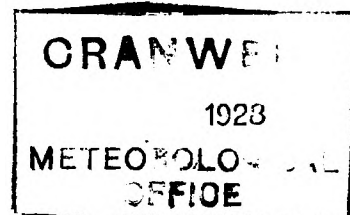


METEOROLOGICAL OFFICE

GEOPHYSICAL MEMOIRS No. 38
(*Eighth Number of Volume IV*).



Electric Potential Gradient Measurements at Eskdalemuir

1913-23

By R. A. WATSON, B.A.

Published by Authority of the Meteorological Committee



LONDON :

PUBLISHED BY HIS MAJESTY'S STATIONERY OFFICE

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Adastral House, Kingsway, London, W.C. 2 ; 120, George Street, Edinburgh ;
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1928

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ELECTRIC POTENTIAL GRADIENT MEASUREMENTS

AT

ESKDALEMUIR, 1913-23

PART I—THE METHOD OF MEASUREMENT

§1. THE OBJECT OF THE PAPER.

Since the start of the Observatory at Eskdalemuir (lat. $55^{\circ} 19' N.$, long. $3^{\circ} 12' W.$) the electric potential at a point near the north wall has been recorded continuously by means of a Kelvin water-dropper connected to a Dolezalek electrometer. The results have been published each year in the *British Meteorological and Magnetic Year Book*¹, or since 1922 in *The Observatories' Year Book*². Dobson³ discussed the results of the first two years' observations. The object of the present paper is to summarize the results for the eleven year period 1913-1923 and to make available other work done which does not find a place in the *Year Book*.

§2. THE INSTRUMENT AND ITS ENVIRONMENT.

The Observatory buildings are placed on a rising shoulder of moorland at the head of the valley of the Esk and about 800 feet above mean sea level. This shoulder lies in the main valley but is raised some hundred feet above the narrow strip of level ground on the banks of the river. The water-jet pipe projects from the north wall of the main building and the water jet itself is double, *i.e.*, it consists of two parts issuing from holes one on either side of the nozzle in such a way that the plane of the jet is parallel to the wall and at a distance of 30 cm. therefrom. A shallow tank within the building contains the water supply for the jet, the head of water varying during the day from 1.73 metres to 1.59 metres. The insulated tank and jet system is connected to the needle of a Dolezalek electrometer, the quadrants of which are maintained at a constant potential difference by means of two or four Weston cadmium cells. The deflections of the electrometer are recorded on photographic paper with a time scale of 2 cm. to the hour and zero marks are made three or four times a day by earthing the tank. No material change has been made in the arrangement of the instrument or in its surroundings during the period considered and the annual change due to the growth of vegetation on the bare moorland surroundings is slight.

§3. THE REDUCTION TO READINGS IN THE OPEN.

To facilitate comparison with other stations it is customary to reduce the potential recorded at the point where the water jet breaks into spray to the potential which would be recorded one metre above level ground. The absolute observations required for the determination of the appropriate reduction factor are made on a level lawn some 20 or 30 yards distant from the jet. A small pit in the centre of this lawn provides accommodation for a Wulf bifilar electrometer and sufficient working space for the observer. From the electrometer a thin metal rod projects upwards through a small hole in the flat metal lid of the pit and carries at its upper end, one metre above the ground, a slow burning fuse. A comparison of the readings of the Wulf electrometer with the simultaneous records of the water dropper gives the reduction factor.

¹ See References on page 16.

Its value has varied somewhat with slight alterations in the position of the nozzle but has remained about 6, *i.e.*, the potential "at one metre in the open" is six times the potential at the nozzle. The method assumes that all bodies in the neighbourhood are sufficiently conducting to equalize potential differences within a very short interval of time and either that there are no electric charges in the air or that these charges are uniformly diffused over distances several times greater than the distance separating the two points where the potential is measured. The approximate constancy of the reduction factor, determined several times each month, and the absence of any diurnal variation (though observations were not actually made in hours of darkness) suggests that these assumptions are not far from the truth, but minute-to-minute observations do vary somewhat more than can be accounted for by errors of reading. Two sets of observations are worthy of notice in this connexion.

On one occasion the Wulf electrometer was taken to the top of a neighbouring hill 400 feet above the water-dropper and about 1,400 yards distant; 100 half-minute readings were taken and compared with readings from the water-dropper which had been arranged to give a "quick run" (4mm. to the minute). During this time a steady and proportionate rise of potential occurred at both places, but superimposed on this were the usual short period variations, and not only was there no correlation between the synchronous variations at the two places, but also, the eye readings having been plotted out on the same time scale, no movement of the one curve relative to the other would produce an obvious relationship. The sky was cloudless at the time and a light wind was blowing.

On the other occasion a pit observation was started in a calm; a few minutes later a light wind suddenly rose which became steady after about two minutes. The reduction factor before and after the onset was steady and the same, but during the onset it was very variable. Such cases are discussed at greater length in Part III; here we may conclude that when there is no reason to suspect the presence of highly charged bodies in the air or when the air in the immediate neighbourhood has no sharp surface of cleavage separating masses of air of different history and, therefore, possibly of different electrical content, then the reduction factor is sufficiently constant over a distance of 30 yards but not over a distance of 1,400 yards or a vertical height of 400 feet. During rain or fog the reduction factor is probably not constant, but measurements have not been made at such times, and absolute values are not then important but only relative changes.

§4. THE THEORY OF THE INSTRUMENT AND ITS CONSTANTS.

If the potential of the air (V_a) at the point where a drop of water breaks away from the main jet is different from the potential of the tank-electrometer system (V), a quantity of electricity will be carried away by the drop proportional to $(V_a - V)$, while V will change by an amount depending on the capacity of the system. The process of charging is thus by a series of jumps, but actually the number of drops becoming detached each second is considerable, and without appreciable error we can use ordinary differential expressions; thus

$$\frac{dV}{dt} = K_2 (V_a - V) \text{ if there is perfect insulation.}$$

K_2 depends on the circumstances of the water jet and the capacity of the instrument.

If V_a is constant the time taken by the instrument to reach a potential $\frac{1}{2}V_a$ after an earth connexion is broken $= \frac{.6931}{K_2}$. Actually the insulation cannot be perfect. The leakage was tested at frequent intervals by charging the system (with the water turned off) by means of a Zamboni pile and timing the decrease of potential—

$$\frac{dV}{dt} = -K_1 V.$$

Taking account of this leakage the charging equation becomes

$$\frac{dV}{dt} = K_2(V_a - V) - K_1 V.$$

K_1 varied considerably; a value considered just satisfactory was $\cdot 0007$, which makes the time of losing half a given potential 1000 seconds approximately.

K_2 could not be measured directly, but a fortunate accident in the construction of the instrument enabled measurements to be made frequently and with considerable accuracy. When the instrument was earthed and the earth connexion suddenly broken, the photographic trace was not at first a continuous line but a series of dots. These dots mark the limits of the swing of the needle. There is thus supplied, if we know the period of vibration, a very fine time scale. The potential represented by these dots is obviously not the true potential, but if the logarithmic decrement of the needle is not too big the interval between any pair of dots will not be very different from the true interval. Measurements of K_2 made in this way (and checked by measuring the current flowing through a galvanometer when a large electric field was artificially produced at the jet) showed that it was a remarkably constant quantity. It varied with the rate of outflow but not very much within the limits ordinarily used. Its value in general was about $K_2 = \cdot 1$, i.e., $\frac{\cdot 6931}{K_2} = 7$ seconds approximately. The electrical capacity of the jet-electrometer-tank system varied slightly with the opening or shutting of doors, the arrangement of insulators and the depth of water in the tank, but was in general equal to that of an isolated sphere 300 cm. in radius.

Using the numerical values given above we can determine the behaviour of the instrument under specified conditions, e.g.,

(a) If V_a is constant the final potential reached by the instrument

$$= \frac{K_2}{K_1 + K_2} V_a = \cdot 9993 V_a.$$

a difference from V_a of no importance.

(b) If V_a undergoes a harmonic change with period T secs. the ratio of amplitude

$$\text{of } V_a \text{ to the amplitude shown on the instrument} = \left\{ \frac{1 + 4\pi^2}{T^2 K_2^2} \right\}^{\frac{1}{2}}$$

T	1 sec.,	10 sec.,	20 sec.,	30 sec.,	40 sec.,	50 sec.,	1 min.,	2 min.,	3 min.,	4 min.
Ratio ...	63·0	6·4	3·3	2·3	1·9	1·6	1·46	1·13	1·06	1·03

The instrument is thus too sluggish to follow changes of less than one minute period with any exactness.

(c) The current flowing through the system when it is earthed $= CK_2 V_a$.

$$= \frac{V_a 10^{-4}}{3} \text{ micro-amps. (if } V_a \text{ is measured in volts).}$$

If K_2 could be made more constant it would thus be possible and it might be advantageous in times of great disturbance, to use a galvanometer with one terminal earthed and the other connected to the jet system. Trials were made and some good records obtained in this way.

§5. THE DETECTION OF LIGHTNING FLASHES.

C. T. R. Wilson⁴ shows that the effect of a lightning flash is an almost instantaneous change of potential followed by an approximately logarithmic recovery curve. Let us assume the recovery is represented by $\frac{dV}{dt} = -\mu V$.

The table below shows the ratio of the maximum charge recorded on the instrument to the instantaneous charge at the jet.

$\frac{K_2}{\mu} =$	·25	·5	1	2	4	6	11	21.
Ratio =	·17	·25	·36	·50	·63	·70	·78	·86.

Wilson found very varying values for μ ; commonly occurring values make $\frac{K_2}{\mu}$ about 1 but much smaller values occurred. It appears therefore that it ought to be possible in favourable cases to detect and to measure, approximately, the potential changes due to lightning flashes even with a comparatively sluggish instrument like the water-dropper. Actually the needle of the instrument is as a rule wildly agitated during thunderstorms and it is only when an isolated flash occurs during an otherwise calm period that it can be detected. An examination of the records during nine years revealed 186 lightning flashes on 33 days. In 135 cases the potential was increased by the flash (positive discharge) and in 51 cases the potential was decreased (negative discharge). The proportion of positive discharges to negative discharges is about the same as that found by Wilson⁵ at Cambridge.

Plate I shows a reproduction of two electrograms associated with lightning flashes.

Throughout this discussion of the theory of the instrument the effect of the inertia of the needle of the electrometer has been neglected.

§6. THE ACCURACY OF MEAN HOURLY VALUES.

The action of the instrument has been referred to as sluggish but lest misunderstanding be caused it is well to point out first, that the water-dropper type of collector is quicker in its action than the radio-active collector frequently used (the instrument installed at Lerwick Observatory for instance only picks up half a given potential in about 60 seconds); secondly, that all the results discussed in Parts II and III are based on mean hourly values, for the determination of which a much slower instrument would be adequate.

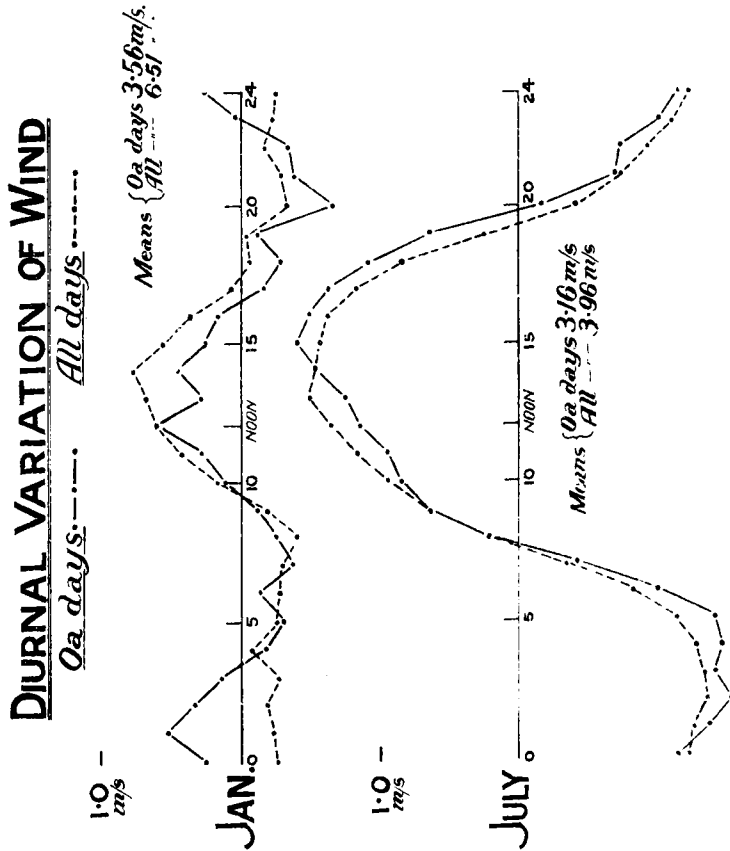
PART II—POTENTIAL GRADIENT ON QUIET (0a) DAYS

§7. DEFINITION OF 0a DAYS.

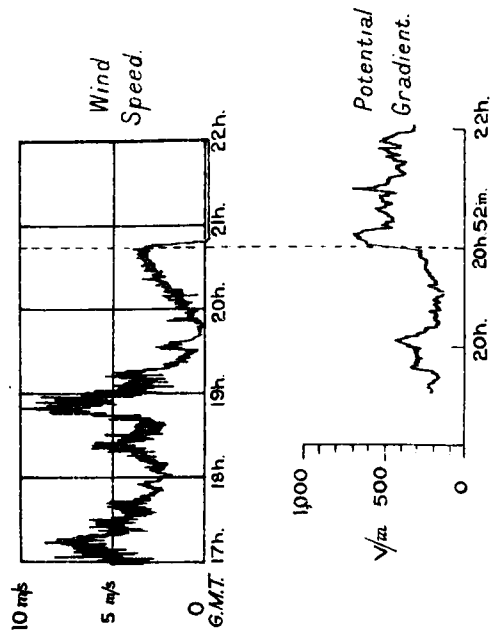
In this summary only days of electrical character "0a" are considered, "0" denoting that the potential did not become negative at any time during the day, and "a" that in no hour was there a range of 1,000 volts per metre. The number of such days averages about nine per month, giving about 100 days for each month in the 11 years considered. Unfortunately, the number varies very greatly in individual months and we are faced with alternative methods—each having certain advantages—of arriving at mean values. We can either treat the day as a unit (thus giving greater weight to some year having a large number of 0a days), or we can form means for each individual month and then treat the month as a unit. To find yearly or seasonal means the latter is the more sound and it was considered that for the sake of uniformity and ease of working the same method should be adopted throughout the discussion. Thus the mean for an individual month is the unit used in all cases.

§8. ANNUAL VARIATION.

Table I shows the mean value of the potential gradient for each individual month in the eleven years and the annual variation. The variability is very great. The outstanding value for February, 1917, is interesting; there was snow lying on the first 20 days of this month and very little wind. The potential gradient always reaches very high values under such conditions. In considering the annual variation it will be seen that two small peaks in February and November disturb to some extent the smooth run of the curve. The exceptional value just referred to for February, 1917, is largely responsible for the former. The peak in November is probably, however, the counterpart of a well-known climatic feature, namely, the tendency for

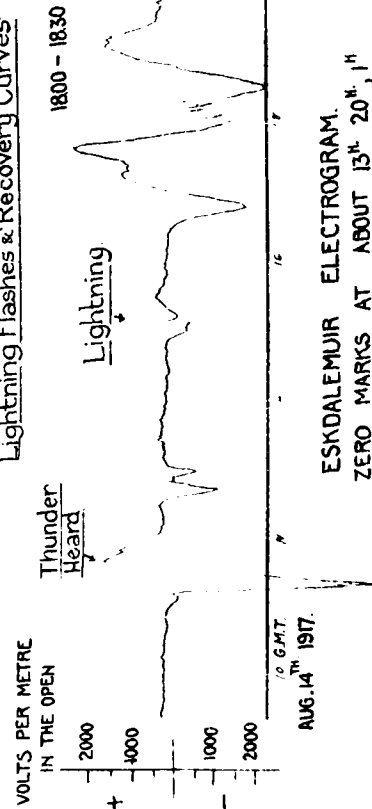


AUTOGRAPHIC RECORDS for SEPTEMBER 15th., 1920.



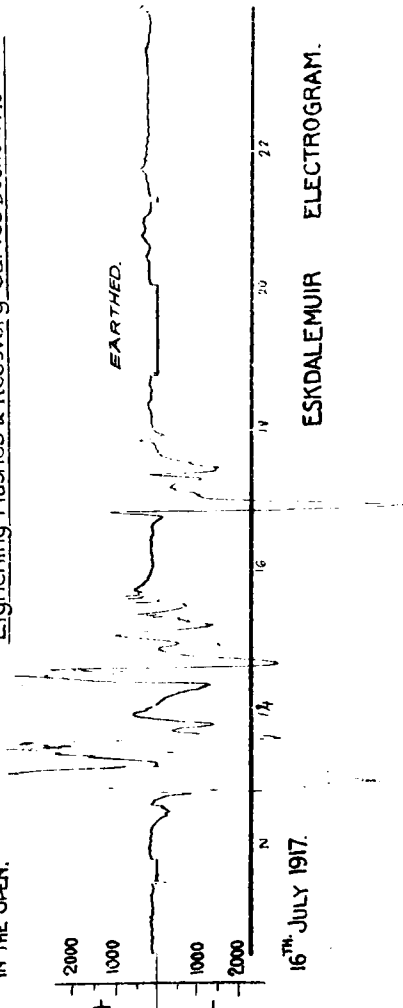
THUNDERSTORM TO N.W.

Lightning Flashes & Recovery Curves



THUNDERSTORM

Lightning Flashes & Recovery Curves between 15^N & 16^N



DIURNAL VARIATION of ATMOSPHERIC ELECTRIC
 POTENTIAL GRADIENT throughout the year at
 ESKDALEMUIR OBSERVATORY on Oa DAYS 191323

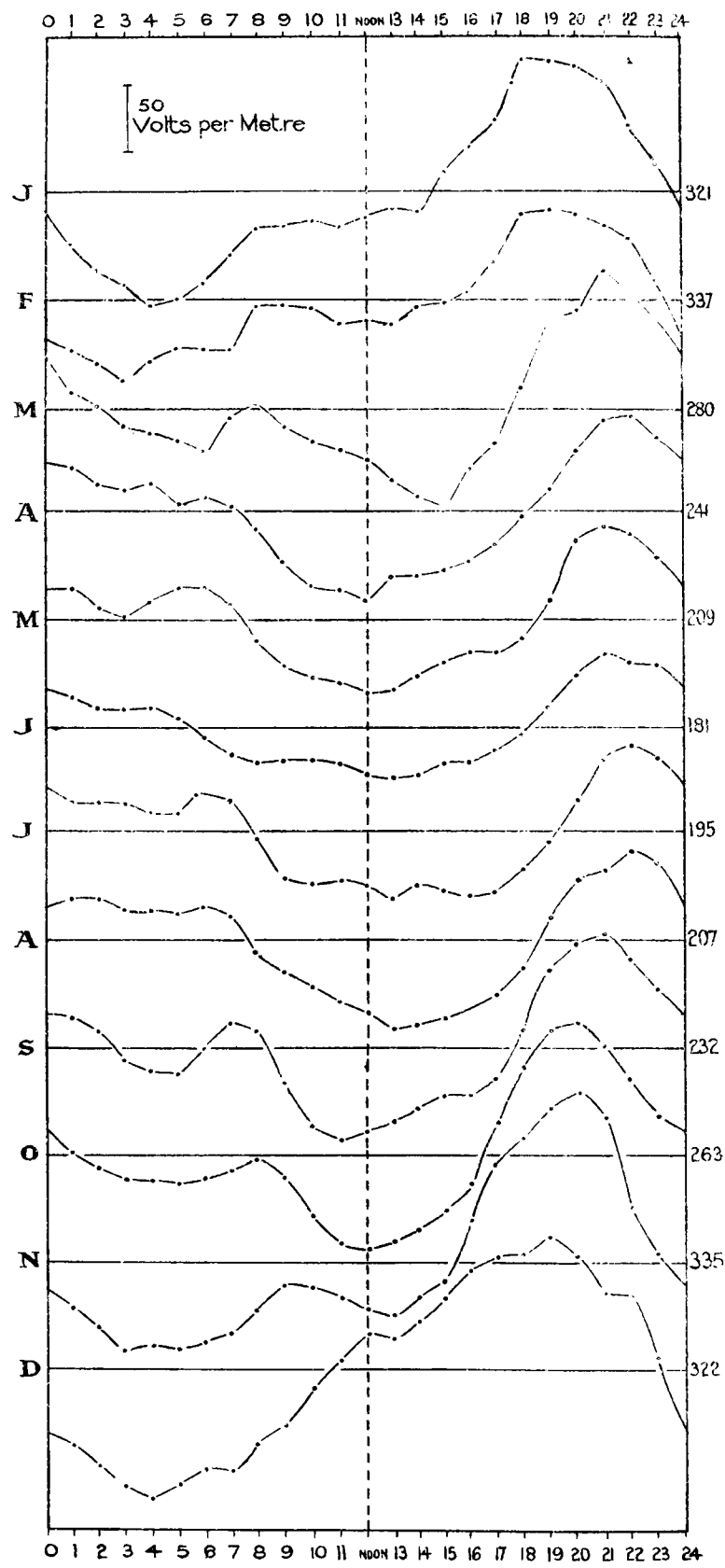


TABLE I.—MEAN POTENTIAL GRADIENT ON 0a DAYS AND NUMBER (IN BRACKETS) OF 0a DAYS AVAILABLE.

Month.	1913	1914	1915	1916	1917	1918	1919	1920	1921	1922	1923	Mean	Total of Days.
Jan. ..	399 (7)	278 (10)	286 (12)	260 (3)	328 (14)	496 (5)	308 (8)	259 (2)	262 (4)	356 (9)	294 (7)	321	81
Feb. ..	382 (11)	252 (3)	321 (5)	281 (3)	623 (12)	313 (4)	276 (16)	307 (7)	313 (17)	328 (7)	306 (3)	337	88
Mar. ..	259 (4)	208 (5)	225 (12)	385 (3)	266 (12)	334 (15)	245 (8)	269 (6)	— (0)	315 (4)	291 (16)	280	85
Apr. ..	170 (7)	247 (11)	256 (11)	239 (8)	319 (7)	230 (14)	241 (6)	222 (4)	247 (14)	204 (9)	279 (7)	241	98
May ..	201 (9)	160 (11)	162 (13)	188 (7)	191 (8)	238 (13)	218 (17)	277 (6)	187 (9)	245 (11)	229 (7)	209	111
June ..	180 (10)	177 (13)	164 (12)	158 (6)	192 (13)	205 (12)	155 (10)	208 (11)	181 (17)	173 (5)	194 (15)	181	124
July ..	208 (15)	169 (13)	206 (7)	220 (10)	192 (13)	187 (8)	190 (12)	144 (4)	160 (11)	165 (9)	299 (5)	195	107
Aug. ..	173 (18)	218 (12)	179 (11)	229 (10)	192 (4)	216 (11)	171 (10)	224 (15)	205 (3)	216 (7)	250 (2)	207	103
Sept. ..	191 (16)	237 (10)	254 (16)	232 (17)	237 (6)	231 (3)	221 (9)	280 (10)	221 (12)	182 (7)	271 (6)	232	112
Oct. ..	206 (8)	207 (10)	280 (14)	214 (7)	272 (4)	286 (5)	270 (12)	359 (18)	242 (14)	352 (12)	209 (4)	263	108
Nov. ..	303 (3)	336 (8)	490 (9)	227 (6)	305 (6)	367 (12)	360 (3)	316 (11)	342 (9)	244 (15)	392 (5)	335	87
Dec. ..	356 (11)	357 (5)	373 (3)	339 (4)	325 (9)	284 (7)	319 (4)	279 (9)	280 (6)	309 (8)	319 (9)	322	75
Year ..	252	237	266	248	287	282	248	262	249	257	278	260	—

the occurrence in that month of a period of a week or more of cold, quiet weather and of considerable atmospheric "stagnation." With the exception of those of 1916 and 1922 all the Novembers under discussion exhibit both the meteorological and the electrical peculiarity. Apart from these irregularities it is probably best to regard the annual variation as a simple one having a minimum at midsummer and a maximum at midwinter, the ratio of the extreme values being 1·8. This type of annual variation is the usual one in the northern hemisphere although local influences may greatly modify it. (See note on Lerwick, § 17.) In the southern hemisphere and near the equator the annual variation is irregular and at places on the Antarctic continent the variation appears to be in the opposite direction (the maximum occurs in the northern hemisphere's winter).

§9. SUNSPOT PERIOD.

The tabulated values start with a sunspot minimum and considering yearly means we find a peak in the potential gradient about the middle of the period. Chree⁶ found some evidence of the same effect at Kew, and Bauer⁷ in the Tortosa and other records. The correlation coefficient between, on the one hand, the departure of the potential gradient in any month from the mean value for that month taken over the 11 years, and, on the other hand, the sunspot number for the same month (as published by Wolfer in *Phys. Zs.*) has been worked out and is found to be +·112, subject to a standard error of ·086. Thus the value has no significance. Bauer⁸, using eight-yearly means, 1912–1919, for Eskdalemuir and a correction for "a time effect," obtains the extraordinarily high value of +·90. The addition of the remaining years of the cycle when the mean potential rose in spite of a decrease of the sunspot number would presumably very greatly reduce this figure, as would the omission of the exceptional month of February, 1917, in which the high potential can be explained by purely local meteorological events.

§10. DIURNAL VARIATION.

Table II and Plate II show the diurnal variation. A non-cyclic correction has been applied in the ordinary way to make the values at oh. and 24h. equal. The magnitude and sign of the non-cyclic correction vary greatly in individual months

TABLE II—DIURNAL AND SEASONAL VARIATION OF ATMOSPHERIC ELECTRIC POTENTIAL GRADIENT AT ESKDALEMUIR OBSERVATORY (0a DAYS 1913-23).

Hrs.	Jan.	Feb.	Mar.	Apr.	May.	Jun.	Jul.	Aug.	Sep.	Oct.	Nov.	Dec.	Hrs.
0	312	312	321	281	232	211	232	236	259	282	317	276	0
1	286	305	295	276	232	203	221	241	257	267	304	266	1
2	265	295	283	263	219	198	220	238	246	255	288	253	2
3	254	281	269	260	212	196	217	233	225	246	272	235	3
4	240	296	263	263	223	197	212	233	217	244	275	227	4
5	242	305	258	250	233	190	210	228	213	243	272	237	5
6	254	305	249	252	232	174	226	235	233	247	277	248	6
7	278	305	274	246	221	161	221	227	252	253	285	248	7
8	296	333	284	230	195	156	193	199	246	262	301	266	8
9	298	335	267	204	175	158	163	185	209	246	320	282	9
10	301	333	255	190	167	159	159	173	174	217	319	307	10
11	298	321	249	182	160	154	161	161	164	197	310	330	11
NOON	303	324	240	176	153	148	157	155	171	193	302	350	NOON
13	311	320	225	192	157	142	146	143	177	198	296	345	13
14	310	333	211	193	168	145	156	146	187	206	311	358	14
15	340	336	205	199	177	153	153	150	196	221	323	374	15
16	359	343	233	204	184	155	150	157	197	243	362	396	16
17	380	367	252	217	184	163	152	167	211	286	408	403	17
18	422	401	298	237	196	175	166	187	246	328	428	407	18
19	421	406	343	260	222	194	188	225	291	355	450	421	19
20	418	400	351	288	268	219	216	252	310	363	462	405	20
21	405	393	381	311	278	234	249	259	315	345	444	380	21
22	373	384	364	313	270	230	260	271	298	321	375	377	22
23	342	351	348	299	254	227	251	266	274	293	340	332	23
24	312	312	321	281	232	211	232	236	259	282	317	276	24

Hrs. Jan. Feb. Mar. Apr. May. Jun. Jul. Aug. Sep. Oct. Nov. Dec. Hrs.

Isopleths at 40 volts per metre Intervals.

Broken Lines 240 v/m and under.

Full Lines 280 v/m and over.

Mean for Year 260 v/m.

and it cannot be stated with confidence that 0a days tend to be days either of rising or of falling potential. The curves for each month and for each season have been subjected to harmonic analysis and the results expressed in the form—

$$G + P_1 \sin(A_1 + 15t) + P_2 \sin(A_2 + 30t) + P_3 \sin(A_3 + 45t) + P_4 \sin(A_4 + 60t)$$

where t is the hour G.M.T. : the details are given in Table III. In order to form some idea of the casual error due to the small number of years considered, the years were formed into two groups—1913-18 and 1919-23, and each group was treated in the same way. The results of this are given in Table IV.

Inspection of Table IV shows that it would be unwise to give too much weight to small variations, even in the eleven-year series ; but certain features appear which it is unlikely would be altered with a hundred years' observations.

The six-hour and eight-hour terms.—The values given for these terms are to be viewed with suspicion. They are very irregular both in amplitude and in phase angle. Only four P_3 terms and one P_4 term exceed 10 volts per metre. The sensitivity of the electrometer has varied considerably, but in general has been of the order of 50 volts per metre = 1 mm. on the photographic trace ; thus, an amplitude of 5 volts corresponds with 0.1 mm. The possibility of undetected systematic errors of reading of this order cannot be ignored. In particular, for a long period the electrometer was earthed while the water tank was filled at fairly regular intervals of about six hours. When measuring this broken piece of curve observers are apt to read too low. This would in itself create a six-hour term with minima at 1h., 7h., 13h., and 19h., which were the hours when the tank was most frequently filled. Any spurious term

TABLE III.—HARMONIC COEFFICIENTS OF THE DIURNAL INEQUALITY OF ELECTRIC POTENTIAL GRADIENT AT ESKDALEMUIR, 1913-1923, in the series $G + P_1 \sin (A_1 + 15t) + P_2 \sin (A_2 + 30t) + P_3 \sin (A_3 + 45t) + P_4 \sin (A_4 + 60t)$.
(P in volts per metre, t reckoned in hours from midnight G.M.T.)

1913-1923.

		G	P_1	G.M.T. A_1	P_2	G.M.T. A_2	P_3	G.M.T. A_3	P_4	G.M.T. A_4
				°		°		°		°
January	.. ..	321	72	176	33	205	5	1	4	349
February	.. ..	337	41	176	29	207	4	283	2	261
March	.. ..	280	52	109	41	180	6	271	3	340
April	.. ..	241	55	93	15	202	12	189	4	241
May	.. ..	209	45	93	18	212	16	194	4	276
June	.. ..	181	38	98	10	167	7	234	6	223
July	.. ..	195	46	75	14	175	16	185	1	304
August	.. ..	207	54	78	19	198	9	210	2	304
September	.. ..	232	51	107	30	207	9	172	16	344
October	.. ..	263	55	126	40	221	5	335	8	350
November	.. ..	335	70	168	42	214	15	325	5	302
December	.. ..	322	88	192	17	197	6	269	3	170
Winter	.. ..	329	67	179	30	208	7	314	2	293
Equinox	.. ..	254	52	109	30	202	4	311	7	338
Summer	.. ..	198	45	85	15	191	11	201	3	258

TABLE IV.—HARMONIC COEFFICIENTS AS IN TABLE III BUT WITH 1913-1918 (A) AND 1919-1923 (B) TREATED SEPARATELY.

Month.	A G	B G	A B P_1	A B A_1	A B P_2	A B A_2	A B P_3	A B A_3	A B P_4	A B A_4
Jan.	341	296	91 52	187° 160°	34 31	204° 206°	5 10	298° 30°	5 14	180° 353°
Feb.	362	306	58 22	172 186	27 34	197 216	6 3	285 257	1 3	190 284
Mar.	279	280	40 72	107 110	32 54	179 181	7 9	350 228	3 13	205 18
Apr.	243	239	50 63	80 106	10 22	220 191	13 10	185 196	3 8	228 331
May	190	231	44 47	92 94	17 22	191 231	12 20	197 191	3 4	277 274
June	179	182	42 34	98 97	13 8	180 144	9 5	247 229	4 6	213 237
July	197	192	57 37	65 82	8 22	166 179	11 20	187 186	0 2	360 286
Aug.	201	213	55 55	68 91	14 23	202 191	7 13	190 226	2 5	68 287
Sept.	230	235	60 44	94 131	23 38	202 211	6 11	181 168	16 17	336 352
Oct.	244	286	51 61	123 130	39 42	216 226	6 5	359 299	6 14	319 7
Nov.	338	331	68 77	180 155	50 32	211 221	17 18	351 291	9 10	247 11
Dec.	339	301	86 94	203 180	17 23	164 228	9 5	253 314	4 3	173 165
Winter	345	308	74 60	186 169	31 30	200 217	7 6	311 317	4 5	212 354
Equinox	249	260	48 59	100 118	25 37	202 202	3 7	220 207	5 13	315 359
Summer	192	204	47 43	79 81	13 17	189 194	9 14	204 200	1 4	239 266

so introduced might be combined with a real term, causing great irregularity. Then there is the possibility of the photographic paper warping on drying in a regular manner which might be extremely difficult to detect, even though it had a very real effect on terms as small as P_3 and P_4 .

The twelve-hour and twenty-four-hour terms.—Data for the comparison of the present values with other stations are given by Mache and Schweidler⁹ or by Chree¹⁰. A general discussion of the diurnal variation is given below in Part III. The phase angle of the 12-hour term is almost constant throughout the year and at all stations. Its amplitude relative to the 24-hour term decreases rapidly with height and decreases in moist tropical countries. Exner¹¹ attributes the effect to a thin atmospheric layer near the ground, and it is of interest that at Kew it seems closely connected with the

variation of atmospheric pollution, with the frequency of low cloud throughout the day, and with the visibility, and at Eskdalemuir with the setting in of night winds. In general, it appears that the larger the diurnal variation of those factors which assist or retard the stirring up of the lower layers of the atmosphere the larger is the 12-hour term.

The 24-hour terms at Kew and Eskdalemuir have some points of resemblance, but also some striking dissimilarities.

- (i) The amplitude decreases in both cases fairly regularly from winter to summer, but the decrease is very much more marked at Kew.
- (ii) The phase angle decreases from winter to summer, *i.e.*, the time of the maximum is retarded from about 17h. to about midnight. The variation is somewhat greater at Kew.
- (iii) The amplitude is considerably greater at Eskdalemuir at all seasons than at Kew, and is always greater than that of the 12-hour term. At Kew the 24-hour term equals the 12-hour term in winter and is very much less in summer.

§II. NOTES ON THE METEOROLOGICAL CHARACTER OF *0a* DAYS.

It is natural to try to connect the curves shown in Plate II with the diurnal inequalities of other meteorological elements, but caution is necessary in using the values ordinarily published, which are means for all the days of the month. *0a* days are selected entirely from their electrical character, and this automatically excludes most days of precipitation; thus, the selected days are far from being a random selection to which the mean meteorological features for all days might apply. Figures have not been abstracted for the whole period of 11 years, but the following notes indicate some of the differences between *0a* days and all days.

As regards precipitation, 80 per cent of *0a* days are rainless, but rain at rates exceeding 0.5 mm. per hour has occurred on *0a* days. On the other hand, small negative potentials frequently occur without precipitation, and sometimes large disturbances, positive or negative, but no case of a large disturbance has been found when it was certain that there was no precipitation within a short distance of the instrument.

As regards sunshine the following table referring to the years 1913-8 indicates that *0a* days have about 50 per cent more sunshine than all days.

Daily Means	Jan.	Feb.	Mar.	Apr.	May	June	July	Aug.	Sept.	Oct.	Nov.	Dec.
All days	1.03	1.56	3.20	4.66	5.03	6.13	4.79	4.18	3.92	2.36	1.62	1.16
<i>Oa</i> days	1.69	2.32	5.01	6.37	8.06	8.60	7.25	6.23	4.57	3.38	2.97	2.56

As regards pressure, 80 per cent of *0a* days have pressures above the normal for the month. The mean daily range of pressure is less on *0a* days than all days. The diurnal variation of pressure in summer is the same on the *0a* days as on all days. In winter there is a conspicuous difference. A sharp peak appears in the pressure curve at 20h. on *0a* days in place of a flat portion from 20h. to 24h. shown by all days. The total number of days available is not sufficient to eliminate the possibility of chance error.

As regards wind, the mean speed is from 30 to 50 per cent less on *0a* days. The diurnal variation is not noticeably different in summer from that for all days; but in January a pronounced secondary minimum appears at 20h. Thus, the curve of wind variation is double peaked with minima corresponding very closely with the maxima of the 12-hour potential curve. (See Plate I.) This relation and the above-

mentioned one in the case of pressure are almost certainly of importance in explaining the origin of the 12-hour period in potential gradient.

PART III—WIND AND POTENTIAL GRADIENT

§12. THE SELECTION AND GROUPING OF DATA.

The dependence of the potential gradient on purely local meteorological events is obvious from casual study of a few days' electrograms; yet in text books and papers on the subject there exist the most conflicting statements. Thus, Chree¹² found a striking relationship between fog and mist and the potential gradient at Kew. Chauveau¹³ finds this "un sujet difficile . . . plein d'obscurités et d'incertitudes. Une suppression complète nous a paru préférable à l'exposé de faits ou de résultats trop souvent mal définis et qu'il ne nous a pas paru possible de co-ordonner." The difficulty is to separate the effects of the different meteorological elements which are themselves correlated and yet to leave sufficient material in each group to have some statistical significance. A further difficulty is the large diurnal and annual variation which it has been suggested may in part be an integration of world-wide or even cosmical causes.

Observations of potential gradient in the following study have been grouped separately at 9h. and 21h. to eliminate the diurnal effect and in the four summer months, May, June, July, August and the winter months, November, December, January, February, to remove annual variations. Further, to remove obvious causes of disturbance all measurements have been rejected which were made during hours of

- (a) precipitation of any kind,
- (b) fog or mist,
- (c) neighbouring thunderstorms,
- (d) negative potential.

§13. THE RESULTS OF THE ANALYSIS.

Plates III and IV present in graphical form the figures given in Tables V and VI. On Plate III some of the frequency curves under higher winds have been dotted to show that the number of observations used is too small to give a reliable form to the curve. It appears that:—

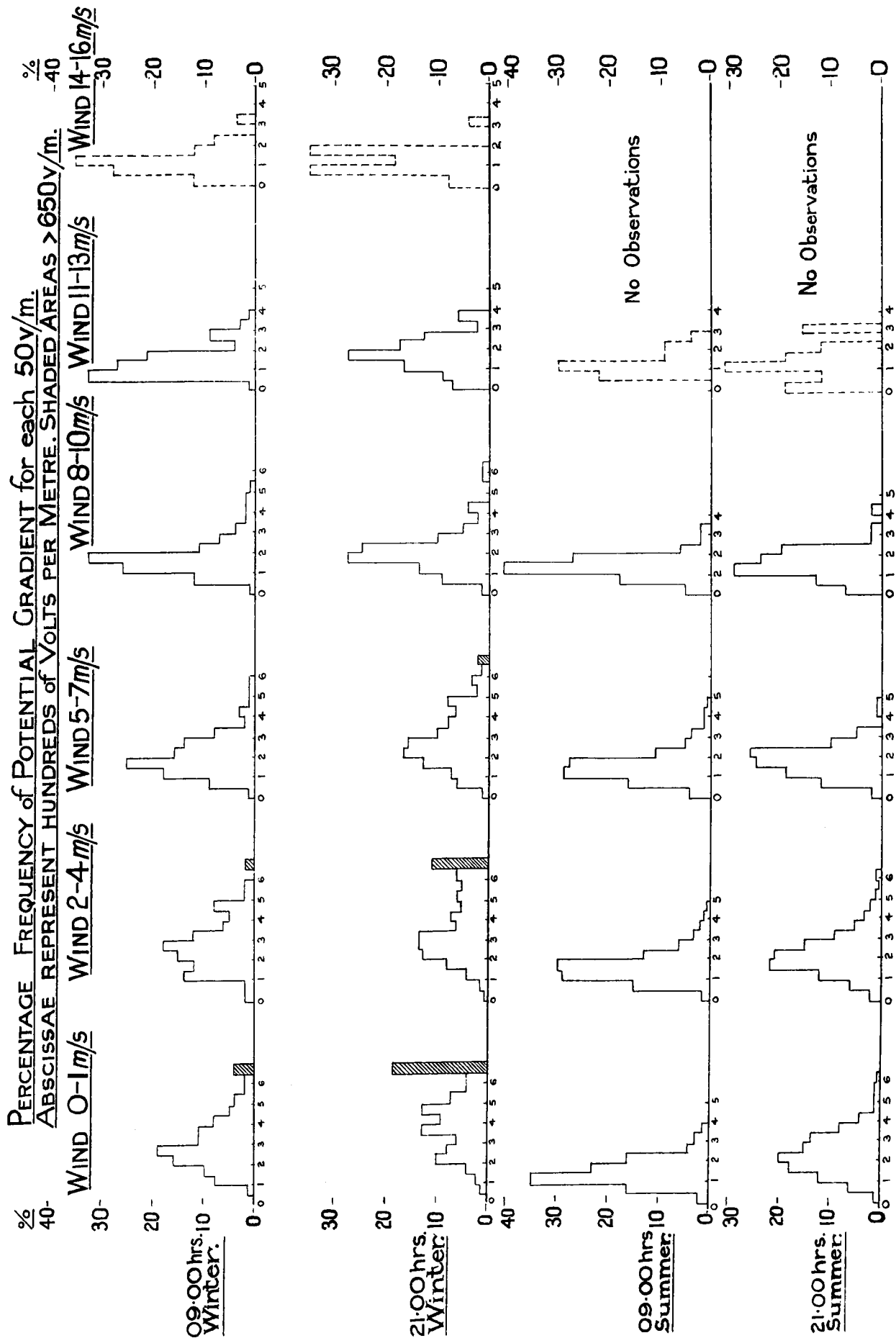
- (a) The potential gradient is very largely dependent on the wind speed, a high wind being associated with a low potential gradient.
- (b) Very high potentials never occur with high winds but low potentials may occur with light winds. These cases are discussed later (§16).
- (c) The effect of the wind is greater in winter than in summer and greater at 21h. than at 9h. Thus, at 21h. in winter an increase of wind from 0 to 15 m/s. reduces the mean potential gradient from about 470 v/m to 120 v/m, but the same increase of wind at 9h. in summer has no noticeable effect on the potential gradient.
- (d) All the effects observed can be explained if we assume that the earth has a charge sufficient to cause a potential gradient of 100 to 150 v/m, and that local atmospheric charges, which increase in the absence of wind or other mixing agents, cause the remainder of the observed potential gradient. A sufficiently high wind in winter annihilates this atmospheric charge but if, as at 9h. in summer, vertical convection has already done this, the wind can produce no further effect. It would have been interesting to see the curves for 21h. in winter become horizontal with still higher winds but, unfortunately, observations were not available.

TABLE V.—PERCENTAGE FREQUENCY OF OCCURRENCE OF GIVEN POTENTIAL GRADIENTS UNDER SPECIFIED WIND SPEEDS AT ESKDALEMUIR.

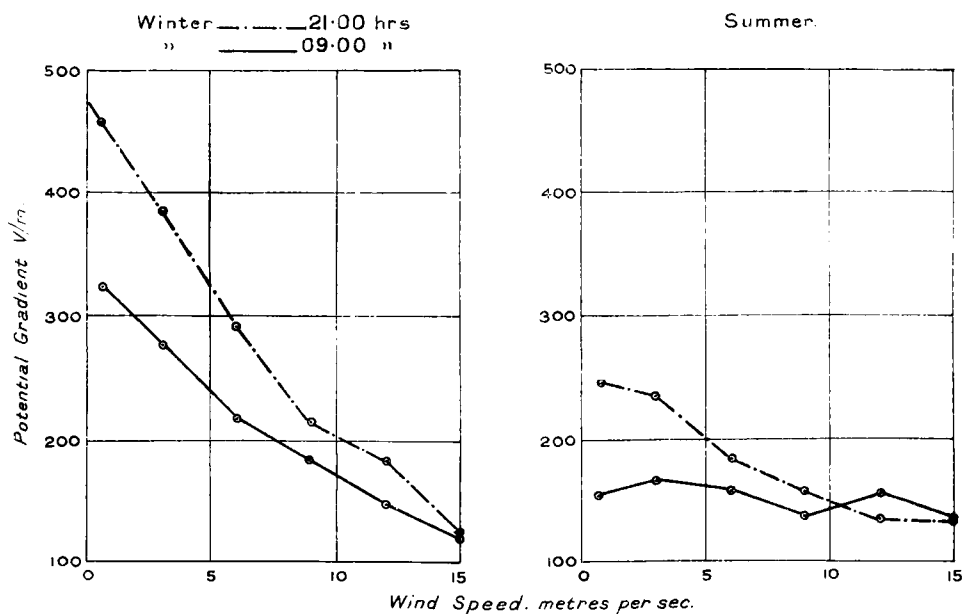
	Metres per Second.	VOLTS PER METRE.														Total No. of Obsns.	Mean Potential Gradient v/m	Standard Deviation v/m
		0-49	50-99	100-49	150-99	200-49	250-99	300-49	350-99	400-49	450-99	500-49	550-99	600-49	>650			
Winter 9h. G.M.T.	0-1	0	1	8	10	16	19	11	11	8	5	4	2	2	3	213	321	144
	2-4	2	2	14	12	15	18	12	6	5	8	2	2	—	2	172	279	137
	5-7	1	9	18	25	16	14	8	2	3	1	1	1	—	—	161	216	105
	8-10	1	12	26	33	11	7	4	2	2	2	1	—	—	—	109	183	97
	11-13	1	33	27	21	4	9	3	1	—	—	—	—	—	—	67	148	70
	14-16	12	28	36	12	8	—	4	—	—	—	—	—	—	—	25	121	68
Winter 21h. G.M.T.	0-1	—	1	2	4	10	8	6	13	9	13	7	4	4	19	214	459	218
	2-4	—	1	4	8	13	14	14	6	7	5	6	5	6	11	210	386	189
	5-7	1	6	7	13	17	16	10	8	6	8	2	3	1	2	156	291	152
	8-10	1	9	14	28	25	10	5	2	4	—	—	1	1	—	100	211	97
	11-13	7	9	17	28	18	13	2	6	—	—	—	—	—	—	54	181	89
	14-16	8	35	19	35	—	—	4	—	—	—	—	—	—	—	26	124	65
Summer 9h. G.M.T.	0-1	2	16	35	23	16	4	3	1	—	—	—	—	—	—	124	155	71
	2-4	1	15	29	30	13	6	3	2	1	0.3	—	—	—	—	359	165	86
	5-7	4	16	29	28	11	5	4	1	1	0.3	—	—	—	—	350	158	82
	8-10	5	18	41	27	6	2	2	—	—	—	—	—	—	—	124	136	55
	11-13	—	22	30	26	9	9	4	—	—	—	—	—	—	—	23	155	75
	14-16	1	6	12	18	20	15	14	8	4	1	1	1	0.3	—	347	247	112
Summer 21h. G.M.T.	0-1	1	6	12	18	20	15	14	8	4	1	1	1	0.3	—	347	247	112
	2-4	2	6	12	22	21	15	9	5	3	2	1	0.5	1	—	401	231	109
	5-7	2	12	19	25	26	10	5	—	1	1	—	—	—	—	177	183	77
	8-10	7	13	29	24	20	2	2	—	2	—	—	—	—	—	45	158	77
	11-13	19	12	31	19	12	—	6	—	—	—	—	—	—	—	16	134	49
	14-16	1	6	12	18	20	15	14	8	4	1	1	1	0.3	—	347	247	112

Studies of the effect of meteorological elements on the potential gradient made at different places have been so contradictory that it was thought advisable to make a similar analysis of the Kew Observatory figures. A smaller number of years was used and full tables are not presented ; but it will be seen that the Kew curves in Plate IV show the same general result as the Eskdalemuir curves, except in the case of 21h. in summer, where the potential at Kew rises with increasing wind strength, though the effect is comparatively small. The confirmation thus afforded is particularly striking when we consider the difference in the environments of Kew and Eskdalemuir, one almost at sea level in a broad, level tidal river valley, amidst a large town and with a continental climate, the other 800 feet above the sea, far removed from large centres of population and with a maritime climate. It may still be questioned however whether the wind effect is a direct one or is merely the result of a correlation between wind speed and some other factor.

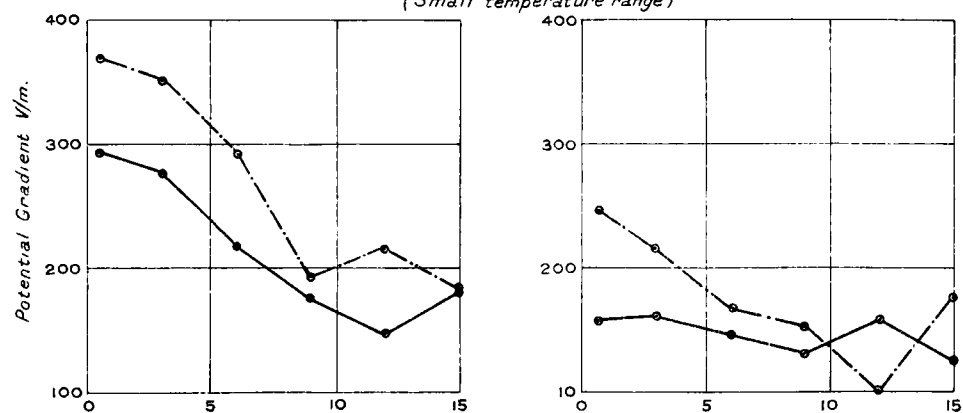
It was considered *a priori* unlikely that there could be a sufficiently well-marked correlation between wind speed and humidity or pressure together with a connexion between either of these elements and the potential gradient. The possible connexion with cloud amount was worked out in detail. The tables are not reproduced here because, owing to the exclusion of all the days mentioned above, they are only of



ESKDALEMUIR.



ESKDALEMUIR. (Small temperature range)



KEW.

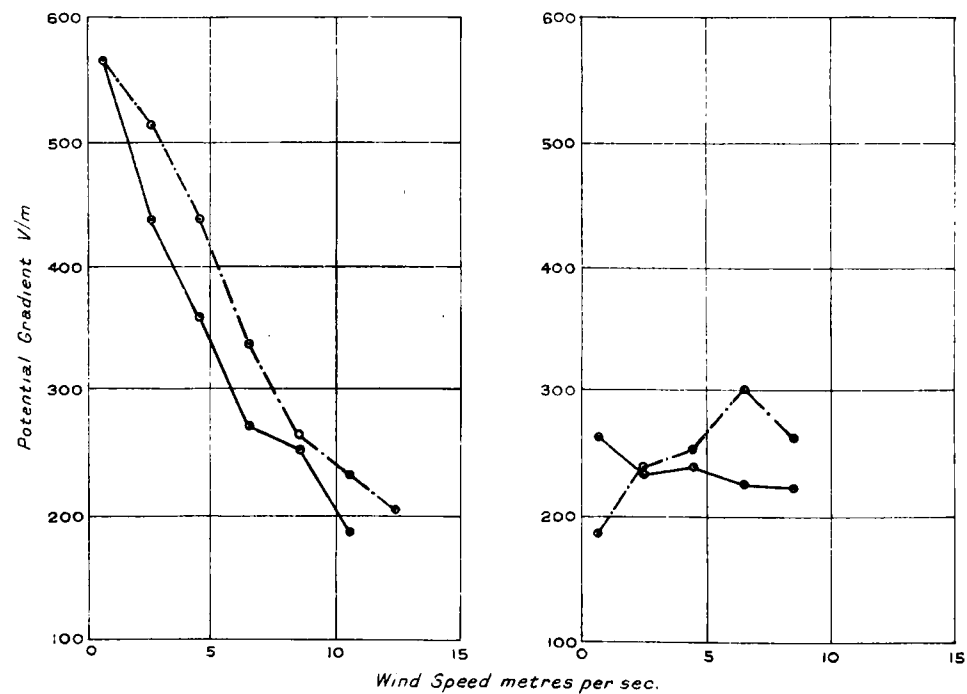


TABLE VI.—MEAN POTENTIAL GRADIENT WITH SPECIFIED WINDS.

	ESKDALEMUIR.					KEW.		
	Wind speed. m/s	Mean. v/m	No. of Observa- tions.	Small tempera- ture range. v/m	No. of Observa- tions.	m/s	v/m	No. of Observa- tions.
Winter 9h.	0-1	321	213	294	41	0-1	571	7
	2-4	279	172	277	60	2-3	439	48
	5-7	216	161	218	66	4-5	358	114
	8-10	183	109	179	44	6-7	273	73
	11-13	148	67	147	20	8-9	255	31
	14-16	121	25	183	4	10-11	189	9
Winter 21h.	0-1	459	214	370	43	0-1	569	20
	2-4	386	210	352	91	2-3	512	138
	5-7	291	156	294	58	4-5	440	141
	8-10	211	100	195	34	6-7	333	94
	11-13	181	54	213	21	8-9	268	38
	14-16	124	26	186	2	10-11	231	10
Summer 9h.	0-1	155	124	157	37	0-1	266	86
	2-4	165	359	160	92	2-3	234	314
	5-7	158	350	147	98	4-5	240	254
	8-10	136	124	130	62	6-7	229	89
	11-13	155	23	159	8	8-9	224	20
	14-16	134	11	—	—	10-11	265	2
Summer 21h.	0-1	247	347	245	99	0-1	187	171
	2-4	231	401	216	109	2-3	240	378
	5-7	183	177	169	88	4-5	256	169
	8-10	158	45	153	17	6-7	300	41
	11-13	134	16	100	1	8-9	262	10

use to answer the particular question with which we are concerned. It suffices to state that there appeared surprisingly little connexion between wind speed and cloud amount, and it can be dismissed as extremely improbable that the wind-potential gradient connexion is to any appreciable extent mixed up with a cloud-potential gradient effect. The case of temperature deserves more consideration: first there must be a wind-temperature connexion, in that very low winter temperatures and very high summer temperatures are never associated with high winds; secondly, we have seen while discussing the annual and diurnal variations of ϕ_a days that the annual variation of potential gradient is not unlike the inverted annual variation of temperature, and in summer the daily variation of potential gradient bears some resemblance to the inverted temperature curve. Tables similar to Table V were prepared, but using only those observations when the temperature fell within small limits, in winter 274.0a—276.9a, and in summer 283.0a—285.9a. The curves on Plate IV were drawn from these tables, and again, comparing this with the others, we see the same characteristics, although in winter with very low winds there is a considerable reduction in the mean potential gradient. It appears then safe to assert that it is the wind speed or the associated turbulence which has so marked an effect on the potential gradient, but it is probable that some temperature effect also exists.

§14. TOTAL CHARGE ON THE EARTH AND LOCAL ATMOSPHERIC CHARGES.

The potential gradient near the earth's surface is a measure of the surface density of the charge on the earth at that point:—

$$\frac{dV}{dz} = -4\pi\sigma.$$

We can consider σ as made up of two parts: (a) the appropriate fraction of the total earth charge, and (b) the "bound" charge induced by a local charge in the neighbouring atmosphere. With regard to (a) we know very little. If we could

integrate the potential gradient over the whole earth at any moment we would get an exact measure of its value, for the total induced charge (b) must be nil. The value of (a) must be such as to cause a potential gradient of about +150 volts per metre. We know that (a) is continually being dissipated, and, therefore, must be continually renewed, but no universally accepted explanation of its mode of renewal is offered. It is important to notice, however, that an addition or subtraction of charge in Australia would almost immediately make itself felt in England. It is evident that though the variations in the rate of dissipation or renewal of (a) are doubtless important in dealing with the diurnal and annual variations of potential gradient, it is with the variations of (b) that we must concern ourselves to furnish any explanation of the observed dependence of the potential gradient and local wind.

Normally the atmosphere has a mixture of negative and positive ions near the surface of the ground, but the positive ions outnumber the negative. Thus, the potential gradient decreases as the height increases. It is evident then, that if the rate of production of ions is constant (and there is no reason to suppose that this depends on wind, temperature, etc.), the excess positive charge will be removed by an increased mixing owing to the number of the excessive positive ions coming in contact with the earth or earth-connected bodies. The amount of mixing taking place in the atmosphere will depend chiefly on the wind speed, but partly on the lapse rate of temperature in the lower levels, and this in turn is likely to be high when the surface temperature is high. Thus, the wind-potential effect is modified by the surface temperature. In a qualitative way, the form of the curves in Plate IV is thus explained. We must suppose that the winter curves have reached their limit and would with stronger winds show a constant potential. At 9h. in summer other mixing agents have already so powerful an effect that the wind can do no more. The anomalous 21h. curve at Kew may be due to the special circumstances of Kew with regard to smoke contamination.

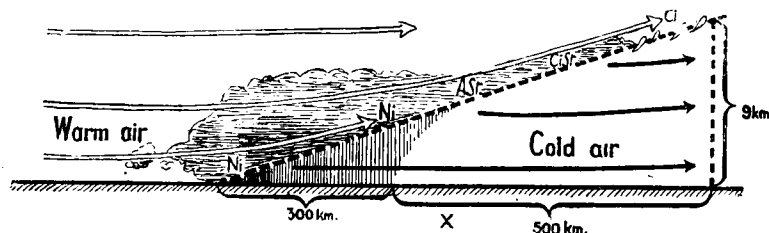
§15. LOCAL ELECTRIC "FRONTS" IN THE ATMOSPHERE.

The different electrical content of neighbouring masses of air of different history can be very clearly seen on individual records. As a pool of cold air collects in the valley the potential in general gradually increases. In the morning the pool is frequently swept away suddenly when the general air stream, which has continued throughout the night at a few hundred feet, re-establishes itself at the surface. The potential gradient then shows a sudden and simultaneous drop. A similar phenomenon, but with a different cause, which may be of importance in explaining the evening winter maximum of the diurnal variation, has been frequently observed. A light North or South wind dies down to a complete calm after sunset as the valley fills with cold air, but later in the evening the calm is broken by an occasional gust of a few metres a second in the opposite direction to the previous wind. Owing to the prevailing wind being southerly, that is up the valley, these night airs were wrongly described at first as katabatic winds flowing down the valley. The work of Goldie¹⁴ on "Waves at horizontal surfaces of discontinuity," makes it seem probable that these uneasy stirrings of the air are the lower parts of waves at the surface of discontinuity between the surface cooled air and the higher warmer air. These waves can only be formed after a certain depth of cold air is reached, and in actual fact appear on the anemograms with some regularity about 20h. in winter. The effect on the potential gradient is out of all proportion to the small wind speeds concerned. Plate I shows the diurnal variations of wind speed on all days and on *oa* days, and brings out the evening minimum of wind on *oa* days very clearly. The use of *oa* days automatically selects days of lighter winds and clearer skies than all days, but had days of light winds and clear skies been selected specifically the evening minimum would be still more pronounced. The sudden fall of a wind to complete calm which sometimes takes place in the evening with a simultaneous rise of potential is probably the result of a globule

of cooled air being rolled along over the Observatory, very much as a drop of heavy oil might be rolled in water. This brings its own electrical content and the potential rise is sudden, not slow as in the ordinary evening cooling. Copies of the autographic records for the 15th September, 1920, illustrate this (Plate I). By analogy with recent meteorological work we might thus speak of electrical "fronts" in the atmosphere.

§ 16. LOW POTENTIALS OCCURRING WITH LIGHT WINDS.

It will be seen from Table V that cases of low potential do occur in winter with very light winds, and it is of interest to examine such cases individually to discover any cause for this. Taking the ordinary meteorological elements measured at Eskdalemuir there appeared to be a resemblance amongst the days, but one difficult to express in terms of any one element. It was not until a wider view was taken with the aid of the daily weather charts that it was seen that the great majority of these cases occurred when Eskdalemuir lay in polar air with equatorial air lying above it. This at first seems surprising, for it is only a repetition on a grand scale of the pool of cold air in the valley which we find associated with very high potentials, but it has to be remembered that the effects of distant precipitation may be considerable. Let us consider a typical "warm front" as depicted by J. Bjerknes.¹⁵



The abnormally low potentials are usually found about the point X beneath the alto-stratus or stratus, but before the rain begins. Simpson¹⁶ has shown that when water drops are broken in an ascending stream of air the water becomes positively electrified and the air negatively; thus, rain carries in general a positive charge to earth. The warm current ahead of the rain area must then be carrying a negative charge, which will weaken or might reverse the normal positive potential at points near X. Stewart¹⁷ reproduces an electrogram from Kew for April 19th, 1911, showing an abnormal wind effect with strong negative potentials without rain. A reliable diagnosis of the structure of the atmosphere cannot be made from the *Daily Weather Report* of that date, but it seems not improbable that the explanation given above might account for this exceptional case.

§ 17. THE DIURNAL AND ANNUAL VARIATIONS IN RELATION TO THE FOREGOING.

It is necessary to consider the possible variations of the total earth charge (*a*), and the local charge (*b*), of § 14.

It has been stated that there is no universally accepted explanation of the replenishment of the earth's charge, but C. T. R. Wilson⁵ has made the suggestion that it is through the mechanism of the lightning flash. Brooks¹⁸ estimates the number of lightning flashes occurring per second over the globe as something of the order of 100. But, owing to the irregular distribution of land and sea over the globe there must be a diurnal variation of this number, and Whipple¹⁹ shows that this variation is not unlike the variation of potential gradient over the oceans, which depends on universal time, not local time (Mauchly²⁰). The variation of (*a*) however depends not only on its rate of renewal but also on the rate of dissipation over the whole globe, which, owing to the non-symmetrical disposition of land and sea in latitude and longitude, must have an annual variation and a diurnal variation; the form of the diurnal variation must change with different seasons of the year. These variations depend

on universal time. As regards the annual variation we would expect world-wide dissipation to be most active when the sun is centred over the biggest land masses, and it is significant that the minimum in all places in the northern hemisphere occurs in summer, but in places in the southern hemisphere the annual variation is irregular, and some give a minimum in winter, *i.e.*, in the northern hemisphere's summer. It must be noted that the local effect next discussed may neutralize the world-wide one so that irregularity is to be expected in the southern hemisphere where the two effects are in opposite phase, and might occur in the northern hemisphere owing to special local circumstances; thus, there is a suggestion in incomplete records from Lerwick²¹ that the minimum there is in winter. This can be explained as a local effect due to diminished turbulence in summer.

The variation of (*b*), the local atmospheric charge, must depend on local agents (and, therefore, on local time) which stir up the atmosphere, chiefly the wind and the vertical convection, controlled by surface heating and the general circulation. This local effect is larger apparently in general over the land than the world-wide one, but over the sea, where the diurnal variation of local agents is small, Mauchly finds the diurnal variation of potential gradient dependent on universal time. Summarizing, we believe that the annual and diurnal variations of potential gradient are controlled by two factors depending on universal time and one depending on local time. Over land the latter in general masks the former and differs from place to place. Over the sea the universal time factors are the important ones. They produce a simple diurnal variation having a minimum at 4h. and a maximum at 19h. G.M.T. It is not possible at this stage of our knowledge to subtract this variation from that observed at a land station to get the true local variation, for two reasons—(1) further sea observations are necessary to determine the magnitude of the universal time variation; (2) the absolute value of potential gradient is difficult, and in many places perhaps impossible, to determine.

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