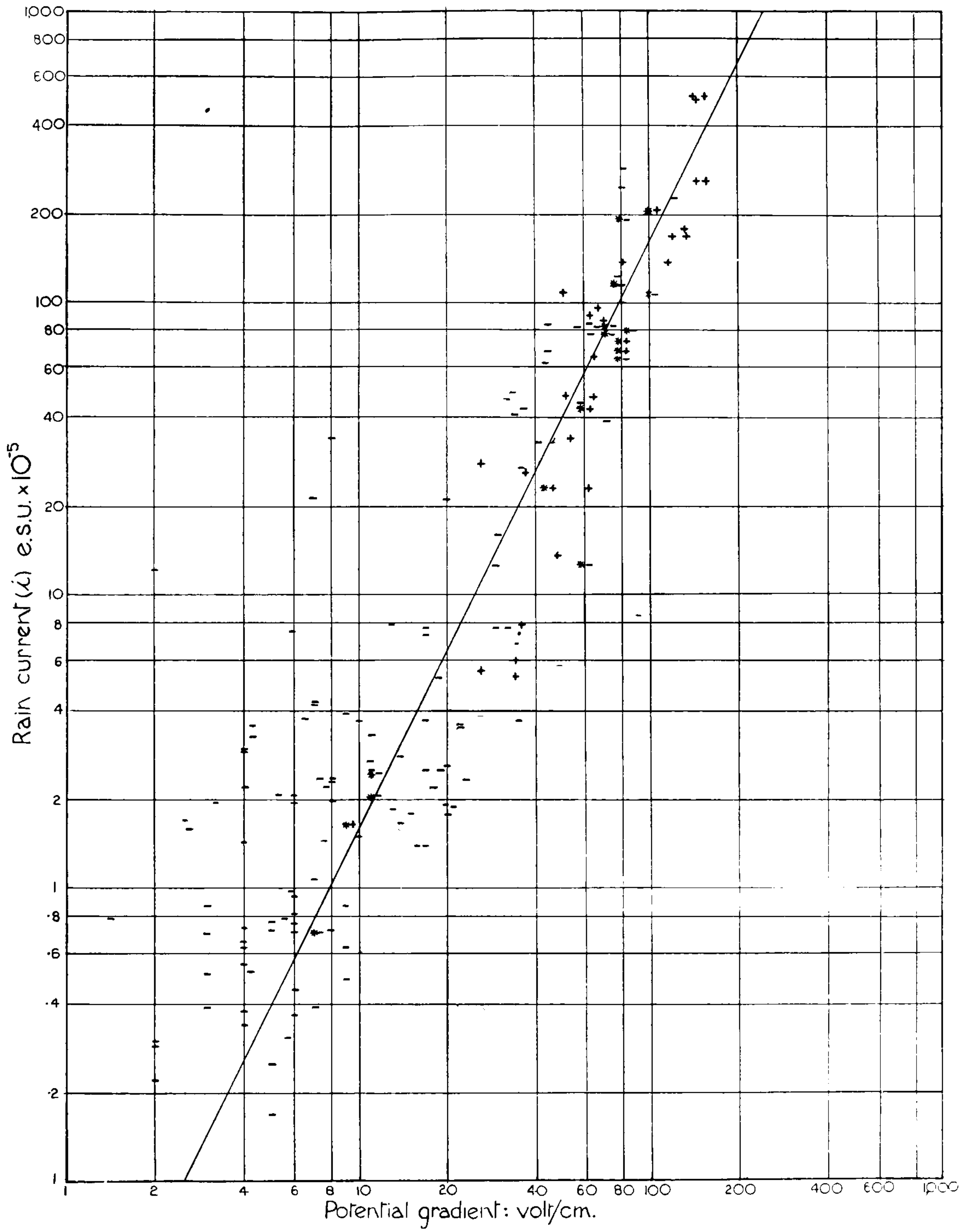
Rain current (i) e.s.u. × 10⁻⁵
Potential gradient: volt/cm.
1,000
800
600
400
200
100
80
60
40
20
10
8
6
4
2
1
·8
·6
·4
·2
·1
1
2
4
6
8
10
20
40
60
80
100
200
400
600
1,000

FIG. 5

PART IV—RAIN ELECTRICITY WITH $P > |20|$ V./CM.

§ 11—EMPIRICAL RELATIONSHIP BETWEEN q, i, P AND I FOR $P > |20|$ v./CM.

We have seen from Figs. 4 and 5 that for potential gradients greater than $|20|$ v./cm. both log q and log i when plotted against log P are represented by straight lines. Now when log y is plotted against log x every straight line represents a function in the form $y = Ax^r$, in which r is the tangent of the angle which the straight line makes with the abscissa. In Figs. 4 and 5 this angle is approximately $63\frac{1}{2}°$ the tangent of which is 2. Hence we have for $P > |20|$ v./cm.

$$q = AP^2 \text{ and } i = BP^2 \qquad \ldots. (1)$$

A and B being constants.

Now all values of P greater than $|20|$ v./cm. (i.e. the values on which this result is based) were not measured direct but were obtained from measurements of the point-discharge current by the use of the relationship $I = 2{\cdot}7\,(P^2 - 8{\cdot}2^2)$. Now for all values of $P > |20|$, $(P^2 - 8{\cdot}2^2)$ is indistinguishable from P^2, hence in this section we can write $I = 2{\cdot}7\,P^2$. Substituting this value for P^2 in equation (1) we have

$$q = A'I \text{ and } i = B'I \qquad \ldots. (2)$$

A' and B' being constants, that is, q and i are both linear functions of I.

Up to this point the point-discharge current has only been considered as a useful means of measuring high potential gradients, no physical significance being attached to the current itself. We now see from equation (2) that the point-discharge current itself is closely related to the rain electricity, at least numerically. I could therefore replace P as an independent variable; which would have two advantages: (*a*) an observed and not a derived value would be used, and (*b*) q and i are related to the first power of I but to the square of P. There is also a physical reason for preferring I to P in this investigation for there is a current through the needle in the conditions of our first problem ($P > |20|$ v./cm.) but not in those of the second problem ($P < |20|$ v./cm.), while potential gradient exists in both: thus I may have some physical significance which P has not. We will therefore use I instead of P as an independent variable in the remainder of this chapter.

§ 12—EMPIRICAL RELATIONSHIP BETWEEN i, I AND R' FOR $P > |20|$ v./CM.

In Figs. 4 and 5 on which equations (1) and (2) are based no account is taken of the rainfall, the relationships found are therefore based on the average rainfall of all the observations. We have now to consider what part, if any, the intensity of the rainfall plays, and this can best be done by plotting a graph on which the rainfall is indicated. We have already decided that the graph should use I as an independent variable and this leaves us with either q or i to use as the measure of the rain electricity.

Now i is an observed quantity depending only on the measurement of one quantity, the deflection of the rain electrometer at the end of each minute; while q is a derived quantity depending on two measurements, those of i and R; thus q is subject to errors in both i and R. Further as the rain takes a fraction of a minute to run from the funnel to the rain-gauge the values of q and R for any given minute do not necessarily apply to exactly the same sample of the rain; therefore q may be in error for this reason also. Thus the values of q are subject to greater errors than i; we will therefore use i instead of q as our second variable. The relationship with R can be shown by entering against each point on a graph of i and I the intensity of rainfall in figures.

Fig. 6 has been prepared along these lines. The co-ordinates are log i and log I; the points, as before, are marked by the sign of the potential gradient; against each point the rate of rainfall in millimetres per hour (R') is entered in figures; and each point for snow is marked with a star.

It will be noticed at once that the points form a band which makes an angle of 45° with the abscissa. As $\tan 45° = 1$ our conclusion that the average i is a linear function of I is confirmed. On examining the distribution of the values of R' within the band it will be seen that high values tend to occur along the upper edge of the band and low values along the lower edge. In fact, a tendency for the values of R' to be arranged in parallel bands one above the other is clearly visible. Thus for any given value of R' we have $i = \text{constant} \times I$, the constant being different for each value of R'. We may therefore write $i = f(R')I$; and our next step will be to determine the form of the function.

As $f(R') = i/I$ we may obtain some information regarding the form of the function by plotting i/I against R'. This has been done in Fig. 7, using all the selected periods for which values of i, I and R' are available. We have now to see if we can find a function of R' which satisfactorily represents these points.

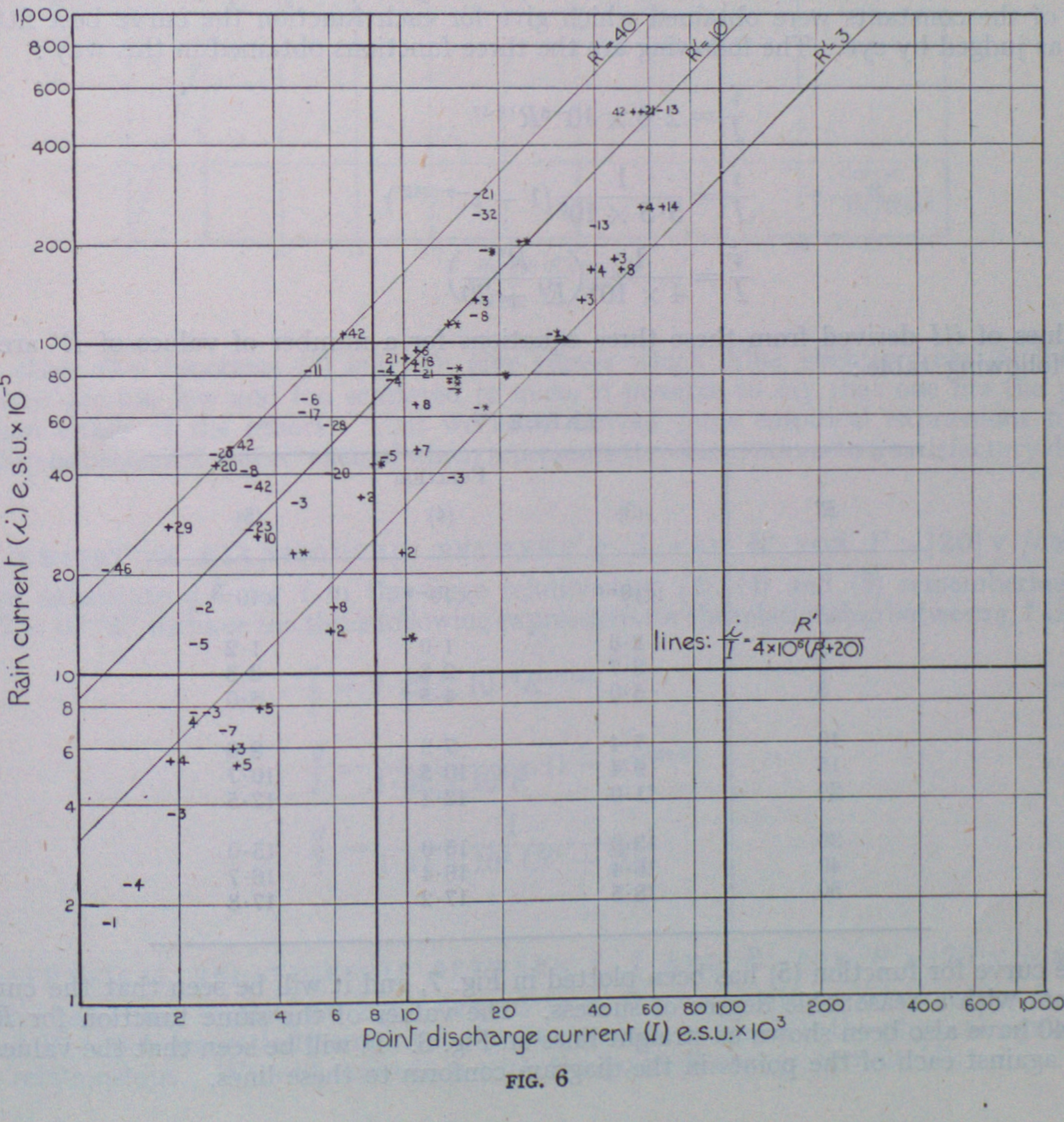

FIG. 6

In spite of the large scatter of the points a definite tendency can be seen for i/I to increase from zero at $R' = 0$, at first rapidly and then at a decreasing rate as R' increases. In other words, if y is written for i/I and x for R', then dy/dx decreases as x increases. A number of functions have this property and from these the three following have been chosen for investigation, because they turned up naturally in the work :

$$y = ax^b$$
$$y = a\,(1 - e^{-bx})$$
$$y = \frac{ax}{x + b}$$

in each of which a and b are constants and e is the base of natural logs. These three functions will now be examined purely from the point of view of fitting them to the observations ; their physical significance, if any, will be considered in a later section.

Each of the functions has two constants and by a suitable choice of these a curve can be obtained for each function which more or less fits the points. By a process of trial and error values of the constants were obtained which give for each function the curve best fitting the points as judged by eye. The following are the three functions obtained in this way :

$$\frac{i}{I} = 2{\cdot}0 \times 10^{-8} R'^{0{\cdot}57} \qquad \ldots . (3)$$

$$\frac{i}{I} = \frac{1}{5{\cdot}5 \times 10^{6}}\,(1 - e^{-0{\cdot}058R'}) \qquad \ldots . (4)$$

$$\frac{i}{I} = \frac{1}{4 \times 10^{6}}\left(\frac{R'}{R' + 20}\right) \qquad \ldots . (5)$$

The values of i/I derived from these three equations for a number of values of R' are shown in the following table :

TABLE V

R'	Function (3)	(4)	(5)
	$\times 10^{-8}$	$\times 10^{-8}$	$\times 10^{-8}$
1	2·0	1·0	1·2
3	3·7	2·8	3·3
5	5·0	4·5	5·0
10	7·4	7·9	8·3
15	9·4	10·5	10·7
20	11·0	12·4	12·5
30	13·9	15·0	15·0
40	16·4	16·4	16·7
50	18·5	17·2	17·8

The curve for function (5) has been plotted in Fig. 7, and it will be seen that the curve fits the points with a reasonable degree of success. The values of the same function for $R' = 3$, 10 and 40 have also been shown as straight lines on Fig. 6. It will be seen that the values of R' entered against each of the points in the diagram conform to these lines.

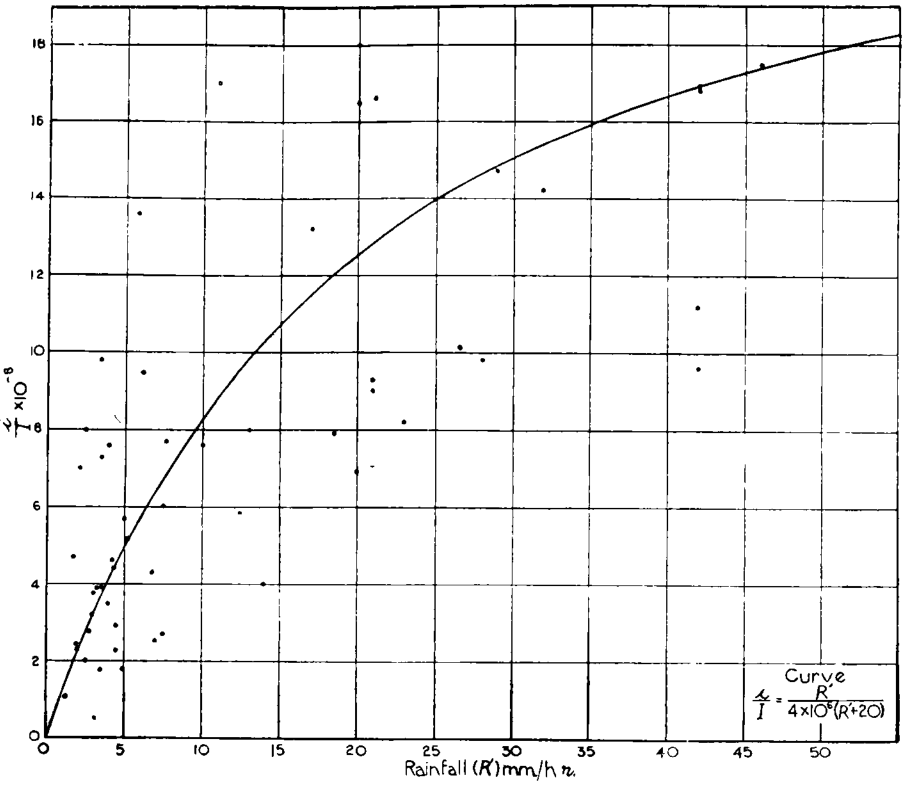

FIG. 7

The other two functions (3) and (4), give curves which differ slightly from (5) but the observations are too few and too scattered to make it possible to say that one fits the points better than either of the others. Thus we have derived three empirical expressions for the relationship between i, I and R' each of which represents the observations to a satisfactory degree.

§ 13—EMPIRICAL RELATIONSHIP BETWEEN q, I AND R' FOR $P > |20|$ V./CM.

If we substitute $q\,R$ for i in the three relationships (3), (4) and (5) remembering that $R = 2{\cdot}77 \times 10^{-5} R'$ we have the three following expressions for the relationship between q, I and R' :

$$\frac{q}{I} = 7{\cdot}22 \times 10^{-4} R'^{-{\cdot}43} \qquad \ldots . (6)$$

$$\frac{q}{I} = \frac{1}{1{\cdot}52 \times 10^{2} R'} (1 - e^{-{\cdot}058R'}) \qquad \ldots . (7)$$

$$\frac{q}{I} = \frac{1}{1{\cdot}11 \times 10^{2} (R' + 20)} \qquad \ldots . (8)$$

§ 14—PHYSICAL RELATIONSHIP BETWEEN i, I AND R' FOR $P > |20|$ V./CM.

In the preceding section we have derived from the observations relationships between q, i, I and R' which are entirely empirical ; in this section we consider the physical significance of these relationships. We will commence with the point-discharge current (I).

It will be remembered that I is the current of electricity which passes from the earth to the atmosphere through a needle point exposed at a height of 8·4 metres in an open situation in the grounds of Kew Observatory. Now it has generally been assumed that the discharge through such a point, which we will call the "reference point", is proportional to the discharge from all natural points such as trees, bushes, grass, etc. from which point discharge takes place on occasions of high potential gradient. On this assumption the discharge from all natural objects could be replaced by the discharges from a number of reference points erected at such intervals that the total discharge from the array of reference points is equal to the total discharge from the natural objects.

Thus if N reference points would be required to represent the natural discharge over an area B cm.^{2} then each reference point represents an area $A = B/N$ and the effective spacing of the points is said to be $l = \sqrt{A}$. In other words an array of identical reference points situated at the corners of squares of l-cm. sides would represent the discharge from all the natural points. We have written I to represent the point-discharge current through the reference point; we will now write J to represent the natural point-discharge current from each square centimetre of the surface. We then have $AJ = I$; hence, if we know A we can find J from the measured values of I.

This simple theory however neglects some important factors. As already stated Scrase found that for the point at Kew Observatory

$$I = a\,(P^2 - M^2).$$

In this expression the constant a depends on the height of the needle above the ground and M depends on the characteristics of its point, chiefly on its sharpness. If we consider the natural points we find that they are at different heights, ranging from the tips of the highest trees to the blades of grass at ground level, and their sharpness varies from that of thorns to that of leaves. Thus, while a and M are quite definite quantities for the reference point they are not for the natural points, each point having its own a and M. The total discharge from the natural points is the sum of the discharges from all the individual points, and it is very questionable whether in such a case we are justified in assuming that the $a\,(P^2 - M^2)$ of the reference point is proportional to the $\Sigma a\,(P^2 - M^2)$ of all the natural points.

Further if we consider a period in which the potential gradient is steadily increasing, the points on the tops of the trees presumably first commence to discharge and their discharge increases with the field according to $I = a\,(P^2 - M^2)$, then as the field increases points lower down come into action and finally if the field increases sufficiently the blades of grass commence to discharge. This introduces another factor, for while there is only one reference point for all fields the number of natural discharging points increases with the strength of the field, and for this cause again the ratio between current through the reference point and the natural discharge current may be far from constant. These considerations must be borne in mind when drawing conclusions based on equating the current through a reference point to the average current from all the natural points over an extensive area.

There can be little doubt that with sufficiently high potential gradients there is appreciable natural point discharge over a region with bushes and trees such as that surrounding Kew Observatory, and we must now consider what happens to the electricity so discharged. The discharge from an active point is really a "brush discharge" which provides large quantities of both positive and negative small ions. If the potential gradient is positive the positive ions are driven downwards and reach the ground, mainly through the points; but the negative ions move upwards towards the positive electricity in the cloud which is the cause of the positive potential gradient.

This stream of ions, all of one sign, gives to the air a volume charge which modifies the initial fields. This effect has been studied by Wilson[8], Whipple and Scrase[2] (p. 17) and by Chalmers[9], and they find that as the steady state is approached the field at ground level is less than at cloud level, the difference being very great with large point-discharge currents. The large volume charge which is introduced in this way by the natural point-discharge current from the ground is generally called the " blanket charge ", because it blankets the ground from the high fields which exist in thunder clouds. Unfortunately, the only observations which we have of the field below thunder clouds, those made at Kew by means of alti-electrographs carried on free balloons (Simpson and Scrase[6] and Simpson and Robinson[10]), do not show any measurable increase in the field between the ground and the clouds, even in well developed thunderstorms. No explanation has yet been found for this discrepancy.

We have then to picture the raindrops falling through an upward moving stream of small ions derived from the natural point-discharge current, and a certain proportion of these ions being captured by the drops. If we assume that the drops are uncharged when they leave the cloud, they will reach the ground with a charge of opposite sign to that of the potential gradient. This at once appears to give us a clue to the origin of the mirror-image effect, for the sign of the charge would always be opposite to that of the gradient and the magnitude of the charge would obviously increase and decrease with the intensity of the natural point-discharge current.

There are, however, a number of serious difficulties when we apply quantitative tests to this simple theory. The process by which raindrops in the presence of ions become charged was first outlined by C. T. R. Wilson[11] and worked out in great detail by Whipple and Chalmers[12]. The actual charge which the raindrops acquire depends on the number of positive and negative ions, on their mobility and on the field. In their work, Whipple and Chalmers show that in an atmosphere of ions, large or small, the maximum charge, Q, which a raindrop of radius a cm. can acquire in a field of X e.s.u. is $-3Xa^2$ e.s.u. From this it follows that the maximum charge per cubic centimetre is given by

$$q_{\max} = -\frac{9X}{4\pi a} \text{ e.s.u./cm.}^3$$

If we assume that the average radius of a raindrop is one millimetre and remembering that X e.s.u. $= P/300$ v./cm. we have

$$q_{\max} = -2{\cdot}4\times10^{-2}P \text{ e.s.u./cm.}^3$$

Now in Fig. 2 the observed values of q have been plotted against P and the straight line $q = -2{\cdot}4\times10^{-2}P$ has been added. It will be seen that for the larger values of P, both positive and negative, the observed values of q are consistently greater than the calculated values, the largest observed value being six times as great as its calculated value.

From this it is clear that the drops cannot have derived the whole of their charge by the process described by Wilson if the field remains unchanged from the ground to the cloud as indicated by the alti-electrograph records. This would appear to confirm the existence of the blanket charge deduced in the theoretical work mentioned above in spite of the alti-electrograph records to the contrary. But even if we accept the presence of the blanket with its associated high fields the problem would not be solved. We should then have to find some process by which the charge gained in the upper atmosphere would be adjusted to the field at the ground some minutes later when the raindrops arrived at the surface. As the upper field is controlled by the volume charge throughout the blanket, and as this charge is derived from the small ions released in the point discharge at the surface which travel upwards quite slowly (1·5 m./sec. in a field of 100 v./cm.) it is difficult to see what that process can be.

Thus we reach the impasse that if the field is the same from the ground to the clouds, as indicated by the only observations available, the rain cannot obtain the charge it is found to carry; while on the other hand if the field in the upper air is much greater than at the ground and the rain receives its charge there, that field would have to adjust itself to the field at the ground much more rapidly than is possible owing to the relatively slow movement of ions. Until a way is found out of this impasse we must acknowledge that the mechanism by which the charge on the rain adjusts itself to the point-discharge current at the ground is unknown. We can, however, learn a great deal about the principles governing that mechanism from the available observations.

In the first place we learn from the persistence of the mirror-image effect whenever there is appreciable natural point-discharge current (this assumes that there is a natural point-discharge current corresponding to, and roughly proportional to, the current through the elevated needle at the Observatory) that the natural point-discharge current is a major factor in providing the charge carried by the rain and that for long periods it so predominates that other factors may be neglected.

Starting from this conclusion—that the charge on the rain is derived from the natural point-discharge current—it is reasonable to assume that if the rate of rainfall remains constant the rain current will increase and decrease with the point-discharge current. In other words, that for R' constant the rain current (i) will be a function of the natural point-discharge current (J), say $i = \phi(J)$ for R' constant.

Further it is equally clear that with a constant point-discharge current the rain current will depend on the rate of rainfall; for the few drops in light rainfall (assuming for simplicity that raindrops are always of the same size) will absorb and bring down a smaller proportion of the ions than the numerous drops of heavy rain. The relationship, however, cannot be linear for as the rainfall increases the number of ions not already captured decreases and further increases of rainfall become less efficient, until finally when the rainfall is very heavy all the ions released in the point-discharge current are captured by the raindrops and returned to the ground in the rain current; the rain current will therefore be a function of the rate of rainfall, say $\theta(R')$.

Thus we are led to the conclusion that whatever the mechanism may be by which the drops receive their charge it results in the relationship

$$i = \psi(J, R') \qquad \ldots. (9)$$

in which $i = 0$ for $R' = 0$, and $i = J$ for $R' = \infty$.

Now remembering that $I = JA$ (see p. 36), two of the three functions which we found empirically to represent the observations (see p. 34) may be written:

$$i = \frac{AJ}{5{\cdot}5 \times 10^6}(1 - e^{-{\cdot}058R'}) \qquad \ldots. (10)$$

$$i = \frac{AJ}{4 \times 10^6}\left(\frac{R'}{R' + 20}\right) \qquad \ldots. (11)$$

both of which are of the same form as (9) above and both fulfil the two conditions regarding the limits of R'.

Thus the observations are consistent with a mechanism such as that described above in which (*a*) the rain current derives its charge predominatingly from the point-discharge current; (*b*) with any given rainfall the electricity captured by the rain increases and decreases with the point-discharge current; and (*c*) with a constant point-discharge current the rain captures a proportion of the natural point-discharge current, which proportion is zero for no rainfall and tends to complete capture as the rainfall increases.

On the assumption that these conclusions are correct we are able to determine the "equivalent area", A, of the discharge point at Kew, that is the area from which the total natural point-discharge is equal to the measured current through the point at the Observatory. When the rainfall is very heavy the bracketed term in each of equations (10) and (11) approaches 1; the interpretation of which, on our assumptions, is that the rain current (i) is then bringing back the whole of the natural point-discharge current (J) leaving the surface.

In these conditions $i = J$; hence from equation (10) $A = 5{\cdot}5 \times 10^6$ cm.^{2} and from equation (3) $A = 4 \times 10^6$ cm.^{2}, which for practical purposes are the same; and there is good reason for believing that approximately the same value of A would be obtained if any other function of R', satisfying the specified conditions, had been used to represent the observations. Thus the observations indicate that if the rain obtains its charge by absorbing the natural point-discharge current the "equivalent area", A, of the reference point at Kew is approximately 5×10^6 cm.^{2}, and that the "effective spacing", $l = \sqrt{A}$, of similar points would be approximately 22 metres. We have no means of checking this value, but F. J. W. Whipple[2] estimated that at Kew $l = 25$ metres. Unfortunately, he gave no information as to the basis of his estimate and no particulars can now be found at Kew. Although of no value as evidence for the correctness of our treatment, this virtual agreement between Whipple's estimated value and our computed value is at least interesting.

§ 15—SNOWFALL ($P > |20|$v./cm.)

So far in this part we have only considered rainfall; we have now to see how far the results we have obtained for rain apply to snow. From Fig. B, Plate XVII it is clear that the mirror-image effect is highly developed with snow; in fact, in no period of rainfall are the smaller fluctuations of I so clearly mirrored in the fluctuations of i as in this case of snowfall.

On Fig. 6 (p. 33) the values of i have been plotted as stars against I for thirteen selected periods of snowfall. All but one of these stars fall within the narrow band between the two outer lines drawn on the diagram, showing that the general relationship between i and I is the same for snow as for rain. In other words the "snow current" like the "rain current" increases and decreases with the point-discharge current. Unfortunately, it is not possible to examine the relationship between the snow current and the intensity of the snowfall for records of the rate of snowfall could not be obtained. Some indications of the connexion, however, can be found. Notes on the character of the precipitation are made as part of the routine weather observations at the Observatory, and in the case of every star entered on Fig. 6 the entry in the observation register is "very light snow" and the observer informed me that this expression would never be used for snowfall as great as 3 mm./hr. Thus, while the positions of the stars on Fig. 6 correspond to rainfalls greater than 3 mm./hr. in all but one case, the snowfall was actually less than 3 mm./hr. Thus, for the same values of precipitation and point-discharge current the "snow current" is several times greater than the "rain current". This indicates that a given weight of snow collects more charge than a similar weight of rain, which is what one would expect if both rain and snow obtain their charge from the ions of the point-discharge current; because mass for mass the superficial area of snow flakes is so much greater than that of raindrops, and the points of the ice crystals may facilitate the rate of charging.

§ 16—SUMMARY

Rain ($P > |20|$*v./cm.*).—From the observations it is deduced that at Kew, when the potential gradient is greater than $|20|$v./cm., the charge on the rain is derived mainly from the natural point-discharge current from surrounding trees, bushes, grass, etc.

The current through the exposed needle point at the Observatory is computed to be equal to the natural point-discharge current from an area of 5×10^6 cm.^{2} of the surrounding country.

The charge on the rain is such that for any given rate of rainfall the "rain current" (i) is directly proportional to the natural point-discharge current (J), and that for any given value of the point-discharge current the rain current varies from 0 to J as R' varies from 0 to ∞.

There are difficulties in explaining how the raindrops acquire their charge from the point-discharge current and this problem is left unsolved; but the observations are consistent with a process in which the rain sweeps up a proportion of the ions released in the point-discharge current, that proportion increasing with the intensity of the rainfall until with very great intensities all the ions are swept up and returned to the ground in the rain current.

Snow ($P > |20|$ *v./cm.*—There appears to be no essential difference between snow and rain in respect to the relationship between the charge carried and the natural point-discharge current, except that the snow collects more charge than a similar quantity of rain with the same point-discharge current.

PART V—RAIN ELECTRICITY WITH $P < |10|$ V./CM.

§ 17—THE PROBLEM AND THE DATA USED

We were led to divide our investigation into two parts (*a*) with $P > |20|$ v./cm. and (*b*) with $P < |10|$ v./cm., from purely empirical considerations; we found that q varied as P^2 above $|20|$ v./cm. but not below $|10|$ v./cm., thus indicating different physical processes acting in the two cases. We have now seen in Chapter IV that with $P > |20|$ v./cm. the charge carried by the rain is governed by the natural point-discharge current. As there can be very little if any natural point-discharge current with $P < |10|$ v./cm. our suspicion of two processes is confirmed, and in this chapter we have to examine the observations with $P < |10|$ v./cm. in the endeavour to find the second process.

Not only are there electrical differences between periods with $P > |20|$ v./cm. and periods with $P < |10|$ v./cm., but there are also meteorological differences; for high potential gradients are almost entirely associated with showers, while gradients below $|10|$ v./cm. are almost as entirely associated with steady rain. This is not likely to be a fortuitous relationship, and therefore it seems desirable that we should limit our investigation at first to periods of " steady rain " and examine subsequently the few cases of showers with low potential gradients to see if they exhibit any essential differences. This procedure has the great advantage that with steady rain the electrical and meteorological conditions change so slowly that it is not necessary to limit the investigation to the " selected periods "; but we may use all the minute values so making use of all the data.

It has already been described on p. 10 how early in the investigation periods of " steady rain " were selected by arbitrary rules, the chief of which are that, during any period the rainfall should undergo no large variations in intensity, the intensity of the rainfall should not fall below 1 mm./hr., and that the duration should be at least one hour. There proved to be 43 such periods varying in duration from 1 hour to 6 hours and having a combined duration of 79 hours. Some of these periods were electrically disturbed with point discharge so it was decided to use only those periods during which a potential gradient of $|20|$ v./cm. was not exceeded. This left 26 periods with a total duration of 45 hours.

These 26 periods provide the main data for investigating the conditions during steady rain with $P < |10|$ v./cm. They proved, however, to contain very few observations with positive potential gradient and more were desirable if they could be obtained. There were in the record a number of periods which would have been included in " steady rain " except that they did not continue for one hour. These periods were examined, and those portions extracted during which the potential gradient was positive for at least 10 consecutive minutes and did not exceed +20 v./cm. In this way 15 "supplementary periods" containing together 386 extra minute observations with positive potential gradient were added to the available data. In the 26 periods of "steady rain" and the 15 "supplementary periods" we have a relatively homogeneous mass of data comprising just over 3,000 minute observations. Table VI contains the analysis of these data.

TABLE VI

P	No. of minutes	Mean q	Mean q smoothed	Mean R'	P	No. of minutes	Mean q	Mean q smoothed	Mean R'
(1)	(2)	(3)	(4)	(5)	(1)	(2)	(3)	(4)	(5)
v./cm.		e.s.u./cm.^{3}	e.s.u./cm.^{3}	mm./hr.	v./cm.		e.s.u./cm.^{3}	e.s.u./cm.^{3}	mm./hr.
+6	3+(22)	·021	—	2·3	− 6	303	·144	·147	2·2
+5	1+(27)	·063	—	2·2	− 7	108	·190	·169	2·4
+4	54+(42)	·026	·016	2·5	− 8	162	·186	·182	3·1
+3	27+(82)	−·015	·012	2·3	− 9	67	·146	·172	2·5
+2	76+(98)	·038	·029	2·2	−10	85	·182	·189	2·4
+1	49+(98)	·042	·043	2·6	−11	48	·273	·230	2·9
±0	144	·050	·053	2·3	−12	52	·230	·247	2·4
−1	161	·066	·075	2·0	−13	40	·254	·274	2·6
−2	355	·093	·089	2·2	−14	46	·358	·320	2·0
−3	198	·090	·100	2·1	−15	28	·349	·336	2·8
−4	367	·117	·114	2·2	−16	28	·304	—	2·2
−5	189	·128	·129	2·0					

Column (2) of Table VI contains the number of minutes for which $P = +6, +5 \ldots -16$ v./cm. The figures in brackets in this column refer to the supplementary observations which were added to increase the number of positive values of the potential gradient; they should therefore be omitted in determining the frequency curve of potential gradient during steady rain. It will be noted that the number of minutes is greater for even than for odd values of P. This is an unfortunate result of the method employed in measuring the record of the Benndorf electrometer. The original tabulations were made to the nearest half volt per centimetre and the practice of throwing the 0·5 values to the neighbouring even number was adopted, thus adding to the number of even values but not to the number of odd values.

In column (3) the mean values of q for each value of P are given. These means are of unequal value because they suffer from the irregular distribution of the observations between the odd and even values of P; they have therefore been smoothed by use of the formula:

$$\bar{q}_b = \frac{\frac{1}{2}\Sigma q_a + \Sigma q_b + \frac{1}{2}\Sigma q_c}{\frac{1}{2}n_a + n_b + \frac{1}{2}n_c}.$$

The smoothed values are entered in column (4).

Column (5) contains the unsmoothed mean values of R' for each value of P.

§ 18—EMPIRICAL RELATIONSHIP BETWEEN q, i, P AND R' FOR $P < |10|$ V./CM.

Frequency of potential gradient.—Column (2) of Table VI, gives the number of minutes the different values of the potential gradient were recorded. These numbers have been plotted as curve I of Fig. 8 after they have been smoothed and converted into percentages of the total number of observations (the supplementary periods being omitted). This curve shows that during steady rain the most frequent value of the potential gradient is between −3 and −4 v./cm. The curve is not symmetrical about this maximum value, falling more rapidly towards the positive than towards the negative side. If the figures in column (2) of the table are examined it will be seen that there is a sudden fall in the number of minutes between $P = +4$ and $P = +5$. In fact for all practical purposes there are no observations of potential gradients greater than

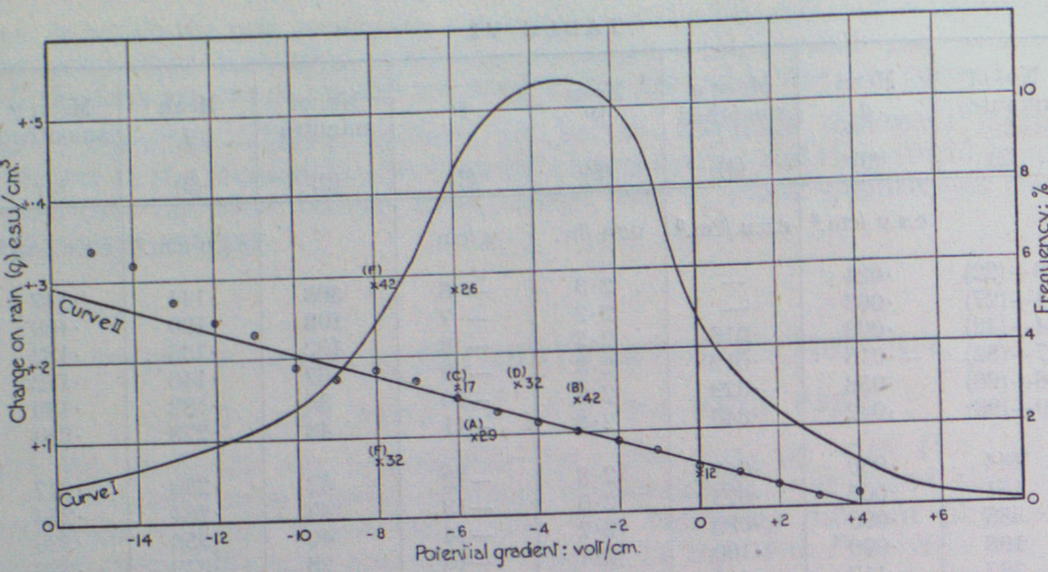

FIG. 8

$P = +4$ v./cm. in steady rain at Kew (the extension of the curve in Fig. 8 beyond $P = +4$ is due to smoothing). At the other end of the curve the frequency falls off more regularly and approaches the zero asymptotically.

Rate of rainfall.—From column (5) it will be seen that the average rate of rainfall is practically the same for all values of the potential gradient. This is an important result for it shows that the potential gradient during steady rain is independent of the intensity of the rain.

The charge on the rain.—The smoothed values of the charge per cubic centimetre (q) from column (3) have been plotted against P as dots in circles in curve II, Fig. 8. It is at once apparent that from $P = +4$ to about $P = -10$ v./cm. the points are well represented by a straight line. Also as the mean rainfall in column (5) is the same for all values of q in column (4) the charge on the rain is independent of the rate of rainfall. Hence, we have for all values of R' and for $+4 > P > -10$ v./cm. :

$$q = -0{\cdot}0145\ (P - 4)\ \text{e.s.u./cm.}^3 \quad \ldots (12)$$

The physical significance of this result is very important :

(*a*) The charge on steady rain with potential gradients between $P = +4$ and $P = -10$ is always positive.

(*b*) The positive charge on the rain increases with increasing values of the negative gradient ; it is not zero, however, when the gradient is zero, but when $P = +4$ v./cm.

(*c*) When the potential gradient is zero the rain carries an appreciable positive charge.

(*d*) Both the potential gradient and the charge on the rain are independent of the intensity of the rainfall.

For negative gradients greater than -10 v./cm. the points in Fig. 8 lie above the straight line which fits the points between $P = -10$ and $P = +4$, and the departures progressively increase with increasing negative gradients. The number of observations in this region is too small to give reliable mean values ; but the tendency for q to increase with P more rapidly for the higher values of the negative gradient is quite clear. There can be little doubt that this is due to the natural point-discharge current which begins to be effective near -10 v./cm. Hence, we have here part of the transition region between point discharge and no point discharge where the relationship between q and P is changing from q varies as P to q varies as P^2.

Rain current.—The rain current (i) and the charge per cubic centimetre (q) are related by the equation :

$$i = qR \text{ e.s.u./cm.}^2 \text{ sec.} \quad (R, \text{ rainfall in cm./sec.})$$

Now we have found that during steady rain $q = -0{\cdot}0145\ (P-4)$ and is independent of the rate of rainfall, hence

$$i = -0{\cdot}0145\ (P-4)R$$
$$= -0{\cdot}040 \times 10^{-5}(P-4)\ R' \text{ e.s.u. /cm.}^2 \text{ sec.} \quad (R', \text{ rainfall in mm./hr.}) \qquad \ldots. (13)$$

In order to confirm that the observations do in fact conform to this relationship which was obtained indirectly through q the following computation was carried out. All the minute values of i and R' for potential gradients -3, -4 and -5 v./cm. were extracted from the steady rain data, giving a little over 700 observations of i and R' with a mean potential gradient of -4 v./cm. These values were then separated according to rainfall into three groups, $R' = 1$–2, 2–3 and 3–4 mm./hr. (there were only a few observations with $R' > 4$ mm./hr.) and the mean value of i obtained for each group, with the result shown in Table VII.

TABLE VII

Mean P = − 4 v./cm.

R'	No. of observations	Mean i observed	Mean i calculated
mm./hr.		$\times 10^{-5}$	$\times 10^{-5}$
1–2	392	−0·39	−0·48
2–3	230	−0·71	−0·80
3–4	72	−1·00	−1·12

In the third column is given the mean value of i for the range of rainfall shown in the first column, and in the fourth column the corresponding values of i calculated from equation (13). The result is unexpectedly good : not only is the increase of i with increasing rainfall quite definite, but the values of i, observed and calculated, are in excellent agreement. Thus, there can be no doubt that with steady rain for a given value of the potential gradient the rain current increases proportionally to the rate of rainfall.

Showers.—All the relationships between P, q and R' for values of P less than $|\ 10\ |$ v./cm. so far discussed have been obtained from observations during steady rain, and now the question arises, do the same relationships hold for showers with their different meteorological conditions and occasional large rates of rainfall ? For the examination of this question the data from the "selected periods" are available, for these periods were chosen without any consideration of the type of rainfall and therefore cover both showers and steady rain.

On a diagram similar to Fig. 8 all the values of q for the selected periods were plotted against P, the observations during steady rain being represented by dots and those for showers by crosses. There is of course a large amount of scatter, but not more for the crosses than for the dots, both of which are distributed on both sides of the straight line drawn through the mean values derived from all the observations with steady rain reproduced on Fig. 8. This diagram is not reproduced here, but all the observations with R' greater than 10 mm./hr. have been shown on Fig. 8 by crosses against each of which the rate of rainfall, R', is entered in figures. It will be seen that in these observations the rainfall reached 42 mm./hr. yet all the crosses fall remarkably near to the straight line and show no consistent tendency to depart from it in any particular way. It is a remarkable fact that rainfall at the rate of 30 or 40 mm./hr. in heavy showers should carry the same charge per cubic centimetre as light steady rainfall of 1 to 5 mm./hr.

In view of the great interest of these exceptionally heavy falls of rain with low potential gradients, copies of the working sheets for six of them are given on Plate XVIII (the letter against each cross on Fig. 8 indicates the corresponding figure on the Plate). It will be seen that in each case the rain occurred as a short sharp shower without continuing rain before or after. In five of the six cases the potential gradient curve showed a typical V pattern (see p. 17).

The conclusion to be drawn from this examination of conditions during showers is that the relationship between P, q, i and R' formulated in equations (12) and (13) are true at Kew for showers as well as for steady rain, provided the potential gradient lies between $+4$ and -10 v./cm.

Snow.—The few observations of snowfall with potential gradients between $+10$ v./cm. and -10 v./cm. show a different relationship between i and P from that with rain. It has already been remarked (p. 14) that with light steady snowfall the potential gradient generally remains positive; but when there are discontinuities in the atmosphere it may oscillate between positive and negative values. In both cases, however, the sign of the charge on the snow is always opposite to that of the potential gradient: thus, between $P = 0$ and $P = +4$ v./cm. the charge on the snow is negative, not positive as with rain (see Figs. A and B, Plate V).

Summary

We may summarise the results obtained in this section as follows :—

Steady rain (rainfall continuing for more than one hour at a rate of not less than 1 mm./hr. and with no large changes of intensity) :—

(i) The intensity of "steady rain" seldom exceeds 5 mm./hr.; heavier rainfall is usually associated with "showers".

(ii) The rainfall tends to make the potential gradient more negative than the normal potential gradient of fine weather.

(iii) The most frequent potential gradient during steady rain at Kew is in the neighbourhood of -3 to -4 v./cm. From this maximum the frequency falls rapidly towards higher positive values of the potential gradient, becoming zero near to $P = +4$ v./cm.; in consequence there are very few occasions of positive gradient greater than $+4$ v./cm. at Kew during steady rain. The frequency decreases less rapidly from the maximum towards higher values of negative gradient; but becomes relatively very small for negative gradients greater than -16 v./cm.

(iv) The potential gradient does not depend on the rate of rainfall; for the average rate of rainfall is practically the same for every value of the potential gradient between $P = +4$ and $P = -10$.

(v) The charge on steady rain (q) is positive in the absence of point discharge. It is zero for $P = +4$ v./cm. and then increases at the rate of 0·0145 e.s.u./cm.³ for each volt per centimetre as P changes from $+4$ to -10 v./cm. At -10 v./cm. the charge increases at a greater rate as the negative gradient still further increases, probably due to point-discharge current. Between $P = +4$ and $P = -10$ v./cm., and for all values of the rainfall,

$$q = -0{\cdot}0145\,(P-4) \text{ e.s.u./cm.}^3 \qquad \ldots (12)$$

(vi) In consequence of (v) rainfall with a potential gradient of $+4$ v./cm. carries no charge, while rainfall with zero potential gradient carries the appreciable charge of $+0{\cdot}06$ e.s.u./cm.³.

(vii) As the charge per cubic centimetre carried by the rain (q) depends on the potential gradient and not on the rate of rainfall (R') the total charge carried to unit area of the ground in unit time (the rain current, i) will, for any given value of P increase with increase of rainfall according to the equation :

$$i = 0{\cdot}040 \times 10^{-5} \, (P-4) \, R' \text{ e.s.u./cm.}^2 \text{ sec.} \qquad \ldots . (13)$$

Showers.—Paragraphs (iv), (v), (vi) and (vii) apply to "showers" as well as to "steady rain".

Snow.—The charge on the snow is always of opposite sign to that of the potential gradient, even between $P = 0$ and $P = +4$ v./cm.

§ 19—PHYSICAL RELATIONSHIP BETWEEN q, i, P AND R' FOR $P < |10|$ V./CM.

We have now to try to find the physical processes behind the empirical relationship set out in the above summary. We have found empirically that a potential gradient of +4 v./cm. is important for two reasons, (*a*) the potential gradient is always less than +4 v./cm. during steady rain and (*b*) the charge on the rain is zero when the potential gradient has this value. Now at Kew the normal fine-weather potential gradient is between +3 and +4 v./cm. It is very unlikely that this is a coincidence ; it is much more probable that the " +4 v./cm." which appears in paragraphs (iii) and (vi) of the summary is not there because a field of 4 v./cm. has any particular property of its own, but because this is the value of the undisturbed potential gradient at Kew. We will adopt this suggestion in what follows.

We are now in a position to draw the conclusion that the effect of steady rain is always to reduce the potential gradient below its fine-weather value and in most cases to reverse the field to negative values. The amount by which the potential gradient is changed from its fine-weather value, which we will call the " displacement ", does not depend, as one might expect, on the intensity of the rainfall, for this was found to be the same for all values of the gradient between +4 and −10 v./cm. It is not clear from the observations what determines the value of the potential gradient from time to time during periods of steady rain ; so we can only accept the fact that during steady rain the potential gradient may have any value less than + 4 v./cm. with a most probable value between −3 and −4 v./cm.

Whatever may determine the actual value of the potential gradient, there is a close connexion between it and the charge on the rain, the charge increasing linearly as the negative gradient increases. It is, however, significant that the charge is not proportional to the potential gradient itself, but to its displacement from the normal fine-weather gradient. From this it would appear that the charge is not determined by the electrical field through which the rain falls ; on the other hand the displacement is directly proportional to the charge per cubic centimetre carried by the rain, not, as would seem more likely, by the total amount of electricity previously carried down, nor by the rate at which it is being carried down.

All this new information, however, does not appear to bring us nearer to a solution of the problem of the origin of the electricity on steady rain ; it has apparently, as is so frequently the case, increased the difficulties. In order to indicate some of these difficulties we will consider the simple case of rain from a horizontal layer of cloud extending uniformly as regards the electrical and other factors over a large area. These conditions are essentially satisfied during steady rain of long duration.

Three theories have been suggested to account for the electricity of precipitation. They are the " influence theory " put forward in slightly different forms by Elster and Geitel[13] and C. T. R. Wilson[11], and the two theories put forward by myself according to which the charge is generated either by the breaking of raindrops[14] or by the impact of ice crystals[15, 16, 17].

The " influence theory " requires the pre-existence of an electrical field through which the rain falls and the consequence is always the same : the drops acquire a charge of the opposite

(vii) As the charge per cubic centimetre carried by the rain (q) depends on the potential gradient and not on the rate of rainfall (R') the total charge carried to unit area of the ground in unit time (the rain current, i) will, for any given value of P increase with increase of rainfall according to the equation :

$$i = 0{\cdot}040 \times 10^{-5} (P-4) R' \text{ e.s.u./cm.}^2 \text{ sec.} \qquad \ldots. (13)$$

Showers.—Paragraphs (iv), (v), (vi) and (vii) apply to "showers" as well as to "steady rain".

Snow.—The charge on the snow is always of opposite sign to that of the potential gradient, even between $P = 0$ and $P = +4$ v./cm.

§ 19—PHYSICAL RELATIONSHIP BETWEEN q, i, P AND R' FOR $P < |10|$ V./CM.

We have now to try to find the physical processes behind the empirical relationship set out in the above summary. We have found empirically that a potential gradient of $+4$ v./cm. is important for two reasons, (a) the potential gradient is always less than $+4$ v./cm. during steady rain and (b) the charge on the rain is zero when the potential gradient has this value. Now at Kew the normal fine-weather potential gradient is between $+3$ and $+4$ v./cm. It is very unlikely that this is a coincidence ; it is much more probable that the " $+4$ v./cm." which appears in paragraphs (iii) and (vi) of the summary is not there because a field of 4 v./cm. has any particular property of its own, but because this is the value of the undisturbed potential gradient at Kew. We will adopt this suggestion in what follows.

We are now in a position to draw the conclusion that the effect of steady rain is always to reduce the potential gradient below its fine-weather value and in most cases to reverse the field to negative values. The amount by which the potential gradient is changed from its fine-weather value, which we will call the " displacement ", does not depend, as one might expect, on the intensity of the rainfall, for this was found to be the same for all values of the gradient between $+4$ and -10 v./cm. It is not clear from the observations what determines the value of the potential gradient from time to time during periods of steady rain ; so we can only accept the fact that during steady rain the potential gradient may have any value less than $+ 4$ v./cm. with a most probable value between -3 and -4 v./cm.

Whatever may determine the actual value of the potential gradient, there is a close connexion between it and the charge on the rain, the charge increasing linearly as the negative gradient increases. It is, however, significant that the charge is not proportional to the potential gradient itself, but to its displacement from the normal fine-weather gradient. From this it would appear that the charge is not determined by the electrical field through which the rain falls ; on the other hand the displacement is directly proportional to the charge per cubic centimetre carried by the rain, not, as would seem more likely, by the total amount of electricity previously carried down, nor by the rate at which it is being carried down.

All this new information, however, does not appear to bring us nearer to a solution of the problem of the origin of the electricity on steady rain ; it has apparently, as is so frequently the case, increased the difficulties. In order to indicate some of these difficulties we will consider the simple case of rain from a horizontal layer of cloud extending uniformly as regards the electrical and other factors over a large area. These conditions are essentially satisfied during steady rain of long duration.

Three theories have been suggested to account for the electricity of precipitation. They are the " influence theory " put forward in slightly different forms by Elster and Geitel[13] and C. T. R. Wilson[11], and the two theories put forward by myself according to which the charge is generated either by the breaking of raindrops[14] or by the impact of ice crystals[15, 16, 17].

The " influence theory " requires the pre-existence of an electrical field through which the rain falls and the consequence is always the same : the drops acquire a charge of the opposite sign to that of the field and the strength of the field is increased. The pre-existing field can only be the fine-weather field and that is always positive; unless we are prepared to assume some second process, other than "influence", by which the field can be reversed; but that would only be begging the question. Thus, the effect of the rain would be to increase the normal positive field and in the process to give a negative charge to the drops. Both these effects are just the opposite to what actually takes place. Thus, influence theories offer no satisfactory solution to the problem.

The theory of charging by the impact of ice crystals, which appears to be so successful in cases of thunderstorms and showers with their strong but localised ascending currents (Simpson[18]), does not appear capable of explaining the electrifications of steady rain which falls from extensive horizontal clouds with only small ascending currents. We assume that the upper layers of the cloud from which the steady rain falls are composed of ice crystals. The ice crystals in this region will become negatively charged, as the result of collisions, and as they fall they will carry negative electricity with them, leaving positive electricity in the cloud. Thus, we should have negatively charged precipitation and positive potential gradient; conditions which are opposite to those observed during steady rain. I have found no way of surmounting this difficulty.

Qualitatively the breaking-drop theory does fit the facts: for the water of a raindrop on breaking becomes positively charged and the air receives a negative charge; thus, the positively charged rain and the negative potential gradient are accounted for. On putting forward this theory more than 30 years ago (Simpson[16]) I expressed doubts as to whether there is sufficient breaking of drops in non-thunderstorm rain to give the charges measured. I still have those doubts and should be surprised if the breaking of drops proves to be the solution of the problem; but until the final solution is found this explanation cannot be entirely ruled out.

But something more than a qualitative solution of the problem is required. Any theory to be satisfactory must explain (*a*) why the charge per cubic centimetre of the rain is proportional to the displacement of the potential gradient from its fine-weather value and (*b*) why the potential gradient is independent of the rate at which the rain carries charge out of the cloud. If, as seems probable, the potential gradient is negative during steady rain because the rain has carried positive charge out of the cloud, it is difficult to see how these two conditions can be satisfied.

PART VI—SUMMARY AND CONCLUSIONS

§ 20—THE OBSERVATIONS

(1) The work described in this paper is based on the following observations made at Kew Observatory mainly between October 1942 and May 1946: continuous records of (*a*) potential gradient over the range -20 to $+20$ v./cm.; (*b*) the discharge from a needle point exposed at a height of 8·4 metres above the ground (from which values of the potential gradient greater than $|20|$ v./cm. can be obtained); (*c*) the charge carried by the rain; and (*d*) the rate of rainfall.

(2) From these records values of the following quantities were obtained for each minute during periods of disturbed weather:

Potential gradient: P v./cm.
Point-discharge current: I e.s.u./sec.
Rain current: i e.s.u./cm.^{2} sec.
Charge per cubic centimetre carried by the rain: q e.s.u./cm.^{3}
Rate of rainfall: R cm./sec.; R' mm./hr. ($R = 2{\cdot}77 \times 10^{-5} R'$).

(3) All the minute values were plotted on the same time base giving four curves for P, I, i and q and a series of short strokes indicating the intervals in which a given amount of rain fell. The curves thus constructed represent rather more than 1,000 hours of disturbed weather, and proved an invaluable aid to the study of the relationships between the five factors, the results of which are described in the following paragraphs.

§ 21—POTENTIAL GRADIENT AND WEATHER

(4) During fine weather the potential gradient is positive and undergoes only small and regular changes, chiefly due to the daily variation. Rapid and irregular variations, especially those leading to negative potential gradient, are signs of atmospheric disturbance generally accompanied by precipitation (at Kew the fine-weather gradient is unusually high, being between +3 and +4 v./cm.).

(5) If during rainfall the potential gradient is negative, but without rapid variations, it is found that the rainfall is associated with a warm front, an occlusion or a cloud sheet not obviously connected with a discontinuity in the atmosphere. In other words when rain falls from a uniform atmosphere without local variations in the vertical component of the air motion the potential gradient is negative without large variations.

(6) Judging from the few observations at Kew, supported by the observations made in polar climates, steady light snowfall does not appreciably disturb the normal positive potential gradient. Negative potential gradients with snow at temperatures below the freezing point practically never occur.

(7) Large and rapid changes in the potential gradient, with the gradient swinging from positive to negative and *vice versa*, are usually associated with the passage of cold fronts, or accompany disturbances in which there are appreciable local ascending air currents. These conditions are generally indicated by the rainfall occurring in showers.

(8) An examination of the simultaneous records of rainfall and potential gradient indicates that the changes in the gradient are not closely, if at all, associated with either the intensity or the variations of the rainfall. The rainfall is frequently heavier with relatively steady negative potential gradient than it is in showers with rapidly fluctuating gradient, and in the latter case the fluctuations of the gradient are frequently as large between the showers as when the rain is falling.

(9) The conclusion drawn from paragraphs (4) to (8) is that both the character of the gradient and the character of the rainfall are governed by the character of the air motion in the upper atmosphere. The association of disturbed potential gradient with rainfall is not that of cause and effect, but that of two secondary effects of the air motion.

§ 22—POTENTIAL-GRADIENT PATTERNS

(10) The variations of the potential gradient during disturbed weather are usually quite irregular, but occasionally, and for short periods, they become regular, so that a curve of potential gradient plotted against time shows a regular pattern. The patterns are of two types : (*a*) wave patterns, and (*b*) symmetrical patterns. The wave pattern consists of a series of waves : the best example consists of four almost perfect harmonic waves with an amplitude of ±20 v./cm. and a period of a little over an hour. The symmetrical patterns, of which five varieties have been recognized, consist of variations of the curve which are symmetrical about an axis through the mid point of the pattern. The range of the potential gradient in the patterns varies largely : identical patterns occur with ranges from 20 v./cm. to more than 200 v./cm. The patterns are

always accompanied by disturbed weather, but not always with precipitation at the ground, and some are associated with definite types of weather. No physical cause has been found to account for these remarkable, controlled variations of the potential gradient.

§ 23—ELECTRICITY CARRIED BY THE PRECIPITATION

(11) The relationship between the rain electricity and the potential gradient is entirely different for gradients greater than $|20|$ v./cm. from what it is for gradients less than $|10|$ v./cm.; it is therefore necessary to consider the two cases separately.

Potential Gradient $> |20|$ *v./cm.*

(12) There is always a current of electricity into the air from a needle point erected at a height of 8·4 metres in the grounds of Kew Observatory when the potential gradient is greater than $|20|$ v./cm. When the curves for this current (I) plotted against time are compared with similar curves for the charge per cubic centimetre of the rain (q) or for the rain current (i) a remarkable relationship is found between them: when I is positive q and i are negative and *vice versa*; the curves rise and fall and cross the zero together, but in opposite directions. This relationship has been called for convenience in description "the mirror-image effect". The mirror-image effect is variable, being much more clearly developed in some periods than in others: in 59 per cent. of the periods with point discharge the effect can be clearly seen; in another 34 per cent. it can be seen more or less clearly; while in the remaining 7 per cent. it is absent.

(13) It is clear from the mirror-image effect that the rain current (i), the point-discharge current (I) and the rate of rainfall (R') are related, that is $i = f(I, R')$. In order to investigate this relationship quantitatively short periods of a few minutes were selected from the records when the mirror-image effect was clearly in evidence, and the mean values I, i, q and R' for each of these "selected periods" were obtained from the observations. The mean values for each selected period were treated as independent observations and formed the data used in the investigation of $f(I, R')$.

(14) By purely empirical methods of plotting and computing it was found that the observations from 54 selected periods can be represented equally well by one or other of the three following expressions:—

$$\frac{i}{I} = 2 \cdot 0 \times 10^{-8} R'^{0 \cdot 57} \qquad \ldots. (3)$$

$$\frac{i}{I} = \frac{1}{5 \cdot 5 \times 10^6}(1 - e^{-\cdot 058R'}) \qquad \ldots. (4)$$

$$\frac{i}{I} = \frac{R'}{4 \times 10^6 (R' + 20)} \qquad \ldots. (5)$$

(15) It is deduced from the observations that at Kew for potential gradients $> |20|$ v./cm.:

(i) The rain current (i) derives its charge from the natural point-discharge current (J).

(ii) With a given rainfall (R') the rain current increases and decreases with the point-discharge current.

(iii) With a constant point-discharge current the rain current increases and decreases with the rate of rainfall.

From (ii) and (iii) we have $i = \psi(J, R')$ and from (i) we have $i = 0$ for $R' = 0$ and $i = J$ for $R' = \infty$. These conditions would be fulfilled if the raindrops falling through the ions in the point-discharge current absorb a proportion of the ions not already absorbed; so that ultimately, with very heavy rain all the ions are swept up and the rain current becomes equal to the natural point-discharge current.

(16) Assuming that the current through the needle point at the Observatory (I) is porportional to the natural point-discharge current (J) then $I = AJ$, in which A is the "equivalent area" of the needle point, i.e. the area of surrounding country from which the total natural point-discharge current is equal to the current through the needle. Writing $I = AJ$ in equations (4) and (5) of paragraph (14), it will be seen that both equations fulfil the conditions of paragraph (15), i.e. $i = \psi (J, R')$ and $i = 0$ for $R' = 0$ and $i = J$ for $R' = \infty$. Either of these equations may therefore represent a possible mechanism. In the limit when $R' = \infty$ and $i = J$ equation (4) gives $A = 5 \cdot 5 \times 10^6$ cm.^{2} and equation (5) gives $A = 4 \times 10^6$ cm.^{2}; as any other equation fulfilling the conditions would give a similar result it is concluded that the "equivalent area" (A) and the "effective spacing" (l) of the Kew discharge point are approximately 500 square metres and 22 metres, respectively.

(17) When an attempt is made to use the conclusions set out in paragraphs (15) and (16) to find a solution to the problem of how the raindrops absorb the ions very great difficulties are encountered. According to Wilson's theory of the absorption of ions by raindrops the field at the ground is found to be too small to account for the observed charges on the rain. On the other hand if the rain receives its charge in the upper air where the fields are supposed to be greater, owing to the formation of a blanket charge, it is difficult to see how the charge on the rain can vary simultaneously with the field at the ground. No final solution of the problem is offered.

(18) Snow.—With potential gradients greater than $|20|$ v./cm. the mirror-image effect is even more pronounced with snow than with rain. As the number of selected periods for snowfall is very small and it was not found possible to record the intensity of the snowfall the exact relationship between i, J and R' for snow cannot be determined. It is clear, however, that, as with rain, the charge carried down by the snow increases and decreases with the natural point-discharge current; but the charge on the snow is several times greater than it would be on rain of the same intensity and with the same point-discharge current.

Potential gradients $< |10|$ *v./cm.*

(19) Potential gradients between $+10$ and -10 v./cm. are usually associated with light steady rain, the intensity of which seldom exceeds 5 mm./hr.; but occasional showers (in which the rate of rainfall may exceed 40 mm./hr.) also occur.

(20) During light steady rain the potential gradient is "displaced" from its normal fine weather value towards the negative, with the most frequent value between -3 and -4 v./cm. Gradients greater than $+4$ v./cm. (the fine-weather gradient) seldom occur at Kew during steady rain.

(21) An analysis of all the observations, both for steady rain and showers, with potential gradients between $+10$ and -10 v./cm. gives the following empirical relationship between q, i, P and R'.

$$q = -0 \cdot 0145 \, (P - 4) \text{ e.s.u./cm.}^3 \qquad \ldots (12)$$

$$i = -0 \cdot 040 \times 10^{-5} \, (P - 4) \, R' \text{ e.s.u./cm.}^2 \text{ sec.} \qquad \ldots (13)$$

From this it will be seen that for $+10 > P > -10$ v./cm. :—

(i) The charge on the rain (q) is independent of the rate of rainfall.

(ii) The charge on the rain is positive for all values of P less than $+4$ v./cm.

(iii) The positive charge is not proportional to P, but to the "displacement" of the potential gradient from its normal fine-weather value; hence, the rain carries no charge when the potential gradient has its fine-weather value, and a positive charge of $+0 \cdot 06$ e.s.u./cm.^{3} when the potential gradient is zero.

(iv) From equation (12), $dq/dP =$ constant, i.e. q varies linearly with P.

(v) From the few observations of light steady snowfall it appears that the charge carried by the snow changes sign when the potential gradient changes sign ; so that the charge on the snow between $P = 0$ and $P = +4$ is negative and not positive as with rain.

(22) The empirical relationships between q, i, P and R' for $P < | 10 |$ v./cm. specified in paragraphs (19) to (21) may be expressed physically as follows. In the absence of local instabilities in the atmosphere which give rise to showers with high potential gradients, rain always carries positive electricity out of the cloud. The negative charge left behind in the cloud reduces the field at the ground and if carried far enough, as is generally the case, reverses it giving negative potential gradient. The positive charge on the rain increases directly proportional to the " displacement " of the gradient from its normal fine-weather value. How and where the rain receives its positive charge, why the potential gradient should be proportional to the charge per cubic centimetre on the rain, and why there is no relationship between the rate of rainfall and the charge on the rain or the potential gradient, remain problems for which no solutions are offered.

ACKNOWLEDGMENTS

Almost from the commencement of this work I have discussed with Dr. A. J. Chalmers, of Durham University, possible explanations of the results from the point of view of Wilson's theory of the collection of charge by falling drops. Although Wilson's theory has not so far provided a solution of the problems, these discussions have been valuable and I wish to express my thanks to Dr. Chalmers for his ready help.

Dr. J. M. Stagg and Dr. G. D. Robinson, of Kew Observatory, read the first draft of this report, and I am very grateful to them for their remarks and suggestions which have led to several important modifications being introduced into the paper as it now appears.

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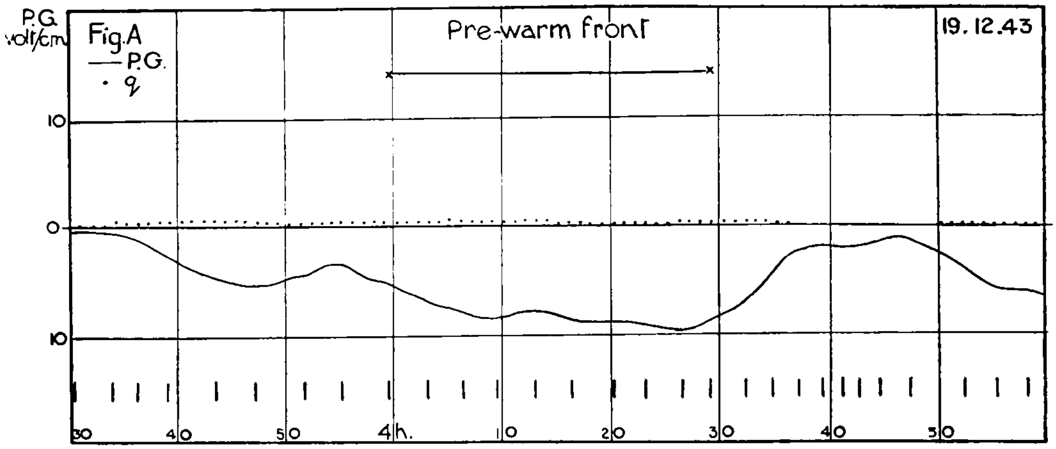
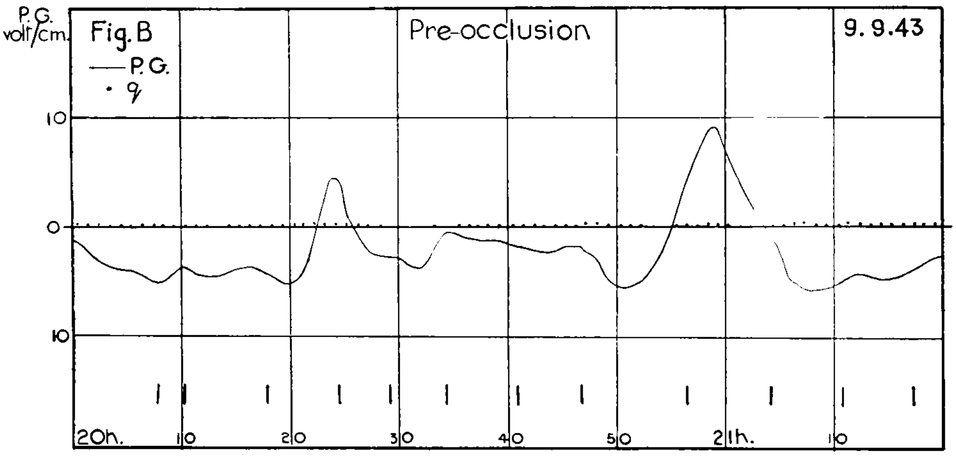
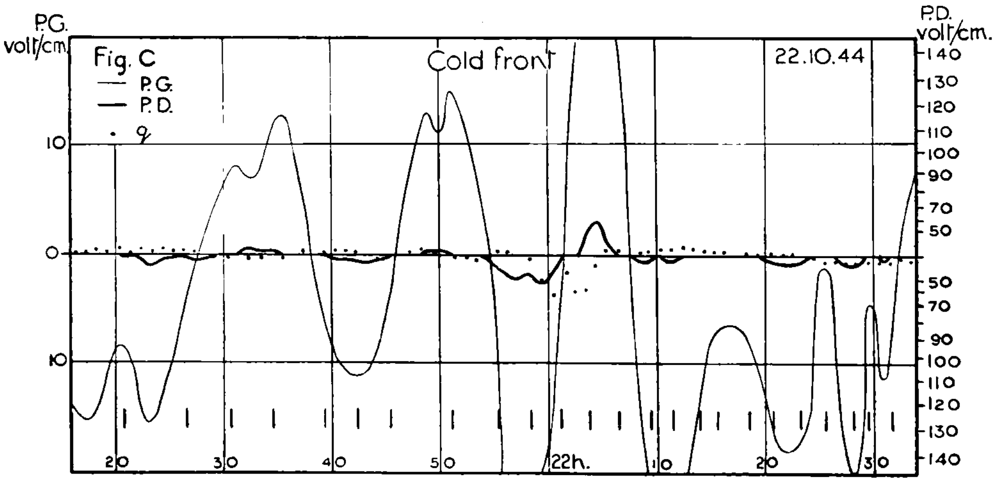

P.G. volt/cm.
Fig. A
— P.G.
· q
Pre-warm front
19. 12. 43
10
0
10
30
40
50
4h.
10
20
30
40
50


P.G. volt/cm.
Fig. B
— P.G.
· q
Pre-occlusion
9. 9. 43
10
0
10
20h.
10
20
30
40
50
21h.
10


P.G. volt/cm.
Fig. C
— P.G.
— P.D.
· q
Cold front
22.10.44
P.D. volt/cm.
140
130
120
110
100
90
70
50
50
70
90
100
110
120
130
140
10
0
10
20
30
40
50
22h.
10
20
30

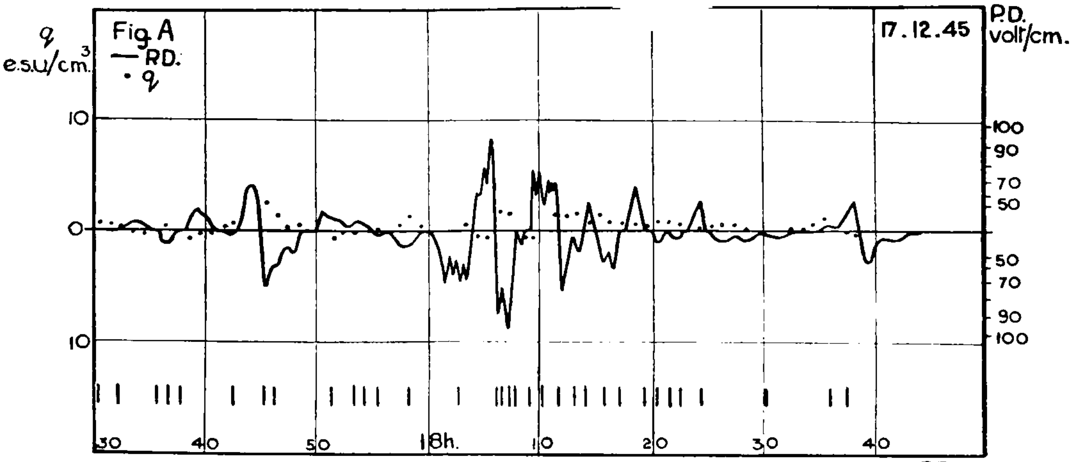


Fig. A
— P.D.
· q
17. 12. 45
q
e.s.u./cm.³
P.D.
volt/cm.
10
0
10
100
90
70
50
50
70
90
100
30
40
50
18h.
10
20
30
40

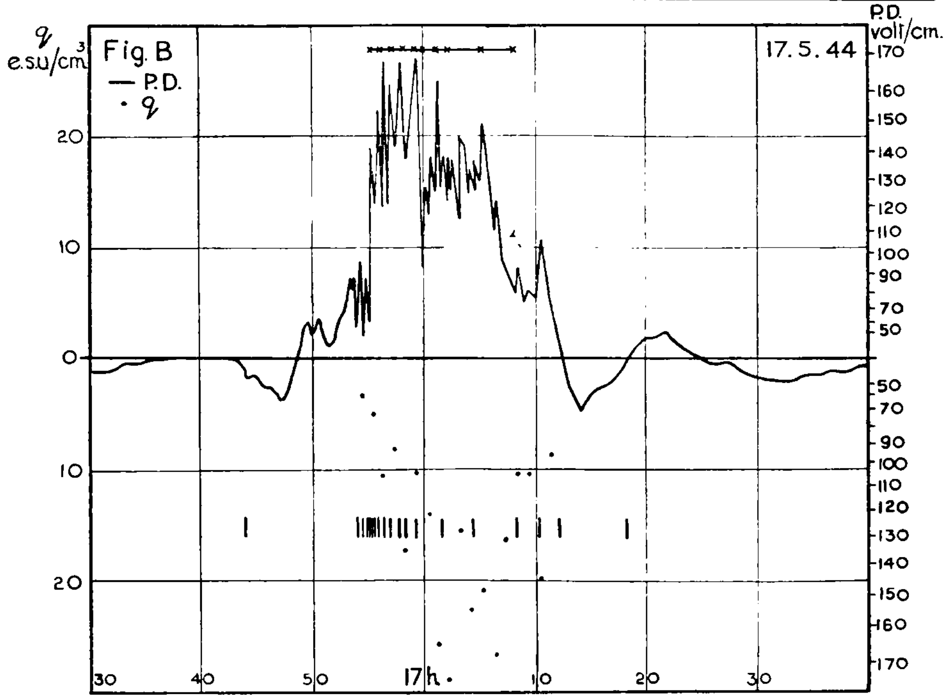


Fig. B
— P.D.
· q
17. 5. 44
q
e.s.u./cm.³
P.D.
volt/cm.
20
10
0
10
20
170
160
150
140
130
120
110
100
90
70
50
50
70
90
100
110
120
130
140
150
160
170
30
40
50
17h.
10
20
30

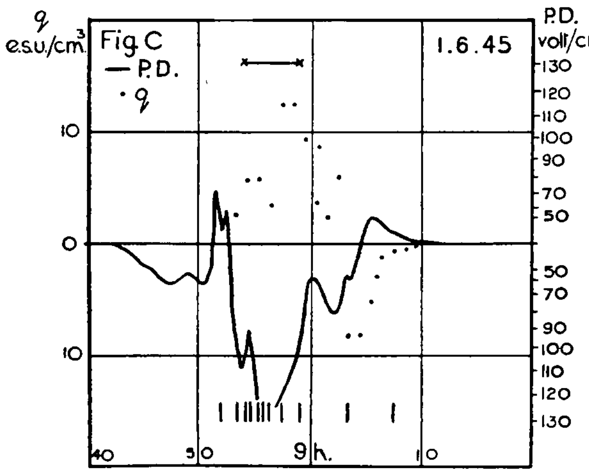


Fig. C
— P.D.
· q
1. 6. 45
q
e.s.u./cm.³
P.D.
volt/cm.
10
0
10
130
120
110
100
90
70
50
50
70
90
100
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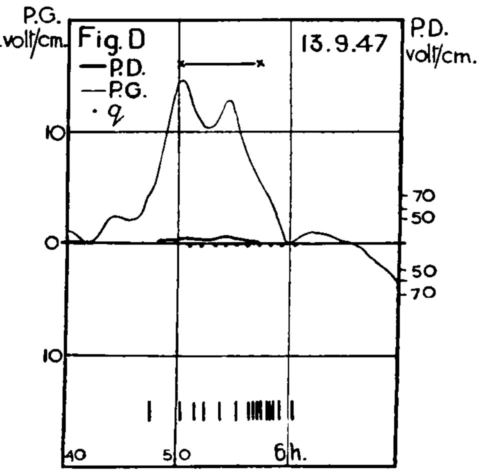
120
130
40
50
9h.
10


P.G.
volt/cm.
Fig. D
— P.D.
— P.G.
· q
13. 9. 47
P.D.
volt/cm.
10
0
10
70
50
50
70
40
50
6h.

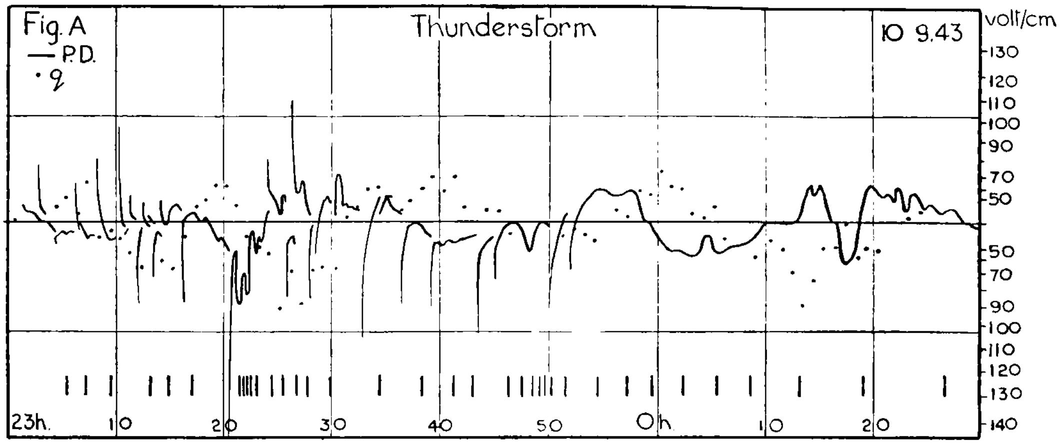


Fig. A
— P.D.
· q
Thunderstorm
10 9.43
volt/cm.
130
120
110
100
90
70
50
50
70
90
100
110
120
130
140
23h.
10
20
30
40
50
0h.
10
20

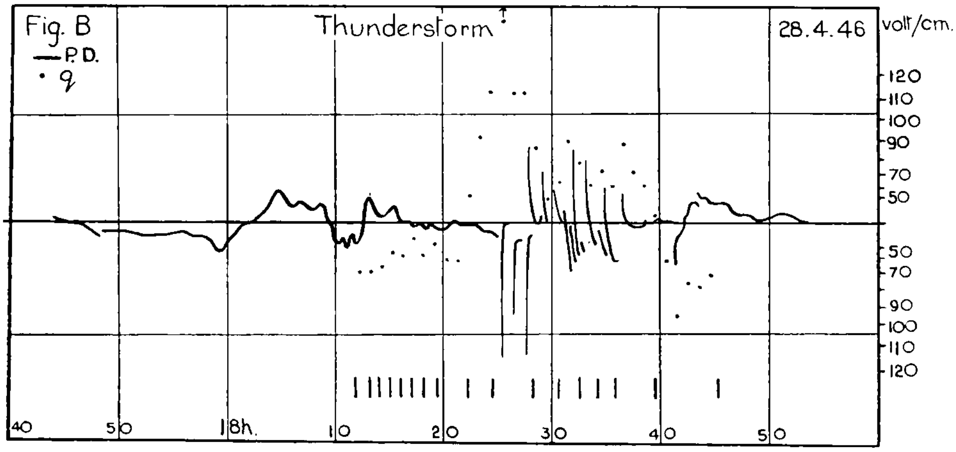
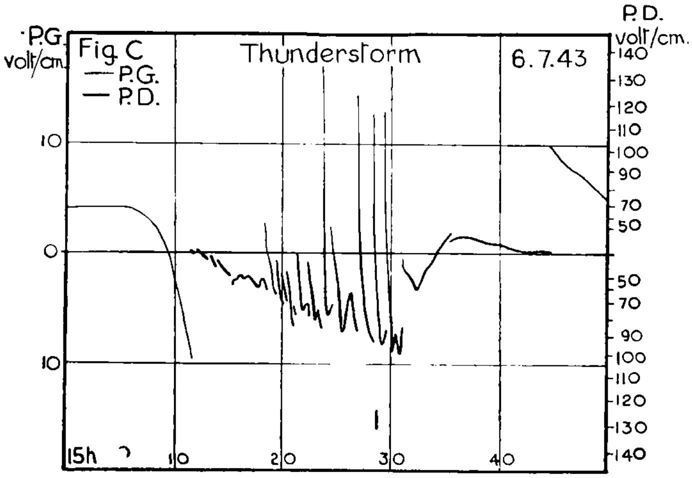
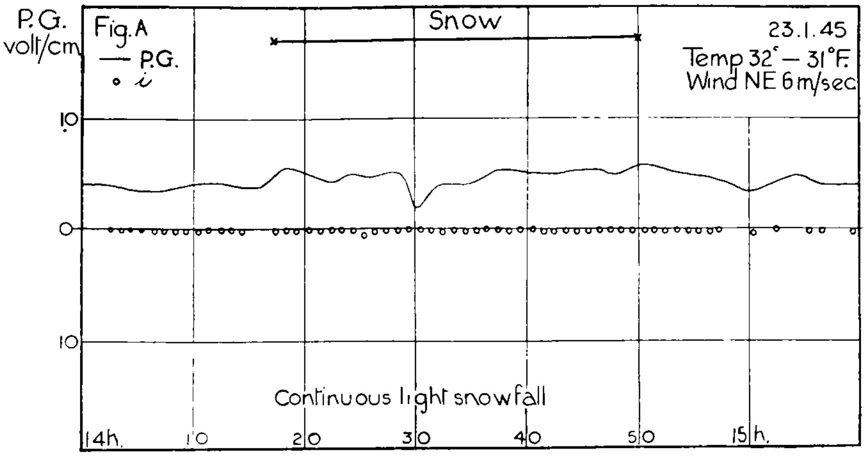
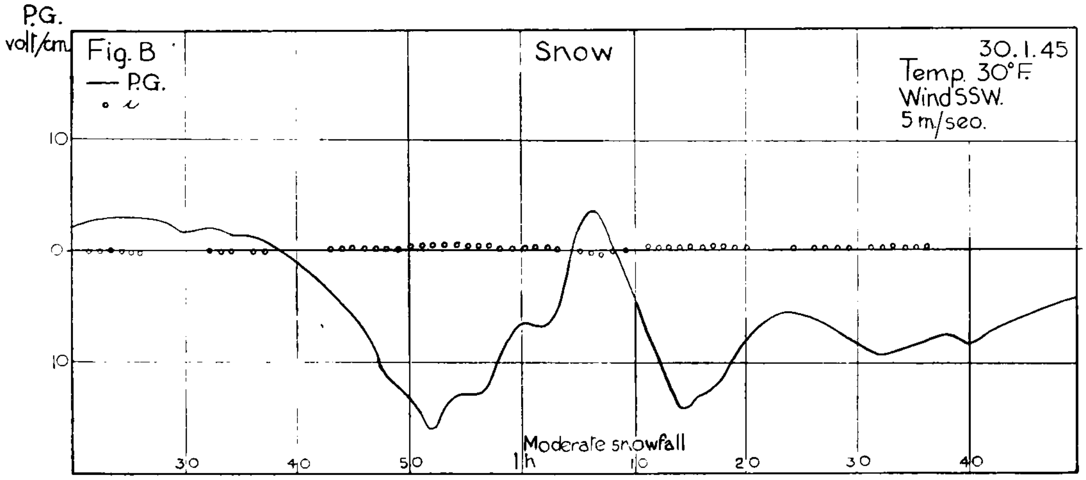


Fig. B
— P.D.
· q
Thunderstorm
28.4.46
volt/cm.
120
110
100
90
70
50
50
70
90
100
110
120
40
50
18h.
10
20
30
40
50


·P.G.
volt/cm.
Fig. C
— P.G.
— P.D.
Thunderstorm
6.7.43
P.D.
volt/cm.
140
130
120
110
100
90
70
50
50
70
90
100
110
120
130
140
10
0
10
15h
10
20
30
40


P.G.
volt/cm
Fig. A
— P.G.
∘ i
Snow
23.1.45
Temp 32° – 31°F.
Wind NE 6 m/sec
10
0
10
Continuous light snowfall
14h.
10
20
30
40
50
15h.


P.G.
volt/cm
Fig. B
— P.G.
∘ i
Snow
30.1.45
Temp. 30°F.
Wind SSW.
5 m/seo.
10
0
10
Moderate snowfall
30
40
50
1h
10
20
30
40

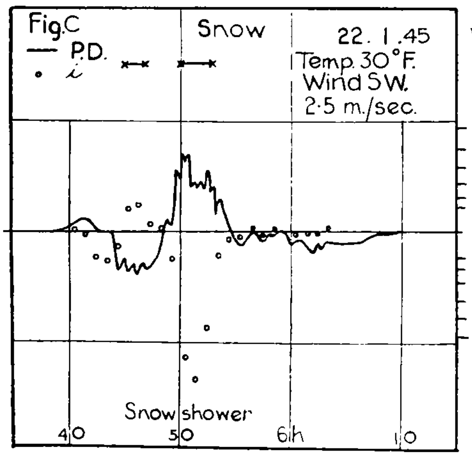
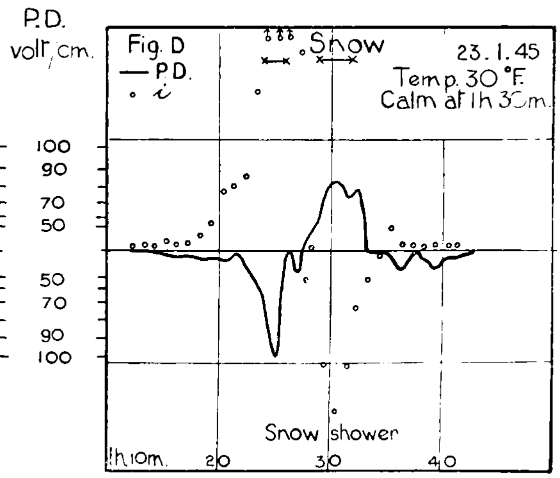


Fig. C
— P.D.
∘ i
Snow
22.1.45
Temp. 30°F.
Wind SW.
2·5 m./sec.
Snow shower
40
50
6h
10


P.D.
volt/cm.
100
90
70
50
50
70
90
100
Fig. D
— P.D.
∘ i
Snow
23.1.45
Temp. 30°F.
Calm at 1h 30m.
Snow shower
1h 10m.
20
30
40

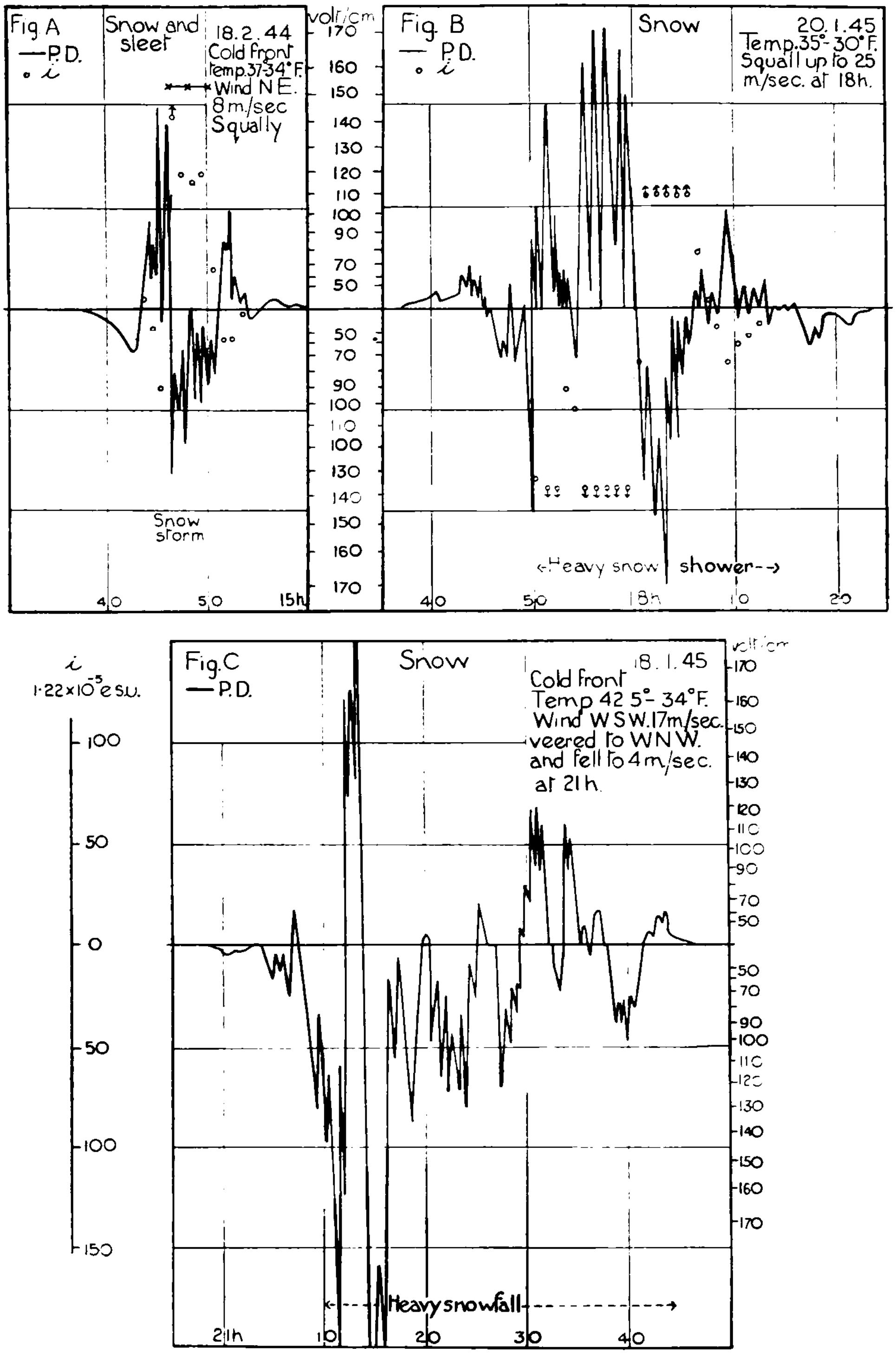
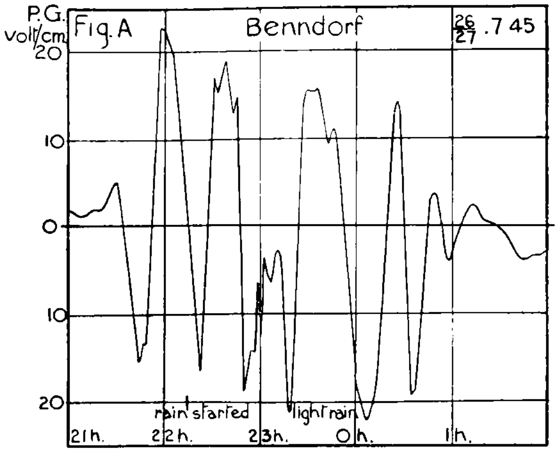
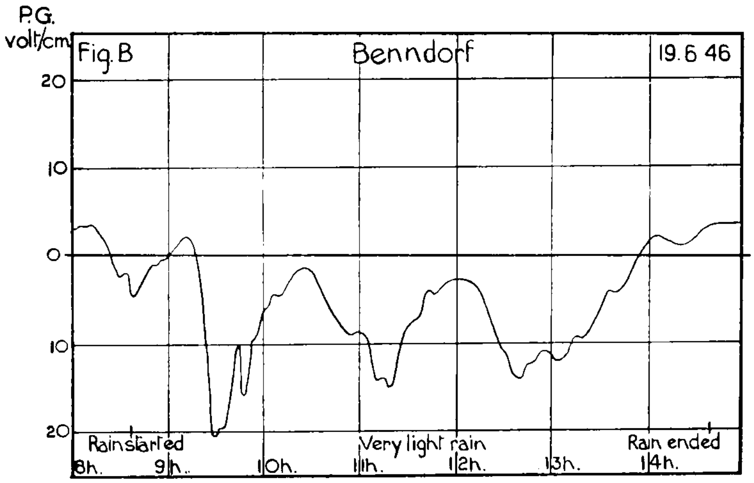


Fig A
— P.D.
∘ i
Snow and sleet
18.2.44
Cold front
Temp. 37-34° F.
Wind N E.
8 m/sec
Squally
Snow storm
40
50
15h
volt/cm
Fig. B
— P.D.
∘ i
Snow
20.1.45
Temp. 35°-30° F.
Squall up to 25 m/sec. at 18h.
←Heavy snow shower-→
40
50
18h
10
20
i
1·22×10⁻⁵ e.s.u.
100
50
0
50
100
150
Fig. C
— P.D.
Snow
18.1.45
Cold front
Temp 42.5°-34° F.
Wind W S W. 17m/sec. veered to W N W. and fell to 4 m/sec. at 21h.
←- - -Heavy snowfall- - - - - - - - - -→
21h
10
20
30
40
volt/cm


P.G.
volt/cm
Fig. A
Benndorf
26/27 .7 45
20
10
0
10
20
rain started
light rain
21 h.
22 h.
23 h.
0 h.
1 h.


P.G.
volt/cm
Fig. B
Benndorf
19.6 46
20
10
0
10
20
Rain started
Very light rain
Rain ended
8h.
9 h.
10h.
11h.
12h.
13h.
14h.

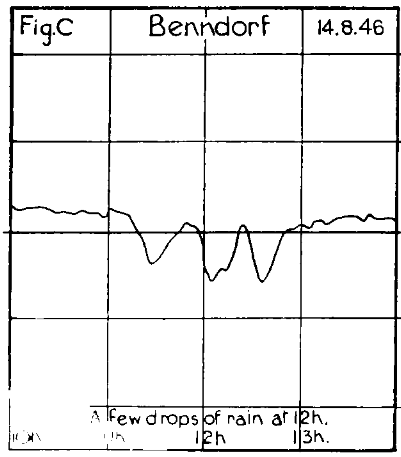


Fig. C
Benndorf
14.8.46
few drops of rain at 12h.
12h
13h.

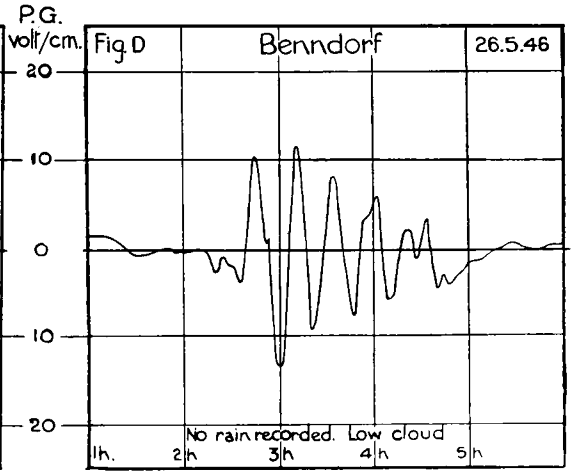

P.G.
volt/cm.
20
10
0
10
20
Fig. D
Benndorf
26.5.46
No rain recorded. Low cloud
1h.
2h
3h
4h
5h

Plate VIII

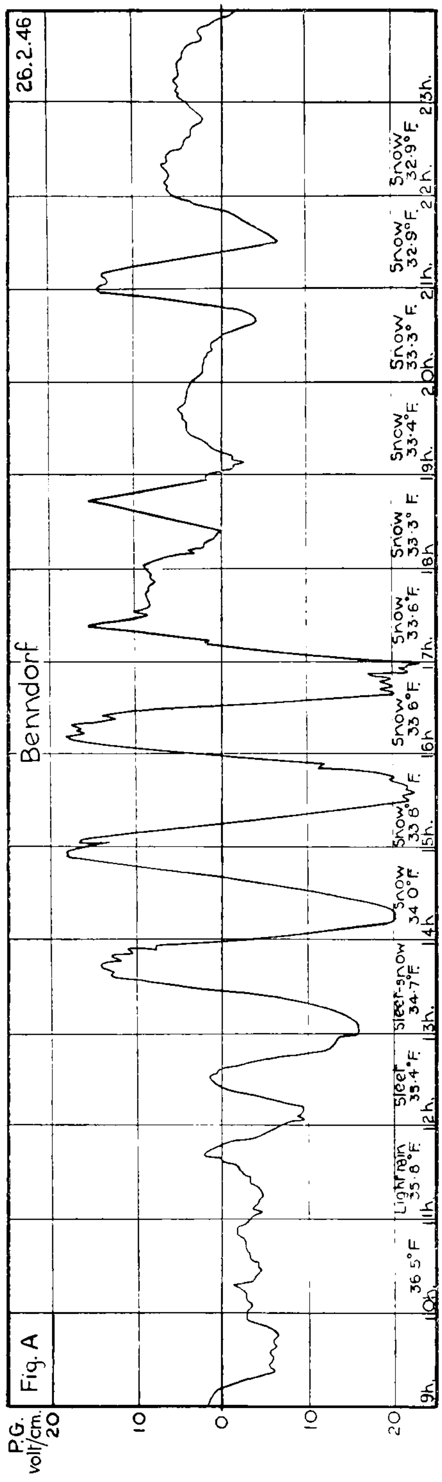


Fig. A
Benndorf
26.2.46
P.G. volt/cm.

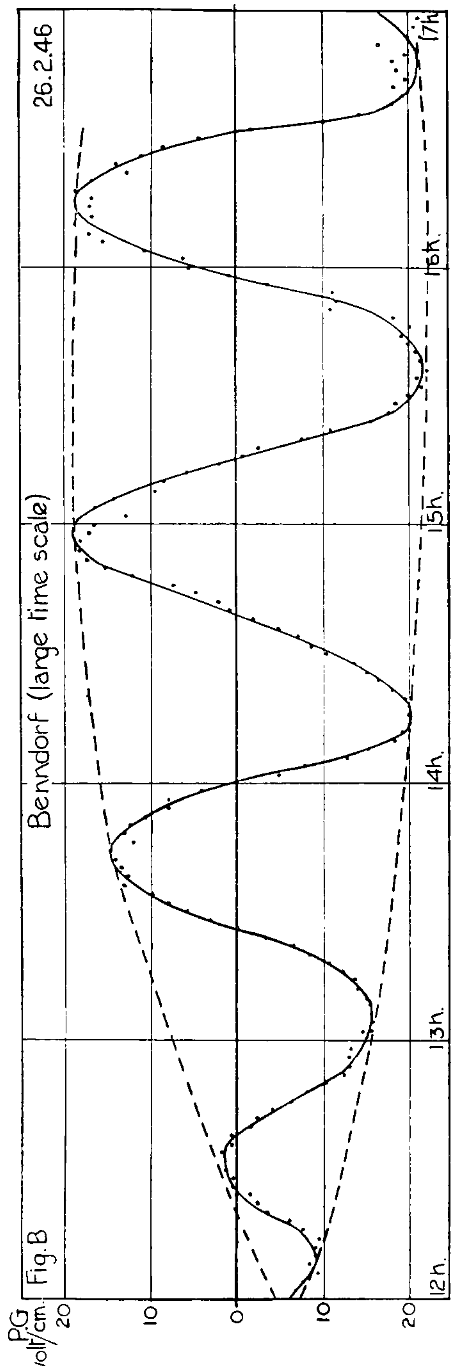
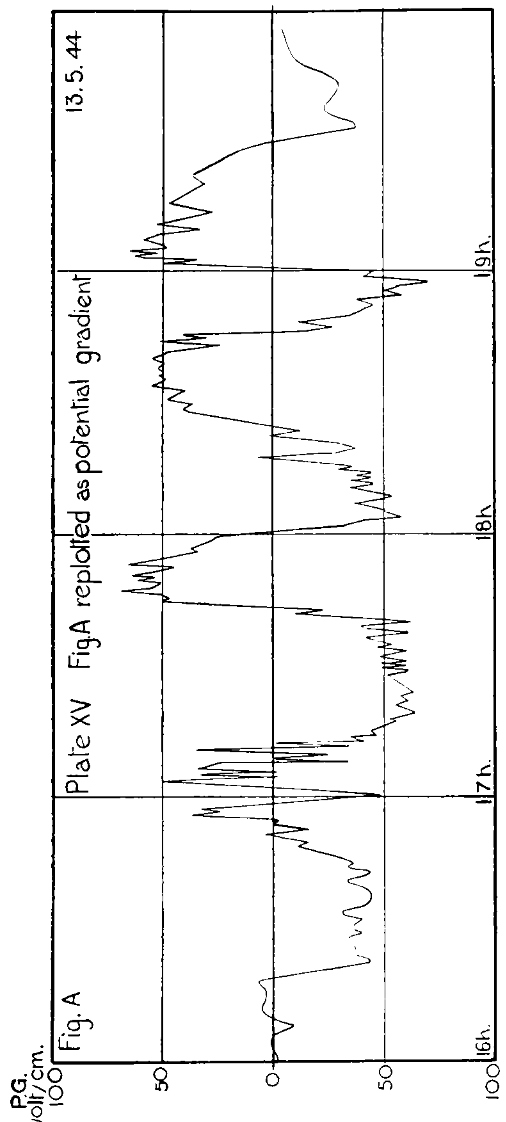
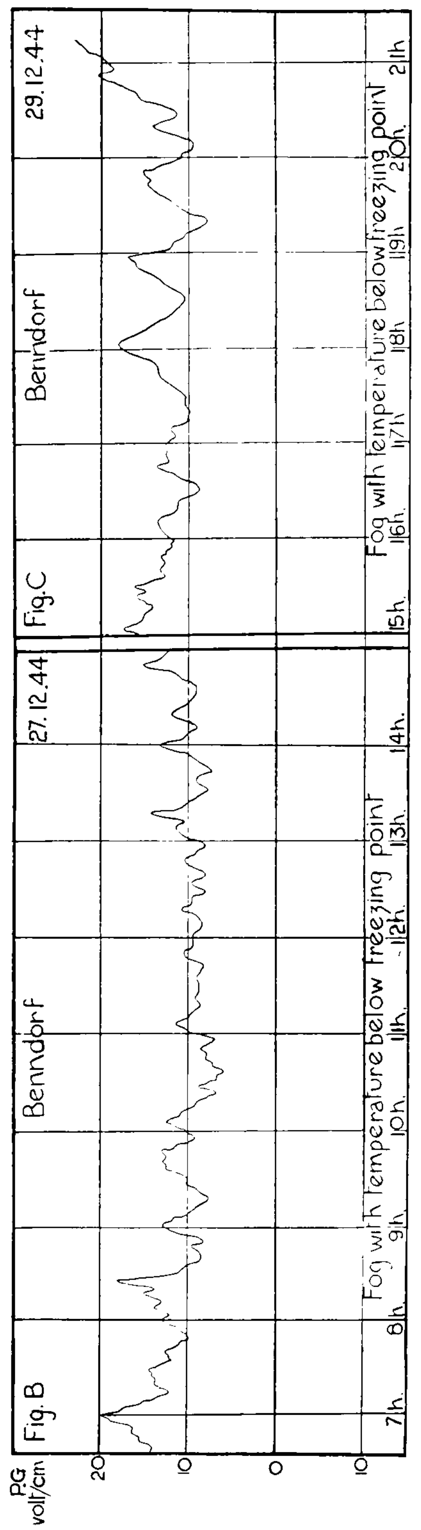
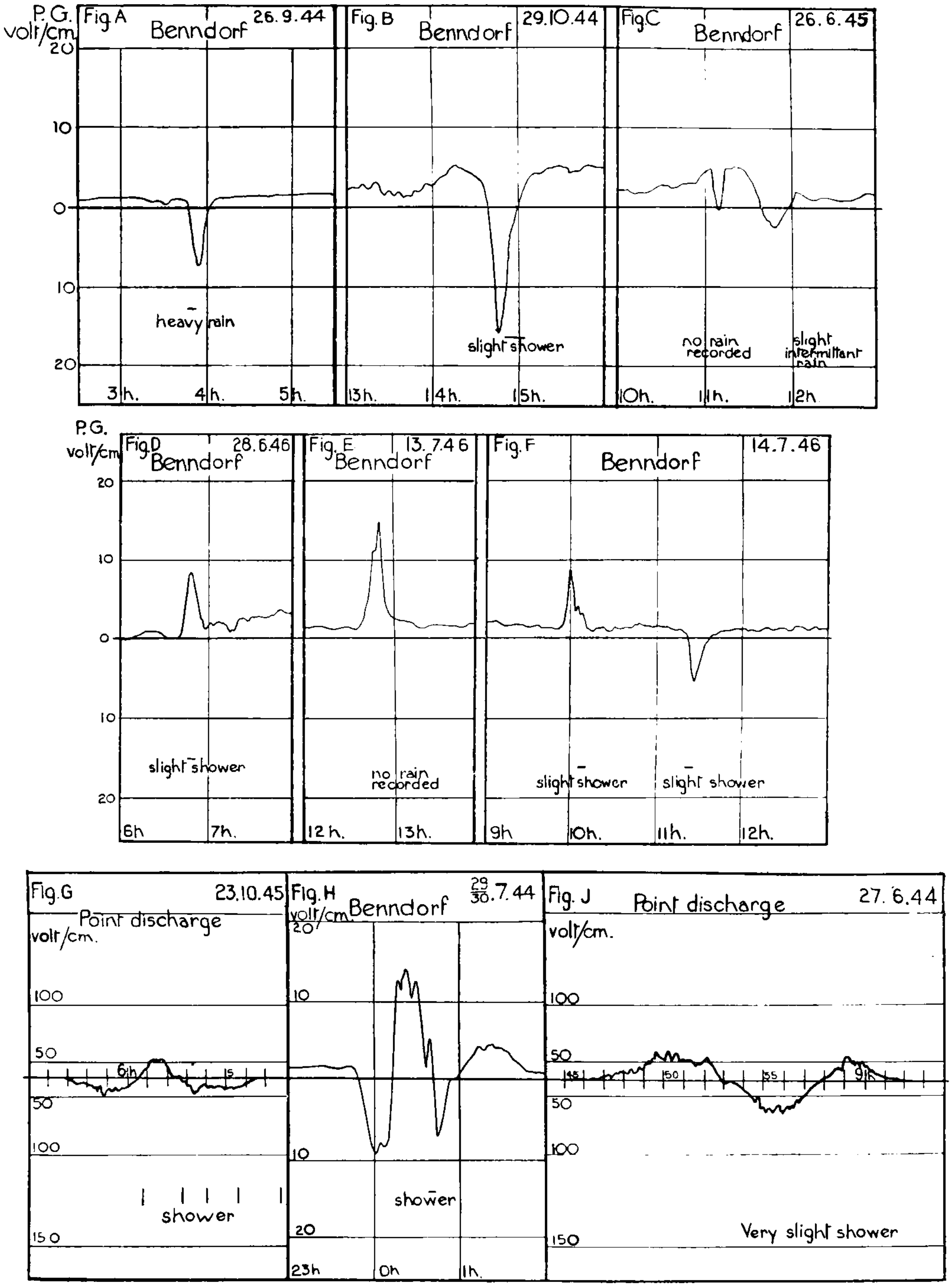


Fig. B
Benndorf (large time scale)
26.2.46
P.G volt/cm.


P.G. volt/cm.
100
50
0
50
100
Fig. A
13.5.44
Plate XV Fig.A replotted as potential gradient
16h.
17h.
18h.
19h.


P.G volt/cm
20
10
0
10
Fig. B
Benndorf
27.12.44
Fog with temperature below freezing point
7h.
8h.
9h.
10h.
11h.
12h.
13h.
14h.
Fig.C
Benndorf
29.12.44
Fog with temperature below freezing point
15h.
16h.
17h.
18h.
19h.
20h.
21h.


P.G. volt/cm
Fig. A
Benndorf
26.9.44
heavy rain
3h. 4h. 5h.
Fig. B
Benndorf
29.10.44
slight shower
13h. 14h. 15h.
Fig. C
Benndorf
26.6.45
no rain recorded
slight intermittant rain
10h. 11h. 12h.
20 10 0 10 20
Fig. D
Benndorf
28.6.46
slight shower
6h 7h.
Fig. E
Benndorf
13.7.46
no rain recorded
12h. 13h.
Fig. F
Benndorf
14.7.46
slight shower
slight shower
9h 10h. 11h. 12h.
Fig. G
23.10.45
Point discharge
volt/cm.
100 50 50 100 150
6h 15
shower
Fig. H
29/30.7.44
volt/cm
Benndorf
20 10 10 20
shower
23h 0h 1h.
Fig. J
Point discharge
27.6.44
volt/cm.
100 50 50 100 150
45 50 55 9h
Very slight shower

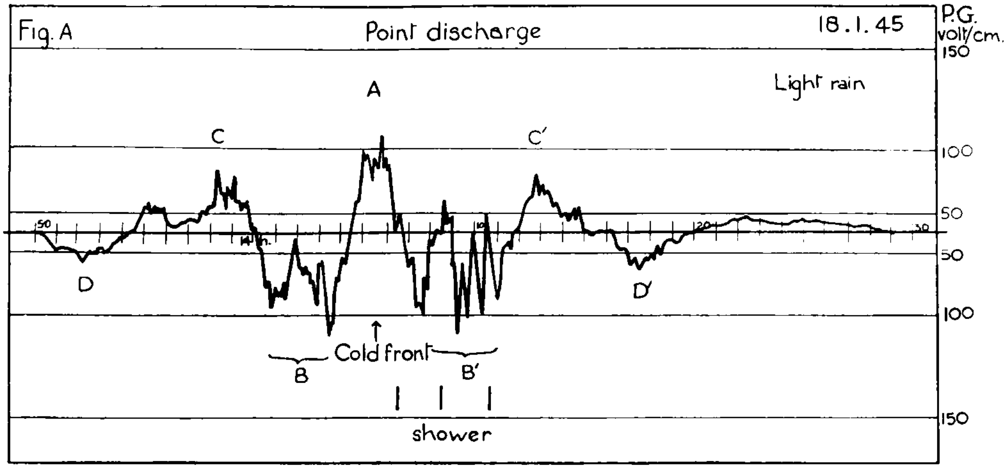


Fig. A
Point discharge
18.1.45
P.G. volt/cm.
Light rain
A
C
C′
D
D′
Cold front
B
B′
shower
150
100
50
50
100
150
14 h.

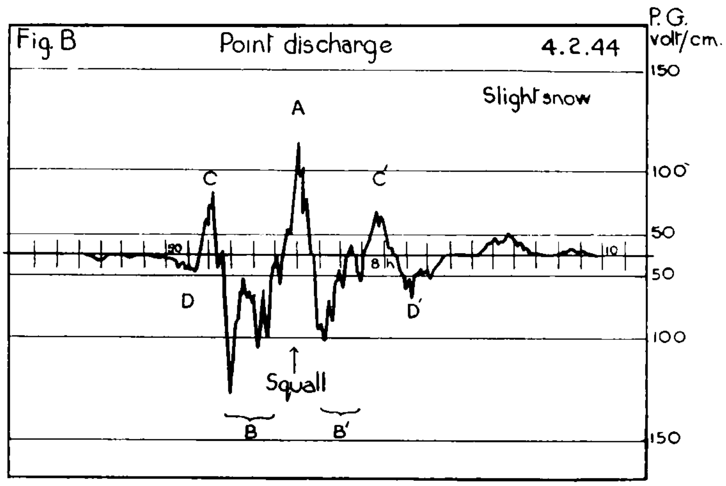


Fig. B
Point discharge
4.2.44
P.G. volt/cm.
Slight snow
A
C
C′
D
D′
Squall
B
B′
150
100
50
50
100
150
8 h.

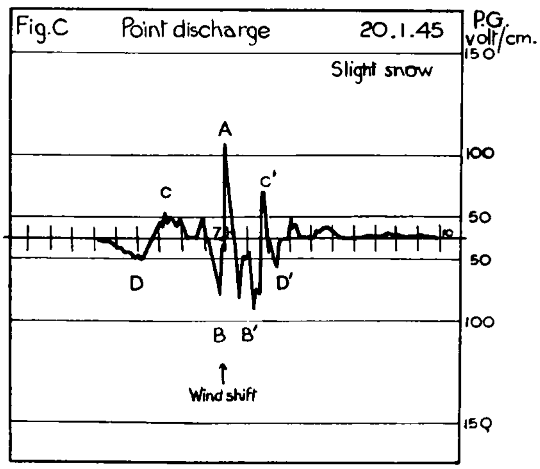


Fig. C
Point discharge
20.1.45
P.G. volt/cm.
Slight snow
A
C
C′
D
D′
B B′
Wind shift
150
100
50
50
100
150

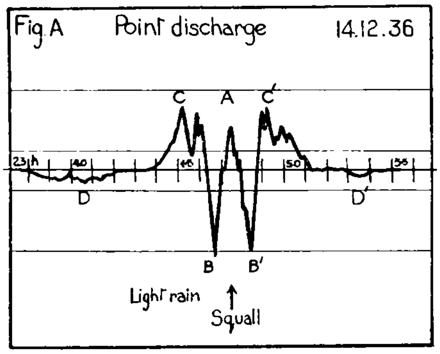


Fig. A
Point discharge
14.12.36
C A C′
D D′
B B′
Light rain
Squall

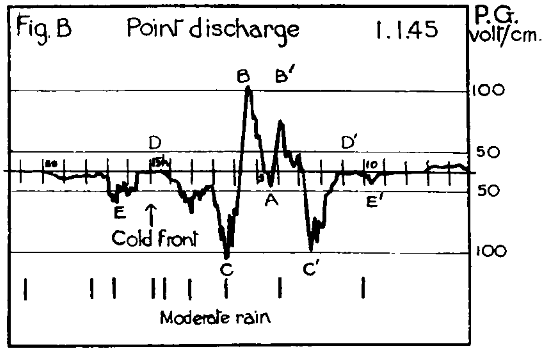


Fig. B
Point discharge
1.1.45
P.G. volt/cm.
100
50
50
100
B B′
D D′
E A E′
Cold front
C C′
Moderate rain

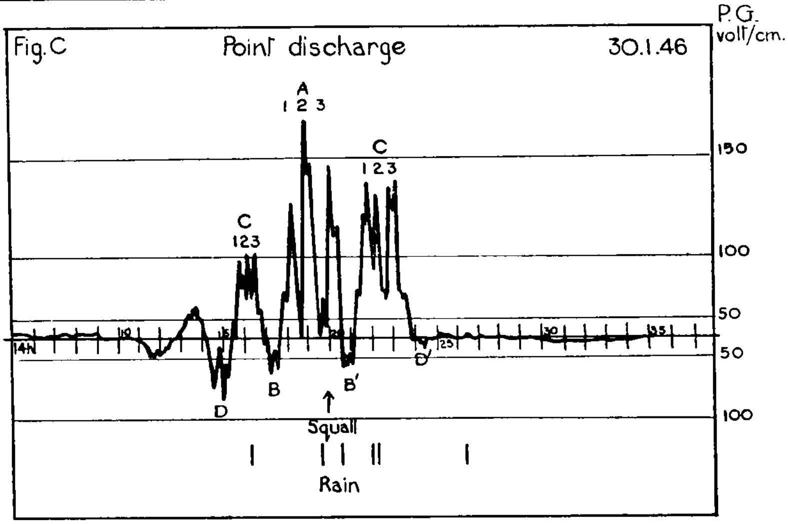


Fig. C
Point discharge
30.1.46
P.G. volt/cm.
150
100
50
50
100
A 1 2 3
C 1 2 3
C 123
D B B′ D′
Squall
Rain

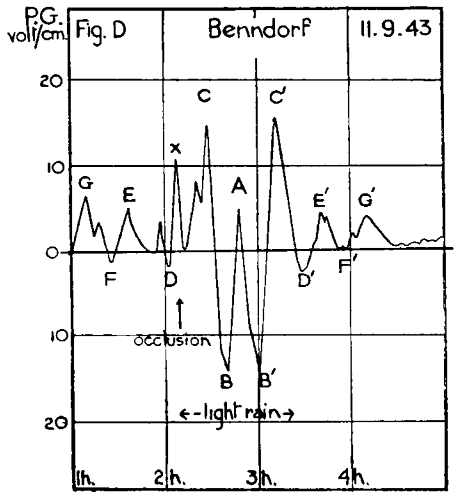
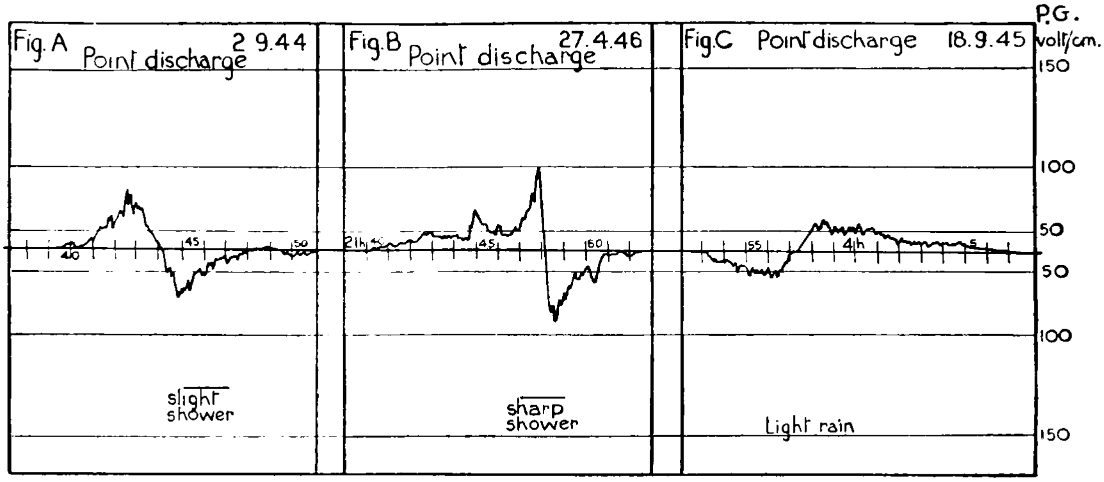
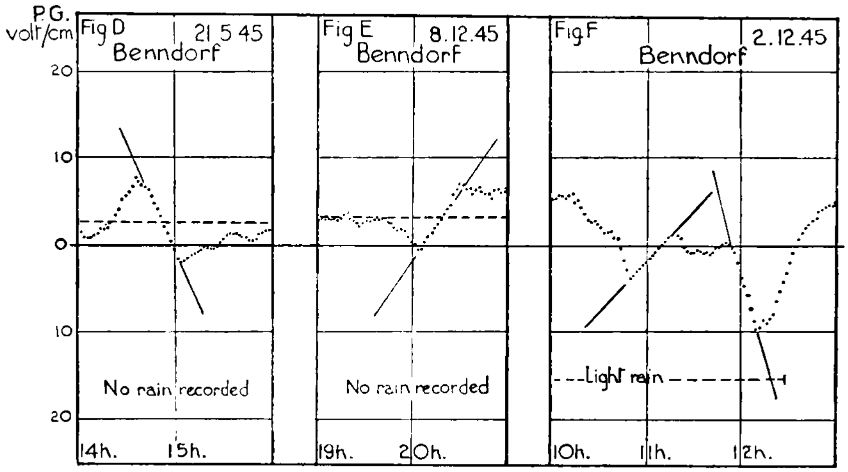


Fig. D
Benndorf
11.9.43
P.G. volt/cm.
20
10
0
10
20
C C′
x
G E A E′ G′
F D D′ F′
occlusion
B B′
←-light rain→
1h. 2h. 3h. 4h.


P.G. volt/cm.
Fig. A Point discharge 2.9.44
slight shower
Fig. B Point discharge 27.4.46
sharp shower
Fig. C Point discharge 18.9.45
Light rain
150
100
50
50
100
150


P.G. volt/cm
Fig D Benndorf 21.5.45
No rain recorded
14h. 15h.
Fig E Benndorf 8.12.45
No rain recorded
19h. 20h.
Fig F Benndorf 2.12.45
Light rain
10h. 11h. 12h.
20
10
0
10
20

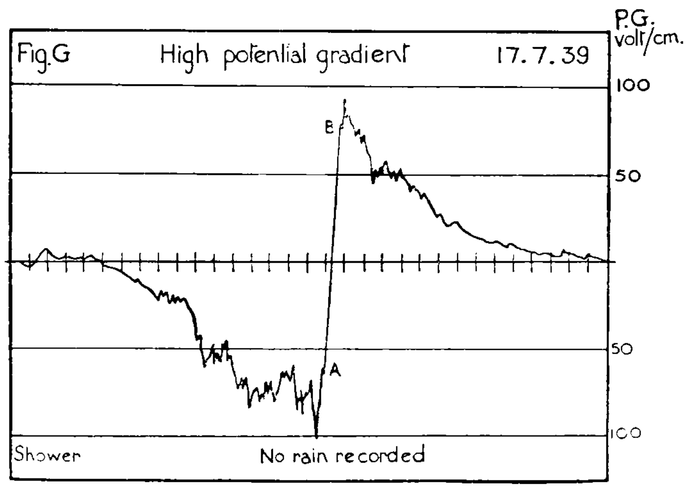
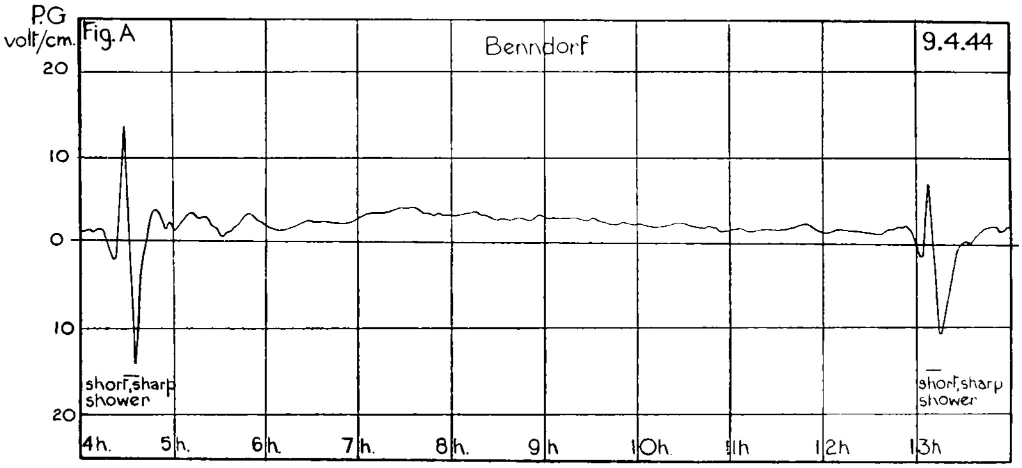


Fig. G High potential gradient 17.7.39
P.G. volt/cm.
Shower
No rain recorded
B
A
100
50
50
100


P.G
volt/cm.
Fig. A
Benndorf
9.4.44
20
10
0
10
20
short, sharp
shower
short, sharp
shower
4h.
5h.
6h.
7h.
8h.
9h
10h.
11h
12h
13h

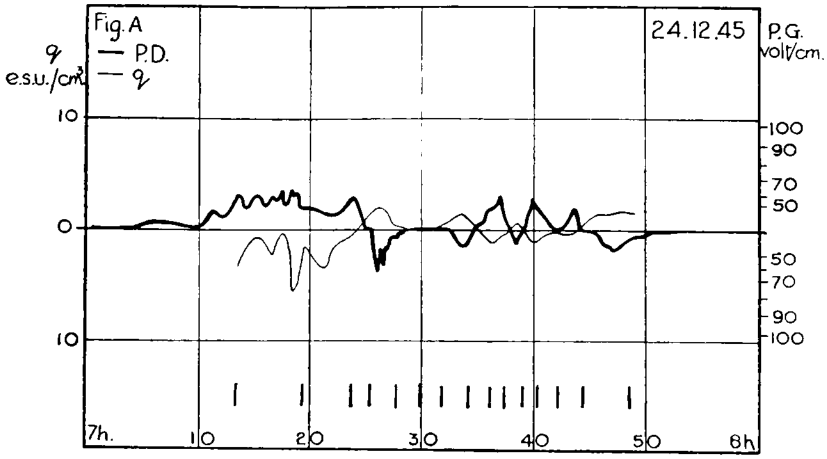


Fig. A
— P.D.
— q
q
e.s.u./cm³
24.12.45
P.G.
volt/cm.
10
0
10
100
90
70
50
50
70
90
100
7h.
10
20
30
40
50
8h

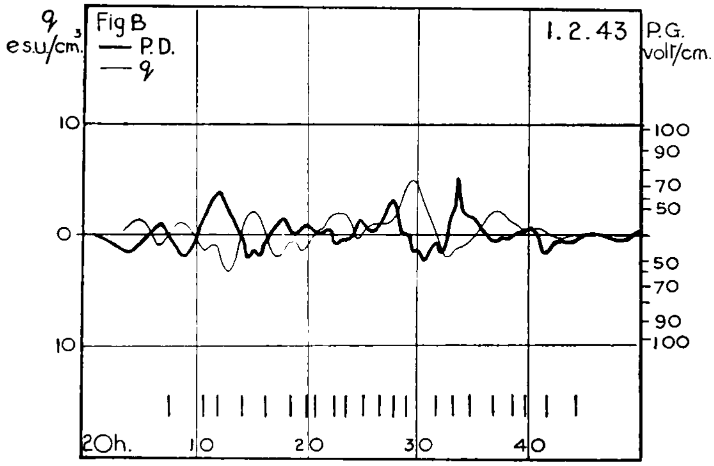


Fig B
— P.D.
— q
q
e.s.u./cm³
1. 2. 43
P.G.
volt/cm.
10
0
10
100
90
70
50
50
70
90
100
20h.
10
20
30
40

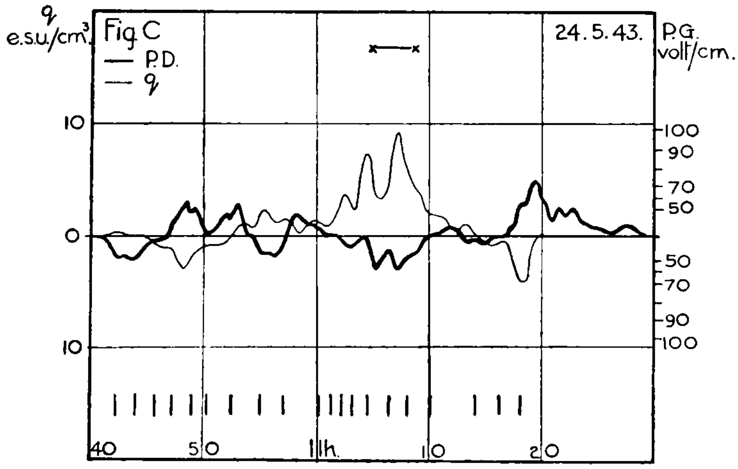


Fig C
— P.D.
— q
q
e.s.u./cm³
24. 5. 43.
P.G.
volt/cm.
10
0
10
100
90
70
50
50
70
90
100
40
50
11h.
10
20

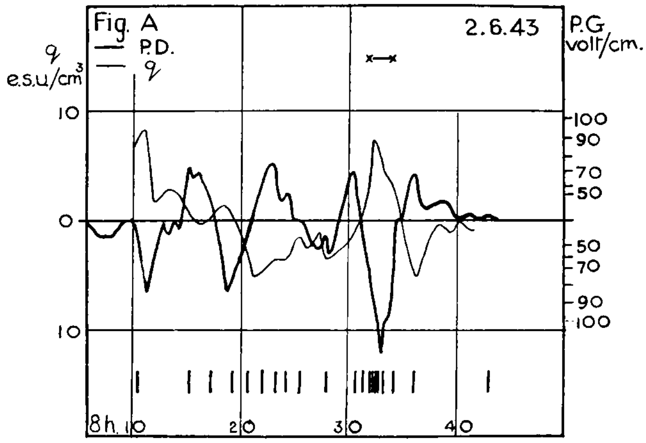


Fig. A
P.D.
q
2.6.43
q
e.s.u/cm³
P.G
volt/cm.
10
0
10
100
90
70
50
50
70
90
100
8h. 10
20
30
40

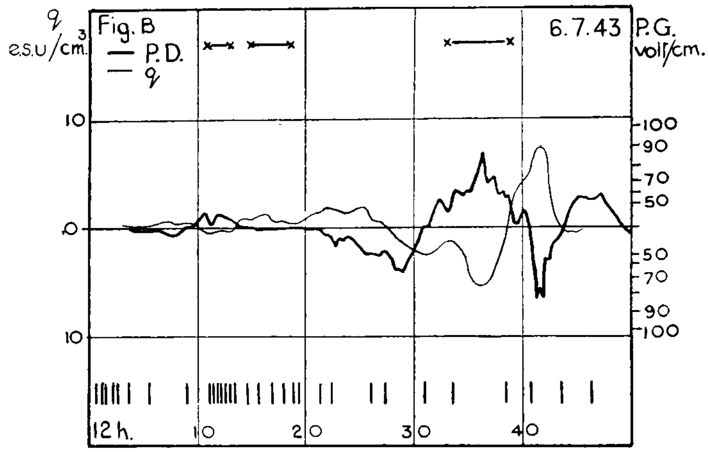


Fig. B
P.D.
q
6.7.43
q
e.s.u/cm³
P.G.
volt/cm.
10
0
10
100
90
70
50
50
70
90
100
12 h.
10
20
30
40

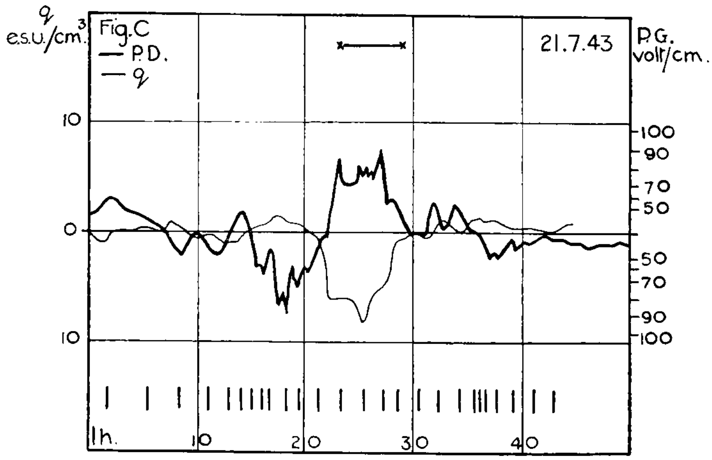


Fig. C
P.D.
q
21.7.43
q
e.s.u./cm³
P.G.
volt/cm.
10
0
10
100
90
70
50
50
70
90
100
1h.
10
20
30
40

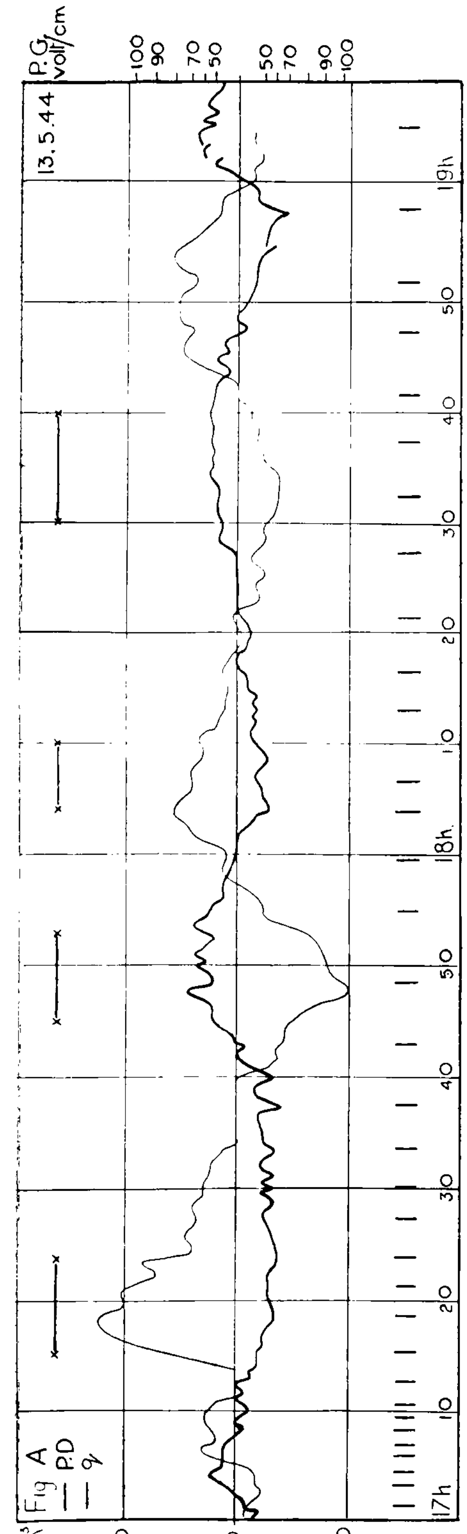


Fig A
P.D
q
13.5.44
P.G. volt/cm
17h
18h
19h

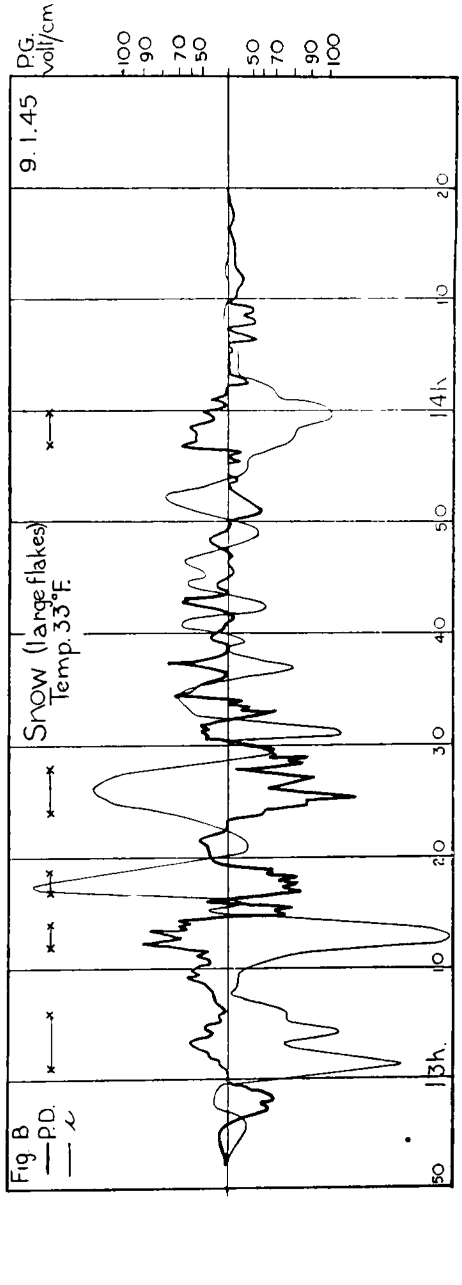
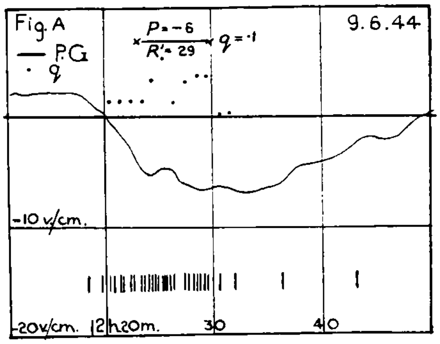
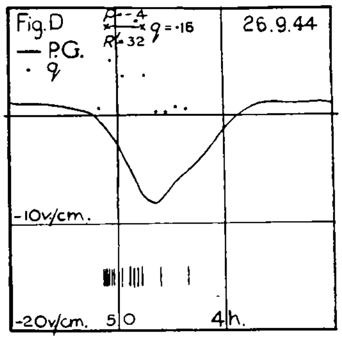
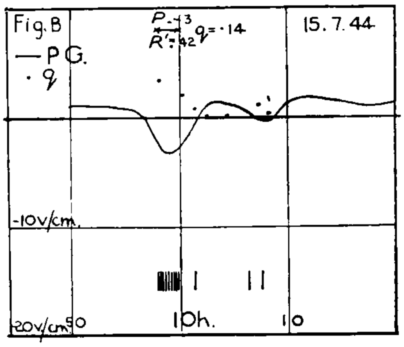
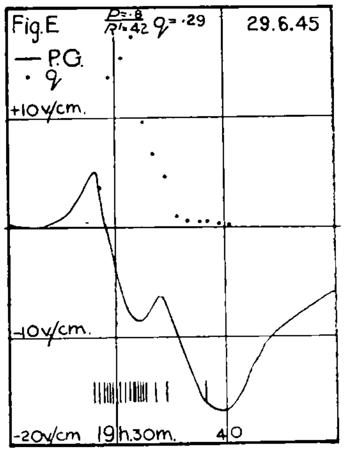


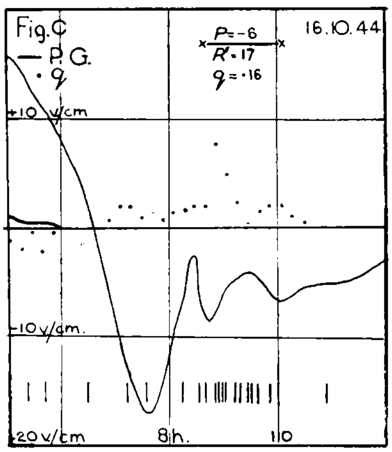
Fig. B
P.D.
λ
9.1.45
P.G. volt/cm
Snow (large flakes)
Temp. 33°F.
13h.
14h

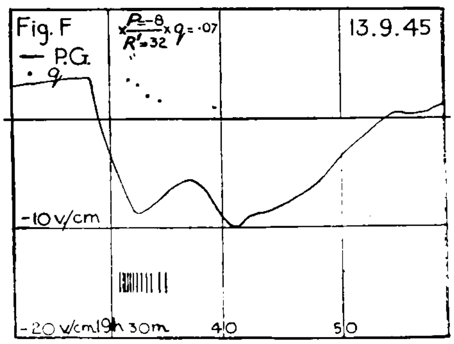












(S0508) Wt. 3622/M.1061 5/49 Hw.

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