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POINT DISCHARGE IN THE ELECTRIC FIELD OF THE EARTH

An analysis of continuous records obtained at Kew Observatory

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ERRATUM

Page 13, line 11, the words "positive" and "negative" should be transposed.

POINT DISCHARGE IN THE ELECTRIC FIELD OF THE EARTH

An analysis of Continuous Records obtained at Kew Observatory

§ 1—INTRODUCTION

The discharge of electricity from a pointed conductor placed in a strong field is a well-known phenomenon and it has been the subject of numerous laboratory investigations. In 1920 it was pointed out by C. T. R. Wilson (1)* that the phenomenon must play an important part in the interchange of electricity between the earth and the atmosphere. Whenever the potential gradient near the ground is sufficiently great point discharge takes place at the ends of conductors such as trees or tall buildings; sometimes the process is accompanied by the luminous effect known as St. Elmo's Fire.

Measurements of the discharge from a single point at the top of an isolated pole exposed to the earth's field were made by T. W. Wormell (2) at Cambridge in 1927. Wormell developed two methods; he obtained continuous records of the discharge current for short periods by charging a condenser and he measured the total flow of electricity, day by day, by means of a specially designed micro-voltameter. B. F. J. Schonland (3) in South Africa, measured the discharge from a small tree connected to earth through a galvanometer. At Kew Observatory autographic records of the discharge from a single point have been made continuously since July 1932; a brief account of the first year's records was given by F. J. W. Whipple (4) at the Lisbon conference of the International Union of Geodesy and Geophysics in 1933. Shortly before this, L. H. Starr (5), who maintained the apparatus in operation during the first year, published a note on an interesting record obtained during a thunderstorm. In the present paper it is proposed to give a detailed account of the installation and to discuss the results obtained from an analysis of the records for the period July 1932—December 1934.

§ 2—DESCRIPTION OF APPARATUS

The discharging system is very similar to that used by Wormell; the construction is shown in Fig. 1. At first a stainless steel needle was used for the discharging point, A, but this was found to corrode and so a fine platinum wire, 0·45 mm. diameter and 2 cm. long was substituted. The wire is soldered to a brass rod, B, 0·4 cm. diameter and 20 cm. long, which is tapered at the end.† The connexion to the recording apparatus is made with lead covered cable, C, one end of which is soldered to the brass rod; this joint is insulated by being embedded in "Bitulac" insulating compound, D, contained in a brass tube. In order to shield the exposed surface of the insulator from rain and dirt it is protected by a metal cover, E, which fits on a rubber cork carried by the brass rod. The insulated system is clamped to the top of a wooden mast, F, which is hinged near the base so

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

† A much shorter rod was used during the first year. The longer rod, giving a better exposure of the point, was fitted in the autumn of 1933.

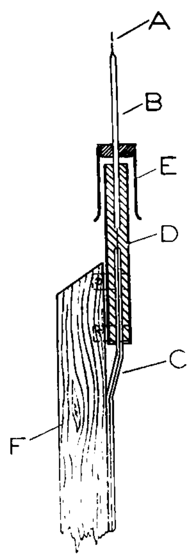

FIG. 1.—DIAGRAM SHOWING CONSTRUCTION OF DISCHARGING SYSTEM.
A = platinum wire
B = brass rod
C = lead covered cable
D = bitumen insulator in brass tube
E = rain shield
F = top of mast

that it can be lowered for examination of the discharging point. The height of the point above the ground is 8·4 m. During practically the whole of the period under discussion the mast was supported by four wire guys fixed at half the height and 2·2 m. from the base. In November 1934 the base of the mast was fitted with counter-weight tackle and the guys were dispensed with.

The exposure in the immediate neighbourhood of the discharging system can be seen in Fig. 2, which also includes part of the recording hut. The ground on which the mast stands is in the Observatory paddock, and the Observatory building which is surmounted by a wind vane at a height of 23 m. is 50 m. away. There are two other masts which were used in another investigation in the same part of the paddock; both are 11 m. high and one is 30 m. and the other 80 m. from the point discharge mast. The hut in which the recording apparatus is housed is 20 m. from the mast and is 6 m. high.

The lead-covered cable runs underground to the recording hut where it is connected to one terminal of a galvanometer, the other terminal of which is earthed. The galvanometer, which is an Ayrton-Mather instrument of standard pattern with an undamped period of 1·5 sec. and a resistance of about 25 ohms, is critically damped by a shunt of about 25 ohms. resistance. During the period under review the sensitivity remained steady at 0·21 cm. per micro-ampere. Movements of the galvanometer coil are recorded photographically on a traversing clock drum, rotating once every two hours. Minute and hour marks are added by the intermittent lighting of a small lamp which is switched on by a relay in the circuit of the standard contact clock of the Observatory. The time-scale of the records is about 4 mm. per minute but owing to the poor quality of the last gear of the driving mechanism the speed of rotation of the drum varies appreciably from minute to minute.* The drum traverses 5 mm. per revolution and a margin of about 3 cm. width is left at the top and bottom of the record.

A daily test of the insulation of the apparatus is made by breaking the earth connexion of the galvanometer and inserting a small dry-cell and a suitable high-resistance; any deflexion of the galvanometer coil then indicates the presence of a leak to earth. Practically no trouble has been experienced with the insulation and there is no appreciable deterioration in wet weather.

§ 3—TYPICAL RECORDS

Two records showing discharge are reproduced in Figs. 3 and 4. It will be seen that they consist of twelve lines with short transverse time-marks; the records run from bottom to top and from left to right. An upward deviation from the straight line indicates a downward current, i.e. a flow of positive electricity into the point and, therefore, a positive potential gradient.

In Fig. 3 most of the discharge is associated with continuous rain; the discharge was comparatively small, however, when the heaviest rain occurred, at about 23h. 55m. It will be seen that there were many reversals in the sign of the current. The discontinuity in the trace at 8h. 4m. is due to a lightning flash; there are many such discontinuities to be seen in the second record, shown in Fig. 4, in which the discharge was associated with a thunderstorm. The storm passed within about 1 Km. of the observatory at about 20h. 10m.; the sudden field changes due to lightning are of various types, in some cases a positive field is

* The clock drum was replaced on September 10, 1935 by a new drum worked by a friction drive from a synchronous electric motor. A time scale of 5 mm. per minute has now been adopted as a standard for this branch of work.

FIG. 2 —POINT DISCHARGE MAST AND RECORDING HUT.

(The test-plate apparatus used in the earlier measurements of thunderstorm fields is to be seen on the side of the hut.)

FIG. 5 · EXPOSURE OF COLLECTOR OF HIGH-RANGE POTENTIAL GRADIENT RECORDER.

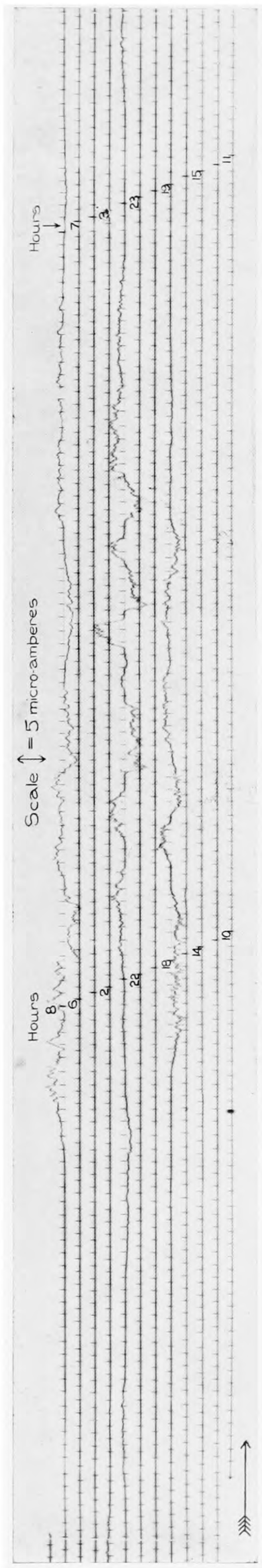

Fig. 3.—Point discharge record including periods of continuous rain, Kew Observatory, May 2 3, 1933.

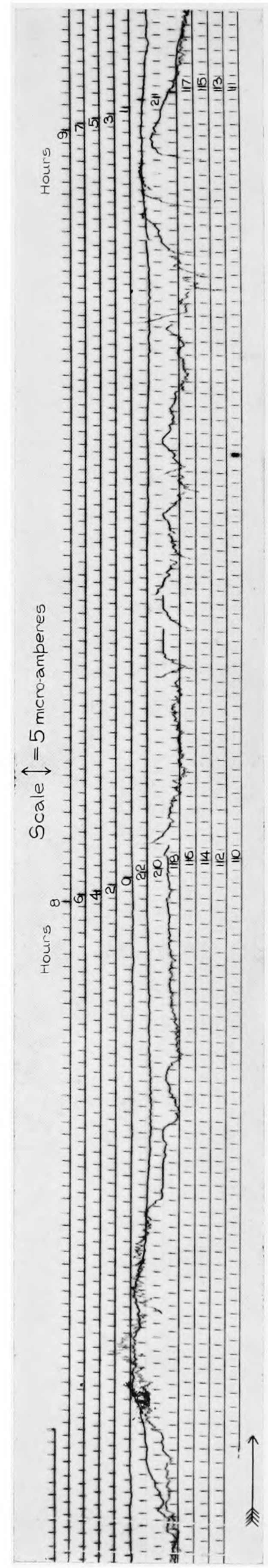

Fig. 4.—Point discharge record during a thunderstorm, Kew Observatory, June 15–16, 1933.

reversed to a high negative value; in others there is a reversal of negative field, whilst there are cases in which there is a sudden increase from a comparatively small field; a discussion of the effects of lightning is given later in the paper. The heaviest point discharge occurred before and after the main electrical disturbance; it was mainly outflow of positive electricity and was associated with fairly heavy rainfall.

For tabulating the records the average deviation upward and downward, over periods of 10 minutes are estimated and the integrated discharge (inflow and outflow) for periods of two hours obtained. Thus for the two records in question the values are as given in Table I. The integrated discharge is expressed in millicoulombs; on May 2—3 there was a net inflow of 1·91 millicoulombs whilst on June 15 there was a net outflow of 5·69 millicoulombs. It may be noted that

TABLE I—MEASUREMENTS OF POINT DISCHARGE FROM TWO TYPICAL RECORDS

Date	Hours G.M.T.	Discharge in millicoulombs		
		Inflow	Outflow	Net outflow
1933 May 2	12–14	—	0·03	+0·03
	14–16	—	0·04	+0·04
	16–18	0·02	0·39	+0·37
	18–20	0·71	0·71	0
	22–24	0·26	0·36	+0·10
May 3	0–2	2·53	1·04	−1·49
	6–8	0·75	—	−0·75
	8–10	1·27	1·06	−0·21
	Total ..	5·54	3·63	−1·91
1933 June 15	18–20	3·73	2·39	−1·34
	20–22	2·15	8·97	+6·82
	22–24	0·37	0·58	+0·21
	Total ..	6·25	11·94	+5·69

a current of one micro-ampere flowing for two hours would transfer a charge of 7·2 millicoulombs. The maximum discharge current recorded on May 3 was +5 micro-amperes at 0h. 27m.; if we exclude the large surges due to lightning the maximum current on June 15 was −9·5 micro-amperes. The largest current recorded during the period under review was −16 micro-amperes; this occurred during a violent storm on February 10, 1933 and the net outflow on that occasion was nearly 14 millicoulombs.(5).

§ 4—CONNEXION BETWEEN POINT DISCHARGE CURRENT AND POTENTIAL GRADIENT

During several thunderstorms in 1934 records were obtained of the potential gradient on an apparatus arranged to register the large and fluctuating fields associated with highly disturbed weather. The apparatus consists of a very efficient polonium collector at the end of a short rod projecting through the wall of the hut housing the point discharge recorder and connected to an insensitive Dolezalek electrometer. The latter is made dead-beat by means of an oil damper; the undamped period is about one second. A metal canopy is fixed above the collector partly to keep off rain and partly to reduce the field in a convenient ratio; a photograph showing the exposure of the collector is reproduced in Fig. 5. Comparisons with measurements made over level ground showed that in fine weather the voltage indicated by this recorder is 1/25 of that at one metre above the ground and the records have been interpreted on the assumption that the scale value is the same under disturbed conditions. The width of the chart is such that fields up to about ± 400 volts per centimetre (v./cm.) can be recorded. The efficiency of the collector is such that 90 per cent. of the full potential is reached in about 1·5 sec., the capacity of the system being 36 cm.; the apparatus is therefore sufficiently quick-acting to record the rapid field-changes due to lightning flashes, i.e. the field before the flash can be compared with the field 2 sec. after the flash. Since the time-scale and the time-marking system are the same as those used for the point discharge records a comparison between the two instruments is straightforward.

Comparisons between the records obtained during six thunderstorms have been made, the mean values of the point discharge current and the potential gradient over a minute being extracted. The readings were confined to those parts of the records in which rapid fluctuations were absent and altogether about 200 measurements from each instrument were compared. The results are shown in Fig. 6 in which the potential gradient is reduced to the value over level ground. There is a considerable scatter in the results but this is not surprising since the magnitude of the current entering the point is probably influenced by the conductivity of the air and by the wind strength as well as by the potential gradient. The rate of increase of the current with increasing potential gradient tends to become more rapid as the gradient increases; this is in accordance with laboratory measurements of point discharge current. The curves drawn through the points represent an empirical relation between the current i and the field F of the form

$$i = a\,(F^2 - M^2)$$

M is an estimate of the minimum field strength at which discharge takes place and a is a constant. For positive currents entering the point, i.e. in positive gradients, M is taken as 7·8 v./cm. and a as 0·0008 (the current being expressed in micro-amperes). For negative currents entering the point M is 8·6 v./cm. and a is 0·0010.

TABLE II—CONNEXION BETWEEN POINT DISCHARGE CURRENT AND FIELD-STRENGTH

Current micro-amperes	Deflexion on record, cm.	Field strength, v./cm.	
		Positive	Negative
0	0	< 8	< 7
1	0·21	36	33
2	0·42	51	45
3	0·63	62	55
4	0·84	71	64
5	1·05	79	71
7	1·47	94	84
10	2·1	112	100
15	3·15	137	123
20	4·2	158	142

Table II, which is based on the empirical curves, gives the field strengths corresponding to currents of various values. Before the alterations to the mounting of the point at the top of the mast were made in the autumn of 1933 the minimum field-strength necessary for discharge was estimated by Starr (5) to be approximately 12 v./cm. Apparently the alterations effected an improvement in the exposure of the point and we should expect the frequency of small discharges to be greater after the change was made. This was found to be the case and it will be referred to later when the observations are discussed.

It may be noted here that Starr's estimates of potential gradient were made by the use of apparatus which recorded the changes of potential of a horizontal plate exposed under a canopy and connected to a Kolhörster electrometer. A cover could be brought up from below to shield the plate at will; the external

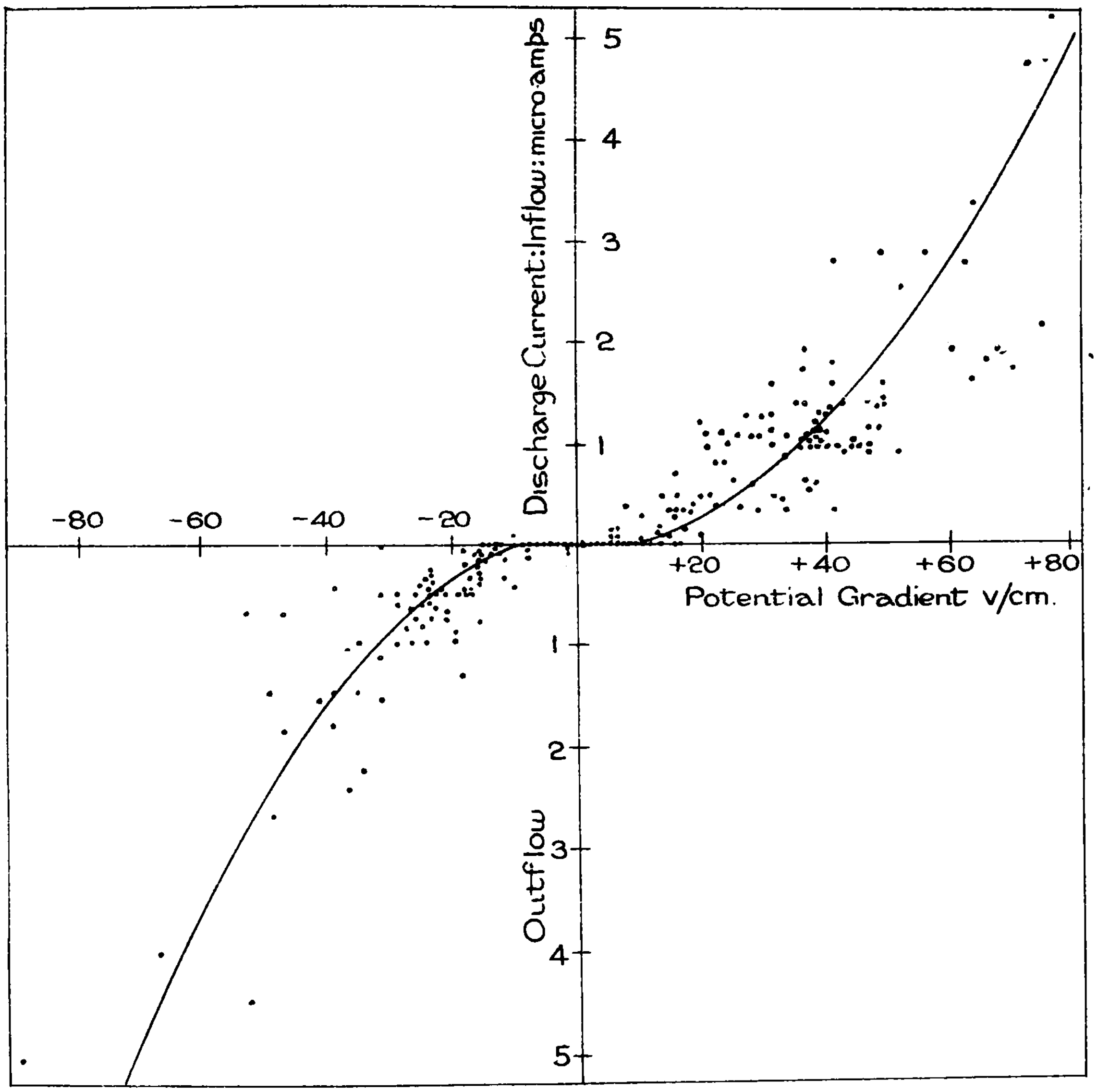

FIG. 6 — COMPARISON OF POINT DISCHARGE CURRENT AND POTENTIAL GRADIENT.

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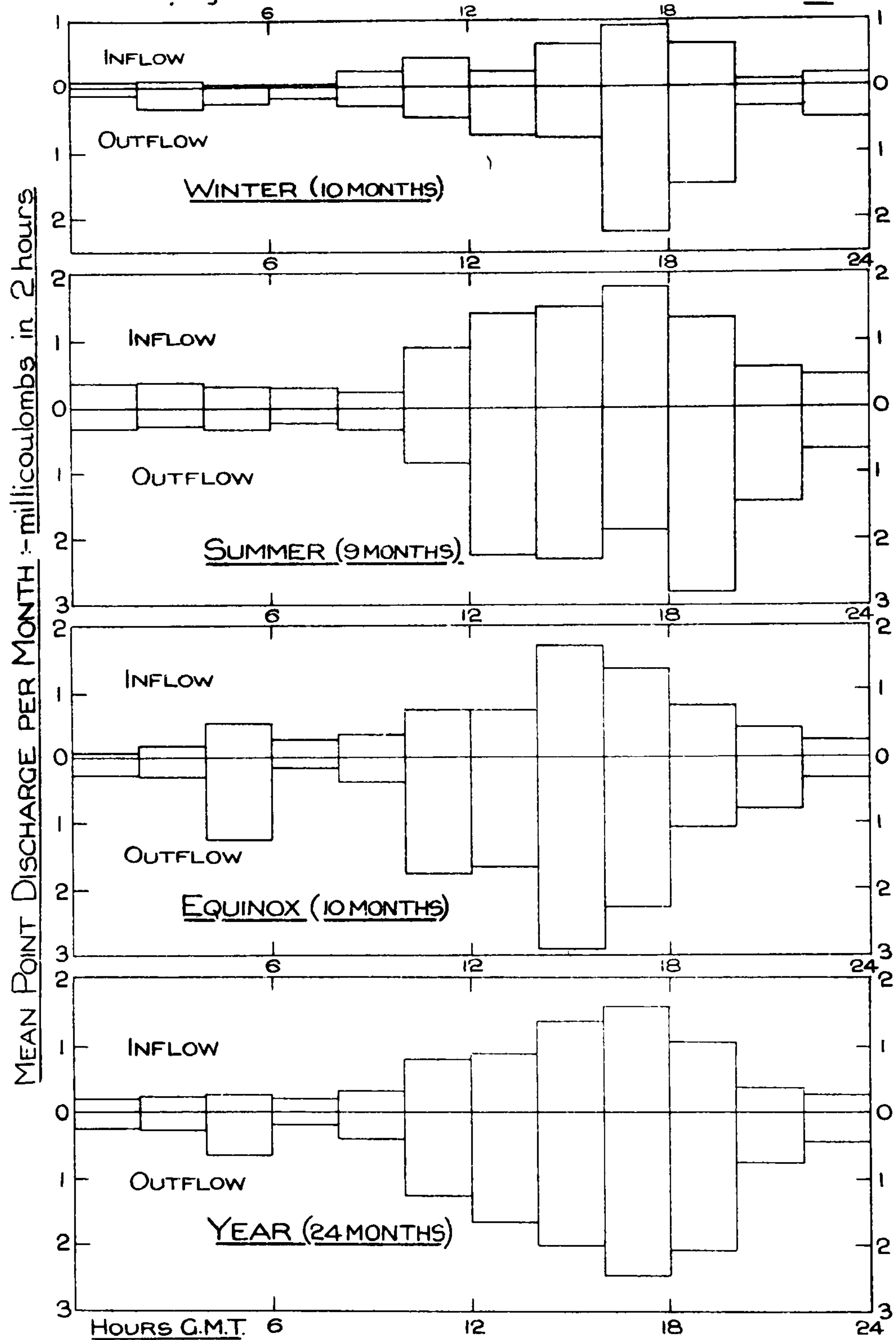

Fig. 7 — DIURNAL VARIATION OF POINT DISCHARGE AT KEW OBSERVATORY

parts of the apparatus are included in the photograph reproduced in Fig. 2. This apparatus suffered from the disadvantage that the plate acted as a collector for the air-earth current so that the changes of potential of the plate due to variations of potential gradient could not readily be separated from those due to the varying charge. C. T. R. Wilson encountered the same difficulty in using the exposed sphere and capillary electrometer in his investigations of the electric field due to thunderstorms. The difficulty is not entirely overcome by the use of the cover.

§ 5—RESULTS OF THE ANALYSIS OF THE RECORDS

The results of measurements of the point discharge records from August 1932 onwards have been analysed and the statistics for each month are summarised (6) in Table III. The inflow and outflow of positive electricity at the discharging point are estimated separately for periods of two hours, 0 to 2, 2 to 4, etc. and the quantities are expressed in millicoulombs.

The most striking feature of Table III is that although the figures for corresponding months show wide variations there is comparatively good agreement between the total discharges for the two complete years. In Table IV these totals are compared with values obtained by Wormell (7) at Cambridge. The net outflow

TABLE IV—TOTAL POINT DISCHARGE FOR A YEAR

		Millicoulombs			Ratio
		Inflow	Outflow	Net Outflow	Out/In
Cambridge	1927	140	280	140	2·0
	1928	120	240	120	2·0
Kew	1933	95	160	65	1·7
	1934	84	139	55	1·7

at Kew was about half that at Cambridge. This may be partly due to meteorological causes but it is important to notice that the exposure of the discharge point at Cambridge is much better than that at Kew : thus at Cambridge currents of about 3 micro-amperes were produced by fields of 30 v./cm. ; at Kew such fields would give less than one micro-ampere. The ratio of outflow to inflow at Kew was about 1·7 to 1 ; at Cambridge according to Wormell's observations, it was higher, namely 2·0 to 1. It must be remembered however that the voltameter method used by Wormell depends on measurements of the sizes of bubbles of gas and the accuracy claimed for the daily totals is only within $\pm$ 0·5 millicoulombs ; moreover a systematic error may have been introduced owing to the solubility of oxygen and hydrogen in water. The accuracy of the daily totals at Kew is within $\pm$ 0·03 millicoulombs so that the Kew value of the ratio in question is to be regarded as the more reliable.

The average current flowing from the air into the earth at Kew in fine weather is 104×10^{-18} amp. cm.$^{-2}$ (8), this represents an annual inflow of 0·0328 millicoulombs per square metre. An annual outflow of 60 millicoulombs from the discharge point is therefore sufficient to neutralise the total fine weather current for a year flowing into an area of 1800 m^2

The statistics given in Table III have been re-grouped according to the seasons, winter (November to February), summer (May to August) and equinox (September, October, March and April). For each season and for the year the mean values of the amount of discharge (in and out) per month have been extracted and these values are shown in Fig. 7. It will be seen that there is a well marked diurnal variation in all seasons, the maximum discharge taking place in the afternoon. In general the fluctuation between 20h. in the evening and 10h. in the morning

TABLE III.—POINT DISCHARGE. KEW OBSERVATORY.

Totals (for months and years) derived from measurements

Hours G.M.T.	0—2		2—4		4—6		6—8		8—10		10—12	
	In	Out	In	Out	In	Out	In	Out	In	Out	In	Out
1932												
August ..	0·33	0·09	0·50	0·86	1·69	2·05	0·89	0·49	..	..	0·41	0·04
September ..	..	..	..	..	..	..	..	..	..	..	..	..
October ..	..	0·75	0·33	1·07	0·58	0·67	0·05	0·53	..	0·26	0·03	0·18
November ..	..	..	..	..	..	..	..	..	..	..	..	..
December ..	..	..	..	..	..	..	..	..	..	..	..	..
Total ..	0·33	0·84	0·83	1·93	2·27	2·72	0·94	1·02	..	0·26	0·44	0·22
Net ..		+0·51		+1·10		+0·45		+0·08		+0·26		−0·22
1933												
January ..	..	0·24	..	1·71	0·03	0·56	..	0·27	..	..	..	0·27
February ..	0·30	0·37	0·01	0·24	..	0·79	0·03	0·79	0·44	0·96	0·22	1·19
March ..	..	0·03	0·46	0·96	0·14	0·11	..	..	0·32	0·57	0·69	0·57
April	..	..	..	..	..	..	..	..	..	..	0·47	1·45
May	2·53	1·04	..	..	0·98	0·99	0·89	0·08	1·27	1·06	..	0·02
June	..	..	..	..	..	..	..	..	0·03	..	3·52	2·62
July	..	0·92	..	0·06	..	..	0·38	0·81	..	..	1·72	1·76
August ..	..	0·03	..	..	..	..	..	..	..	..	..	0·23
September ..	..	..	0·06	..	0·40	0·37	0·86	0·52	0·37	..	1·50	3·43
October ..	0·78	1·09	0·06	..	..	..	..	..	..	0·55	..	2·25
November ..	..	..	..	..	0·03	0·46	..	..	..	..	0·66	1·50
December ..	..	0·20	..	0·03	0·03	0·12	..	0·03	0·09	0·03	0·06	0·03
Year ..	3·61	3·92	0·59	3·00	1·61	3·40	2·16	2·50	2·52	3·17	8·84	15·32
Net ..		+0·31		+2·41		+1·79		+0·34		+0·65		+6·48
1934												
January ..	0·55	0·15	..	0·03	..	..	..	..	0·60	0·64	1·73	0·17
February ..	..	..	..	..	..	..	..	..	0·48	0·26	0·52	..
March ..	..	0·06	0·49	0·20	1·24	8·33	0·20	..	0·21	0·37	..	4·55
April	0·03	0·55	0·23	0·03	1·58	3·00	1·44	0·69	2·28	2·02	3·29	5·01
May	0·03	0·03	..	..	..	..	..	0·06	0·26	0·17	0·58	0·40
June	0·35	0·87	2·16	0·63	..	..	..	..	0·03	..	0·03	0·40
July	..	0·03	0·63	1·04	0·20	..	0·58	0·84	0·52	1·87	0·78	1·64
August ..	..	..	..	..	..	..	..	..	0·06	..	1·06	0·52
September ..	..	0·03	..	0·29	..	..	..	..	..	..	0·12	..
October ..	..	..	0·26	0·26	1·10	0·55	..	..	0·21	..	0·95	0·40
November ..	..	0·14	0·92	1·12	0·26	0·63	..	..	0·14	..	0·60	0·55
December ..	..	0·14	..	0·20	..	..	0·17	0·55	0·40	1·03	0·38	1·09
Year ..	0·96	2·00	4·69	3·80	4·38	12·51	2·39	2·14	5·19	6·36	10·04	14·73
Net ..		+1·04		−0·89		+8·13		−0·25		+1·17		+4·69

is insignificant ; the subsidiary maximum at 4h.–6h. in the equinoctial values is due to the especially high discharge during heavy rain on March 14, 1934. The high afternoon maximum for the winter values is mainly due to the exceptional discharge which occurred in the notable storm of February 10, 1933, in which the maximum discharge current was —16 micro-amperes.

In Table V the seasonal and annual means of the total discharge per month are given. It will be seen that the discharge is considerably greater in summer

AUGUST 1932—DECEMBER 1934

of amounts passing in periods of two hours

Millicoulombs

12—14		14—16		16—18		18—20		20—22		22—24		Total.	
In	Out	In	Out	In	Out	In	Out	In	Out	In	Out	In	Out
0·51	3·44	1·22	4·17	..	..	..	..	0·17	0·96	1·47	1·73	7·19	13·83
..	..	0·03	0·30	..	..	0·83	0·30	..	..	..	..	0·86	0·60
..	0·90	2·92	4·57	1·14	2·70	0·33	0·36	2·60	4·99	0·52	1·27	8·50	18·25
0·31	0·38	..	..	0·04	..	0·06	0·11	..	..	..	..	0·41	0·49
..	0·01	..	..	..	0·04	..	0·12	0·01	0·01	..	..	0·01	0·18
0·82	4·73	4·17	9·04	1·18	2·74	1·22	0·89	2·78	5·96	1·99	3·00	16·97	33·35
..	+3·91	.. ..	+4·87		+1·56		−0·33		+5·18		+1·01		+16·38
..	0·67	0·09	0·38	..	..	..	1·44	..	..	0·01	0·09	0·13	5·63
0·09	4·27	3·09	4·42	5·05	17·28	4·48	8·69	0·06	1·62	0·23	0·55	14·00	41·17
2·28	4·39	1·12	1·76	3·00	4·50	0·88	1·67	0·05	0·14	0·05	0·19	8·99	14·89
1·18	1·33	0·48	1·35	1·10	0·58	1·53	1·41	0·03	..	..	..	4·79	6·12
0·68	3·43	2·29	5·66	1·50	2·51	1·32	0·97	..	..	0·26	0·35	11·72	16·11
1·29	2·72	3·80	4·24	5·87	5·27	4·79	4·10	2·15	9·09	0·37	0·58	21·82	28·62
2·78	0·94	1·86	1·76	4·56	1·34	0·98	7·03	0·67	0·44	1·20	2·27	14·15	17·33
0·26	1·50	1·18	2·39	0·43	0·46	0·03	0·12	..	0·40	..	0·03	1·90	5·16
0·23	1·41	0·20	0·23	0·03	..	..	..	0·12	0·32	..	..	3·77	6·28
1·44	3·06	3·02	2·19	2·25	2·94	..	..	1·35	2·02	1·21	0·03	10·11	14·13
0·12	0·06	0·03	0·09	0·03	0·03	0·03	0·72	0·23	0·14	..	..	1·13	3·00
..	..	0·03	..	0·61	0·26	1·19	0·81	0·12	..	0·03	..	2·16	1·51
10·35	23·78	17·19	24·47	24·43	35·17	15·23	26·96	4·78	14·17	3·36	4·09	94·67	159·95
	+13·43		+7·28		+10·74		+11·73		+9·39		+0·73		+65·28
0·81	0·40	0·69	0·35	0·49	..	0·03	0·03	0·23	0·40	0·54	2·44	5·67	4·61
..	..	0·09	0·15	0·87	0·86	..	..	..	..	..	..	1·96	1·27
..	1·82	3·45	6·54	0·61	3·72	..	3·88	0·06	0·32	0·12	0·40	6·38	30·19
2·02	3·78	4·00	11·35	5·07	8·01	3·48	2·85	..	0·06	0·49	1·24	23·91	38·59
0·14	0·06	0·51	0·03	0·03	..	0·06	0·03	..	..	..	..	1·61	0·78
0·12	1·01	..	..	0·81	3·05	0·55	8·81	1·76	1·21	0·89	0·52	6·70	16·50
3·02	4·75	1·32	2·07	1·84	1·35	3·72	3·68	1·76	0·86	..	..	14·37	18·13
3·83	2·41	1·49	0·52	1·47	2·70	0·78	0·69	..	..	..	0·26	8·69	7·10
..	..	0·09	0·03	0·03	..	0·29	0·26	0·03	0·09	..	0·03	0·56	0·73
..	..	1·58	0·95	0·15	0·43	0·26	0·03	..	..	0·06	0·03	4·57	2·65
0·13	..	1·67	2·16	1·18	1·30	0·29	2·19	..	..	..	0·49	5·19	8·58
0·69	1·50	0·52	0·09	0·98	2·22	0·09	0·52	0·23	0·95	1·13	1·30	4·59	9·59
10·76	15·73	15·41	24·24	13·53	23·64	9·55	22·97	4·07	3·89	3·23	6·71	84·20	138·72
	+4·97		+8·83		+10·11		+13·42		−0·18		+3·48		+54·52

and equinox than it is in winter. The difference would be even greater were it not for the large contribution to the winter discharge due to the storm of February 10, 1933; if the discharge on that day is omitted the winter means are reduced by about 20 per cent. The ratio of outflow to inflow is about 2·2 to 1 in winter and 1·8 to 1 in the equinox; in summer it is considerably smaller, viz. 1·4 to 1. It will be noticed from Fig. 7 that in summer at some hours of the day between 20h. in the evening and 12 noon the inflow exceeded the outflow; the equinoctial values show

TABLE V—AVERAGE POINT DISCHARGE PER MONTH AT KEW

	Number of months	Millicoulombs			Ratio
		Inflow	Outflow	Net Outflow	Out/In
Winter	10	3·53	7·60	4·07	2·2
Summer	9	9·79	13·73	3·94	1·4
Equinox	10	7·24	13·25	6·01	1·8
Year	24	7·45	12·46	5·01	1·7

the same effect at 6h.–8h.; in such cases the excess of inflow over outflow was quite small. In the winter months the outflow exceeded the inflow at all hours of the day. It is thought likely that in averages covering a large number of years there would be an excess of outflow at all hours and in all seasons.

The numbers of days on which the predominating flow (not the net flow), in or out, fell between specified limits have been counted and Table VI gives the frequencies for the seasons of the two years 1933–4 as well as the annual frequencies

TABLE VI—FREQUENCY OF DAYS WITH DISCHARGE BETWEEN SPECIFIED LIMITS AT KEW

The greater discharge, inflow or outflow. Millicoulombs	In two years						In one year			
	Winter		Summer		Equinox		1933		1934	
	In	Out	In	Out	In	Out	In	Out	In	Out
10 to 20	0	1	0	2	0	2	0	2	0	3
5 to 10	0	1	2	5	1	2	2	5	1	3
3 to 5	0	3	3	1	2	4	3	4	2	4
1 to 3	3	12	8	12	6	15	9	23	8	16
< 1	29	32	18	7	22	23	22	31	47	31
Total ..	32	49	31	27	31	46	36	55	58	57
Total ⩾ 1	3	17	13	20	9	23	14	24	11	26

NOTE.—In this table five days on which the estimates of inflow and outflow were equal (and < 1 millicoulomb) are omitted.

for each of these two years. For discharges of less than one millicoulomb the number of days of predominating inflow was very much greater in 1934 than in the previous year. This is partly due to the improvement in the exposure of the point when slight modifications were made in the autumn of 1933. As already mentioned the minimum field-strength necessary for discharge was found to be lower after the change was made and as a result of the change small discharges were recorded during comparatively undisturbed weather conditions when the potential gradient was positive but above about 8 v./cm. Thus, during the winter of 1933–4 there were 6 days on which slight discharge occurred during fog, which at Kew is often associated with gradients of 8–10 v./cm.; on 7 other days discharge was produced by the high gradients set up by pollution blown from London by NE. winds. The chief cause of the excessive number of days of inflow in 1934 was traced however to the effect of local atmospheric pollution produced by pile-driving operations which commenced at the end of 1933 and continued through the whole of 1934. These operations took place at Isleworth Ait about 500 metres to the west of the observatory and were the source of thick smoke clouds which, in favourable wind, caused high potential gradient at the observatory; on 14 days (2 in December, 1933) the gradient was high enough to cause point discharge. For these reasons two sets of totals are given in Table VI; one set includes all the discharges and in the other set the days on which the predominating discharge was less than one millicoulomb are omitted. When the small discharges re omitted the frequencies for the two years are in fairly good agreement and there is a predominance of outflow in all seasons.

For comparison with Wormell's statistics (9) the frequencies for the period of two years (1933–4) are given in Table VII together with Wormell's frequencies for the two years, 1927–8, at Cambridge. This table includes the few occasions,

TABLE VII—FREQUENCY OF DAYS WITH DISCHARGE BETWEEN SPECIFIED LIMITS AT KEW AND CAMBRIDGE.

The greater discharge, inflow or outflow. Millicoulombs	Kew, 1933–4			Cambridge, 1927–8		
	In	Out	Equal	In	Out	Equal
> 20	0	0	0	1	4	0
10 to 20	0	5	0	0	8	0
5 to 10	3	8	0	1	15	1
3 to 5	5	8	0	7	18	2
1 to 3	17	39	0	14	32	3
< 1	69	62	5	11	26	4
Total . .	94	122	5	34	103	10
Total ⩾ 1	25	60	0	23	77	6

omitted from Table IV, on which the net discharge was zero. It will be seen that the number of days of discharge of less than one millicoulomb is very much greater at Kew than at Cambridge but when these days are omitted the figures are in good agreement, the predominance of outflow being well-marked at both places.

§ 6—LIGHTNING DISCHARGES

The point discharge apparatus affords a very convenient means of recording the rapid fluctuations of field which occur in thunderstorms; some good examples of these fluctuations are to be seen in the record reproduced in Fig. 4. The effect of a lightning discharge in the neighbourhood is to cause a sudden change in the point discharge current, followed by a more or less gradual recovery. It is not proposed to discuss here the effects associated with individual storms; such a discussion is reserved for a future date when it is hoped to include information obtained from other apparatus. For the present it is considered sufficient to give some statistical results obtained from an analysis of the effects of lightning discharges on the point discharge records.

C. T. R. Wilson (10) compared the magnitude of field changes with the distance of lightning discharges and found that the field change decreased with distance, the rate of decrease becoming smaller with increasing distance. An analysis of the sudden changes in discharge current produced at Kew by about 50 flashes, for which the time interval between the thunder and lightning had been observed, showed a roughly similar relationship between the magnitude of the change and the distance of the flash. It was found that the smallest amplitudes which could be measured with any accuracy, viz. 1 mm. on the trace (i.e. 0·5 micro-amperes) were associated with flashes at a distance of about 5 Km. This distance may be taken as the maximum range at which useful records of lightning discharges can be obtained with the apparatus in use at Kew.

During the period of 29 months under review there were 48 days on which thunder or lightning was observed at Kew but on 20 of these days no effects of lightning discharges were detected on the records; presumably the discharges took place beyond the range of the apparatus. For the remaining 28 days a total number of about 560 flashes were recorded; this represents an annual frequency of roughly 220 flashes within a radius of 5 Km. or in an area of 80 Km^2. For storms within this radius the average number of flashes in each storm was 20; the largest number of discharges recorded in one storm was 111, on July 24, 1934. The estimate of 3 flashes per Km^2. per annum may be compared with the estimate of 5 flashes adopted by Wormell in his discussion of the exchange of electricity between the earth and the atmosphere. Wormell utilised the known frequency of days on which thunder is reported at the climatological station at Cambridge, 12 per annum, and based an estimate on Brooks' surmise that "thunder is audible from all storms in an area of 200 square miles and that an average storm produces 200 flashes." On the same basis, reckoning 20 as the annual frequency of days with thunder at Kew we should have derived the estimate 8 flashes per Km^2 per annum, nearly three times the estimate based on the autographic records. It is clear that a reliable average is not to be obtained without a long series of observations.

In Table VIII the discharges have been classified into various types; there are three main classes depending on whether the preliminary field was positive, negative or indeterminate and further sub-divisions depending on whether the

TABLE VIII—ANALYSIS OF FREQUENCY OF LIGHTNING DISCHARGES (JULY, 1932–DECEMBER, 1934)

Type	Preliminary Field	Field Change	Frequency
pP	Positive	Positive	56
pND		Negative (diminishing +field)	38
pNR		Negative with reversal	27
nN	Negative	Negative	35
nPD		Positive (diminishing −field)	105
nPR		Positive with reversal	146
sP	Small and indeterminate	Positive	130
sN		Negative	25
		Total ..	562

Preliminary Field		Field Change		Field Change (preliminary field appreciable)	
Positive *p*	121	Positive *P* ..	437	Increase (*P* or *N*) ..	91
Negative *n* ..	286	Negative *N* ..	125	Decrease *D* ..	143
Indeterminate *s* ..	155			Reversal *R* ..	173
	562		562		407

temporary change of field was positive or negative and whether it entailed a reversal of the preliminary field. Thus type *nPD* represents a negative preliminary field followed by a positive field change less than the initial field whilst type nPR indicates a negative preliminary field followed by a positive field change large enough to reverse (temporarily) the initial field. In all of the eight types the sudden field change is followed by an asymptotic recovery, within a few seconds, of the field to roughly the initial value. There were no cases in which the sudden change was followed by an asymptotic change in the same direction.

The figures in Table VIII show that the ratio of the number of discharges causing a positive field change to the number causing negative field change is 3·5; such a preponderance of positive field changes in near thunderstorms has been well established by numerous investigators. The preliminary field just before a lightning flash was more often positive than negative, the ratio being about 2·4 but there were a large number of cases in which the preliminary field was too small (less than 8 v./cm.) to cause point discharge.

There is something paradoxical about these statistics. On any theory of the nature of a thunderstorm it must be supposed that the charge increases in one part or another of a cloud until the electric force becomes so great that a spark takes place. The discharge produces a reduction in the electric force where it was excessive. What effect is to be expected in the strength of the electric force near the ground? It is natural to expect a reduction. In so much as in cases in which the previous field is appreciable a decrease of the field is more frequent than an increase, this expectation is met by the statistics. It is surprising however to find that in this class of cases a reversal of the field is as frequent as a mere reduction and moreover that there is another very large class of cases in which the field which was previously too weak to produce point discharge becomes appreciable after the lightning. Some light is thrown on these questions by consideration of the distribution of space-charge in the atmosphere.

§ 7—SPACE-CHARGE BLANKET

A mathematical theory of the distribution of electrification in the space below a cloud was sketched by Wilson (11) in 1925. The theory is based on simplifying assumptions which must be clearly realised. These are (1) the vertical field is uniform over an area of dimensions great compared with the height of the base of the thunder-cloud, (2) the whole of the space-charge is carried by small ions produced by point discharge

The first of these assumptions is not in violent disagreement with the truth in the case which Wilson had in mind, the discharge from blades of grass. On the other hand discharge from the tops of trees must be accompanied by great distortion of the electric field. The lines of force are indicated by the streamers of St. Elmo's Fire. With trees and low buildings of a height such as 10 metres, the irregularities of the field may perhaps be smoothed out at a height of 50 metres. For the space between this height and the base of the cloud Wilson's first assumption is reasonable.

As to the second assumption it is to be remembered that under normal conditions the large ions far outnumber the small ions though on account of the high mobility of the small ions the air-earth current is mostly carried by them. The assumption that in disturbed weather the space charge is carried by small ions requires further examination.

Following Wilson we now consider the case in which the cloud can be regarded as a uniformly charged horizontal sheet. The potential at height h is V and the density of the space-charge at that height is ρ. Conditions are steady and there is a current of strength i flowing from the ground to the cloud.

If V is expressed in volts, ρ in coulombs per cubic centimetre and h in centimetres, Poisson's equation takes the form

$$\frac{\partial^2 V}{\partial h^2} = -4\pi\zeta\rho \qquad \text{(i)}$$

where* $\zeta = 9 \times 10^{11}$.

The charge being carried by ions of one sign with mobility k the current is such that

$$i = -k\rho\frac{\partial V}{\partial h} \qquad \text{(ii)}$$

Combining these two equations we find that

$$4\pi\zeta i = k\frac{\partial V}{\partial h} \cdot \frac{\partial^2 V}{\partial h^2} \qquad \text{(iii)}$$

The integral of this equation is

$$k\left\{\frac{\partial V}{\partial h}\right\}^2 = 8\pi\zeta i(h+c) \qquad \text{(iv)}$$

where c is constant.

Hence
$$V = \left\{\frac{32\zeta i}{9k}\right\}^{\frac{1}{2}}\left[(h+c)^{\frac{3}{2}} - c^{\frac{3}{2}}\right] \qquad \text{(v)}$$

and
$$\rho = -\left\{\frac{i}{8\pi\zeta k}\right\}^{\frac{1}{2}}(h+c)^{-\frac{1}{2}} \qquad \text{(vi)}$$

The time taken by a small ion to travel from a point at $h = o$ to the height h is

$$\int_o^h \left\{k\frac{\partial V}{\partial h}\right\}^{-1} dh \text{ or } \frac{(h+c)^{\frac{1}{2}} - c^{\frac{1}{2}}}{(2\pi\zeta i k)^{\frac{1}{2}}} \qquad \text{(vii)}$$

Wilson applied the formulæ to the case in which the electric force just below the cloud was 3×10^4 v./cm., which he assumed to be nearly the sparking value, whilst the force near the ground was comparatively small. W. A. Macky's (12) experiments on the discharge from water drops in high fields indicate that the sparking value of the field in a thunder cloud may be more like 1×10^4 v./cm. Using this value with $h = 2$ Km. $= 2 \times 10^5$ cm., c small compared with h, $k = 1{\cdot}0 \dfrac{\text{cm./sec.}}{\text{v./cm.}}$ equation (iv) gives $i = 0{\cdot}22$ amp./Km^2. Schonland (15) has recently used the same formulæ but started from the assumption that the potential of the cloud sheet at a height of 2 Km. was 10^9 volts. He adopted $k = 1{\cdot}5 \dfrac{\text{cm./sec.}}{\text{v./cm.}}$ and deduced from an equation equivalent to (v) that $i = 0{\cdot}16$ amp./Km^2.

In accepting this result as a basis of further discussion Schonland remarks that currents of this magnitude have been found by himself and by Wormell below active storms. This statement must be accepted with some reserve. Wormell counted the trees that were higher than his discharge point and estimated that there were 800 per square kilometre and he adopted the working hypothesis that the total current could be found by simple multiplication. The strongest current he recorded was 15 micro-amperes so that according to his hypothesis the maximum rate of discharge was $0{\cdot}012$ amp./Km^2.

Schonland observed a maximum current of $4{\cdot}5$ micro-amperes from his tree and estimated that the number of trees per square kilometre was 4×10^4. On this basis the maximum current was $0{\cdot}18$ amp./Km^2.

Thus the calculated amount $0{\cdot}16$ amp./Km^2 is in good agreement with Schonland's own observations but the support from Wormell's work is not very strong. Wilson's assumption that the electric field just below the cloud is everywhere on the verge of producing sparking gives a reasonable value for the current when the

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* There is no generally recognised symbol for the constant here called ζ. It may be noted that $\zeta = c^2.10^{-9}$, c being the velocity of electromagnetic waves in cm./sec. and also that in electrostatic measure 1 farad. = ζ cm.

sparking field is taken to be 10^4 v./cm. and not, as he assumed, 3×10^4 v./cm. From Schonland's data we find the potential gradient just below the cloud to be 6000 v./cm. According to his observations in South Africa the current of 0·16 amp./Km^2 would correspond with a gradient of 160 v./cm. near the ground so that it is suggested that the ratio of the charge in the air to the charge on the ground would be 5840 : 160 or 35 : 1.* The value of the constant c, found by putting $h = 0$ and $\frac{\partial V}{\partial h} = 160$ v./cm. in equation (iv), is 1·4 metres but this is a detail of little interest since the mathematical analysis is not valid for expressing conditions near the discharge points and 1·4 metres is a small length in comparison with the scale of the array of points.

The time taken by a small ion to travel from a discharge point to the cloud can be found from equation (vii). With $h = 2$ Km., c negligible, $i = 0{\cdot}16$ amp./Km^2 and $k = 1{\cdot}5 \frac{\text{cm./sec.}}{\text{v./cm.}}$ the time is 40 seconds. This is comparable with the life of a small ion in air under ordinary conditions : the assumption that all the small ions can travel up to the cloud without colliding with condensation nuclei is therefore not justified. No doubt many large ions with multiple charges are formed by such collisions. As these large ions are much less mobile than small ions the effect must be to retard the passage of electricity from the discharge points to the cloud and to increase the space-charge. It is not practicable however to calculate the magnitude of this effect.

If the cloud could be replaced by a conductor, the potential gradient below the cloud remaining the same, then the surface density of the electricity on the conductor could be defined by the equation

$$\frac{\partial V}{\partial h} = 4\pi\zeta\sigma$$

This value of σ may be referred to as the effective charge per unit area of the cloud.

Using Schonland's data we have $\frac{\partial V}{\partial h} = 6000$ v./cm. and

$$\begin{aligned} \sigma &= 5 \times 10^{10} \text{ coulombs/cm.}^2 \\ &= 5 \text{ coulombs/Km.}^2 \end{aligned}$$

For comparison we note that the amount of electricity discharged by a lightning flash is of the order 20 coulombs.

Wilson's analysis is adapted only for the simple case of a uniformly charged and widespreading cloud. In reality we are confronted with clouds covering a limited area and the charge is certainly by no means uniformly distributed. Moreover the part played by rain is ignored.

It is instructive however to consider what would be the result of a lightning flash between the wide-spreading cloud and the ground. We may think of the effective charge as distributed in packets of 20 coulombs each covering an area of 4 square kilometres. The flash deprives the cloud of one of these packets of electricity. A fraction of the charge neutralises the space charge throughout the large volume into which the flash branches, the remaining fraction passes into the ground. Let us consider what change takes place in the electric field near the ground in the neighbourhood of the flash.

Let σ be the initial effective charge per unit area of the cloud and $-\sigma'$ the initial charge per unit area in the space below the cloud. Let Q be the quantity of electricity lost by the cloud from a volume centred at a height h and $-Q'$ the quantity of space charge which is neutralised, the centre of the space occupied having been at a height h'. Let F_0 and F_1 be the initial and final potential gradients

* It will be noted that the gradient 160 v./cm. is of the same order as the strongest gradient at Kew.

at a point on the ground in the neighbourhood of the place struck by the lightning. We have the equations

$$F_0 = 4\pi\zeta(\sigma-\sigma')$$

$$F_1 = 4\pi\zeta(\sigma-\sigma') - \frac{2Q\zeta}{h^2} + \frac{2Q'\zeta}{h'^2}$$

and
$$F_0 - F_1 = \frac{2Q\zeta}{h^2} - \frac{2Q'\zeta}{h'^2}$$

With $Q = 20$ coulombs and $h = 2{\cdot}5$ Km. $= 2{\cdot}5 \times 10^5$ cm.
we find that $2Q\zeta/h^2 = 575$ v./cm.

Let us suppose that the initial field, as in Schonland's example, was 160 v./cm. and that this field was reversed by the discharge. Further let us suppose that $h' = 1$ Km. : it follows that

$$320 \text{ v./cm.} = 575 - 2Q'\zeta/h'^2$$

$$Q' = 1{\cdot}4 \text{ coulombs.}$$

Thus it appears that in this rather artificial case 7 per cent. of the electricity discharged from the cloud is used in neutralising the space charge. If none had been used in this way there would have been a reversal from 160 v./cm. to −415 v./cm. The reversed field is due of course to the space charge which remains after the flash. In practice it is found that the reversal of the field is usually of short duration ; this is due, in part, to the efficiency of point discharge which temporarily feeds into the air ions of the sign opposite to the existing space charge. The recovery is also encouraged by the process, whatever it may be, that is charging up the cloud.

The idea has been entertained that it might be practicable to use the records of potential gradient to determine the rate at which electricity is supplied to the atmosphere by point discharge, the weak part of Wormell's calculation being avoided. It appears however that there are too many other processes at work and that the effect of point discharge can not be isolated.

The theory of space charge provides an explanation in general terms of the cases in which a lightning flash produces a reversal of field. There is a large class of cases in which the lightning flash increases the strength of the field without any change of sign. Various explanations can be imagined. For instance it may have happened that there was a positively charged portion of the cloud overhead, a negatively charged portion some distance away. The resultant field was positive but small. The negative charge was discharged to earth and the field due to the positive charge above remained. A similar explanation can be given for the numerous instances in which the preliminary field was small and indeterminate and a positive change occurred. The observations can also be explained in terms of discharges within the cloud. Suppose that there are three charged regions in a cloud, two at the bottom of opposite signs, one at the top with a positive charge. A flash occurs between the latter charge and the negative charge at the bottom of the cloud. Below the other positive charge there is an increase in the strength of the positive field. Numerous observations of flashes would be needed to determine which type of explanation is more frequently valid.

In connexion with the discussion of Wilson's theory of space charge it has been mentioned that the electric field immediately over an array of discharge points must be far from uniform. It is not easy to picture just what happens but presumably the streams of ions from the individual points spread out as brushes and retain their individuality to a great height. Turbulence in the atmosphere will blend the streams eventually.

The air-earth current over level ground has not yet been measured during a thunderstorm ; there is however information about ionization and conductivity. At Kew Observatory apparatus was in continuous operation during 1933 for recording these elements. Mr. Starr, who examined the records obtained during thunderstorms found no abnormality in mean values over 5 minute intervals, but there were slight indications of temporary changes of conductivity associated with lightning flashes and lasting but a few seconds. The conclusion is that during the greater part of the time that point discharge from elevated points is going on the conduction current through the air near the ground is but moderate.

Consider for example a rectangular array of discharge points at intervals of 25 metres. This corresponds very roughly to the state of things at Kew. With a gradient of 80 v./cm. the discharge from each point is 5 micro-amperes. On the other hand the air-earth current over the flat ground is 80×10^{-16} amp./cm. and therefore the current over a square of side 25 metres is 0·05 micro-amperes. Accordingly the current passing through the ground is only one hundredth of the current from the points. Of course this very rough calculation can only give an order of magnitude but the picture of the isolated brushes of point discharge need not be modified seriously on account of such flow as is independent of the points.

§ 8—POINT DISCHARGE AS A FACTOR IN THE CIRCULATION OF ELECTRICITY THROUGH THE ATMOSPHERE

That point discharge was probably an important factor in the exchange of electricity between the atmosphere and the earth was stated by C. T. R. Wilson in 1920. This suggestion is supported by the observations at Kew as well as by the pioneer work of Schonland in South Africa and of Wormell at Cambridge. Wormell made rough estimates of the quantities of electricity conveyed in the course of a year from the atmosphere to a square kilometre of ground by four processes, fine weather current, precipitation, lightning and point discharge. The first of these estimates was based on the assumption that the air-earth current was 2×10^{-16} amp./cm². This is in accordance with the statistics usually quoted in the text books but these are derived from the erroneous hypothesis that the air-earth current can be found by multiplying the potential gradient by the sum of the conductivities for positive and negative electricity whereas the correct value is found by multiplying the potential gradient by the positive conductivity alone. The value 1×10^{-16} amp./cm.² is in accordance with the direct measurements of the current.

With this amendment Wormell's table becomes :—

Electricity transferred from atmosphere to one square kilometre of ground in one year

Fine weather current	..	+ 30 coulombs.
Precipitation ..	..	+ 20 ,,
Lightning ..	..	− 20 ,,
Point discharge ..	..	−100 ,,

As Wormell writes. "The estimates are admittedly very rough ones: it would appear however to be quite possible that the four processes balance one another approximately or even that in this locality the earth on the whole gains a negative charge."

To establish Wilson's theory it will be necessary to demonstrate that above the storm clouds negative potential gradient predominates so that a positive current flows up from the clouds to the highly conducting layers in the upper atmosphere, this upward current compensating the downward current of fine weather. It may be mentioned here that a series of balloon soundings to determine the sign of the potential gradient in and above the clouds is now in progress at Kew Observatory.

Further evidence that there is a physical connexion between the air-earth current of fine weather and the transfer of electricity between the ground and the clouds in disturbed weather is provided by the diurnal variation of the phenomena. The diurnal variation in the potential gradient of fine weather over the oceans and in the polar regions was found by Mauchly and by Hoffmann to depend on universal time, the gradient having maximum and minimum values at about 19 h. and 4 h. G.M.T. As the parts of the world in which this type of diurnal variation is found are those in which the conductivity of the lower atmosphere is probably nearly constant throughout the day it is likely that the air-earth current varies with the potential gradient and that the potential of the Kennelly-Heaviside layer varies in the same way.

It was pointed out by Appleton in 1924 (13) that this could be explained by the effect of thunderstorms; over land areas thunderstorms are most numerous in the late afternoon; further, the land areas are irregularly distributed in longitude, and the areas famous for thunderstorms, central Africa and South America, are not far from the longitude of Greenwich. Thus it is to be expected that the action of thunderstorms in conveying electricity into the upper atmosphere will be most vigorous when it is late afternoon at Greenwich.

This was borne out by a closer analysis (14) in which statistics of thunderstorms over the whole globe were utilised. In this analysis the following scheme (Table IX) was adopted for the diurnal variation of thunderstorm frequency by local time. The table was based on observations in south India and central Europe.

TABLE IX

Local Time	0–2	2–4	4–6	6–8	8–10	10–12	12–14	14–16	16–18	18–20	20–22	22–24
Relative frequency of thunder storms.	4	3	2	1	2	5	15	25	19	12	7	5

These numbers are plotted in Fig. 8 for comparison with the results of the observations of point discharge at Kew Observatory. The resemblance between the two diagrams in this figure is striking. If the Kew observations are typical the diurnal variations in the quantities of electricity transferred to the atmosphere is in step with the diurnal variation in the frequency of thunderstorms. It was not obvious that this would be the case for there is a great range in the efficiency of storms and a considerable proportion of the point discharge occurs without the development of thunderstorms.

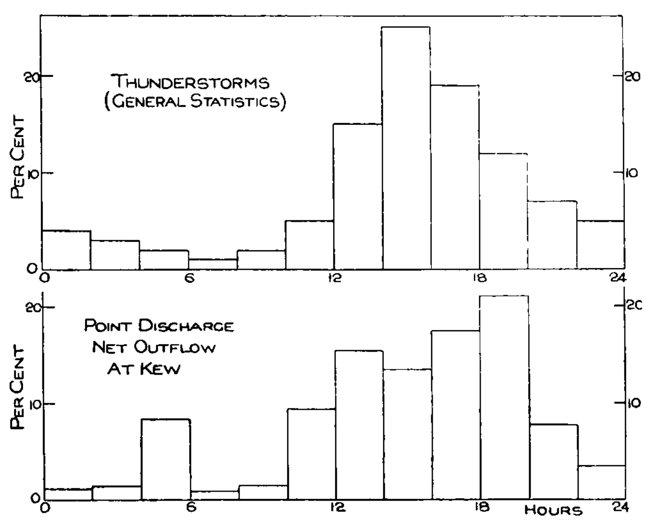

Fig. 8.—Comparison of the diurnal variation of thunderstorms (according to statistics) and of net point discharge (according to two years' observations, 1933–4 at Kew).

A rough measure of the activity of thunderstorms in all parts of the world is the area in which storms are in progress. We may regard a place as having been in a thunder area at a specified time if thunder was audible in the interval from 60 min. before to 60 min. after that time. The area can be calculated by evaluating the integral in the equation

$$F(t) = \int \frac{n}{N} \frac{f(t-l)\, dS}{100}$$

$F(t)$ being the total area over which storms occur on the average on a given day within the two hours centred at Greenwich time t, whilst n is the average number of days with thunderstorms in the course of a season of N days at a given place in longitude l. $f(t)$ is the percentage of storms occurring within the two hours centred at local time t and dS is the element of area.

The values of the function f can be taken from Table IX. For our purpose the values of n were derived from maps kindly lent by Dr. C. E. P. Brooks. In the earlier paper the integrals covered the whole globe and referred to seasons of six months as well as to the whole year. The integrals for four segments of the globe have now been evaluated separately.

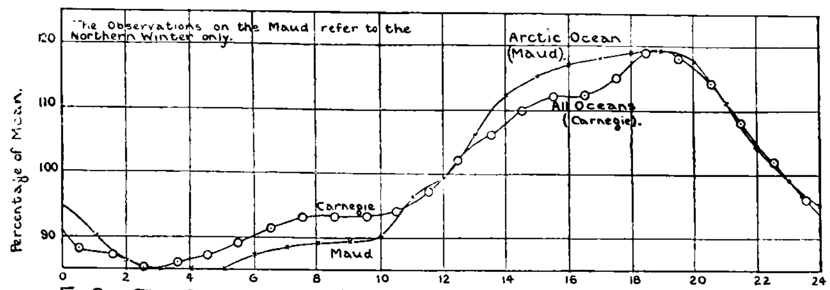

Fig 9a.—The Diurnal Variation of Potential Gradient over the Oceans.

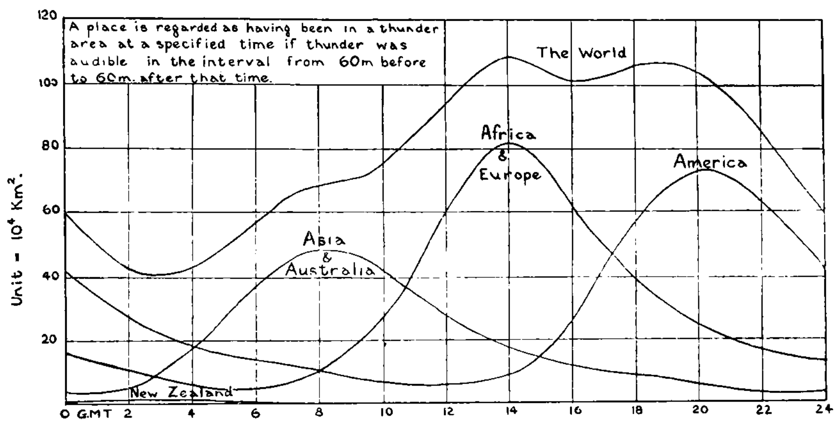

Fig 9b.—The Diurnal Variation of Land Thunder Areas.

The curve marked New Zealand refers to the segment between 120°W. and 150°E.
" " " Asia & Australia " " " " " 150°E. and 60°E
" " " Africa & Europe " " " " 60°E and 30°W
" " " America " " " " " 30°W. and 120°W

In Fig. 9b four curves represent the variation in the course of the Greenwich day of the activity of thunderstorms over the land areas in four segments of the globe. The resultant variation of the activity over the land areas of the whole globe is represented in the same way by the uppermost curve. There is no good evidence for diurnal variation in the frequency of thunderstorms at sea, so that to allow for such storms we must add a constant representing the "sea thunder areas" to the variable "land thunder areas" of Fig. 9b. The constant may be taken as 111×10^4 Km.^{2} to agree with Brooks' statistics. For comparison the variation of the potential gradient of fine weather over the ocean and arctic regions is illustrated in Fig. 9a. The agreement between these diagrams confirms Appleton's explanation of the Hoffmann-Mauchly phenomena and provides support for Wilson's theory.

§ 9—ACKNOWLEDGMENTS

The first measurements of point discharge to be made at Kew Observatory were with voltameters of Wormell's type set up by Mr. P. A. Sheppard. Subsequently Sheppard planned the arrangements for obtaining continuous records and the apparatus was nearly ready for operation when he was called away to join the British Polar Year Expedition. The apparatus was taken charge of by Mr. L. H. Starr who measured the records for the latter part of 1932 and for most of 1933.

The remaining records have been measured by Mr. L. C. Burridge. We are glad to have the opportunity to acknowledge our indebtedness to these colleagues.

§ 10—SUMMARY

The apparatus used at Kew Observatory for recording point discharge in the atmosphere is described in detail and two typical records, illustrating the effects associated with continuous rain and with thunderstorms, are discussed.

The connexion between potential gradient and point discharge current is investigated, and it is found that above a critical minimum value of the field the current is roughly proportional to the square of the gradient.

The main part of the paper deals with the results of an analysis of continuous records obtained during a period of 29 months. Outflow of positive electricity from the point exceeded inflow in the ratio 1·7 : 1 and the net outflow amounted to about 60 millicoulombs in a year. There is a well-marked diurnal variation in all seasons, the maximum discharge taking place in the afternoon.

A statistical analysis of the sudden field changes caused by lightning flashes showed a preponderence of positive over negative changes in the ratio 3·5 : 1. There were a large number of cases in which the preliminary field just before a flash was very small (not much greater than the fine weather field). When the preliminary field was appreciable a reversal of the field was as frequent as a mere reduction.

Some speculations on the effect of a space charge blanket on the vertical distribution of field below thunder clouds are put forward in explanation of results obtained in the investigation. The importance of point discharge as a factor in the exchange of electricity between the atmosphere and the earth is discussed.

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