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ELECTRICITY ON RAIN

A discussion of records obtained at Kew Observatory, 1935-6

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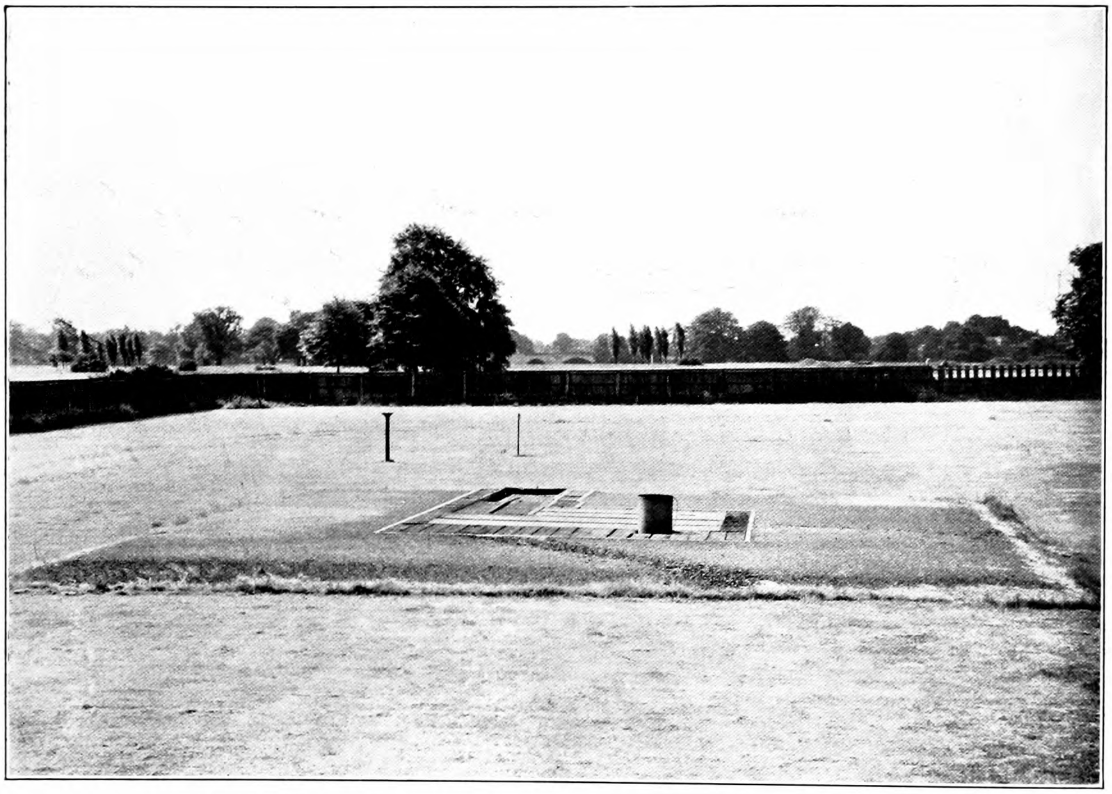


Fig. 2.—The underground laboratory with rain receiver in position.

ELECTRICITY ON RAIN

A discussion of records obtained at Kew Observatory, 1935-6

§ 1—INTRODUCTION

In comparatively few of the investigations on the electricity of precipitation have the measurements been made continuously over long periods. Most workers have preferred to confine their attention to eye-observations made spasmodically on suitable occasions. Such a procedure has the advantage that a close watch can be kept on conditions at the times of the observations. But it has the disadvantage that the samples of rain investigated may be very unrepresentative of the total rainfall at the place of observation and any estimates of the total amount of electricity brought down by rain in, say, a year, would be subject to large errors of sampling. The alternative procedure of providing continuous automatic registration is liable to be more expensive but it offers better chances of obtaining representative sampling. Even with recording apparatus, however, sampling may still be far from perfect for breakdowns are bound to occur (especially through insulation leaks) and important occasions may be missed ; as will be seen later the loss of a few days', or even a few hours', records may seriously affect the average and total values for a year's precipitation. If such losses can be reduced to small proportions then continuous recording over a reasonably long period may be expected to yield reliable averages.

The most notable investigations, by means of continuous records, of the electricity on precipitation are those of Simpson (1),* whose records covered two monsoon seasons in Simla in 1908 and 1909, and Schindelhauer (2), whose investigations at Potsdam extended over the three years 1909–11. Their results are probably the most complete that are available at the present time and may be regarded as well-representative of the conditions at the places where they were obtained.

As part of a scheme, initiated by Dr. F. J. W. Whipple, for obtaining continuous records of all of the more important factors in atmospheric electricity, apparatus for registering automatically the electric charge brought down by rain was installed at Kew Observatory towards the end of 1934. Two years' records have now been obtained and the purpose of this paper is to present the results of an analysis of these records and to discuss some of the more important features of the electricity on rain.

§ 2—THE APPARATUS

The three main parts in the assembly of the apparatus are the rain-receiver, the electrometer with its recording drum, and the gauge for measuring the amount of rain. After the apparatus had been in use about 16 months, some slight modifications were made ; these will be mentioned in due course but otherwise the description which follows refers to the apparatus in its present form.

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

* The numbers in brackets refer to the bibliography on p. 20.

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 (frontispiece). A 15 watt lamp fitted near the stand A helps to keep the insulation of the receiver satisfactory.

A Dolezalek electrometer is used for measuring the charge caught by the insulated funnel. By decreasing the size of the needle and fitting an abnormally

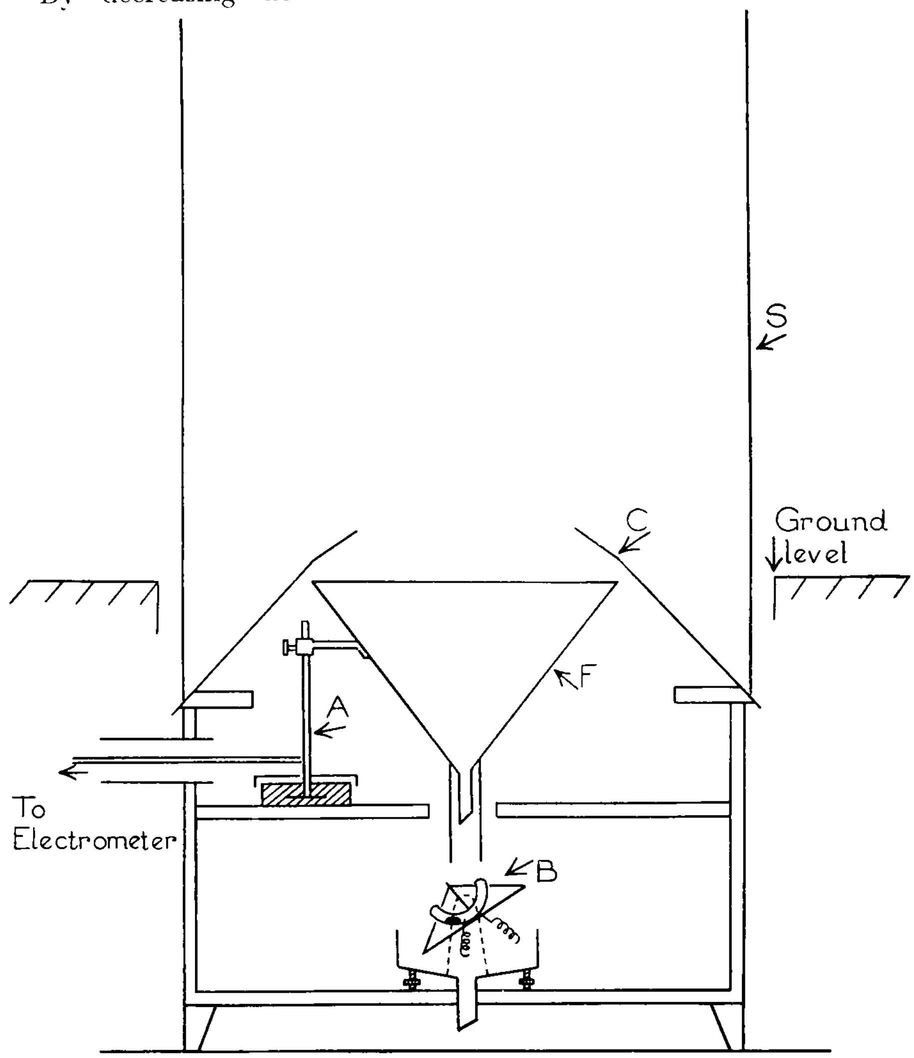


FIG. 1.—THE RAIN RECEIVER AND TILTING BUCKET.

stout suspension the period of the instrument, when undamped, was reduced to about one second. A small oil damper of the vane and dash-pot type is fitted below the needle, making the electrometer practically aperiodic (the oil vessel is mounted on a sulphur base). With 6 volts on each quadrant the sensitivity of the instrument is 0·21 mm./volt or 0·79 mm./e.s.u. of charge, the capacity of the apparatus being 80 cm. 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 bucket in use at first was arranged to tilt for every 1·15 $cm.^3$ of rain falling into it but when the rate of fall exceeded a certain value the volume necessary for tilting increased suddenly (to about 1·55 cm.^{3}) owing to the fact that the water was unable to drain away completely between the tilts. This trouble was avoided when the gauge at present in use was installed; this gauge, which is larger than the earlier one, tilts for 3 cm.^{3} of water; rapid emptying of the buckets is ensured by fitting them with V-shaped spouts, split along the angle of the V, and allowing the spouts to tilt on to a piece of porous porcelain. The gauge carries an enclosed mercury switch which, at each tilt, turns on the same light spot* that 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 cylindrical shield is high enough to stop splashes from the surrounding ground from entering the gauge; very few splashes from the surface of the conical shield or from the inside surface of the cylinder are likely to fall into the funnel. A small proportion of drops may hit the edge of the cone but since this is efficiently screened from the earth's field these drops will carry no large charges into the funnel. The only serious source of error of this kind is the risk of drops bouncing into the funnel from the edge of the outer cylinder which may carry a high induced charge, but the proportion of drops which do this must be very small.

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.

One further point which should be mentioned is that if the rate of rainfall were extremely heavy the water would drain from the funnel into the tilting bucket in a continuous stream and the funnel would remain earthed so long as this was happening. Some tests showed that for this to occur the rate of fall into the gauge would have to exceed 150 mm./hour; it is rarely that the rate of rainfall at Kew exceeds this figure. A Jardi rain-gauge (3), which is designed to provide a continuous record of the rate of rainfall, showed that during the two years under review, 1935–6, the rate exceeded 100 mm./hr. on five occasions and it exceeded 150 mm./hr. on one occasion (during a thunderstorm on September 5, 1936). The maximum rate of fall in this latter case is not known since the range of registration of the Jardi gauge at Kew does not exceed 150 mm./hr. Apparently the high rate only lasted a few seconds for the highest fall in one minute was only 1·2 mm. This figure was recorded by a "minute by minute" rain-gauge designed by F. J. W. Whipple (4) and it is worth mentioning that the highest rainfall in one minute which has been recorded by this gauge since 1931, is 5 mm.; it occurred on July 18, 1934.

§ 3—MEASUREMENT OF THE RECORDS

Some examples of records obtained in various types of rain are reproduced in Figs. 4 to 7. These examples will be discussed in some detail later in the paper; for the present we may note that when no rain is being caught the record consists of a series of straight lines with time marks at the hours and that when charged rain is entering the funnel the trace deflects up or down the sheet according to whether the rain is charged positively or negatively. The deflection continues until sufficient rain has fallen to tilt the bucket, when the trace momentarily returns to the zero position and at the same time a mark is recorded just below the trace. From a measurement of the extent of the deflection just before earthing occurs the amount of charge brought down by a known volume of rain (equal to the capacity of the bucket) is derived. When uncharged rain is entering the funnel the electrometer trace shows no discontinuities but the marks made by the tilting of the bucket show how much rain is being caught; the heavier the rain the closer together are these marks.

* The mercury switch causes a momentary contact which is too short to give sufficient exposure of the light spot on the record, so a delayed-action relay is interposed allowing the light to remain on for 2 seconds.

In tabulating the records the time at which each tilt of the bucket occurred is noted—normally to the nearest minute but to the nearest tenth of a minute when the intervals between tilts are less than one minute. The deflection on the record immediately before each tilt is measured to the nearest 0·1 mm. ; this gives the charge caught to the nearest 0·1 e.s.u. and the charge per cubic centimetre of rain is obtained by dividing by the capacity of the bucket, 3 cm.³. Thus the charge per cubic centimetre is obtained to within about 0·05 e.s.u. When the deflection is less than 0·1 mm. the charge is entered as zero. In addition to the measurements for each bucket-full of rain the total number of cubic centimetres of positive, negative and uncharged rain and the total charges, positive and negative, caught in the intervals of two hours, 0–2, 2–4, etc., are tabulated.

Since the diameter of the opening of the cone over the funnel is 16 cm. one cubic centimetre of rain caught in the gauge is equivalent to 0·05 mm. of rainfall (or one bucket-full to 0·15 mm. of rainfall) provided that a fair sample enters the gauge ; owing, however, to the screening effect of the outer cylinder this is not usually the case and on the average the rainfall caught by the gauge is roughly half that given by a meteorological rain-gauge exposed in the normal way on an open site.

§ 4—THE RESULTS OF THE OBSERVATIONS *

(*a*) *Annual Values*.—A summary of the totals and averages for the two years' records is given in Table I. The total rainfall in each year was roughly the same but owing to losses of record about 50 per cent of the fall in 1935 was missed and 20 per cent of the fall in 1936. The actual volume of rain investigated was much greater in 1936 not merely because the losses of record were less frequent, but also because the diameter of the receiver-opening was increased in the early part of the year from 12·7 cm. to 16 cm. As already mentioned the rainfall caught in the electrical receiver is usually less than that caught in a well-exposed meteorological gauge owing to the screening effect of the outer cylinder ; the ratio varies with the strength of the wind, but on the average the electrical gauge catches half the standard amount of rain.

In Table I the totals and averages for the two years together are included, but the data for 1936 are much more representative of a complete year's rain than the data for 1935 since the losses of record were much less frequent in the second year. The amounts of rain with positive charge, negative charge and no measurable charge are in roughly the same proportions in both years ; nearly 30 per cent of the rain had no measurable charge and the amount of positively charged rain was three times the amount of negatively charged rain. Of the total quantities of electricity recorded positive was in excess in 1936 and negative in 1935. This difference is

TABLE I

	1935	1936	1935–6	Units used.
Total rainfall in 8-inch meteorological gauge	652	603	1255	mm.
Rainfall investigated	310	476	786	mm.
Volume of rain collected	1972	4382	6354	cm.³
Volume of rain with no measureable charge	479	1367	1846	cm.³
Volume of rain with positive charge	1117	2322	3439	cm.³
Volume of rain with negative charge	376	693	1069	cm.³
Ratio of volume with positive charge to volume with negative charge	3·0	3·3	3·2	
Total positive charge collected	620	1592	2212	e.s.u.
Total negative charge collected	885	1122	2007	e.s.u.
Ratio of positive to negative charge	0·70	1·42	1·10	
Average positive charge per cm.³	0·56	0·69	0·64	e.s.u.
Average negative charge per cm.³	2·36	1·61	1·87	e.s.u.
Estimated total quantity of positive electricity carried by rain to each cm.² of surface	21·5	22·4	43·9	e.s.u.
Estimated total quantity of negative electricity carried by rain to each cm.² of surface	28·1	15·3	43·4	e.s.u.

NOTE.—1 Coulomb $=3\times10^{9}$ e.s.u. ; electronic charge $=4\cdot8\times10^{-10}$ e.s.u.

* It should be borne in mind that the observations refer to the charges on unit quantities of rain and not to the charges on individual drops.

probably due to the fact that heavy thunderstorms were more frequent in 1936 and to the fact that during some of the storms of 1935 records were lost owing to insulation failures. In both years the negatively charged rain was much more highly charged on the average.

Since the screening of the apparatus prevents the receiver from catching as much rain as an equal area of open surface and since the proportion caught by the receiver depends on the wind strength, it is not possible to obtain direct measurements of the charge per unit area carried to earth by the rain. It is thought, however, that a fairly reliable estimate of this can be obtained by multiplying the apparent charge per unit area (*i.e.*, the charge actually measured divided by the area of the opening of the receiver-cone) by the ratio of the rainfall measured in the standard meteorological gauge to that recorded by the electrical gauge. This method of adjustment has been applied to each of the two-hourly totals for the three seasons, the appropriate factor in each case being dependent on the efficiency of the sampling. The annual totals of the estimates obtained in this way are included in Table I. It will be seen that the amounts of positive electricity conveyed to unit area were practically the same in each year, but the amounts of negative electricity differed considerably. From records extending over two rainy seasons at Simla in 1908-9, with a total rainfall of 1721 mm., Simpson (1) found the total quantity of positive electricity which fell on each square centimetre of surface to be 44·0 e.s.u., *i.e.*, almost exactly the same as the estimated amount for the two years at Kew, but the corresponding quantity of negative electricity at Simla was 13·8 e.s.u., which is about the same as the amount for the second year at Kew and considerably less than that for the first year. It is concluded that large negative charges are more prevalent at Kew than at Simla ; as will be seen later, it is in showers rather than in thunderstorm or continuous rain that those large negative charges usually occur.

Schindelhauer's (2) measurements at Potsdam for the three years 1909–11, for which the total rainfall was 1719 mm., gave 17·10 e.s.u./cm.^{2} for positively charged rain and 12·17 e.s.u./cm.^{2} for negatively charged rain. These values are totals for the whole period, but they do not include occasions when the deflection of the electrometer needle exceeded the range of registration ; this may account for their being considerably lower than the totals for two years at Kew. Schindelhauer points out that on the occasions when the range of registration was exceeded the charge was more frequently negative than positive.

Some of the results obtained by other investigators are included in Table II ; they show that positively charged rain is roughly three times as frequent as negatively charged rain. The excess of positive charge is smallest at Kew and greatest at Dublin. The large ratios of positive to negative charge at the latter place appear

TABLE II

Observer	Place	Date	Ratios ; positive to negative		
			Quantity of charge	Quantity of rain	Duration of rain
Simpson (1)	Simla	1908–9	2·4	...	2·9
Baldit (5)	Puy-en-Velay	1910–1	2·4	...	2·9
M'Clelland and Noland (6)	Dublin	1911–2	4·5	5·2	...
M'Clelland and Gilmour (7)	Dublin	1919	4·8	2·6	...
Berndt (8)	Buenos Aires	1911–2	...	...	2·0
Schindelhauer (2)	Potsdam	1909–11	1·4	...	2·2
Marwick (9)	Otago	1922	1·9	3·2	...
Scrase	Kew	1935–6	1·1	3·2	...

to be due to the fact that relatively few observations were made in some of the summer months ; this would have an important effect on the ratio because, as McClelland and Gilmour remark, there is an increasing tendency for rain to be negatively charged towards summer and for the charges to be higher at that time of the year.

(*b*) *Seasonal Variation.*—In Table III the seasonal totals of the quantity of rain and the amount of charge recorded in each, and in both, of the years 1935 and 1936 are given. The winter season includes January, February, November and December; the equinox March, April, September and October; the summer, May to August.

TABLE III

	Volume of rain recorded, cm.³			Total charge recorded, e.s.u.		Net charge e.s.u.	Ratio Positive/negative	
	Uncharged	Positive	Negative	Positive	Negative		Volume	Charge
1935								
Winter ...	190	372	70	183	151	+ 32	5·3	1·2
Equinox ...	179	319	139	82	261	−179	2·3	0·3
Summer ...	110	426	166	355	473	−118	2·6	0·7
Year ...	479	1117	376	620	886	265	3·0	0·7
1936								
Winter ...	323	579	137	290	80	+211	4·2	3·6
Equinox ...	387	702	174	629	450	+179	4·1	1·4
Summer ...	657	1041	383	673	592	+ 82	2·7	1·1
Year ...	1367	2322	693	1592	1122	+472	3·3	1·4
1935–6								
Winter ...	513	951	207	473	231	+243	4·6	2·1
Equinox ...	566	1021	313	711	711	0	3·3	1·0
Summer ...	767	1467	549	1028	1065	− 37	2·7	1·0
Year ...	1846	3439	1069	2212	2007	+205	3·2	1·1

So far as the relative amounts of positive, negative and uncharged rain are concerned the two years were not markedly different; in both years there was a greater proportion of positively charged rain in the winter than in the other seasons. The two years show striking differences in the net charges; in 1936 the net charge was positive in all three seasons, whilst in 1935 it was negative in the summer and equinox and positive in the winter. As already mentioned, however, the data for 1935 are not nearly so representative of a complete year's rain as the data for 1936. Taking the two years together it is clear that there is a predominance of positive charge in the winter and that this predominance tends to diminish or even disappear in the equinox and summer. The seasonal variation at Potsdam showed a similar tendency; from the three years' records at that station, Schindelhauer found the greatest excess of positive charge in the winter and an excess of positive also in autumn; in the summer months positive and negative charges were practically equal, but in spring, if deflections which exceeded the range of registration were taken into account, there was an excess of negative charge. At Potsdam, as at Kew, the frequency of occurrence of positively charged rain was greatest in the winter. McClelland and Gilmour (7) found an increasing tendency for non-thunderstorm rain at Dublin to be negatively charged in summer.

We may conclude that in western Europe winter rain is associated with a marked excess of positive charge and that with summer rain this excess tends to disappear.

(*c*) *Daily Variation.*—The daily variation of the charge carried down by rain on to unit area of surface is shown in the upper part of Fig. 3; the diagram gives the annual totals, for 1936, of the charge per unit area in the intervals of two hours, 0 to 2, 2 to 4, etc., the values being obtained from the amounts of charge actually collected by applying the factors given by the ratios of the rainfall measured in the standard meteorological gauge and the rainfall caught in the electrical gauge. The values are expressed in coulombs per Km.² (1 coulomb$=3\times10^{9}$ e.s.u.). For comparison with the daily change of the charge due to rain the corresponding values

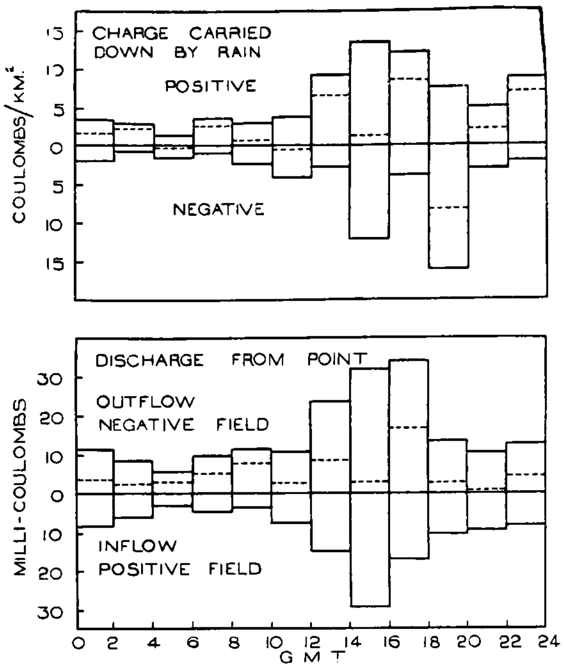


FIG. 3.—DIURNAL VARIATION OF POINT DISCHARGE AND OF CHARGE CARRIED DOWN BY RAIN IN 1936. The broken lines indicate the net amounts.

of the quantity of electricity entering or leaving the earth by discharge at an exposed point are given in the lower part of Fig. 3. A description of the point-discharge recorder, by means of which these values have been obtained, and a discussion of the variations of point discharge has been published recently [Whipple and Scrase (10)]. It suffices here to note that the point is 8·4 m. above the ground, the time scale of the recorder is exactly the same as that of the rain recorder and a flow of positive electricity into the point (denoted as inflow in Fig. 3) corresponds with a positive potential gradient.

There is a close similarity in the diurnal variations of the two elements, point discharge and charge carried down by rain. In both cases the maximum activity occurs in the afternoon hours and the minimum in the early morning. This is to be expected since the most strongly electrified clouds are those produced by convexion which tends to occur during the afternoon. There appears to be no very close correlation between the signs (and amounts) of the net point discharge and the net charge brought down by rain. The net point discharge was outwards (corresponding with negative field) throughout the 24 hours but the net charge on rain, though mainly positive, was reversed in sign at some hours. The large reversal at 18h. to 20h. was, however, due to a single thundery shower which occurred in October.

The total net outflow of positive electricity by point discharge in 1936 was 57·1 millicoulombs, whilst the estimated net transfer of positive electricity to one square kilometre of ground by the rain was 23·6 coulombs. Thus the discharge from the point would be neutralised by the charge due to the rain over an area of 2400 m.² For comparison we may note that the average fine-weather air-earth current at Kew which is 104×10^{-18} amp./cm.², gives a total annual inflow of positive electricity of 32 coulombs/Km.². In 1935, when the net charge collected from the rain was negative, the net outflow of positive electricity by point discharge was 25 per cent higher than the average net outflow for the four years 1933–6.

(*d*) *Connexion between rate of rainfall and charge carried by rain.*—In Table IV all the measurements of the charge per cubic centimetre of rain in 1935–6 have been grouped according to the time interval between consecutive tilts of the bucket. On account of the shielding effect of the cylindrical screen the rate at which rain falls into the collecting funnel is usually less than the rate of fall in a standard meteorological gauge, but a rough estimate of the true average rate of fall for each group has been obtained by allowing for the fact that on the average the screen prevents about 50 per cent of the rain from entering the funnel ; the estimated rates of fall are given in the second column of the table.

The most striking feature of the results is the variation in the ratio of the amounts of positively and negatively charged rain as the rate of fall increases. Practically all the very light rain was positively charged but the ratio decreased to a minimum of 1·5 when the rate of fall was about 0·2 mm./min. and then increased again for the heavy rains. The variation in the ratio of the total charges collected in each group showed the same tendency ; for rates of fall between about 0·15 and 0·8 mm./min. more negative electricity was recorded than positive, but for rates of fall outside these limits positive electricity was in excess. The charge per unit volume was a maximum, for both signs, when the rate of fall was about 0·2 mm./min. and the negative charge per unit volume was greater than the positive for every group except that of the lightest rain. Simpson found that the charge per unit volume on negatively charged rain became very small when the rate of fall exceeded 0·85 mm./min.; our measurements show a tendency for the negative charge to decrease when the rate of fall is high, but the mean charge for rates exceeding 0·8 mm./min. is 0·96 e.s.u./cm.³ which is very much larger than Simpson's value of 0·05 e.s.u./cm.³; this difference may be due to the fact that rates of fall considerably in excess of 0·8 mm./min. were probably much less frequent at Kew than at Simla. Both Simpson and Schindelhauer found that very light rain was relatively highly charged; our results show a tendency in the opposite direction.

TABLE IV

Time interval between tilts of bucket	Approx. rate of rainfall	No. of cm.³ of rain collected (N)			Ratio	Charge collected (Q) e.s.u.		Ratio	Mean charge (q) per cm.³ e.s.u.		Ratio	Average current amp. × 10⁻¹⁵ cm.⁻²	
min.	mm. min.	Uncharged	Positive	Negative	N+/N−	Positive	Negative	Q+/Q−	Positive	Negative	q+/q−	Positive	Negative
> 24	< 0·01	263	342	24	14·3	159	8	19·8	0·46	0·33	1·40	< 3	< 2
11—24	0·01—0·03	251	410	68	6·0	180	101	1·8	0·44	1·49	0·30	5	17
6—10	0·03—0·05	321	517	98	5·3	223	163	1·4	0·43	1·66	0·26	10	37
3—5	0·05—0·1	497	639	241	2·7	475	420	1·1	0·75	1·74	0·43	31	73
1·6—2·4	0·1—0·15	279	544	213	2·6	485	407	1·2	0·89	1·92	0·46	62	130
0·8—1·5	0·15—0·3	153	404	262	1·5	468	630	0·7	1·16	2·40	0·48	140	290
0·4—0·7	0·3—0·8	48	255	128	2·0	121	224	0·5	0·47	1·75	0·27	140	530
< 0·3	> 0·8	52	321	45	7·1	196	43	4·6	0·67	0·96	0·63	> 300	> 430

In the last two columns of Table IV estimates of the average current densities carried by the rain are given. These have been obtained by multiplying the mean charge per cubic centimetre by the approximate rate of rainfall in each group. The current density varies over a very wide range—from values nearly as small as the fine-weather air-earth current, which is about 10^{-16} amp./cm.² to values several thousand times as large. After weighting the averages for each group according to the quantity of rain collected, the average values for the whole series of observations are about 50×10^{-15} amp/cm.² in the case of positive currents and 200×10^{-15} amp./cm.² in the case of negative currents.

(*e*) *Frequency of occurrence of rain carrying different charges per unit volume.*—In Table V the observations for the two years have been grouped according to the charge per cubic centimetre carried by the rain; the numbers of cubic centimetres, positive and negative, are given, as well as the ratios of the numbers for each group. The results confirm those of other observers in showing a large preponderance of positively charged rain when the charge per unit volume was small and a diminution in this preponderance when the charge increased; for charges exceeding 6 e.s.u./cm.³ negatively charged rain was in excess. The highest charge on positive rain was 22 e.s.u./cm.³; this occurred during a thunderstorm on May 17, 1936. For negatively charged rain the highest charge was 20 e.s.u./cm.³; it was recorded during a very heavy instability shower of rain and hail on April 26, 1936.

It has been mentioned that the lower limit of measurement on the records corresponds to a charge of about 0·05 e.s.u./cm.³ and rain with a smaller charge than this has been entered as uncharged. The results given in Table V show that if there is any charge at all on such rain it is almost certainly positive. If we assign a positive charge of 0·05 e.s.u./cm.³ to all the "uncharged" rain, of which 1846 cm.³ were collected, this would only increase the total positive charge collected by 92 e.s.u., *i.e.*, by about 4 per cent.

It is evident from the data in Table V that estimates of the total charge brought down by rain in, say, a season or a year, cannot be very reliable unless they include all the occasions when the rain is highly charged ; the loss of a few millimetres of rain on such occasions may mean the loss of a considerable proportion of the total charge. The data in Table V indicate that of the total amount of rain which was collected (6354 cm.³), as little as 9 per cent contributed half the total positive charge and as little as 2 per cent contributed half the total negative charge. Thus the loss of a small percentage of the rainfall might easily cause an estimate of the net charge to be incorrect not only in amount, but also in sign.

TABLE V

Charge per cm.³	No. of cm.³ for which charge was		Ratio of cm.³ positive to cm.³ negative
	positive	negative	
e.s.u.			
0·05— 0·9	2839	569	5·0
1— 1·9	255	200	1·3
2— 2·9	153	95	1·6
3— 3·9	69	55	1·3
4— 4·9	33	31	1·1
5— 5·9	25	25	1·0
6— 7·9	10	43	0·2
8— 9·9	8	24	0·3
10—11·9	6	10	0·6
12—24	7	11	0·6

(*f*) *Relationship between sign of potential gradient and sign of electricity on rain.*— The records of point-discharge current which were made on the same time scale as those of the charge on rain, afford a direct means of comparing the sign of the charge on rain with the sign of the potential gradient. The comparisons are limited to the occasions when the gradient was sufficiently high to cause point discharge ; with the apparatus in use at Kew the minimum field necessary to give a measurable current is about 8 v./cm.

The results of the comparisons are summarised in Table VI.

TABLE VI

Charge on rain	Number of buckets for which potential gradient was		Percentage occurrence of negative potential gradient
	positive	negative	
Positive ...	220	487	69
Negative ...	247	230	48
	467	717	60

These results are in fairly good agreement with the data obtained by Simpson at Simla ; the potential gradient was more often negative than positive during rain. There is apparently a strong tendency for negative potential gradient to be associated with positively charged rain but when the gradient is positive there is no marked tendency for the charge on the rain to be of one sign rather than the other. As at Simla, there appears to be no definite relationship between the magnitude of the potential gradient and the charge per unit volume of the rain, apart from a general tendency for highly charged rain to be associated with high gradient.

(*g*) *The electricity associated with different types of rain.*—In order to see how the charge carried by rain differs with the meteorological conditions governing the production of the rain the observations have been classified into three groups. Rain associated with active thunderstorms has been put in the first group. The second group has been restricted to showers in which no thunder or lightning occurred. The third group comprises all the rain not included in the first two groups and it may be taken to represent the ordinary continuous or intermittent rain which is referred to as *Landregen* by German investigators. In general, it was fairly easy to classify the rain into these three types by making use of synoptic charts and eye observations ; rain in advance of fronts and occlusions is usually of the *Landregen* type. Some of the showers were of the " instability " type that occurs in polar air after the passage of a cold front, but some occurred in conditions favourable for the development of thunderstorms of the " heat " type.

The results of this classification are given in Table VII. Roughly 15 per cent of the rain collected was associated with thunderstorms, 15 per cent was of shower type and the remaining 70 per cent *Landregen* type. Of the total charge collected, irrespective of sign, showers and thunderstorms were each responsible for about 30 per cent and *Landregen* for about 40 per cent. For all three types of rain there

TABLE VII

Type of rain	Number of Occasions	Number of cm.³(n)			$n+/n-$	Total charge, (Q) e. s.u.		$Q+/Q-$	Average charge per cm.³, e.s.u.		Percentage frequency of negative potential gradient
		uncharged	positive	negative		positive	negative		positive	negative	
Thunderstorm	14	82	597	246	2·4	734	349	2·1	1·23	1·42	57
Shower ...	43	153	515	260	2·0	479	961	0·5	0·93	3·69	57
Continuous ... (*Landregen*)	...	1611	2327	563	4·1	909	697	1·4	0·43	1·24	70

was a greater quantity with positive charge than with negative ; the preponderance was greatest in continuous rain. The most striking difference between the three types is to be seen in the ratios of the amounts of positive and negative electricity brought down. For thunderstorms there was a preponderance of positive charge in the ratio of 2·1 : 1 ; for continuous rain the preponderance was rather less, viz., 1·4 : 1 ; whilst for showers negative electricity was in excess, the ratio of positive to negative being 0·5. In all three cases the average negative charge per unit volume was greater than the average positive charge. The latter was greatest for thunderstorm rain and least for continuous rain, whilst the average negative charge per unit volume was very much greater in showers than in the other types of rain.

These results bear out those of Schindelhauer who found that an excess of negative charge was associated with squally showers (*Böenregen*). Gschwend (11), who measured the charge on single drops, also found that squally showers gave an excess of negative electricity, the ratio of positive to negative being 0·55 ; in thunderstorm rain the ratio was 1·51 and in continuous rain 2·12.

It might be expected that the large differences in the ratios of the amounts of positive and negative charges in the three types of rain would be associated with similar differences in the ratios of frequencies of positive and negative potential gradients. Actually, however, the predominance of negative gradient was the same for thunderstorms and showers, the ratio of the quantities of rain associated with negative and positive gradients respectively being about 1·4 ; for continuous rain the predominance of negative gradient was considerably higher, the corresponding ratio being 2·3. On most occasions when light or moderate steady rain continued for more than three hours the charge on the rain was positive and the potential gradient negative practically all the time. For example, on April 7, 1935, there was a period of continuous rain lasting more than four hours, the charge being positive and the potential gradient negative for the whole of the period, except for about ten minutes when both signs were reversed. Again, on November 7, 1935, during three hours of continuous rain there was no negative charge at all and no positive potential gradient. Many other examples could be given of long spells of steady rain showing these characteristics.

§ 5—SOME INDIVIDUAL RECORDS

A few records have been selected to illustrate some of the more interesting features of the electricity of precipitation ; these records are reproduced in Figs. 4 to 7, together with the simultaneous records of point-discharge current, the variations of which are a rough indication of the variations in the potential gradient. Movements up the sheets indicate positive charge in the case of the rain records and positive potential gradient in the case of the point-discharge records ; in both cases time progresses from left to right. On the rain records there are time marks at the hours, whilst on the point-discharge records there are time marks every minute as well. The deflections on the point-discharge records are proportional to the strength of the current flowing through the apparatus ; for our purpose it is more convenient to give the scale values in terms of potential gradient, but owing to the fact that the relationship between potential gradient and current is not a very rigid one, the scale values given are very rough ones.

(a) *Instability shower, April* 26, 1936 : *Fig.* 4.—These records refer to an instability shower in which heavy rain and hail fell. The total fall in the standard gauge amounted to 4·3 mm. and the duration was about half an hour. For a few seconds, soon after the commencement of the shower the rate of fall, recorded by a Jardi rate of rainfall recorder, was 111 mm./hr., but for the rest of the time the rate was mostly between 5 and 10 mm./hr. It will be seen that practically the whole of the charge brought down was negative ; a small amount of positive charge occurred at the very end of the shower, but it was insignificant compared with the large negative charges. The total negative charge collected in this shower was 235 e.s.u. ; this amounts to 20 per cent of the total negative charge caught in the whole of 1936, and to as much as 50 per cent of the net positive charge caught in that year. The average charge on the rain in this shower was $-7\cdot 1$ e.s.u./cm.^{3}, and the maximum, which occurred at 15h. 36m. was -20 e.s.u./cm.^{3}. This shower was associated with very high point discharge and potential gradient ; the point discharge record ran off the sheet soon after the rain started and it is estimated that at this stage the potential gradient exceeded $+250$ v./cm., which is considerably higher than the gradient recorded at the ground in many thunderstorms. There appears to have been little connexion between the potential gradient and the charge on the rain ; the gradient became negative during the middle part of the shower and then returned to positive again. The charge on the rain fell to a minimum negative value when the negative gradient was at its maximum ; the maximum negative charge was associated not with the very high positive gradient at the beginning of the shower, but with the smaller peak in the latter half of the shower. Another shower cloud which passed over about two hours earlier showed the same type of potential gradient variation but on a considerably smaller scale, the second positive maximum being only just sufficient to cause any point discharge ; there was not sufficient rain in this earlier shower to fill the bucket of the gauge, but the small amount that was caught was positively charged.

(b) *Two thunderstorms, June* 19, 1936 ; *Fig.* 5.—The electrical conditions during these storms were discussed in some detail in a recent paper dealing with electrical measurements obtained by balloon soundings in thunderclouds (12). On the record of point discharge there are numerous discontinuities in the trace ; these are due to the sudden changes in the potential gradient produced by lightning discharges. The storms were two of a notable series which lasted from June 18 to 21. Distant thunder was heard from 10h. 30m. on the morning of the 19th and light thundery rain occurred between 13h. 10m. and 13h. 25m. This rain was positively charged but there was not sufficient quantity to fill the tilting bucket so that when the rain ceased the electrometer needle remained deflected from zero ; the rain was accompanied by high potential gradient, positive and negative. The main thunderstorm centre was approaching by 13h. 40m. and at 13h. 50m. it was overhead. Heavy rain and hail commenced at 13h. 48m. and the potential gradient increased rapidly from almost zero to about $+50$ v./cm. ; during this increase the rain and hail were negatively charged but the charge was only about $-0\cdot 3$ e.s.u./cm.^{3}. At 13h. 50m. a violent lightning flash at a distance of about 300 m. caused a sudden reversal of the field to about −50 v./cm. and at the same time the charge on the rain and hail changed from negative to positive. The precipitation lasted for about 8 minutes, and during this time the rate of fall was extremely heavy, reaching a maximum of 129 mm./hr. ; the total fall was 4·7 mm. The charge per unit volume carried by the precipitation was surprisingly small, the average charge being about 0·4 e.s.u./cm.^{3} and the maximum about 0·9 e.s.u./cm.^{3} ; this part of the record may be deceptive, however, for with such rapid discharges of the bucket the electrometer needle may not have had sufficient time to respond correctly. Positive charge was much in excess, the totals collected being 31·1 e.s.u. positive and 1·8 e.s.u. negative. From evidence obtained by balloon soundings in this storm it was concluded that there was a diffuse negative charge in the main body of the thundercloud, a region of positive charge at the top and, in the early stages, a concentration of positive charge at the base. This concentration at the base was almost certainly generated by the breaking-drop process and would account for the heavy fall of rain with positive charge. Had the latter half of the storm been accompanied by rain we should have expected this rain to be associated with a larger proportion of negative electricity.

The second storm which occurred on June 19 (at about 21h.) was widespread and there appeared to be several centres of activity within a few kilometres of the Observatory. One of these centres passed overhead between 21h. 30m. and 21h. 45m.; during its approach the potential gradient was mostly positive, but when it was overhead, fairly heavy rain started and the gradient reversed. The rain which fell at this stage was positively charged, but the charge was not particularly high, the maximum being about +2 e.s.u./cm.^{3} The rate of fall of the rain during this part of the storm reached a maximum of 32 mm./hr. After the centre had passed over, light rain continued for about 40 minutes ; the electricity on this rain fluctuated in sign, but positive charge predominated. The balloon soundings in this storm showed that the main body of the cloud was negatively charged, the upper part positively charged, and that there were at least two concentrations of positive charge in the lower part of the cloud, one towards the front and another towards the rear. During the latter half of the storm the potential gradient at the ground showed several gradual alternations of sign, but the changes in the sign of the electricity on the rain were not closely correlated with these alternations. The total positive charge collected from the rain in this storm was 45·5 e.s.u. as against 7·8 e.s.u. of negative charge.

The sudden changes in the potential gradient due to lightning flashes are an interesting feature of the point-discharge record for these two storms. As is usually the case, the majority of these sudden changes are followed by a rapid recovery of the potential gradient (and therefore of the point-discharge current) to its original value, the record having the appearance of being interrupted temporarily by disturbances superimposed on the relatively steady field. There were a number of cases, however (notably the flash at 13h. 50m. and those between 21h. 30m. and 21h. 50m.), in which complete recovery did not take place, the disturbance causing a more or less permanent change in the steady field. It is as if in those latter cases the effect of the lightning is not only to discharge part of the electricity in the cloud, but also to destroy the mechanism by which the electricity is normally rapidly regenerated.

(c) *Thundery shower, June* 29, 1936 ; *Fig.* 6.—This is a case of a long and heavy shower of thundery character. One clap of thunder was heard at 17h. 35m., about 10 minutes before rain commenced, but no lightning discharges were observed or recorded throughout the shower. It will be noticed that the charge on the rain showed gradual but well-marked changes in sign and magnitude. At the beginning when the rate of fall was highest (34 mm./hr.) the charge was positive and small, but in the middle of the shower the rate of fall decreased to about 3 mm./hr. and the charge became negative and increased in magnitude to a maximum of −8·3 e.s.u./cm.^{3}. Then the rate of fall increased again slowly to about 8 mm./hr., and the charge reversed, reaching a positive maximum of 5·2 e.s.u./cm.^{3}. Finally, as the rain was ceasing, the charge became negative and small. Again there appears to be little or no

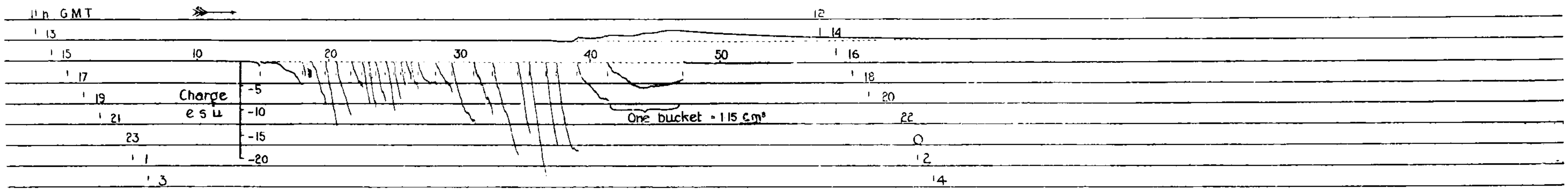


Fig. 4 (a).—Charge on rain.

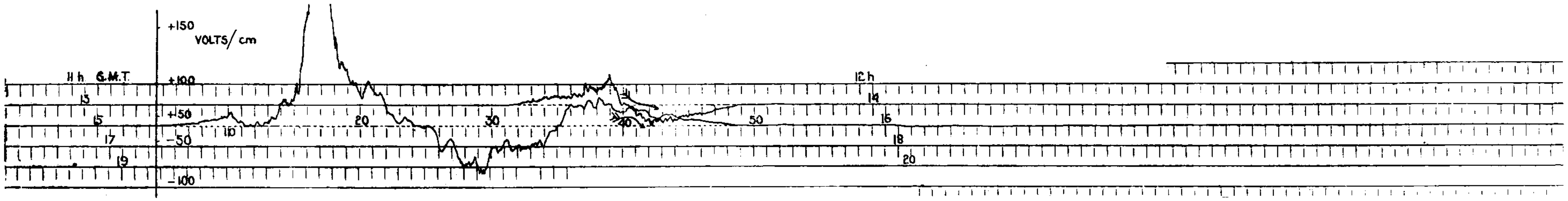


Fig. 4 (b).—Potential gradient.

FIG. 4.—INSTABILITY SHOWER; APRIL 26, 1936.

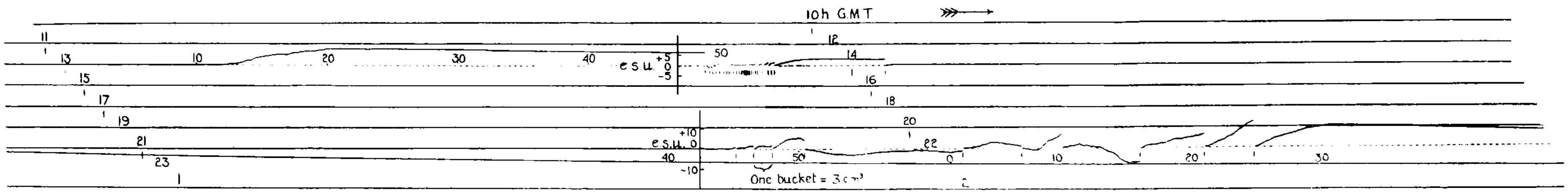


FIG. 5 (a).—Charge on rain.

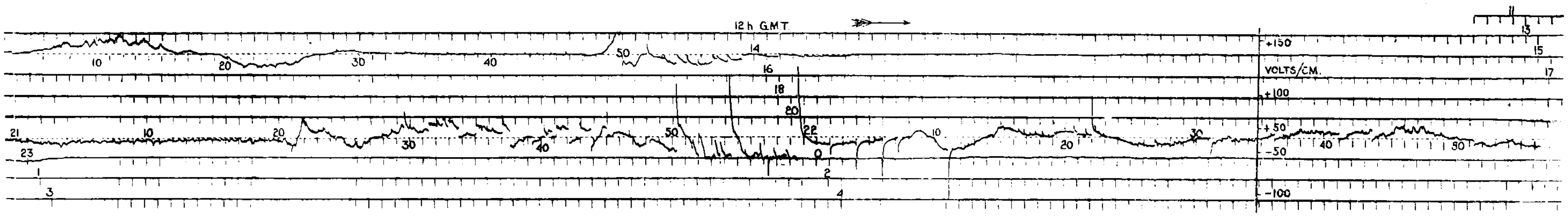


Fig. 5 (b).—Potential gradient.

FIG. 5.—TWO THUNDERSTORMS; JUNE 19, 1936.

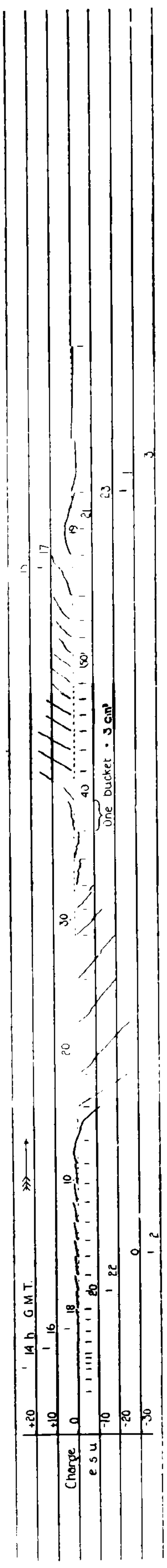


Fig. 6 (a).—Charge on rain.

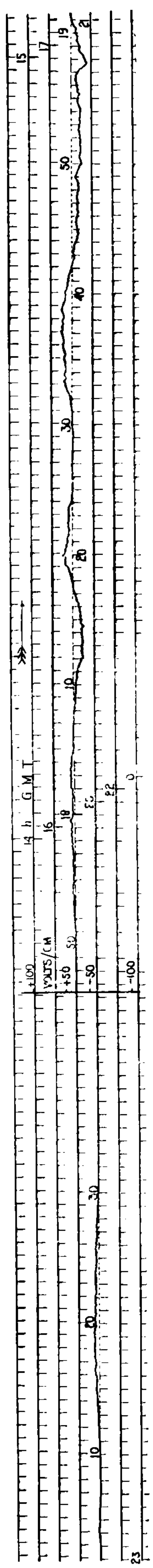


Fig. 6 (b).—Potential gradient.

FIG. 6. THUNDERY SHOWER; JUNE 29, 1936.

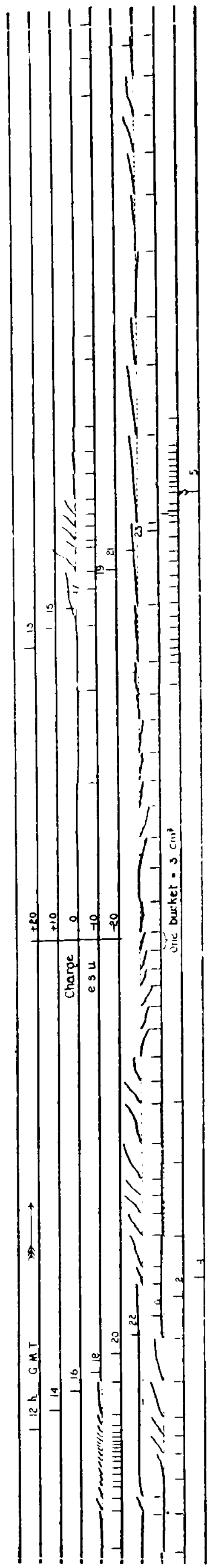


Fig. 7 (a).—Charge on rain.

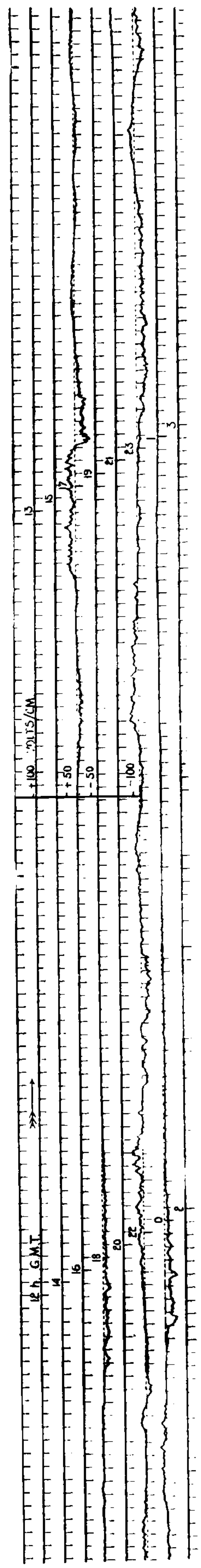


Fig. 7 (b).—Potential gradient.

FIG. 7.—CONTINUOUS RAIN; SEPTEMBER 20-1, 1936.

correlation between the potential gradient and the electricity on the rain ; in the earlier part of the shower the signs of the gradient and of the charge on the rain were in agreement, but in the later part they were in opposition. The rainfall in this shower was 8·6 mm. ; the total positive charge collected was 143 e.s.u. and the total negative, 125 e.s.u. ; inflow and outflow of point-discharge current were in almost exactly the same proportion.

(d) *Continuous rain, September* 20, 1936; *Fig.* 7.—These records illustrate a period of heavy continuous rain. As a rule the records of continuous rain were not sufficiently striking to warrant reproduction; in most cases small positive deflections occurred on the records of charge whilst the potential gradient was generally too small to cause much point discharge. In this particular case (and in one or two others), however, the electrical activity was greater. It is probable that the rain was thundery in character, for thunderstorms were reported on the south coast on that day. The total rainfall for the period covered by the records was 19·8 mm. ; 188 e.s.u. of positive charge were collected and 39 e.s.u. of negative charge. Negative potential gradient preponderated and the outflow of electricity by point discharge was nearly double the inflow. On this occasion there does appear to be some correlation between the potential gradient and the charge on the rain, the gradient generally being positive when the charge was negative and *vice versa*. Another point which is very noticeable is that the very heavy rain just before 18h. on the 20th (when the maximum rate of fall was 40 mm./hr.), and also at about 1h. on the 21st (when the rate of fall reached 26 mm./hr.), was associated with small charges of about 0·5 e.s.u./cm.^{3} or less, whilst the lighter rain between 22h. and 23h. with a rate of fall generally less than 10 mm./hr. was relatively highly charged, the maximum charge being about 3 e.s.u./cm.^{3}.

§ 6—DISCUSSION

In at least one respect the results of this investigation confirm very definitely those of other workers ; it is that much more rain is charged positively than negatively. The evidence as to the relative amounts of positive and negative charge is not so conclusive ; information on this point can only be reliable when the data are fully representative of all types of rain. If we allow greater weight to the more complete series of records obtained in 1936 then we may say, in agreement with the majority of other observers, that over the period of a year the positive charge predominates.

The main results obtained in this investigation are summarised below.*

A. Average results for all rain

(1) 29 per cent of the rain has a charge of less than 0·05 e.s.u./cm.^{3}.
(2) 75 per cent of the rain with measurable charge is charged positively.
(3) A slight excess of positive charge is brought down by the rain.
(4) The average charge per unit volume on negatively charged rain is three times that on positively charged rain.
(5) The potential gradient at the ground is more often negative than positive during rain, but in general there is no close correlation between the sign of the gradient and that of the charge on the rain. Highly charged rain is usually associated with high potential gradient.

B. *Continuous rain*

(6) 35 per cent of the rain has a charge of less than 0·05 e.s.u./cm.^{3}.
(7) 80 per cent of the rain with measurable charge is charged positively.
(8) 60 per cent of the charge is positive.
(9) The charge per unit volume is smaller than with other types of rain.
(10) The potential gradient is more often negative than positive ; the predominance of negative gradient is greater than it is in other types of rain.

* See footnote on page 5.

C. *Thunderstorm rain*

(11) 9 per cent of the rain has a charge of less than 0·05 e.s.u./cm.^{3}.
(12) 70 per cent of the rain with measurable charge is charged positively.
(13) 70 per cent of the charge is positive (a larger proportion than with other types of rain).
(14) The positive charge per unit volume is higher than with other types of rain.
(15) The potential gradient undergoes rapid changes of sign, but negative gradient predominates.

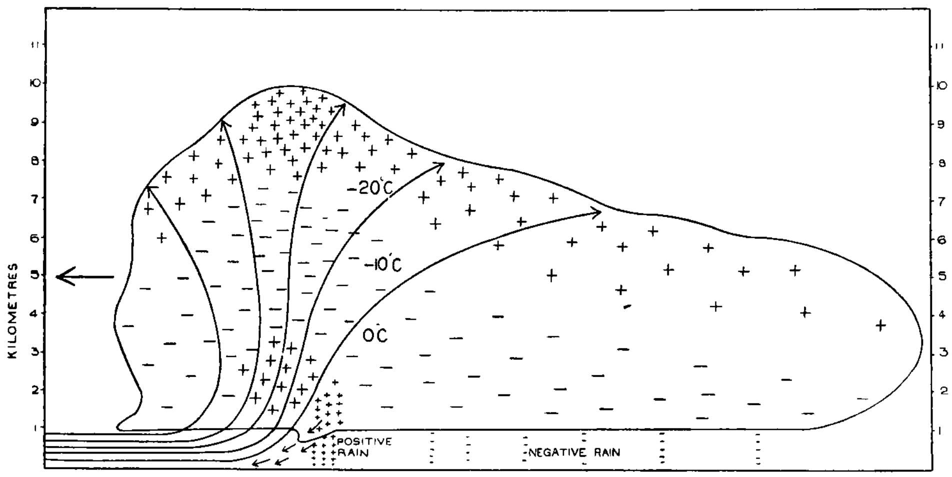
D. *Showers*

(16) 16 per cent of the rain has a charge of less than 0·05 e.s.u./cm.^{3}.
(17) 70 per cent of the rain with measurable charge is charged positively.
(18) 35 per cent of the charge is positive (much smaller than with other types of rain).
(19) The negative charge per unit volume is very much higher than with other types of rain.
(20) The potential gradient undergoes rapid fluctuations but negative gradient predominates.

It is beyond doubt that on the average at Kew, thunderstorm rain and continuous rain bring down an excess of positive charge and that showers bring down an excess of negative charge ; in showers high negative charges per unit volume are quite frequent, especially when the showers are of the "instability" type occurring in polar air. It appears that rain produced by ascent of air up a gradual slope, such as continuous rain of frontal origin, is less intensely electrified than rain produced by the convectional ascent of air, and it seems fairly certain that the intensity of the electrification is governed mainly by the rate of ascent of the air, which is usually more rapid in the case of convection. This explains why more electricity is brought down by rain in the summer months than in the winter months and during the afternoon hours than during the other hours of the day.

The most interesting feature of the results of the investigation is the striking difference in the electricity of the rain in thunderstorms and showers, the one type showing a large preponderance of positive charge, the other a large preponderance of negative charge. Both showers and thunderstorms are produced by large scale convection, which may be regarded as the ultimate cause of the generation of large charges in the clouds. We should expect that any difference between the two types of conditions would be one of degree and not a constitutional difference, the thundercloud being a larger and more highly developed form of shower cloud. There is no obvious reason for believing that the mechanism by which the charges are generated in the clouds is any different in the two cases ; the main distinction is that the generation proceeds to a higher limit in the case of the thunderstorm than it does in the case of the shower. It might have been expected, therefore, that the positive and negative charges brought down by rain would be in roughly the same proportion in showers as in thunderstorms, but that the showery rain would be less highly charged. Actually, we find not only are the proportions of positive and negative charges reversed, but also that the predominating electrification of the rain in showers is more intense than it is in thunderstorms, the average negative charge in showers being 3·7 e.s.u./cm.^{3} as compared with the average positive charge in thunderstorms of 1·2 e.s.u./cm.^{3} In the case of potential gradient at the ground there is no such contrast, the relative frequencies of positive and negative gradients being about the same in showers and in thunderstorms ; it is noteworthy, too, that the magnitude of the gradient in showers is generally about the same as it is in thunderstorms.

In attempting to understand these differences it will be helpful if we consider briefly the electrical structure of a thundercloud. The results obtained by Simpson and Scrase (12) from sounding-balloon ascents made in thunderstorms, show that in general the upper part of a thundercloud is positively charged and the lower part negatively charged ; frequently, however, there are very definite indications of regions of positive charge near the base of the cloud. It was concluded that the average well-developed thunderstorm could be represented diagrammatically, as in Fig. 8. In the diagram the charges within the cloud and on the rain, are indicated by positive and negative signs, whilst the stream lines of air-flow, relative to axes moving with the cloud, are shown by unbroken lines whose distance apart are roughly proportional to the wind velocity. The air entering the cloud from the left, passes under the front of the cloud and then sweeps upwards. It is just above the strongest part of this upward current that the lower region of positive charge is situated and this forms the active centre of the storm ; in the rear of this region the upward current is weaker and the heavy rain which falls at this stage of the storm is generally positively charged. Away from this local region of positive charge the lower half of the cloud is negatively charged, and the charge on the moderate rain which falls from the main body of the cloud is more variable in sign than that on the heavy rain. The upper part of the cloud is positively charged and the region of separation between this upper charge and the lower negative charge is generally at a height where the temperature is from 10° C. to 20° C. below the freezing point. It was concluded that the electrical effects in a thunderstorm are produced by two different physical processes : one occurs in the upper parts of the cloud and is believed to be associated with the presence of ice crystals, the impacts of which result in the ice becoming



[*Reproduced from* London, *Proc. roy. Soc.*, *A*, 161, 1937, *p*. 350.

FIG 8.—ELECTRICAL STRUCTURE OF A THUNDERCLOUD ACCORDING TO SIMPSON AND SCRASE.

negatively charged and the air positively charged, the general settling of the crystals relative to the air producing a separation of electricity with the positive charge above the negative. The second process occurs in the region of positive charge at the base of the cloud and is associated with the presence of rain drops probably in the way described by Simpson in his " breaking-drop " theory (13).

The differences we have found between the charges on the rain brought down in shower clouds and thunderstorms might well be explained by the suggestion that the lower region of positive charge, which is characteristic of the active centre of a thunderstorm, is absent, or at any rate less well-developed, in a shower-cloud. With no positive region near the base there would certainly be less positively-charged rain falling to the ground. On this view, we should regard a shower cloud as having simply a positive charge in the upper layers and a negative charge in the lower layers, the process of generation of the charges being associated with ice crystals. In the initial stages a thundercloud would have a similar structure, but as soon as the meteorological conditions were favourable for very rapid ascent of air into the front of the cloud, the generation of a local region of positive charge near the base by the breaking-drop process, would commence. The production of a relatively concentrated positive charge in the negatively charged base, would undoubtedly lead to higher fields inside the clouds, though not necessarily to higher fields at ground level. It seems likely that unless a local region of positive charge develops in the base of the cloud the field will not become high enough for large discharges to take place.

There is another explanation which may partly account for the fact that a smaller proportion of negative charge is brought down by thunderstorm rain than by showers. It is well established that the majority of lightning discharges are accompanied by a positive change of field at the ground near the discharge and that they generally occur when the preliminary field is negative (10). Such discharges result in a destruction or diminution of negative charge in the lower half of the cloud, the negative electricity going either to earth or to a positive charge in another part of the cloud. It is probable that part of the negative charge in the base of the cloud is carried by raindrops, and if these are in the neighbourhood of a lightning flash, their charges will be reduced or destroyed. We should expect, therefore, that the proportion of negative charge brought down by rain would be less in a violent storm in which most of the discharges are accompanied by positive field changes, than in a shower or in a storm in which positive field changes are infrequent. This expectation is borne out by the observations ; in the majority of well-developed storms, positive field changes are predominant and the net charge on the rain is positive. Of the fourteen thunderstorms for which the charge on rain was recorded, there were only two cases in which an appreciable excess of negative charge was brought down by the rain. In one case (9h., June 18, 1936), the storm was of a feeble character, and only two lightning flashes were recorded ; these were accompanied by positive field changes. The other case (19h., June 21, 1936) was of an abnormal type, in which the potential gradient at the ground was predominantly positive, and of the very numerous discharges which occurred, 80 per cent caused negative field changes (indicating decreases in positive charge in the lower part of the cloud). Unfortunately, a balloon sounding which was attempted in this storm was unsuccessful, but the record of potential gradient at the ground showed that the excess of negative charge brought down by the rain in this case was not due to the absence of concentrations of positive charge near the base of the cloud. Although it was concluded from the results of the sounding-balloon experiments that Wilson's theory (14) of the charging of water drops would not account for the main development of electricity in a thundercloud, there remains the possibility that it does play a minor part in the lower part of the cloud, and between the cloud and the ground where the precipitation may be in the liquid form. If such be the case, the charge on the rain reaching the ground would be affected to some extent. According to Wilson's theory, water drops falling in an electric field, by virtue of the induced charges on their upper and lower halves, tend to attract ions of opposite sign to that of the field (so long as the drops fall faster than the field drives ions downwards). It might be thought that this process offers the true explanation of the abnormal predominance of negatively charged rain in the storm of June 21, 1936, in which positive potential gradients below the cloud were more frequent than usual. Against this, however, is the fact that although the potential gradient at the ground was more often positive than negative, there was almost an entire absence of correlation between the changes in the sign of the gradient and those of the sign of the charge on the rain. We must conclude that the electricity of thunderstorm rain is not always due to any single process of generation of charge, and that several factors such as the breaking of drops, the impact of ice crystals, the Wilson mechanism and the effect of lightning discharge, may operate together to determine what shall be the sign of the charge on the rain when it reaches the ground.

Turning now to the question of the electricity of continuous rain, we may note the following differences between the effects associated with this type of rain and those associated with the showery type :

	Continuous rain	Showers
Potential gradient ...	Generally negative	Sometimes positive, sometimes negative
Electricity on rain ...	Generally positive	Generally negative
Charges	Low	High

Clouds which produce showers are generally of small horizontal extent compared with those which cause continuous rain, the latter usually being associated with the stratified type. It is quite common for an extensive cloud layer to persist for hours without producing precipitation and in such cases there is rarely any noticeable disturbance of the potential gradient at the ground from its normal fine-weather value. As a general rule it is only when the cloud layer reaches the rain stage that the gradient becomes abnormal, and there is no doubt that the occurrence of the rain is directly connected with the disturbance of the gradient. Now, in the case of an extensive cloud layer, the mere vertical separation of electricity within the layer cannot cause any marked effect on the electric field below the cloud ; it certainly cannot reverse the field. As soon, however, as there is removal of electric charge of one sign rather than the other from the cloud, then the field below the cloud will become disturbed. It is natural to conclude, therefore, that the falling out of charged rain from the cloud layer is the cause rather than the effect of the disturbed potential gradient. Although very little evidence was obtained from sounding-balloon experiments as to the vertical distribution of electricity during continuous rain (owing to the apparatus not being sufficiently sensitive to record the relatively weak fields), the few results that were successful showed that the vertical separation of charge in continuous rain clouds is the same as it is in shower clouds, *i.e.*, a positive charge in the upper layers and a negative charge in the lower layers. Moreover, since the temperature in the upper parts of continuous rain clouds is generally below the freezing point, it is possible that the effective mechanism of separation of electricity is the impact of ice crystals, as it is believed to be in shower clouds. Further experimental evidence is desirable, however, before putting forward a theory of the electrification of continuous rain.

It is not expected that in individual cases the separation of electricity in a cloud is always as simple as we have indicated ; the shearing effect of the change of wind velocity and direction with height, and the effect of turbulence and convection will certainly tend to complicate the distribution of charge. Moreover, in the lowest layers of the cloud and in the space between the cloud and the ground where precipitation may have reached the liquid state, the breaking-drop process and the Wilson influence mechanism may play some part in determining the charge on the rain.

The main points of this discussion may be summed up briefly in the following remarks :

From the investigation by Simpson and Scrase into the distribution of electricity in thunderclouds, it was concluded that there are two distinct physical processes by which the separation of electricity in the clouds is brought about ; one is due to the impact of ice crystals and produces a positive charge at the top of the cloud and a negative charge in the lower part, whilst the other is due to the breaking of water drops and accounts for local regions of positive charge near the base of the cloud. To account for the preponderance of negatively charged rain in showers, it is suggested that the impact of ice crystals is the more effective process in shower clouds and that there is no marked development of local regions of positive charge in the lower part of these clouds ; if in such cases the bulk of the precipitation originates in the middle and lower layers of the cloud, it will carry down more negative charge than positive.

It seems probable that violent thunderstorms develop initially in the same way as shower clouds, but that the stronger vertical air currents with which they are associated cause the development, by the breaking-drop process, of regions of positive charge in the lower parts of the clouds. These regions are associated with the positively charged heavy rain which is usually a marked feature of violent thunderstorms. The proportion of negative charge on the rain is less than it is in shower clouds, not only on this account, but also because the majority of lightning flashes tend to decrease negative charge in the base of the thundercloud.

Further experimental evidence is required before the electrification of continuous rain can be satisfactorily explained, but it is believed that the prevalence of negative potential gradient in this type of rain is the result rather than the cause of the transfer of positive charge from the clouds to the ground by the rain.

§ 7—ACKNOWLEDGMENTS

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§ 8—SUMMARY

The data on which this investigation is based were obtained from continuous photographic records of the charge brought down by unit amounts of rain at Kew Observatory during the years 1935–6 ; a detailed description of the apparatus is given.

The results of an analysis of the records showed that about three-quarters of the rain was positively charged, but owing to the fact that the charge per unit volume was, on the average, much greater in the case of negatively charged rain, the total quantities of positive and negative electricity brought down were not very different. On the whole, positive charge was slightly in excess. Showers were responsible for most of the high negative charges, whilst continuous rain and thunderstorms were generally associated with excess of positive charge.

The potential gradient at the ground was much more often negative than positive during positively charged rain, but in negatively charged rain there was no marked tendency for the gradient to be of one sign rather than the other.

The results appear to be consistent with the view that the electrification of shower clouds is brought about by the impact of ice crystals. It is suggested that the same process is responsible for the initial separation of electricity in a thundercloud, but that as a result of the more violent ascent of air local regions of positive charge are generated near the base of the cloud by the breaking-drop process.

It is not clear how the electrification of continuous rain is produced, but it is believed that the prevalence of negative potential gradient in this type of rain is the result rather than the cause of the transfer of positive charge from the clouds to the ground by the rain.

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