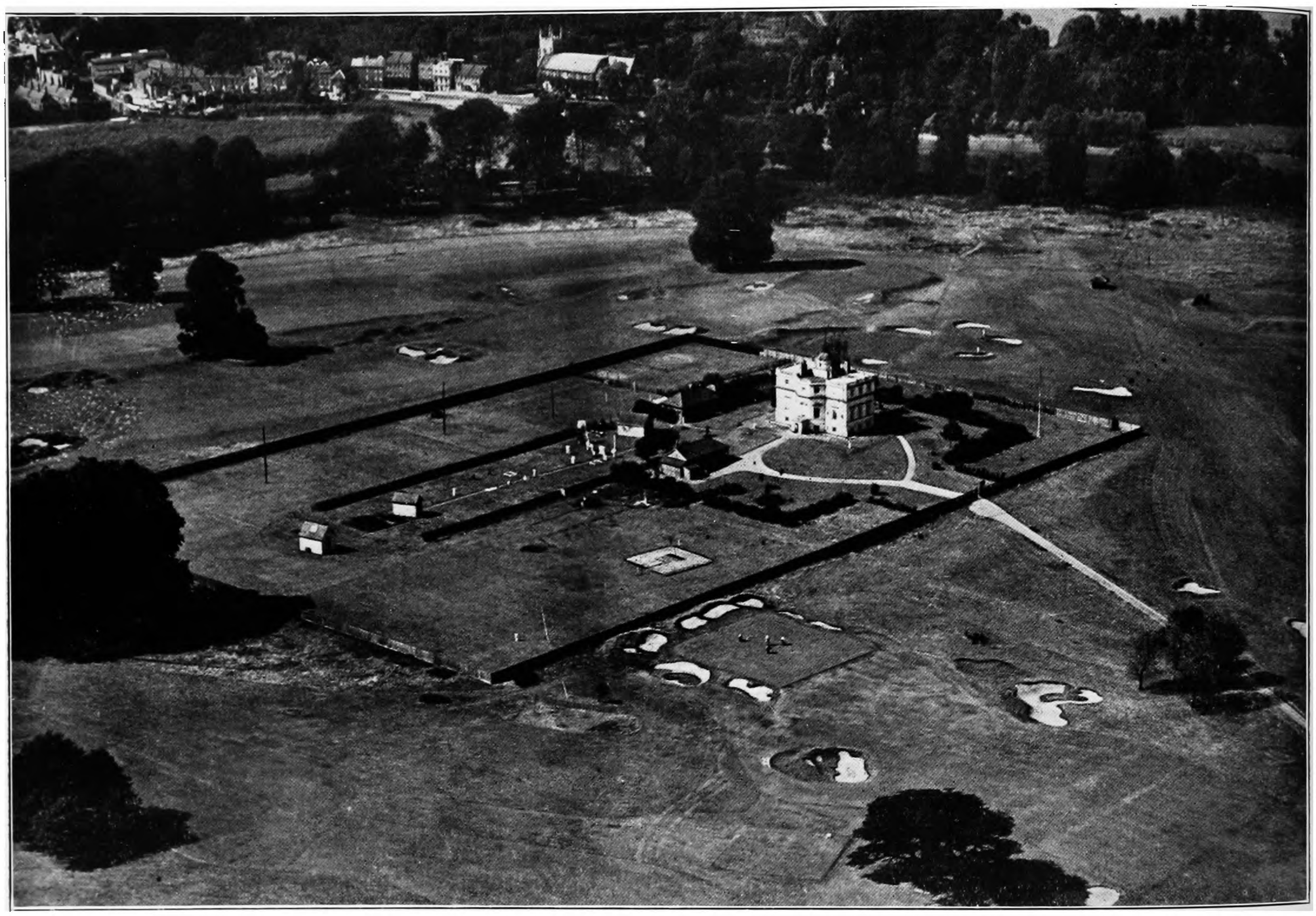

Frontispiece.]	KEW OBSERVATORY, FROM THE AIR.	[*Royal Air Force Official—Crown Copyright reserved.*

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METEOROLOGICAL OFFICE

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OBSERVATIONS OF ATMOSPHERIC ELECTRICITY AT KEW OBSERVATORY

A Survey of Results obtained from 1843 to 1931

By F. J. SCRASE, M.A., B.Sc.

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OBSERVATIONS OF ATMOSPHERIC ELECTRICITY AT KEW OBSERVATORY

A SURVEY OF THE RESULTS OBTAINED FROM 1843 TO 1931

§ 1—HISTORICAL INTRODUCTION

Observations of atmospheric electricity have been made at Kew Observatory for a very long period and although in the present survey we are concerned mainly with the measurements which have been made since 1898, it is of historical interest to include a brief account of the earlier observations. The first systematic measurements of atmospheric electricity at Kew were started by Francis Ronalds in 1843, ninety years ago. Ronalds' apparatus, which is described and illustrated in the *Report of the British Association* for 1844, included a collector in the form of a lantern which was erected 16 feet above the dome of the Observatory. The exposure of the collector is shown in Fig 1a (H) which is a reproduction of a drawing made by Ronalds. The potential of the collector, or as it was then called the electric tension, was read on Volta's scale on straw electrometers.* For two years observations four times a day were made and for three more years there were observations every two hours, the readings for the night hours being taken from electrometers which were disconnected from the collector at the appropriate times by clockwork. These early observations, most of which were actually made by Sergeant Galloway, were discussed in a long report prepared by W. R. Birt for the British Association in 1849. Ronalds also made some experiments on the photographic registration of meteorological and electrical elements and on September 24, 1845, he obtained the "first good specimen of registered atmospheric electricity." He remarks in an epitome of his observations (1) † that the apparatus enabled him to observe the "curious fact that the electric tension increased with the light of the sun, under certain circumstances, but that such increased tension did not continue."

In 1861 the Kew water-dropping electrograph, the earliest it is believed in regular operation (2), was erected under Lord Kelvin's personal supervision. The apparatus has been in continuous operation ever since, but the tabulation of the records did not become part of the Observatory routine until 1902. A description of the apparatus in its original form is to be found in a paper by Dr. J. D. Everett (3); a divided-ring electrometer was used and the records were made photographically. Everett's paper also includes a discussion of the records obtained with the apparatus during the years 1862 to 1864; the measurements were in terms of arbitrary units.

After a few years the divided-ring electrometer was replaced by a quadrant electrometer, and by means of a large silver-chloride battery G. M. Whipple was able to determine the absolute measure of the deflections of the electrometer needle and so express the potential of the collector in terms of volts instead of arbitrary units. G. M. Whipple analysed the records for the year 1880 and his discussion of the results was communicated to the British Association (4) a year later.

In these early measurements the relation between the voltage shown by the instrument and the true potential gradient in the open was not considered, so the observations cannot be used for determining whether there has been any change in

* It appears that the electrometers in use were calibrated in terms of one of them. This one was constructed according to Volta's specification, but as there is no record of the weight of the original straws the readings can not now be reduced to any absolute standard.

† The numbers in brackets refer to the bibliography on p. 27.

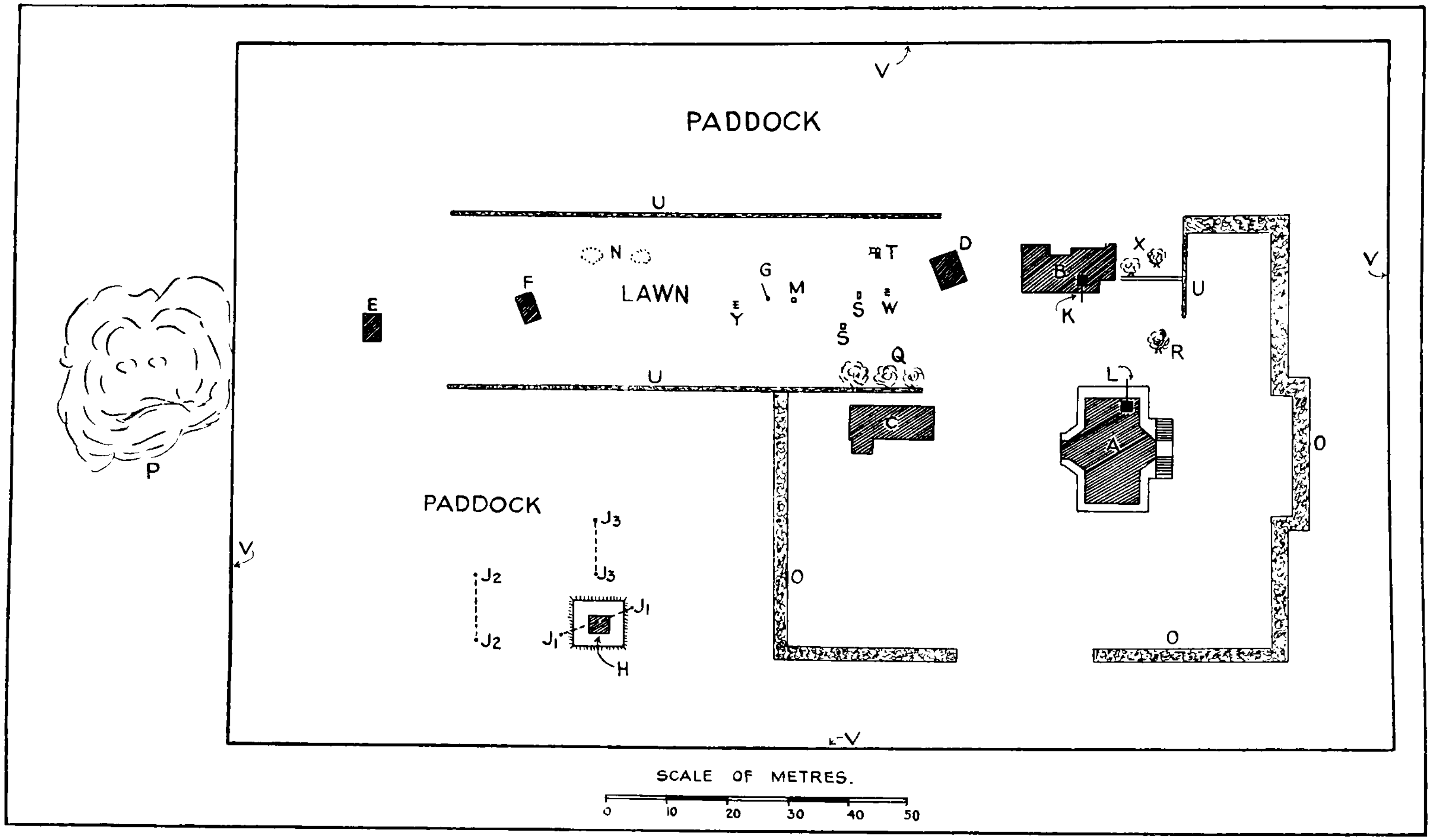

FIG. 1.—KEW OBSERVATORY: SITE PLAN.

KEY TO HEIGHTS OF MAIN FEATURES (IN METRES).

A.	Main Observatory building	15
B.	"Clinical house"	5·5
C	Workshop	5
D.	Experimental house	4·5
E.	"New" magnetic hut	4·5
F.	"Old" magnetic hut	4·5
G.	Pillar for absolute electrometer, 1898-1909	1·5
	Support for bamboo rod, 1910-31 ..	1
H.	Underground laboratory	0·2
J1, 2, 3	Posts for stretched wire apparatus	1
K.	Kelvin electrograph, after May, 1915	2
L.	" before " "	3·5
M.	Stone pillar	1·5
N.	Fruit trees, removed 1909	4
O.	Shrubbery	2·5
P.	Two tall trees, maple and oak ..	26
Q.	Fruit trees	5
R.	Yew bush	2·5
S.	Thermometer screens	1·5
T.	High thermometer screen	5
U.	Hedge	1·5
V.	Wooden fence	1·5
W.	Besson nephoscope	3·5
X.	Fruit trees	3
Y.	Thermometer stand	1·5

the mean potential gradient at Kew since 1845. The results are available, however, for comparisons of the types of annual and diurnal variations and they will be referred to later in the paper.

Special observations were commenced in 1894 by Dr. C. Chree (5) with the object of determining the influence of the position of the water dropper, which at that time projected from a window (L, Fig. 1) in the main Observatory building, on the measurements. This investigation led to some modification in the installation and to the introduction of a regular system of standardization by absolute observations on the Observatory lawn at the position indicated by G in Fig. 1 (a bird's-eye view of the Observatory and grounds is reproduced in the Frontispiece). These observations were intended to give the potential gradient in the open and an appropriate reduction factor was applied to the electrograph readings. The data published in the Observatory reports from 1902 to 1909 were obtained in this way. Chree (2) computed comparable results for the years 1898 to 1901 and included these in a discussion of the data for the period 1898 to 1904.

Experiments made in 1909 showed that the apparatus used for the absolute observations was not satisfactory in that the electrical field was distorted by the presence of the instrument stand and of the observer (Fig. 2). Improvements in the routine of observation were introduced at the beginning of 1910 and in a discussion of the records up to 1912 Chree (6) corrected the data obtained during the twelve years previous to 1910 with a view to making them comparable with the data obtained with the new routine. Apart from some small changes, details of which will be given later, this routine remained unaltered until the end of 1931, so we have 34 years of observations all referred to the same site. These observations were published regularly from 1911 to 1921 in the *British Meteorological and Magnetic Year Book* and from 1922 onwards in the *Observatories' Year Book.*

In 1926 Dr. R. E. Watson (7) commenced some experiments to ascertain how nearly the potential gradient obtained by the method of observation introduced in 1910 approached that over a plane surface. Watson's results showed that the gradient at the lawn site (G, Fig. 1) was appreciably affected by elevated objects in the neighbourhood ; it was in fact about 12 per cent lower than the gradient in the Observatory paddock near the site J_1, Fig. 1. The experiments led to the building, in 1930, of an underground laboratory at this site in the paddock which enabled measurements to be made over a flat surface free from near obstacles. After some preliminary investigations the laboratory was modified in certain respects and finally adopted as the standard site for the routine absolute measurements of potential gradient at the beginning of 1932. The use of the laboratory not only introduced a change of site, but also a change in the method of observations, for the procedure was adopted of obtaining the potential gradient immediately above the roof by measuring the surface density of charge on an insulated plate flush with the roof. A check on the new method was provided, however, by an observation once a month by the normal collector method in the paddock. It is hoped that no further alterations will be necessary for many years, and it is desirable that the data which had accumulated from 1898 to 1932 should be brought into line with those now being obtained under the improved conditions.

Other routine observations which were affected by the changes following the building of the underground laboratory in 1930 are those of the air-earth current and the conductivity of positive electricity. These observations have been made regularly on fine afternoons since 1909. Until 1931 the measurements were made with the Wilson apparatus (8) on a tripod on the lawn near site G, Fig. 1. At first it was thought that the increase in the field over the apparatus due to distortion would increase the current in the same proportion, so this effect was allowed for by multiplying the observed current by the ratio of the potential gradient in the open (derived from the electrograph) to that observed over the Wilson apparatus. This procedure assumed that the conductivity was unaffected by the distortion of the field. Investigations by G. Dobson (9) in 1914 and by R. E. Watson (7) in 1926 showed that this assumption was not, in general, correct ; the conductivity as measured over the tripod was found to be lower than that measured at ground level.

When the underground laboratory was completed the writer continued the investigation with a Wilson apparatus built into the roof and obtained sufficient information to be able to apply corrections to the tripod observations and make them comparable with the measurements made at ground level. The tripod observations were discontinued in 1931 and since then the measurements have been made under the improved conditions provided by the underground laboratory.

§ 2—METHODS OF OBSERVATION

(i) *Potential gradient.*—Until 1915 the electrograph was housed in the main Observatory building (L. Fig. 1); the water jet which projected 1·27m. through a window in the west wall was 3·35m. above the ground (2). At the end of May 1915, the instrument was moved to a one-storied outbuilding (the "clinical house"), which is situated to the west of the Observatory. At this position the jet was 1·73m. above the ground and 1·5m. out from a window in the east wall (K, Fig. 1). No further alteration was made until December 1931, when the water-dropper was replaced by a polonium collector, the coating of which is renewed every six months. A photograph showing the exposure of the collector rod is reproduced in Fig. 2. The position of the radio-active collector is not exactly the same as that of the water jet, the distance from the window being 1·21m. and the height above ground being 1·87m. The effective resistance of the polonium collector when new is about $0{\cdot}2\times10^{11}$ ohms; the resistance of the water dropper was about $0{\cdot}5\times10^{11}$ ohms.

The recording electrometer is of the Kelvin quadrant type and the scale value in use is about 115 volts per cm. deflection on the recording drum which is about 1m. away. The time scale of the drum is 0·94 cm. per hour and the width of the chart allows a range of about ±900 volts.

Insulation tests are made every morning and evening; the insulation is considered to be satisfactory if the fall of potential from 350 volts in 3 minutes is less than 50 volts. The capacity of the whole system being about $400/(9\times10^{11})$ farads, this rate of fall corresponds to an insulation resistance of about 30×10^{11} ohms.

For the regular control observations of potential gradient in the open which were introduced in 1898, a Kelvin portable electrometer with a fuse attached directly to the terminal was used. At first the apparatus was exposed on a stone pillar (M, Fig. 1) on the Observatory lawn, but the use of the pillar was soon discontinued and a small stand on a brass rod (G, Fig. 1) was used instead. The height of the fuse was fixed at 1·465 m. above ground level. A photograph showing the apparatus in use is reproduced in Fig. 3. At the beginning of 1909, after some preliminary experiments which showed that the disturbing effect of the apparatus and the observer was much greater than had been anticipated, an improved form of apparatus was constructed. This has been described by C. Chree (6). It consisted essentially of an insulated bamboo rod about 2·5 m. long supported horizontally by a vertical rod, the height of which could be varied so that a fuse attached to the free end of the bamboo could be adjusted to a height of 1 or 2 m. above the ground. The fuse was connected by a wire running along the rod to the electrometer which was supported on a tripod about 2 m. back from the vertical rod. This apparatus was in continuous use until December 1931, but from January 1923 Ayrton-Mather electrostatic voltmeters were substituted for the Kelvin portable electrometer. A photograph showing the apparatus in position on the lawn is reproduced in Fig. 4. After 1931 an entirely different method of making the absolute observations was adopted; this will be described later in connexion with the use of the underground laboratory.

The absolute measurements are made on about a dozen days a month and a mean factor for each month is applied in the reduction of the electrograph readings.

(ii) *Conductivity and air-earth current.*—In 1909 observations of electrical conductivity were commenced, the apparatus used being that devised by C. T. R. Wilson (8). The instrument consists of an insulated test plate, 7 cm. in diameter, connected to a gold-leaf electrometer and surrounded by an earthed guard ring. The test plate can be covered by means of a cylindrical metal cover. A

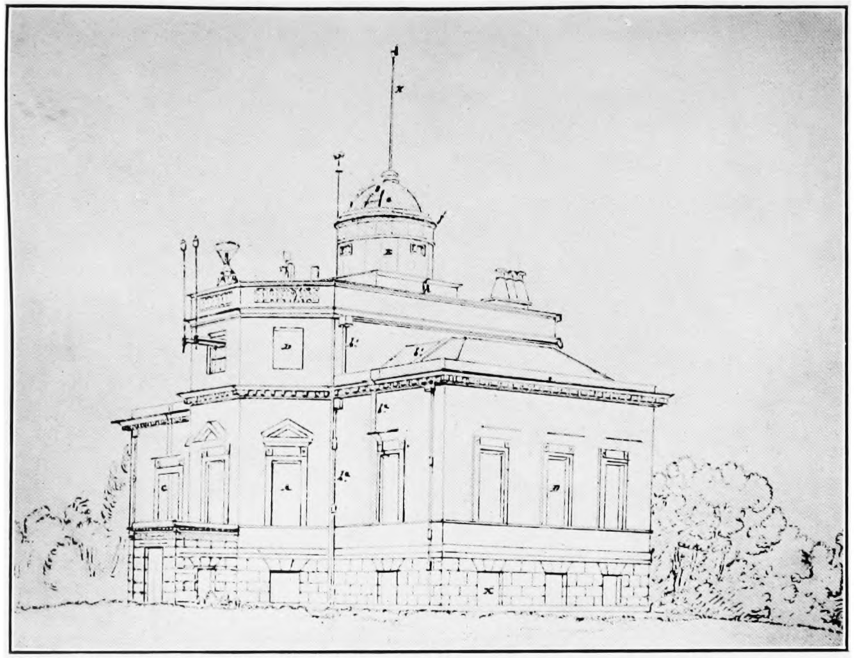

FIG. 1A.—KEW OBSERVATORY IN 1844, FROM A DRAWING BY RONALDS ILLUSTRATING THE EXPOSURE OF HIS ELECTRICAL APPARATUS.

FIG. 2.—THE COLLECTOR OF THE KELVIN ELECTROGRAPH PROJECTING THROUGH A WINDOW OF THE "CLINICAL HOUSE."

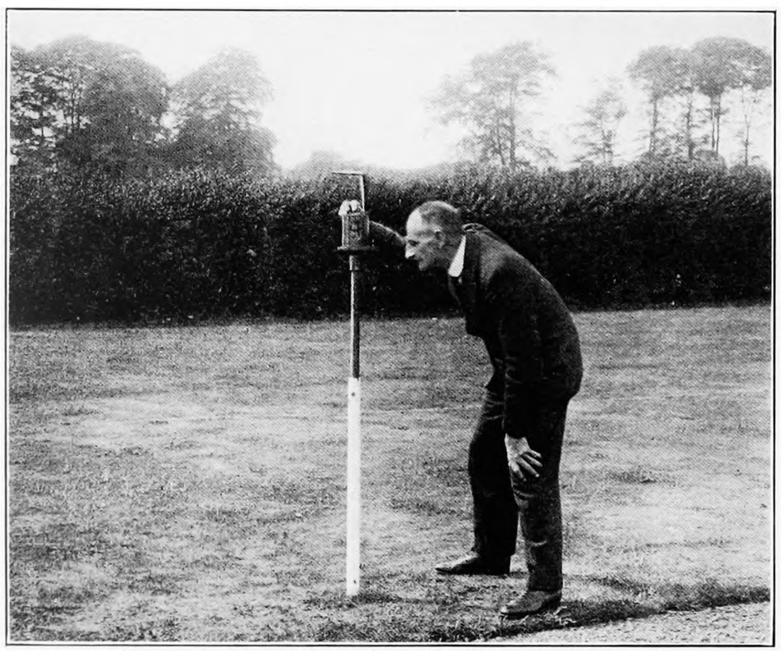

FIG. 3.—MEASUREMENT OF POTENTIAL GRADIENT OVER THE OBSERVATORY LAWN BY MEANS OF THE KELVIN PORTABLE ELECTROMETER, 1898-1909.

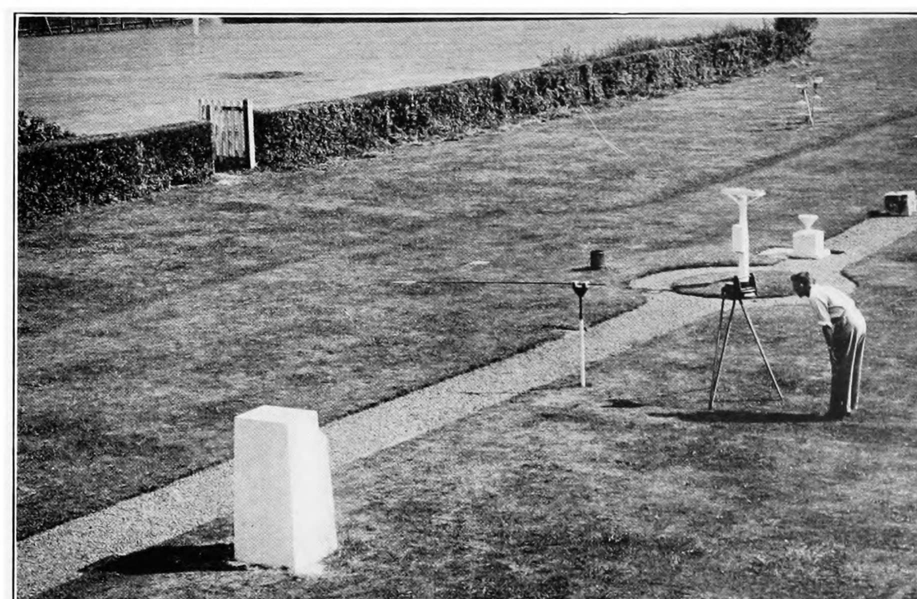

FIG. 4.—MEASUREMENT OF POTENTIAL GRADIENT OVER THE OBSERVATORY LAWN BY MEANS OF THE BAMBOO-ROD APPARATUS, 1910-1931.

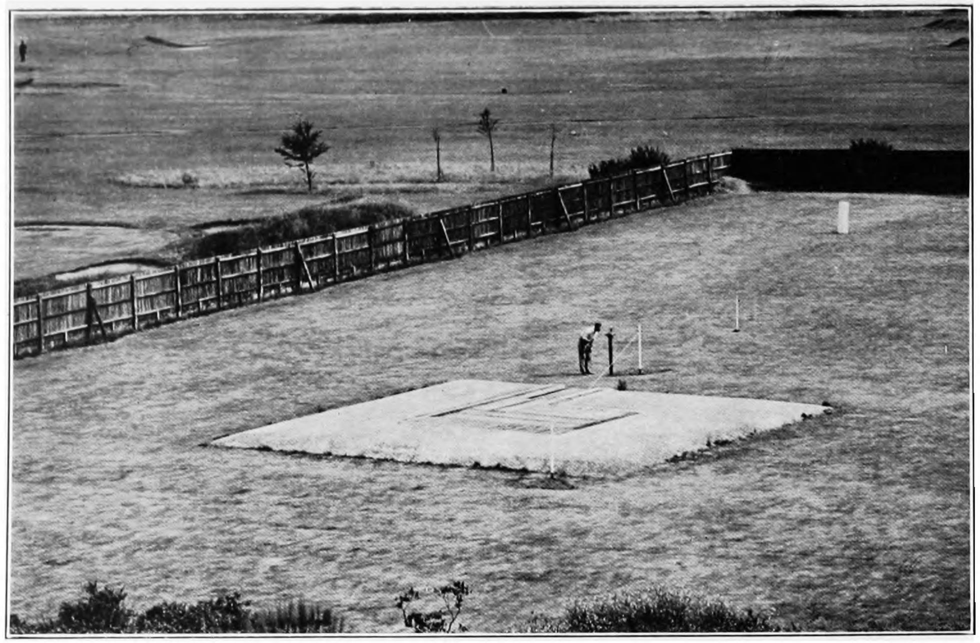

Fig. 5.—View of paddock showing underground laboratory with stretched-wire apparatus erected.

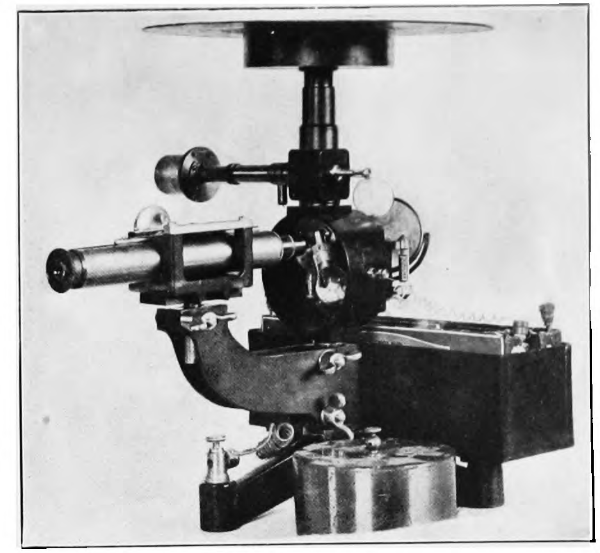

Fig. 6.—Modified Wilson apparatus with Lindemann electrometer.

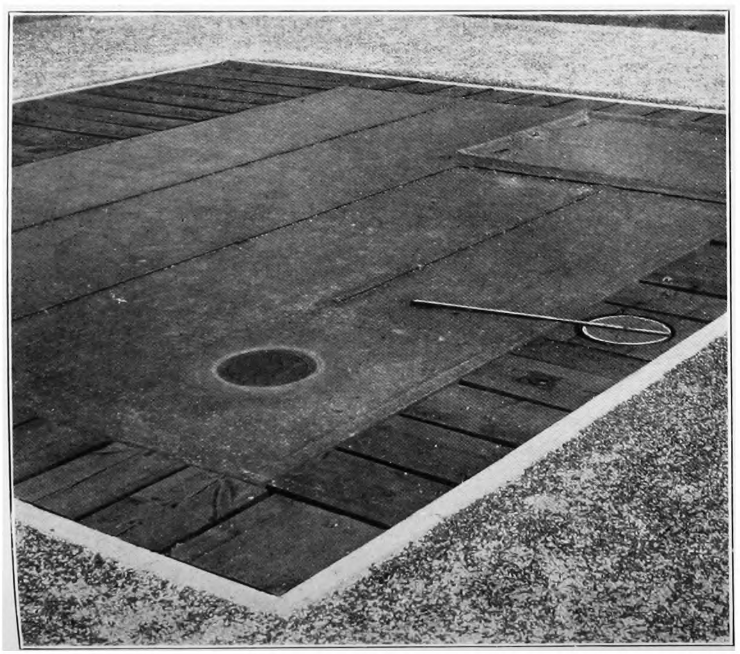

Fig. 8.—Roof of underground laboratory with test plate exposed

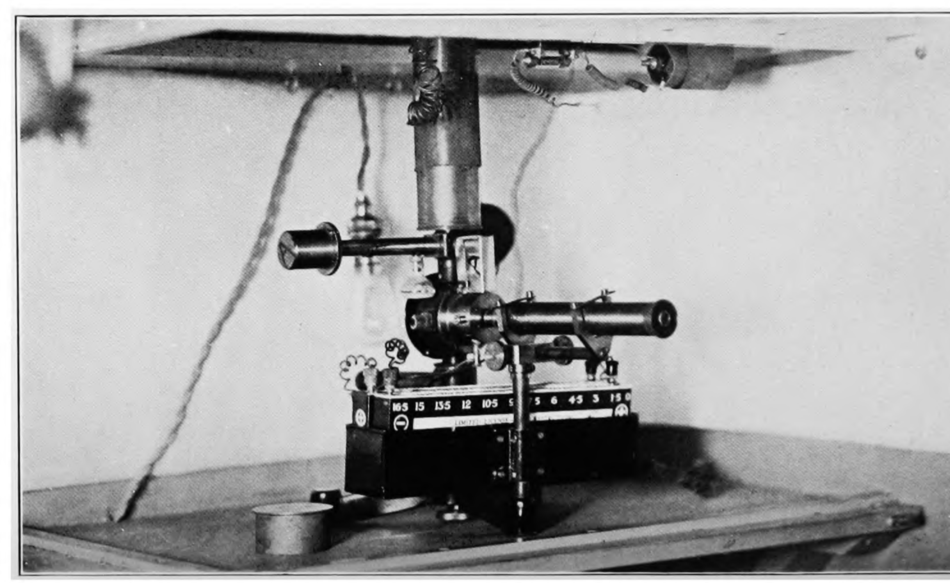

Fig. 5.—The test-plate electrometer in the underground laboratory

small cylindrical condenser is attached to the test-plate system and is kept charged by a small Leyden jar; the purpose of this "compensator" is to maintain the test plate at any desired potential (usually zero). The method of using the instrument at Kew differs from that adopted by Wilson, who used the readings of the position of the compensator to obtain the charge on the test plate. At Kew the compensator is used merely to keep the plate at zero potential and the charge is measured by reading the deflexion of the electrometer. The conductivity is estimated by comparing the charge collected by the plate in a known time, generally five minutes, with that produced on the plate when it is exposed to the earth's field. The deflexions are read with the cover in position and the "compensator" out. A noteworthy feature of the method is that it requires no knowledge of the instrumental constants since in electrostatic measure the dimensions of specific conductivity are the inverse of those of time. The only absolute measurement required therefore is that of time.

Until the end of 1930 the practice was to use the portable Wilson apparatus, set up on a tripod on the Observatory lawn near the site G, Fig. 1. The height of the test plate above the ground was 1·35 m. The observations, each lasting about 20 min., were carried out on most fine days at 15h. A slight modification was made to the apparatus in 1929 by replacing the gold-leaf electrometer by a Lindemann electrometer; the greater sensitivity of the latter enabled more accurate measurements to be obtained. A photograph of the modified apparatus is reproduced in Fig. 6.

The distortion of the electric field over the test plate when the instrument is used on a tripod was found by R. E. Watson (7) to be such that the field strength over the plate is about five times as great as that over level ground. The current entering the plate is larger than that entering the ground by roughly the same proportion. To allow for this, and to obtain an estimate of the current flowing into an approximately flat surface, the conductivity was multiplied by the potential gradient in the open which was obtained from the electrograph records, the mean value for the hour at which the conductivity measurement was made being used.

Some experiments by G. M. B. Dobson (9) and later by R. E. Watson (7) showed that the values of conductivity obtained with the Wilson apparatus on the tripod were in general lower than those obtained with the apparatus on the ground. On this account it appeared desirable to provide facilities for making the routine observations at ground level and to this end an underground laboratory was built in the best exposed part of the Observatory paddock. The first use to which the laboratory was put was to continue the investigation of the difference between the measurements of conductivity on the tripod and at the ground; a discussion of this will be given later. On the completion of this preliminary work it was decided to discontinue the tripod observations and to make the routine measurements of conductivity and air-earth current in the underground laboratory.

(iii) *The underground laboratory and test-plate apparatus at ground level.*—The laboratory consists of a brick-built chamber about 3 m. square with a flat lead roof almost at ground level. As a precaution against floods the roof was arranged to be about 25 cm. above the surrounding paddock, but after preliminary experiments an asphalt platform was built up to this level round the roof so that the latter is in the middle of a flat square with sides about 10 m. long. At the edges of the square the asphalt slopes away to the level of the grass. The entrance to the chamber is by means of a sliding door flush with the roof. A photograph of the site is reproduced in Fig. 5.

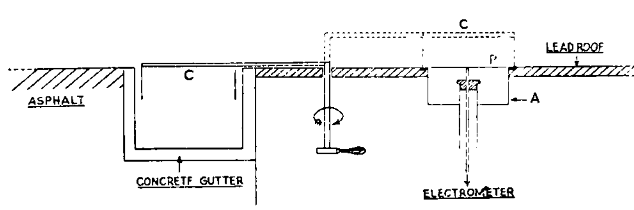

FIG. 7.—ARRANGEMENT OF TEST PLATE AND COVER IN THE UNDERGROUND LABORATORY.

The construction of the test-plate apparatus in the roof is shown in Fig. 7. A brass container, A., 10 cm. deep, is sunk into the roof and fixed by means of a flange. The test plate P, 20 cm. in diameter, is supported by means of an ambroid insulator which rests in a wide brass tube connecting the container with the case of the electrometer inside the laboratory. The electrometer is a Lindemann pattern and it is fitted with the compensator portion of the Wilson apparatus. For shielding the test plate a brass cover about 10 cm. deep is fitted to a spindle which can be turned from inside the laboratory. When the plate is exposed the cover sinks into a hole in a boarded gutter which surrounds the roof ; the external appearance of the laboratory with the test plate exposed can be seen in Fig. 8. A photograph of the internal apparatus is reproduced in Fig. 9. When not in use the test plate is removed and placed with the electrometer which can be boxed in and kept dry. To prevent water entering the roof through the container, a brass plate with a rubber washer is held in place by a bolt running through the connecting tube

The observations carried out with the apparatus are exactly the same as those previously made with the Wilson apparatus on the tripod, but as the plate is now at ground level the measurements are used for obtaining absolutely the potential gradient and the current as well as the conductivity. For this purpose it is necessary to know the capacity of the apparatus as well as the sensitivity of the electrometer.

Normally the electrometer is used at a sensitivity of about 30 divisions per volt, the plate potentials being $\pm 16\frac{1}{2}$ volts, but in winter it is sometimes necessary to reduce the sensitivity. The capacity of the apparatus has been measured by means of a Wulf standard condenser and also by means of an artificial field above the test plate. Both methods gave a value of $54{\cdot}0/(9\times10^{11})$ farads.

The potential gradient F is given by $F=4\pi\times9\times10^{11}\sigma=4\pi\times9\times10^{11}Cv/A$ volts/cm. where σ is the surface density of charge in coulombs produced on the test plate after being exposed to the field, earthed and then shielded, C is the capacity in farads of the system (when covered), v the voltage acquired by it and A the area of the test plate. The air-earth current is given by $i=C\,\delta v/At$ amp./cm.^{2} where δv is the voltage reached by the plate in t seconds. The conductivity λ is i/F i.e., $\delta v/(4\pi tv\times9\times10^{11})$ ohm^{-1} cm.$^{-1}$

For the year 1931 the conductivity was observed in the underground laboratory, but owing to the fact that during the whole of that year the test plate was not quite flush with the roof and the asphalt platform was not laid until November the air-earth current was obtained, as in the earlier years, by using the potential gradient derived from the electrograph records. This year should therefore be regarded as a transitional year. From the beginning of 1932, when the test plate was made quite flush, the three elements were observed absolutely at the underground laboratory. Furthermore the observations of potential gradient with the test plate were from that time onwards used in place of those with bamboo rod and fuse apparatus for standardizing the electrograph. It was felt, however, that a check on the new method was desirable, and for this purpose weekly simultaneous comparisons were made for a year between the test-plate observations of potential gradient and the potential measured by means of a stretched wire and fuse (J_1, Fig. 1) one metre above the roof of the laboratory. The results of these comparisons will be dealt with in the next section.

§ 3—POTENTIAL-GRADIENT REDUCTION FACTORS

It is now considered that the absolute potential gradient at Kew Observatory is best represented by the gradient either over mown grass in the paddock or immediately above the roof of the underground laboratory. On account of the presence of the Observatory building, which is 15 m. high and 90 m. away, and two large trees 26 m. high and 85 m. away, there must be a slight distortion of the field over the laboratory. A rough calculation shows that the effect is such as to cause a reduction of the gradient of less than 2 per cent, but this is counterbalanced to some extent by the effect of the roof and the asphalt platform being 25 cm. above the surrounding paddock. The point of greatest importance is that the exposure of the site is not likely to be altered for a large number of years and for this reason alone the site is a very suitable one for the control observations.

To make the earlier values of potential gradient comparable with those obtained since the beginning of 1932 we require to know the factors connecting the earlier absolute observations with those obtained at the underground laboratory. The period under review may be divided into three parts, thus :

Years.		*Absolute Observations.*
1898–1909	.. ..	Pillar on lawn.
1910–31	.. ..	Bamboo rod on lawn.
1932–	.. ..	Test plate of underground laboratory.

Before dealing with the first period we shall discuss the correction that has to be applied to the second period to make the data comparable with those obtained in 1932. It should be mentioned that in the spring of 1924 there was a change in the surroundings of the site on the lawn (G, Fig. 1) where the observations with the bamboo rod were taken ; previously there had been fruit bushes and vegetables on either side of the grass plot. The ground was dug up in the spring and grass was sown. There is no indication in the run of the exposure factors that this had any effect.

The first comparisons between the potential gradient over the lawn site and that over the paddock were made by R. E. Watson (7) in the autumn of 1926 and spring of 1927. He used the bamboo rod with an electrostatic voltmeter at the lawn site (G, Fig. 1) and a stretched wire with a Wulf electrometer in the paddock near the site where the underground laboratory was afterwards built ; when used at the same site the apparatus gave results in good agreement. Watson found that the gradient over the paddock was 13 per cent higher than that over the lawn The comparisons were continued by the author in order to cover other seasons of the year. The results are given in Table I, which also includes Watson's figures.

TABLE I—COMPARISONS OF POTENTIAL GRADIENT : PADDOCK AND LAWN

Year	1931	1931	1927, 30	1927, 30	1930	1930	1930	1930	1926	1930
Month	Jan.	Feb.	Apr.	May	June	July	Aug.	Sept.	Oct.	Dec.
No. of Obs. ..	6	4	3	9	4	8	8	6	3	5
Potential gradient Paddock/lawn ..	1·13	1·12	1·125	1·125	1·125	1·105	1·09	1·09	1·13	1·13

The mean ratio is 1·12, but the values for July, August and September are appreciably lower than those for the other months. The most likely explanation of this is that the insulation of the bamboo-rod system, which is now known to be less efficient and more variable than that of the stretched-wire system, was at its best in the summer months. Comparisons of the two systems at the same site showed that they were in good agreement in summer, but in winter the bamboo-rod system gave results which were on the average 4 per cent lower than those given by the stretched-wire system.

For our purpose it is hardly worth while taking the annual change of the ratio into account, so the mean value of 1·12 will be adopted as the factor connecting the gradient over the lawn with that over the paddock.

Watson's experiments included some observations in the Old Deer Park (in which the Observatory is situated) as far away as possible from trees or other obstructions. He found that the gradient in the more open positions was no greater than that in the paddock. We can therefore regard the disturbance of the earth's field in the paddock by the Observatory building and by the larger trees as negligible.

The next step was to see whether the potential gradient over the roof of the underground laboratory is the same as that over the grass surface of the paddock. Some indirect comparisons, using the stretched-wire apparatus with the test plate as a control, showed that the potential at 1 m. above the roof (J_1, Fig. 1) is 4 per cent higher than that at 1 m. above the grass at the site J_3, Fig. 1*. Further, a long series of direct comparisons showed that on the average the potential gradient measured by means of the stretched wire 1 m. above the laboratory is 4 per cent higher than that measured at roof level by means of the test plate. The gradient at roof level, therefore, agrees exactly with the mean gradient in the first metre above the grass in the paddock and the factor 1·12 connects both these exposures with the lawn exposure.

The difference of four per cent between the gradient at roof level and the average gradient in the first metre above the roof is almost certainly due to some small irregularities in the roof itself; these can be seen in Fig. 8. The joins in the lead covering form ridges about 1 cm. high and 3 cm. wide, and some of the wooden boards covering a gutter between the lead roof and the asphalt platform are also about 1 cm. above the test-plate level. These projections are roughly 1 m. away from the test plate and by making some observations with and without some temporary ridges of about the same dimensions it was estimated that the effect of the permanent projections would account for the difference of four per cent. This difference may be regarded as a lucky accident, for it means that the very small projections on the roof near the test plate just compensate the effect of the roof itself being above the level of the paddock, and so the field as measured by the test plate is in agreement with the field measured above the grass in the paddock.

One minor objection to the use of the underground laboratory as a site for the absolute observations is that the lead roof and the asphalt platform do not represent the average natural conditions of the surface of the ground so well as turf. It is partly to overcome this objection that the monthly check observation by means of the stretched-wire method will, in the near future, be carried out over a grass plot (J_2, Fig. 1) in the paddock which is being specially prepared for the purpose.

We can now turn our attention to the first period, 1898–1909. Just before the change in the absolute apparatus was made at the beginning of 1910 a few direct comparisons between the old apparatus (Fig. 3) and the new (Fig. 4) were carried out. Simultaneously with the change of apparatus, however, some fruit trees (N, Fig. 1) near the observation lawn were removed and circumstances did not allow of any direct estimation of the effect of their removal. The comparisons which were made, therefore, did not suffice for the determination of a factor which could be applied to the results obtained prior to 1910 to bring them to what they would have been under the conditions introduced in that year. An attempt to do this in another way was made by C. Chree (6). He adopted the hypothesis that the true mean potential gradient for the three years 1910–2 was the same as that for the previous twelve years. This gave 1·91 as the factor by which the older readings were to be multiplied to make them comparable with the new. Although this factor is very large (owing to the very unsatisfactory arrangement of the old absolute apparatus, as can be seen from Fig. 3), we now find it necessary to increase it, because the mean potential gradient for the three years 1910–2 happened to be lower than that for the much longer period 1910–31. By adopting Chree's method of correction and using this longer period of years we obtain a factor 2·04 connecting the older readings with those obtained from 1910 to 1931. As the data for the later years have to be increased by 12 per cent to make them comparable with observations in the paddock, the original observations of 1898–1909 must be multiplied by the factor 2·28, which is of course equal to the product $2{\cdot}04 \times 1{\cdot}12$. This factor, 2·28, takes account of three changes, viz. the change in the absolute apparatus in 1910, the removal of the fruit trees at the same time and the change of site from the lawn to the paddock in 1931.

The revision of the annual means is set out in Table II which includes also the original published values. For the period 1910–31 the mean of the annual values referred to the lawn site is 324 volts per metre; after the annual values have been converted to the paddock exposure by multiplying by the factor 1·12 the mean

* Some direct comparisons made recently by Mr. L. H. G. Dines show that the potential at 1 m. above the roof is 3 per cent higher than that at 1 m. above the grass at the site J_3, Fig. 1.

TABLE II—POTENTIAL GRADIENT : ORIGINAL AND REVISED ANNUAL MEANS FOR QUIET DAYS

(Volts per metre)

(a) Lawn exposure G, Fig. 1 ; fruit trees N present ; fuse attached directly to electrometer (Fig. 3).

(b) Lawn exposure G, Fig. 1 ; fruit trees N removed ; bamboo rod apparatus (Fig. 4).

(c) Ground level exposure in paddock H, Fig. 1.

Year	(a)	(c) $=\frac{363(a)}{159}$	Year	(b)	(c) $=1\cdot12(b)$	Year	(b)	(c) $=1\cdot12(b)$
1898	161	368	1910	310	347	1921	281	315
1899	179	409	1911	301	337	1922	318	356
1900	141	322	1912	300	336	1923	318	356
1901	156	356	1913	335	375	1924	329	368
1902	145	331	1914	345	386	1925	326	365
1903	162	370	1915	354	397	1926	279	313
1904	167	381	1916	367	411	1927	315	353
1905	167	381	1917	354	397	1928	298	334
1906	156	356	1918	346	388	1929	338	379
1907	163	372	1919	331	371	1930	333	373
1908	148	338	1920	315	353	1931	338	379
1909	164	374						
Means	159	363				Means 1910–31	324	363

becomes **363** volts per metre. The mean of the original annual values for the period **1898–1909** is **159**, so these values have been multiplied by the factor **363/159**, i.e., **2·28**, to bring them into line with observations in the paddock. In considering any secular variation we must bear in mind the arbitrary method of revising the earlier figures and keep a discontinuity between the years **1909** and **1910**. The mean potential gradient for the first **11** years of the period **1910** to **1931** is **373** volts per metre while the mean for the last **11** years is **354** volts per metre, so the factor **363/159** which we have adopted for the first period, and therefore our adopted mean of **363** volts per metre for this period, may be ± 3 per cent in error.

One further point concerning reduction factors is that since the introduction of the test-plate method for the absolute observations the monthly mean exposure factors between the potential of the electrograph and the potential gradient in the open have been less variable. It is suspected that the observations obtained with the bamboo-rod system were subject to appreciable errors due to insulation leak. Variations in the individual observations still occur under the new procedure and they probably depend on a number of factors, such as the strength of the wind and differences in pollution due to local influences.

§ 4—THE VARIATION OF POTENTIAL GRADIENT IN FINE WEATHER

In the following account of the variation of the potential gradient all the data for Kew from **1898** onwards refer to the level exposure in the paddock. The practice is to tabulate the hourly values of potential gradient for **10** quiet days in each month (measurements are also made on all days when possible at **3h.**, **9h.**, **15h.**, and **21h.**) The quiet days chosen are normally days on which the gradient was positive throughout the **24** hours. If there are more than **10** such days in the month those in which abnormally high gradients, usually associated with fog, occur are rejected. If there are not **10** calendar days satisfying the condition of no negative gradient the number is made up by using runs of **24** consecutive hours which do satisfy the condition, and in computing the diurnal variation the appropriate allowance for any progressive " non-cyclic " change is made.

TABLE III.—DIURNAL INEQUALITIES OF POTENTIAL GRADIENT

Mean values for the

Unit—volts

Month and Season	Hour 1	G.M.T. 2	3	4	5	6	7	8	9	10	11	12
Jan.	− 75	− 98	−114	*−131*	−127	−100	− 45	+ 17	+ 60	+ 71	+ 54	+ 40
Feb.	− 51	− 83	−111	*−121*	−114	− 95	− 43	+ 26	+ 73	+ 83	+ 53	+ 22
Mar.	− 39	− 68	− 88	*−104*	− 95	− 60	− 4	+ 55	+ 72	+ 48	+ 4	− 28
Apr.	− 34	− 56	− 74	*− 80*	− 65	− 28	+ 31	+ 69	+ 64	+ 30	− 14	− 35
May	− 23	− 45	*− 56*	− 53	− 40	− 6	+ 37	+ 59	+ 55	+ 23	− 10	− 30
June	− 25	− 36	*− 43*	− 39	− 27	0	+ 34	**+ 59**	+ 55	+ 32	+ 6	− 16
July	− 25	− 43	*− 48*	− 45	− 28	+ 6	+ 51	**+ 70**	+ 64	+ 36	+ 3	− 20
Aug.	− 28	− 44	*− 53*	− 50	− 34	+ 4	+ 47	**+ 67**	+ 62	+ 35	+ 4	− 17
Sept.	− 44	− 58	− 65	*− 66*	− 53	− 23	+ 22	+ 55	+ 54	+ 35	− 3	− 20
Oct.	− 62	− 72	*− 74*	− 71	− 59	− 33	+ 4	+ 50	+ 61	+ 43	+ 8	− 17
Nov.	− 56	− 79	*− 92*	− 91	− 85	− 65	− 22	+ 28	+ 54	+ 52	+ 32	+ 14
Dec.	− 72	− 96	−109	*−110*	−103	− 86	− 42	+ 23	+ 63	+ 67	+ 48	+ 27
Year	− 45	− 65	− 77	*− 80*	− 69	− 41	− 6	+ 48	+ 61	+ 45	+ 15	− 7
Winter	− 63	− 89	−107	*−113*	−107	− 87	− 38	+ 23	+ 63	+ 68	+ 47	+ 26
Equinox	45	− 63	− 75	*− 80*	− 68	− 36	+ 13	+ 57	+ 63	+ 39	− 1	− 25
Summer	− 25	− 42	*− 50*	− 47	− 32	+ 1	+ 42	**+ 64**	+ 59	+ 31	+ 1	− 21

(i) *Diurnal variation.*—Monthly and seasonal* means for the whole period 1898 to 1931 of the diurnal inequalities are given in Table III. The values are plotted in Figs. 10 and 11. The general form of the curves is not perceptibly different from that of corresponding curves obtained with shorter periods of years; with the great length of the period now available there are no appreciable irregularities in the mean hourly values and practically no smoothing was necessary in drawing the curves.

The double oscillation is well marked throughout the year, and in all months except June, July and August the evening maximum is greater than the morning maximum. It is now generally accepted that daily variation of potential gradient at land stations is largely governed by the variation of atmospheric pollution (dust and nuclei of condensation). This has been discussed in detail by F. J. W. Whipple (10) who showed that the introduction of "summer time" in 1916 had the effect of moving back the morning minimum and maximum approximately one hour. Since Whipple's analysis

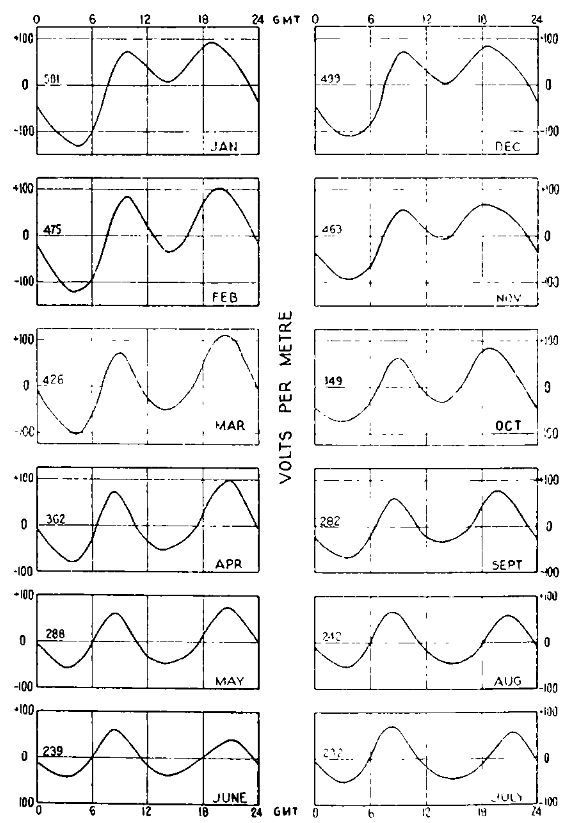

FIG. 10.—MONTHLY MEANS OF DIURNAL INEQUALITIES OF POTENTIAL GRADIENT 1898—1931.

* The seasons are each composed of four months, viz., winter, including November to February; equinox, including March, April, September and October; and summer, including May to August.

ON QUIET DAYS (reduced to level surface in the paddock).
period 1898–1931.
per metre.

13	14	15	16	17	18	19	20	21	22	23	24	Mean Values
+ 18	+ 7	+ 15	+ 31	+ 62	+ 83	+ **92**	+ 80	+ 61	+ 37	+ 1	− 41	501
− 12	− 33	− 30	− 10	+ 30	+ 73	+ **98**	+ **98**	+ 86	+ 60	+ 19	− 19	475
− 45	− 50	− 41	− 27	− 1	+ 49	+ 93	+ **109**	+106	+ 84	+ 40	− 7	426
− 52	− 51	− 45	− 31	− 13	+ 28	+ 71	+ 90	+ **97**	+ 68	+ 33	− 7	362
− 44	− 46	− 40	− 34	− 18	+ 15	+ 47	+ 70	+ **71**	+ 54	+ 24	− 5	288
− 31	− 36	− 35	− 24	− 13	+ 7	+ 21	+ 35	+ 41	+ 32	+ 10	− 12	239
− 34	− 42	− 42	− 40	− 29	− 9	+ 13	+ 36	+ 56	+ 51	+ 26	− 5	232
− 33	− 41	− 42	− 39	− 29	− 2	+ 29	+ 53	+ 57	+ 46	+ 21	− 12	242
− 30	− 31	− 26	− 15	+ 7	+ 47	+ 73	+ **75**	+ 60	+ 32	− 1	− 26	282
− 28	− 31	− 13	+ 9	+ 49	+ 80	+ **81**	+ 70	+ 49	+ 17	− 16	− 44	349
− 1	− 9	+ 8	+ 37	+ 59	+ **66**	+ 64	+ 55	+ 44	+ 25	− 6	− 37	463
+ 13	0	+ 13	+ 36	+ 58	+ **80**	+ **80**	+ 69	+ 51	+ 32	0	− 42	499
− 23	− 30	− 23	− 9	+ 13	+ 43	+ 63	+ **70**	+ 65	+ 45	+ 13	− 21	363
+ 5	− 9	+ 1	+ 23	+ 52	+ 75	+ **83**	+ 75	+ 61	+ 38	+ 3	− 35	485
− 39	− 41	− 31	− 16	+ 11	+ 51	+ 79	+ **86**	+ 78	+ 50	+ 14	− 21	355
− 35	− 41	− 40	− 34	− 22	+ 3	+ 27	+ 49	+ 56	+ 46	+ 20	− 9	250

was made records for three more years have become available, making 16 years with "summer time." Fig. 12 gives the seasonal curves of the percentage diurnal variation for this period, 1916–31, together with curves for 1898–1909 and 1910–5 (as already mentioned the end of 1909 marks a discontinuity in the series of observations). In Great Britain "summer time" commences in the last half of April and ends early in October ; the period during which it is in force therefore includes the whole of our summer season and roughly one quarter of the equinoctial season. It will be seen that during the winter and the equinoxes the times of the morning minimum and maximum have not changed appreciably since the introduction of "summer time" ; on the other hand, the times of the morning extremes on the summer curve have advanced by about one hour. Another noteworthy feature of the summer curve for 1916–31 is that the evening maximum is considerably smaller than the corresponding maxima of the earlier periods. This again may be partly due to the effect of the introduction of "summer time."

The masking of the universal time variation of potential gradient by the effect of local conditions at Kew is shown in Fig. 13. This diagram gives the mean diurnal variation at Kew (for all months of the period 1898 to 1931) and the mean diurnal variation over the oceans as obtained from observations on the *Carnegie* during the periods 1915 to 1921 and 1928 to 1929 (11). The third curve in the diagram is the diurnal variation of the ratio of the gradient at Kew to that over the oceans ; the significance of this curve is explained roughly in terms of a theory sketched by F. J. W. Whipple (12). The circulation of electricity in the atmosphere above any place may be expressed by the simple equation $i = V/R$ where i is the air-earth current, V is the potential difference between the Kennelly-Heaviside layer and the ground while R, as defined by this equation, is the total effective resistance of the air column above the place. In general R may be considered as the integral with respect to height of the reciprocal of the total conductivity but a complete theory would take account of the diffusion of electricity by turbulence and convection. The potential gradient, F, at the surface is the product of the current and the specific resistance of the air, γ (i.e., the reciprocal of the positive conductivity) at the surface.

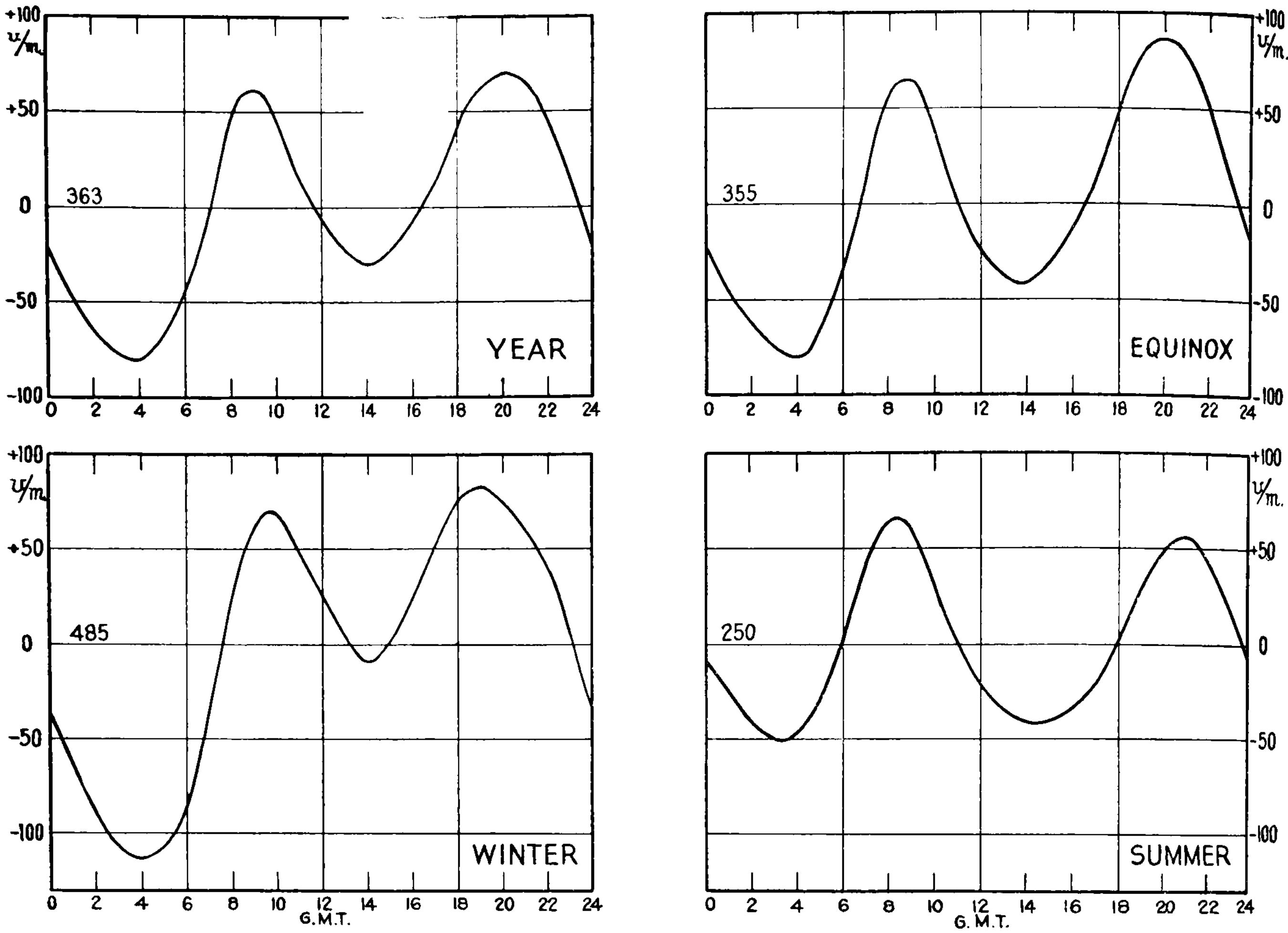

FIG. 11.—SEASONAL AND ANNUAL MEANS OF DIURNAL INEQUALITIES OF POTENTIAL GRADIENT 1898—1931.

Thus we may write $F = i\gamma = V\gamma/R$. The potential of the K.H. layer is the same all over the world, therefore by taking the ratio of F_K to F_O (the suffixes indicate Kew and oceans) we eliminate the effect of the daily variation of V and we have $F_K/F_O = \gamma_K R_O/\gamma_O R_K$. Now observations of conductivity over the oceans indicate that γ_O varies only very slightly through the course of the day ; this is to be expected since pollution is almost entirely absent over the sea. It is reasonable also to expect R_O to be practically constant. Our ratio therefore reduces to $F_K/F_O = \text{constant} \times \gamma_K/R_K$, and the curve tells us how the ratio of the local specific resistance to the total effective resistance at Kew varies in the course of the day. Some information about the daily variation of the specific resistance at Kew was obtained by the author (13) by means of simultaneous records of potential gradient and air-earth current and it showed that γ_K undergoes a marked double oscillation during the course of the day. This double oscillation is very similar to that shown by atmospheric pollution as observed near the ground. It has been explained by Dr. G. C. Simpson (14) as due to the combination of two effects, the variation in the rate of production of smoke and the variation in the rate at which pollution is diffused upwards by convection. Smoke production increases from about 5h. to 9h., and since convection is small at that part of the day the pollution accumulates near the surface and causes the specific resistance to increase. Convection is effective during the daytime and we find the air near the ground becoming cleaner at the expense of the air at higher levels ; this process is accompanied by a decrease in the specific resistance. Towards evening convection diminishes and pollution

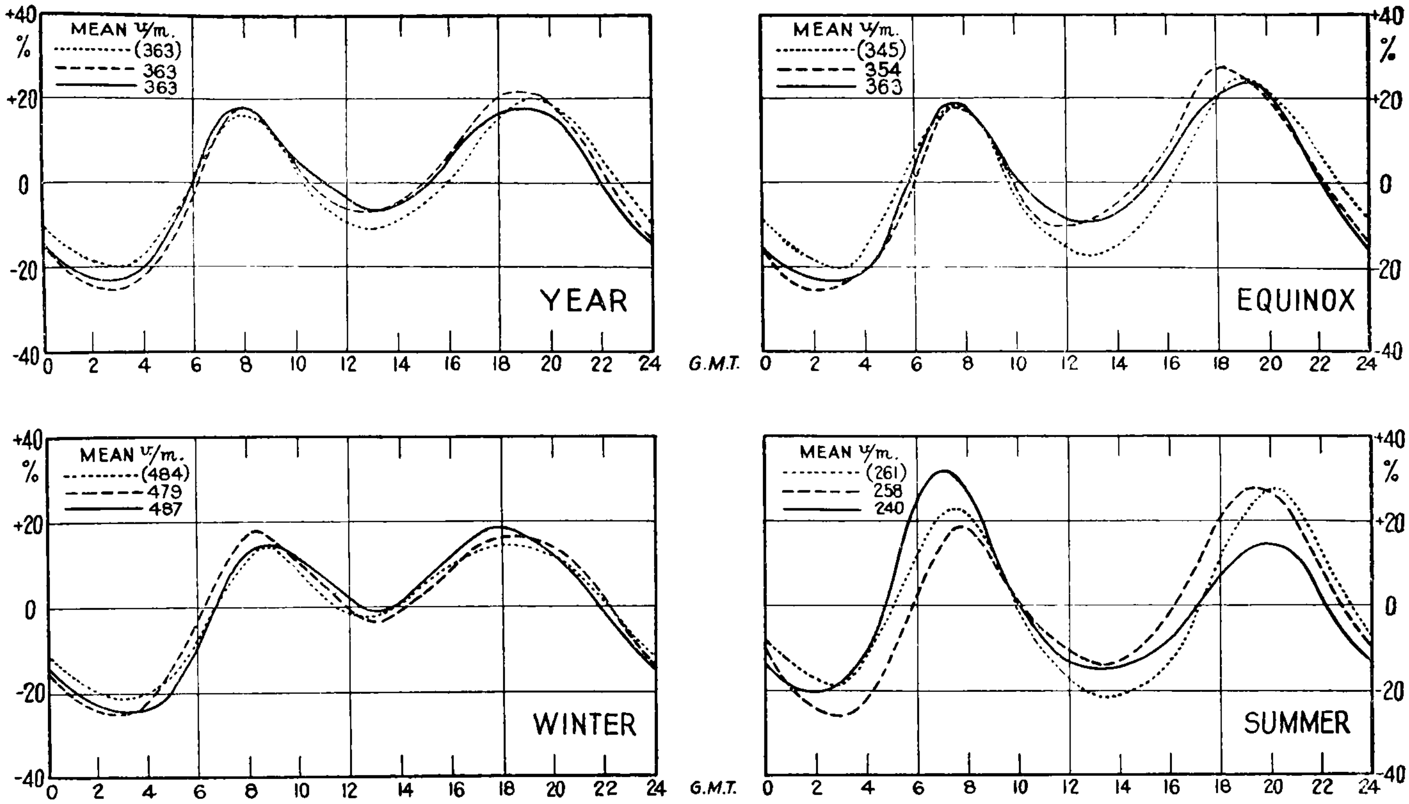

FIG. 12.—DIURNAL VARIATION OF POTENTIAL GRADIENT: 1898-1909......; 1910-5- - -; 1916-31——.

again accumulates in the lower layers causing some increase in γ_K. During the night smoke production falls off and both pollution and γ_K tend to a minimum. In the case of the total effective resistance R_K it is the total amount of pollution in the air column above Kew which is the main factor, and this is independent of any convectional effects. Whipple (12), using the data obtained by the author (13), has deduced that the total effective resistance increases steadily during the hours in which pollution is being produced. Now it has already been explained that the curve of the daily variation of the ratio F_K/F_O which is shown in Fig. 13 also represents the variation in the ratio γ_K/R_K. This curve, as we should expect, brings out very clearly the effect of convection which, by causing the pollution due to smoke to be diffused upwards to great heights, produces a very marked minimum of the ratio in the middle of the day.

The processes described above also largely govern the shape of the curve of the diurnal variation of potential gradient, but there is in addition the world-wide effect of the variation in the potential of the Kennelly-Heaviside layer, for according to our formula $F = V\gamma_K/R_K$. At Kew the variations of γ_K are larger than the corresponding variations of V and R_K and therefore we find that the changes in potential gradient are very similar to the changes in the local resistance.

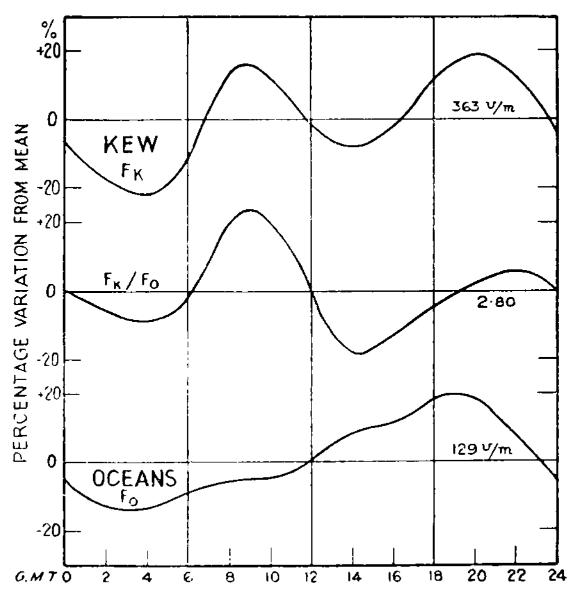

FIG. 13.—DIURNAL VARIATION OF POTENTIAL GRADIENT AT KEW AND OVER THE OCEANS.

Our method of separating the local effects from the universal effect is not intended to give a rigid representation of all the factors at work, but to give merely a simple sketch of the main processes governing the diurnal variation of potential gradient near a large town. It may be doubted whether all pollution is due to smoke since a double oscillation of potential gradient is found at some places which are not near large sources of smoke. To settle this question G. R. Wait (15) selected Penalosa in Kansas as a place on land far removed from smoke and found a single oscillation of potential gradient in agreement with the variation according to universal time which Mauchly derived from the observations over the oceans. The question is answered also by the Kew observations alone for H. L. Wright (16), in a statistical study of the effect of atmospheric suspensoids on potential gradient at Kew, has deduced that in the complete absence of pollution the potential gradient at Kew, at 15h., would be about 140 volts per metre, which is about the same as the value observed over the oceans. This suggests that pollution accounts for the whole of the difference between the gradient at Kew and that over the sea.

(ii) *Annual variation.*—The monthly means for all the years considered are given in Table IV and the means for the whole period are plotted in Fig. 14. For comparison the annual variations at Eskdalemuir, Potsdam and Tortosa are also plotted in this diagram. All four stations show the type of variation that is observed at most places in the northern hemisphere, i.e., a maximum in the winter and a minimum in the summer. The relative ranges of variation are roughly the same at Kew, Eskdalemuir and Potsdam, but at Tortosa the relative range is much smaller. The Kew curve is not quite symmetrical about the minimum (July), the slope down from January to July being rather more gentle than the slope up from July to December. This is probably because the use of domestic fires is prolonged well into the spring, while in the autumn the tendency is to put off the use of fires until as late in the year as possible.

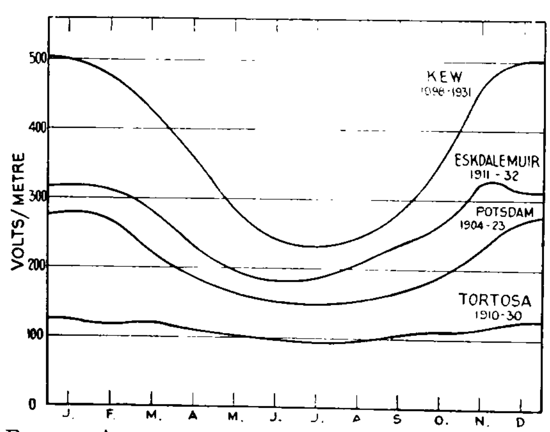

FIG. 14.—ANNUAL VARIATION OF POTENTIAL GRADIENT.

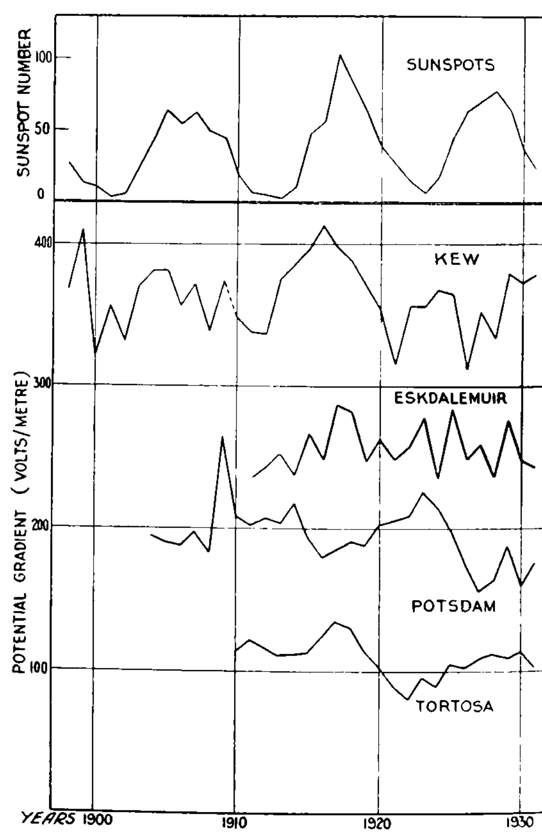

FIG. 15.—SECULAR VARIATION OF POTENTIAL GRADIENT AND OF SUNSPOT NUMBERS.

TABLE IV—MEAN POTENTIAL GRADIENT ON QUIET DAYS

(Reduced to level surface in the paddock). (Volts per metre).

	Jan.	Feb.	Mar.	Apr.	May	June	July	Aug.	Sept.	Oct.	Nov.	Dec.	Year
1898	397	557	494	249	221	238	238	286	372	368	570	420	368
1899	650	680	464	317	344	240	206	291	190	399	381	749	409
1900	432	416	411	244	219	166	196	238	269	304	359	600	322
1901	544	565	322	319	291	261	216	198	267	437	491	369	356
1902	374	530	347	341	213	263	196	253	238	281	407	542	331
1903	370	397	437	377	381	356	240	294	308	322	393	570	370
1904	444	434	404	366	297	241	267	269	297	336	592	623	381
1905	500	386	377	372	297	381	308	347	381	370	552	407	381
1906	434	454	420	359	215	288	288	240	327	319	384	557	356
1907	452	520	439	336	329	228	354	263	283	286	515	445	372
1908	630	364	477	427	235	251	201	238	238	258	402	344	338
1909	457	475	370	454	352	198	201	304	297	281	517	570	374
1910	447	484	432	293	306	227	260	226	231	370	504	392	347
1911	512	386	423	320	279	245	234	243	280	418	410	301	337
1912	586	377	255	304	228	187	290	259	374	447	354	372	336
1913	534	507	345	379	340	217	234	241	301	418	380	610	375
1914	638	426	335	433	361	190	230	259	282	296	474	715	386
1915	559	468	491	413	352	372	172	228	268	385	557	495	397
1916	619	604	710	444	245	209	212	222	323	288	468	590	411
1917	606	539	467	401	386	225	262	213	301	437	337	586	397
1918	517	429	519	454	357	291	218	204	286	388	549	442	388
1919	715	540	427	318	367	179	227	183	272	330	442	445	371
1920	412	438	357	316	254	194	231	281	271	440	506	528	353
1921	337	544	363	328	187	202	174	202	265	234	564	382	315
1922	470	516	501	423	224	198	195	255	248	413	473	355	356
1923	524	382	479	452	279	184	263	185	254	323	504	445	356
1924	491	539	618	428	231	211	207	204	215	318	459	534	368
1925	455	420	421	379	292	281	208	223	278	310	570	540	365
1926	516	334	319	337	254	204	228	171	221	343	353	472	313
1927	413	474	414	287	296	291	253	204	230	354	486	525	353
1928	454	411	306	360	282	253	187	196	293	325	412	525	334
1929	588	599	514	308	324	217	250	228	254	296	439	528	379
1930	427	536	416	411	274	300	215	254	274	351	423	595	373
1931	525	428	410	375	290	251	223	310	395	421	516	394	379
Mean	501	475	426	362	288	239	232	242	282	349	463	499	363

(iii) *Secular variation.*—Table IV also contains the annual means of potential gradient for 34 years and these values are plotted in Fig. 15. The curve between 1909 and 1910 is dotted in order to emphasize the fact that the values obtained prior to 1909 are not absolutely comparable with those obtained after that year. This diagram also shows the variation of the same element at three other stations, Tortosa, Potsdam and Eskdalemuir, where records of potential gradient have been obtained over long periods of years though none quite so long as at Kew. The variation of sunspot activity is plotted at the top of the diagram. L. A. Bauer (17) claimed to find the sunspot period well defined in the Kew, Eskdalemuir and Tortosa observations during the cycle 1913 to 1922. More recently R. P. L. Rodés (18) has discussed the Tortosa data up to 1932, thus covering a second sunspot cycle, and he remarks that apart from some accidental anomalies the parallelism between sunspot activity and potential gradient is shown in both cycles. C. Chree (19) studied the Kew data up to 1922 and concluded that they are not inconsistent with the existence of a small 11-year variation, but that they do not suggest such a considerable effect as Bauer claimed to find. Our extension of the period studied by Chree makes any connexion out of the question. The annual means are subject to irregular fluctuations which may be due in part to comparatively local causes. For example the low values of the gradient in 1921 and in 1926 are almost certainly due to diminished atmospheric pollution following the diminution in industrial activity during prolonged strikes in England in those years.

The data for Eskdalemuir and for Potsdam show little or no connexion with sunspot fluctuations. This is further evidence that there is no relation of cause and effect in the case of Eskdalemuir, since that station is much less affected by atmospheric pollution than Kew.

(iv) *Comparisons with the results of early observations.*—In the introduction it was mentioned that the early measurements initiated by Ronalds, Everett and G. M. Whipple do not give us any information about the absolute potential gradient in the open. Their results can, however, be used for comparisons of the types of annual and diurnal variation, and in Fig. 16 we have plotted the curves derived from the early observations together with corresponding curves obtained in more recent years. In comparing one series with another, it is important to bear in mind the circumstances under which the observations were made.

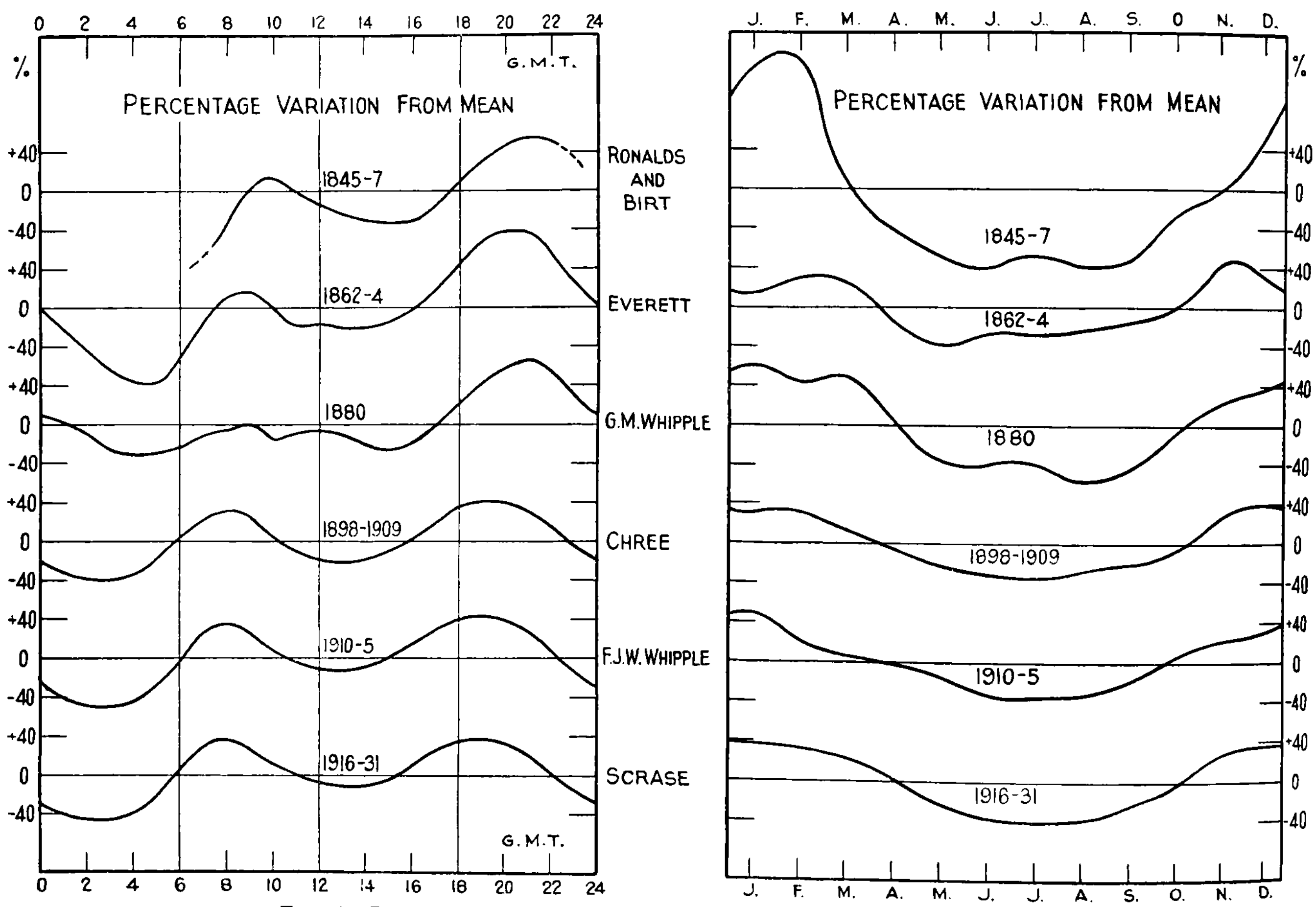

FIG. 16.—DIURNAL AND ANNUAL VARIATIONS OF POTENTIAL GRADIENT, 1845–1931.

The observations of Ronalds during the three years 1845 to 1847 consisted of measurements on an arbitrary scale, at every even hour, of the potential 16 feet above the dome of the Observatory. In view of a statement made by B. Chauveau in his book *Electricité Atmosphérique* (Vol. I, p. 42) to the effect that the observations were made with a point collector, it should be emphasized that the collector which

Ronalds used was a Volta lamp. The measurements at 0, 2 and 4h. were obtained with " night-registering " electrometers which were disconnected from the collector at the appropriate times by clockwork. Corrections for insulation leak, proportional to the interval between the time these electrometers were disconnected and the time they were read, were made, but since the rate of loss of charge of the instruments became inconsistent at potentials exceeding a certain value (equal to about 75 per cent of the mean potential) any readings exceeding this value were rejected by Ronalds. We must infer therefore that the mean values for 0, 2 and 4h. published in Birt's report (20) are too low so we have neglected them. We have also omitted the observations at 6h. since very few were made at that hour during the winter. The percentage variations for 1845–7 which are plotted in Fig. 16 are therefore variations from a mean which is not representative of a complete day, but of the period 8h. to 22h. The data refer to readings of positive electricity only, but they represent all conditions of weather in which it was possible to make observations.

Everett's observations cover the period June 1862 to May 1864, and they were based on records obtained by means of Kelvin's water dropper with the divided-ring electrometer. The data are for all days of the year and they include the negative readings. The results for corresponding months of the two years vary somewhat largely and there are considerable differences between the mean results for the two years.

G. M. Whipple's analysis for the year 1880 was also based on records of the Kelvin water dropper, but the electrometer was of the quadrant pattern. The curves we have reproduced from Whipple's report are restricted to positive readings. In the curve of the daily variation there is a kink between the hours of 9 and 10, i.e. at about the time the records were changed. This suggests that the night and early morning readings suffered from poor insulation, which was improved when the apparatus received attention at the time of changing. There is a slight indication that the same effect was present on Everett's records between the hours of 10 and 11.

A comparison of the curves of diurnal variation in Fig. 16 shows that the general form of the variation has changed very little since 1845 ; the double oscillation is present throughout the series. Considering the great increase in the sources of pollution which must have taken place in the neighbourhood of Kew during the last 100 years it is surprising that the changes in the type of the daily variation of the gradient are so small. In the earlier years the evening maximum was more prominent and it occurred between one and two hours later than it does at the present time. This change in the time of the evening maximum is of interest in connexion with the idea that there may be some significance in the fact that the north magnetic pole happens to be nearest the sun at 19h. when the evening maximum now occurs. No determination of the position of the north magnetic pole seems to have been made since that by Ross in 1830 until Amundsen's *Gjoa* expedition in 1903–5. The position assigned by Ross was 70° 5′ N., 96° 46′ W., while Amundsen's results indicated that the position 75 years later had moved to 70° 40′ N., 96° 5′ W. This shift, which is equivalent to a change of about two or three minutes in the time at which the pole is nearest the sun, is clearly much too small to account for the large advance in the time of the evening maximum of the gradient. We must conclude, therefore, that the time of the evening maximum at Kew is governed by some factor other than the position of the north magnetic pole. If, on the other hand, we adopt the view that the world-wide fluctuations of potential gradient are closely associated with thunderstorm activity, it is equally difficult to explain the change in the time of the evening maximum, for there is no reason to believe that the time of maximum thunderstorm frequency can have changed appreciably in 100 years. Probably the explanation is to be found in changes in local conditions at Kew.

The curves of the annual variation all show the maximum of potential gradient in the winter and the minimum in the summer. The curve of Ronalds and Birt is not strictly comparable with the later results because the observations of Ronalds, which we have utilized, are limited mainly to the daylight hours. This partly explains why the Ronalds curve has such a large range, for the more complete data show that the annual range derived from observations confined to the daylight hours is about 20 per cent greater than that derived from observations at all hours. Even when allowance is made for this, the range of Ronalds' observations is still comparatively high. It is by no means certain, however, that the method of calibration employed by Ronalds gave him a uniform scale of "electric tension." It is curious that the three earlier curves all show a tendency to rise slightly between June and July; this tendency is almost entirely absent in the more recent observations.

§ 5—COMPARISONS OF CONDUCTIVITY AS MEASURED BY THE WILSON APPARATUS AT GROUND LEVEL AND ON A TRIPOD

Reference has already been made to the experiments of G. M. B. Dobson and of R. E. Watson with the Wilson apparatus at ground level and on a tripod. Their investigations were confined mostly to spring and summer months when the conductivity is high. It fell to the present writer to extend the comparisons so as to cover conditions in the other seasons of the year. These later comparisons were all made after Lindemann electrometers had been fitted to the Wilson apparatus, so the accuracy of the measurements is greater than that of the earlier comparisons. A brief account of the more recent experiments will now be given.

The underground laboratory was used for the measurements at ground level, while the portable apparatus was used on the tripod, the test plate being at a height of 135 cm. above the ground. On most occasions the tripod was set up on the Observatory lawn near site G, Fig. 1 (i.e., in the position used for the routine observations), but on a few occasions it was used in the paddock at a distance of about 10 m. from the underground laboratory. The total number of comparisons (each covering a period of 20 min.) was 88. The monthly means of the conductivities and their ratios are given in Table V. Watson's results for May and June, 13 in all, are included in this table in order to complete the year. It will be seen that the ratio of the conductivity at ground level, λ_G, to that over the tripod, λ_T, is appreciable in summer and becomes quite large in winter. On the average λ_G is 25 per cent larger than λ_T.

TABLE V—COMPARISONS OF CONDUCTIVITIES: MONTHLY MEANS

		No. of Obsns.	λ_T (ohm^{-1} cm.$^{-1}\times 10^{-18}$)	λ_G (ohm^{-1} cm.$^{-1}\times 10^{-18}$)	λ_G/λ_T	F_G/F_T
1931	Jan.	3	16·2	20·7	1·29	·25
1931	Feb.	9	16·5	20·9	1·34	·24
1931	Mar.	13	21·5	24·0	1·21	·23
1931	Apr.	11	25·6	28·3	1·16	·24
1927	May	7	33·6	39·1	1·25	..
1927	June	6	34·2	38·7	1·18	..
1931	July	5	45·0	49·3	1·11	·25
1930	Aug.	13	58·0	59·6	1·04	·22
1930	Sept.	11	36·3	41·7	1·16	·22
1930	Oct.	6	28·6	35·2	1·43	·24
1930	Nov.	10	15·8	20·4	1·35	·25
1930	Dec.	11	6·7	10·8	1·61	·24
	Mean		28·2	32·2	1·25	·24

The ratio of the field strength over the ground plate F_G to that over the tripod plate F_T is also given in Table V. The field over the tripod is about four times that over the ground plate; this is lower than Watson's value because the ground plate used in the later experiments was not quite flush with the surface. It will be noticed that the ratio of the fields varies much less than the ratio of the conductivities; the range of variation of the monthly means of λ_G/λ_T is 46 per cent of the mean while the monthly means of the ratio of the fields vary over 12 per cent. Moreover, the variation of the one appears to be quite independent of the variation of the other.

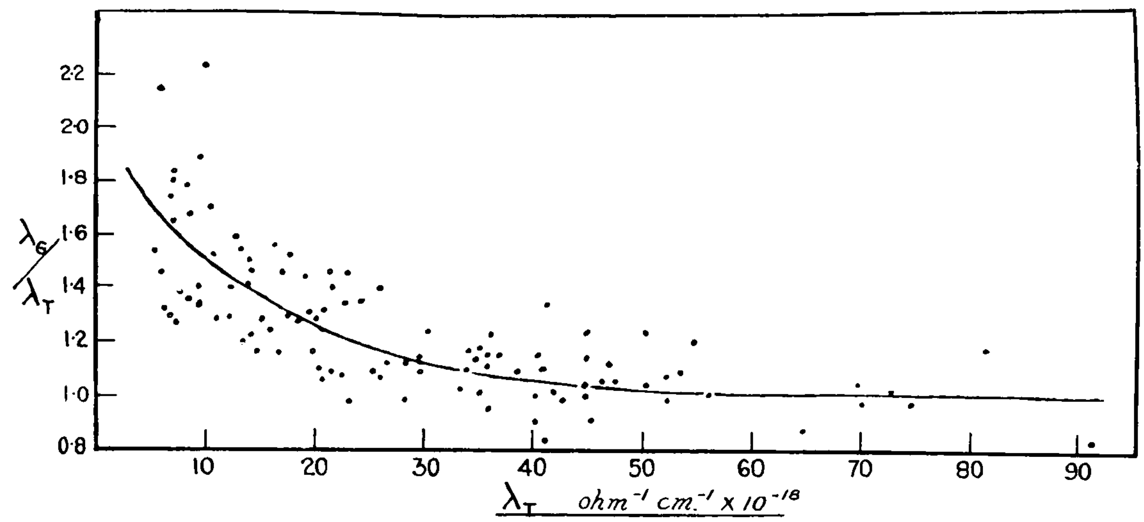

FIG. 17.—RESULTS OF COMPARISONS OF CONDUCTIVITY OVER TRIPOD AND AT GROUND LEVEL.

The factor on which the ratio appears to be mainly dependent is the conductivity itself. The connexion is shown in Fig. 17, in which the observations of λ_G/λ_T are plotted against λ_T; a mean curve is drawn through the points. The mean ratio is very nearly unity when the conductivity exceeds 50×10^{-18} ohm^{-1} cm.$^{-1}$, but at low conductivity it increases rapidly to more than 1·5. The scatter of the points in Fig. 17 is much greater than can be accounted for by experimental errors. Part of this scatter appears to be due to variations in wind velocity. The effect of wind velocity is shown in Fig. 18 in which the deviations of the individual values of the ratio from the mean curve of Fig. 17 are plotted against the wind velocity recorded by the anemometer above the dome of the Observatory.* The points represent means of groups of 17 observations arranged in order of increasing wind speed. From the curve it will be seen that if we take the mean value of the ratio, 1·28, to correspond with the mean wind velocity of 5·5 m./sec. then for a wind of 12 m./sec. the mean ratio would be about 1·16, whilst in a calm it would be about 1·4.

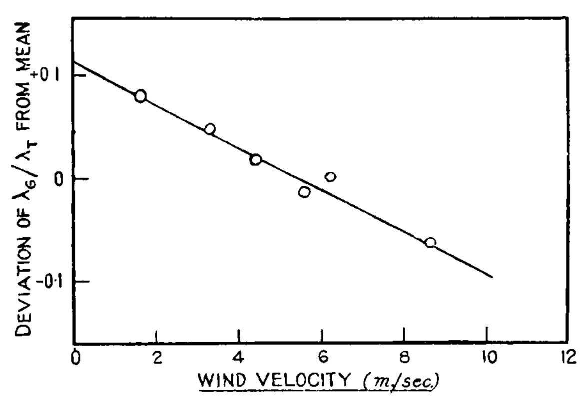

FIG. 18.—VARIATIONS OF CONDUCTIVITY RATIO WITH WIND VELOCITY.

It is found that the values of the ratio show practically no consistent variation with the potential gradient when the effects of varying conductivity and wind velocity are removed.

It was very desirable to settle whether the discrepancies between the ground and the tripod observations are due to real differences in the conductivity of the air near the ground and of that at the height of the tripod, or whether they are due to some effect associated with the highly distorted field over the tripod. Dobson made some simultaneous measurements on two tripods, using the ordinary small guard ring, 25 cm. diameter, of the Wilson apparatus in one case and a much larger guard ring, 80 cm. square in the other. The values of the conductivity which he obtained were considerably greater in the case of the large ring, the ratios being of the order of 1·2. This result alone indicates that the effect is in some way connected with the highly distorted field over the small guard-ring apparatus rather than with any real difference in the conductivity.

* A direct comparison between a portable air-meter placed on the Wilson tripod in the paddock and the Dines anemometer above the dome showed that the wind velocity at the height of the tripod is about 0·75 of that above the dome.

Confirmation of this point has been obtained from experiments in which artificial fields were used over the test plates. The procedure adopted was to support an insulated wire net a few cm. above the test plate and to apply a fixed potential to the net so that the field between it and the plate was well below the saturation strength for small ions. The saturation potentials were calculated roughly from the wind velocity and the dimensions of the apparatus. Thus if, in Fig. 19, TP represents the test plate, CD the guard ring and AB the plate of the artificial field, then the motion of the ions in the field is composed of a horizontal velocity U due to the wind (neglecting any eddying) and a downward velocity Fu due to the field F, u being the mobility. If these velocities are such that the ions approach the plate at an angle greater than BTD saturation will take place, the saturation field being given by $F_S = U.\text{BD}/u.\text{TD}$. Fields well below the saturation values were used in the measurements of the conductivity and before or after each artificial field experiment a corresponding measurement with the test plates freely exposed to the natural field was made. The results are summarized in Table VI.

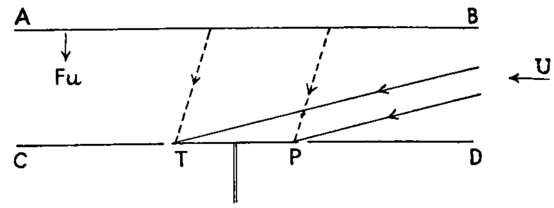

FIG. 19.—ARTIFICIAL FIELD OVER TEST PLATE.

TABLE VI—COMPARISONS OF CONDUCTIVITY WITH NATURAL AND ARTIFICIAL FIELDS

	Control	Varied conditions		
Field over ground .. Field over tripod ..	Natural Natural	Natural Artificial	Artificial Natural	Artificial Artificial
Mean values of the ratio λ_G/λ_T	1·53 1·47 1·59	1·02	1·47	0·95

The experiments were all made on days of low conductivity when the ratios obtained in the control observations were high; but since the three series of comparisons were made on different days the mean control ratios, given in the second column, differ slightly from one another. It will be seen that when an artificial field is used over the tripod, the conductivity is in good agreement with that over the ground. Moreover the same value of the conductivity is obtained at ground level whether the natural field or an artificial field is used over the ground plate. We may conclude then that there is no real difference between the conductivity at ground level and at the level of the apparatus on the tripod. The low values obtained with the apparatus on the tripod must be associated with the non-uniformity of the natural field over the apparatus.

We may sum up the results of the conductivity comparisons as follows:

(1) The conductivity ratio λ_G/λ_T is about unity when the conductivity exceeds 50×10^{-18} ohm^{-1} cm.$^{-1}$, but as λ_G falls the ratio increases, becoming about 1·5 for very low conductivities.

(2) The ratio is higher in light winds than in strong winds, other things being equal.

(3) The ratio is not affected appreciably by the absolute value of the potential gradient.

(4) When the conductivity over the tripod is measured in an artificial field the value is in good agreement with that obtained at ground level.

(5) The ratio of the electric field over the tripod to that over the ground does not vary nearly so much as the ratio of the conductivities; moreover the variations of the two ratios appear to be quite independent of each other.

No satisfactory explanation of these effects has so far been found. It is difficult to see how the distortion of the field over the tripod can have any effect on the ionic content of the air flowing past the plate, and it is hardly likely that it can cause any reduction in the mobility of the ions entering the plate.

§ 6—CONVERSION OF THE TRIPOD OBSERVATIONS OF CONDUCTIVITY AND CURRENT TO VALUES PERTAINING TO GROUND LEVEL

The results obtained in the conductivity comparisons enable us to revise the data obtained from the routine tripod observations from 1909 to 1930 and to derive the values which would have been obtained had the observations been carried out at ground level. To correct all the individual values of conductivity and current for the 22 years (nearly 4000 of each) would entail a considerable amount of labour, so it was decided to confine the revision to the monthly mean values. The corrections were made as follows.

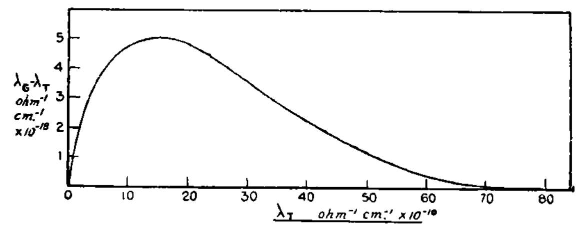

FIG 20.—CURVE USED IN REDUCING TRIPOD OBSERVATIONS TO GROUND LEVEL.

From the mean curve in Fig. 17 the differences ($\lambda_G-\lambda_T$) were extracted for various values of λ_T and the curve given in Fig. 20 so obtained. Additive corrections for λ_T could then be read from this curve and applied to the monthly mean values. In this way the revised set of monthly means of conductivity corresponding to an

TABLE VII—CONDUCTIVITY AT 15H. BY WILSON METHOD

Mean values reduced to ground level in paddock. Unit=$ohm^{-1}\ cm^{1}.\times 10^{-18}$.

	Jan.	Feb.	Mar.	Apr.	May	June	July	Aug.	Sept.	Oct.	Nov.	Dec.	Year
1909	..	19	21	40	41	43	48	39	28	33	..	12	..
1910	19	25	25	..	..	..	..	..	..	..	..	..	..
1911	..	..	..	..	..	..	58	52	41	29	24	23	..
1912	17	22	34	39	58	54	60	48	38	28	19	14	36
1913	21	26	34	32	40	50	48	49	43	40	24	33	37
1914	16	24	36	37	61	75	63	45	58	38	22	21	41
1915	19	28	26	36	40	49	84	48	49	33	24	16	38
1916	24	28	25	35	43	54	44	48	36	48	22	12	35
1917	20	15	24	..	..	..	..	48	49	39	23	17	..
1918	26	40	41	47	45	49	57	53	69	29	21	23	42
1919	23	17	28	35	40	69	53	70	56	38	23	24	40
1920	22	32	34	49	48	60	48	47	47	35	23	18	39
1921	19	25	36	37	58	52	54	71	62	71	16	22	44
1922	25	26	26	31	56	52	50	54	43	34	18	19	36
1923	23	24	29	29	38	50	53	72	53	32	19	17	37
1924	17	19	25	39	47	53	56	57	48	29	19	28	36
1925	22	24	29	34	52	47	53	44	39	26	18	16	34
1926	15	27	28	36	39	51	48	54	55	38	23	16	36
1927	18	22	28	34	40	49	52	41	42	22	16	12	31
1928	19	22	29	40	38	60	55	57	45	34	18	15	36
1929	14	18	24	48	48	59	59	55	58	38	21	22	39
1930	16	14	28	33	34	43	57	61	42	32	20	11	33
1931	17	22	23	29	40	44	51	39	41	29	21	14	31
No. of Years	21	22	22	20	20	20	21	22	22	22	21	22	19
Means	20	24	29	37	45	53	55	52	47	35	21	18	36

exposure at ground level were obtained and they are given in Table VII. This table also includes the **1931** values which were made near ground level and require no correction. In the case of the air-earth current the monthly means were first multiplied by the ratio of the revised conductivity (at ground level) to the original tripod value and then multiplied by the factor **1·12** connecting the potential gradient over the lawn with that measured at ground level in the paddock. The revised monthly means of air-earth current at ground level are given in Table VIII; those for the year **1931** were derived from conductivity measurements made near ground level, so it was only necessary to apply the potential gradient factor, **1·12**, in these cases.

TABLE VIII—AIR-EARTH CURRENT AT 15H. BY WILSON METHOD

Mean values reduced to ground level in paddock. Unit=amp. cm.$^{-2}\times10^{-18}$.

	Jan.	Feb.	Mar.	Apr.	May	June	July	Aug.	Sept.	Oct.	Nov.	Dec.	Year
1909	..	85	61	71	69	62	54	81	76	79	..	65	..
1910	80	91	83	..	..	..	..	..	..	..	..	..	..
1911	..	..	..	..	..	..	77	121	81	77	77	83	..
1912	85	75	63	91	59	86	129	95	122	78	72	58	84
1913	115	135	84	113	97	75	92	100	144	144	81	120	108
1914	77	92	93	119	113	116	109	110	136	103	101	76	104
1915	111	111	83	88	113	120	95	92	105	122	112	54	101
1916	97	114	111	117	87	59	85	60	85	106	90	65	90
1917	106	76	81	..	..	..	..	94	123	131	75	85	..
1918	131	132	146	177	116	117	110	94	162	109	74	89	121
1919	116	93	97	95	130	101	97	94	124	104	112	88	104
1920	90	106	91	112	84	119	88	96	112	134	102	80	101
1921	62	98	101	104	84	85	79	92	112	141	91	84	94
1922	91	93	93	89	109	81	74	116	92	128	77	82	94
1923	106	102	101	105	94	85	102	91	121	102	85	83	98
1924	82	85	111	117	94	100	91	105	108	100	86	148	102
1925	99	82	144	113	133	97	107	93	106	79	80	55	99
1926	70	80	85	105	73	84	90	99	113	108	75	99	90
1927	64	113	89	80	94	101	119	87	92	81	75	84	90
1928	83	79	106	97	98	114	81	86	115	105	77	85	94
1929	80	105	104	83	112	103	110	96	122	103	106	126	104
1930	73	81	100	120	64	90	107	141	112	109	89	63	96
1931	82	85	95	80	110	78	111	101	109	104	87	76	93
No. of Years	21	22	22	20	20	20	21	22	22	22	21	22	19
Means	90	96	96	104	97	94	96	97	112	107	87	84	98

§ 7—THE VARIATION OF AIR-EARTH CURRENT AND CONDUCTIVITY

The mean values of the conductivity and air-earth current at 15h. given in Tables VII and VIII refer to ground level, the corrections having been made in the manner already described. In most cases the number of observations from which the monthly means are derived is about 15, but occasionally only a few observations were available. In deriving the final means for the whole period equal weight has been given to each monthly mean and it is considered that the period is sufficiently long to smooth out any abnormal values which may have occurred in a month of few observations. The year **1918** appears to have been an abnormal one as regards air-earth current; in eight months out of the twelve the mean values are much above the average. The explanation may be connected with the fact that the year was decidedly wetter than usual ; the effect of the rain would be to reduce the pollution and so increase the conductivity and the current.

The mean annual variations of the air-earth current and the conductivity at 15h. are plotted in the upper part of Fig. 21 ; the curve of potential gradient shown in the same graph refers to means of values at 15h. for the same peiiod of years, but the means are for the 10 quiet days of each month and these were not necessarily the days on which the Wilson observations were made. The conductivity curve is a smooth one and it is practically a mirror image of the potential-gradient curve. There is not complete compensation between the one element and the other and so the air-earth current shows some variation, but the changes are comparatively small and irregular. The lack of complete balance between the gradient and the conductivity is more evident in the lower part of Fig. 21. In this graph the curves represent the annual variation of the logarithms of the monthly means of the elements and instead of conductivity we have used its reciprocal—the resistance. The variation of the arithmetical difference between the logarithms of the gradient and the resistance should correspond with the variations of the logarithms of the current. This is the case so far as the main fluctuations are concerned ; the departures from exact correspondence are due to the differences which arise in statistical treatment when the mean of individual values of a ratio of two quantities is compared with the ratio of the mean values of the two quantities.

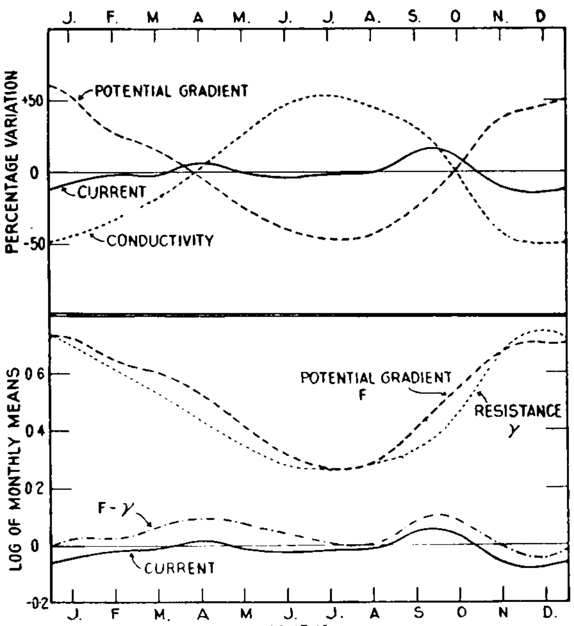

FIG. 21.—ANNUAL VARIATION OF ELECTRICAL ELEMENTS AT KEW.

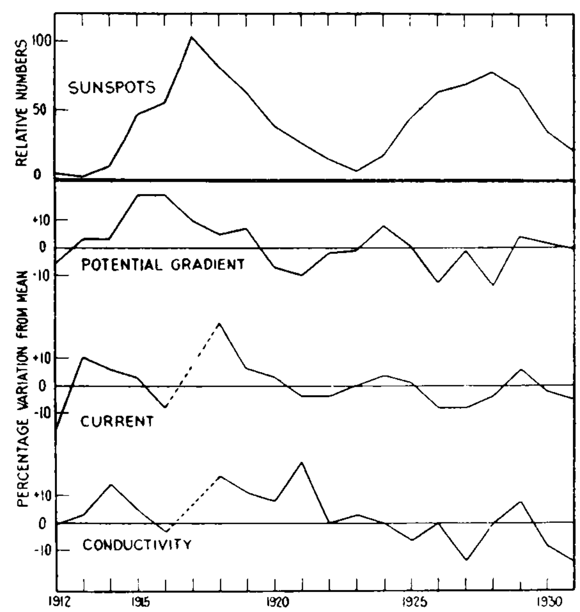

FIG. 22.—VARIATION OF ANNUAL MEANS OF ELECTRICAL ELEMENTS (15H. VALUES) AND SUNSPOT NUMBERS.

The air-earth current at 15h. has maxima in spring and autumn, a definite minimum in winter and a slight minimum in summer. A variation of similar type was found by the author (13) from an analysis of a year's records of air-earth current obtained with an apparatus which gives a continuous record of this element. The values at 15h. are not very representative of the mean values for complete days, especially in summer, and when all hours are taken into account the tendency for a double oscillation in the annual variation is much less marked. The shape of the annual curve of the afternoon air-earth current appears to indicate that in the winter and the equinoctial months the current is governed mainly by the local resistance of the air while in the summer months, when the local resistance of the air is lowest, the total resistance of the atmosphere above Kew becomes high enough to cause a slight drop in the current. Probably the strong convection which occurs on summer afternoons is an important factor, for by carrying pollution up from the ground it increases the resistances at higher levels.

The secular variation of the three electrical elements is shown in Fig. 22 ; the data refer to values at 15h. A curve of relative sunspot numbers is also included. The proportional ranges of variation of the electrical quantities are roughly equal and there is some tendency for the changes in current to follow those of conductivity. If the means are restricted to the summer months, as is done in Fig. 23, the variations in the current resemble those in the gradient.

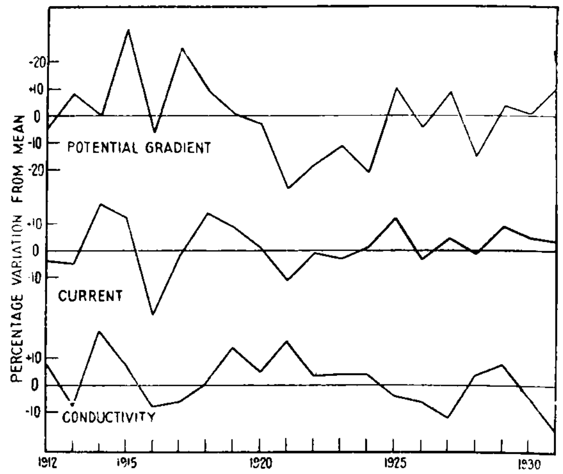

FIG. 23.—VARIATION OF SUMMER MEANS OF ELECTRICAL ELEMENTS (15H. VALUES).

The final mean of the air-earth current obtained from the 19 annual means (1912–31) is 98×10^{-18} amp. cm.$^{-2}$ By using the results obtained with the recording apparatus we can adjust this value to what it would have been had all hours of the day been represented. The analysis of the records showed that the annual mean for all hours was 6 per cent higher than that derived from the values at 15h. only. We should therefore increase our final mean value of the air-earth current to 104×10^{-18} amp. cm.$^{-2}$ to obtain an estimate representative of all hours. The corresponding value, referred to the same exposure, obtained from a year's records during 1930 and 1931 was 112×10^{-18} amp. cm^{-2}. In comparing these values with those obtained by continental workers it must be remembered that the usual continental practice is to estimate the vertical electric current in the air indirectly from measurements of the potential gradient and the positive and negative conductivities by means of the formula $i = (\lambda_+ + \lambda_-)\ F$. Whipple (21) has shown how it is that the current flowing from the air into the earth is better represented by the product of the potential gradient and the positive conductivity and this product is what is measured in the test-plate method of observation. This procedure gives a value roughly half of that obtained by the indirect method.

The final mean of the conductivity is 36×10^{-18} ohm^{-1} cm.$^{-1}$ It agrees exactly with the annual mean of values at 15h. obtained during **1930** and **1931** with the recording apparatus. The latter gave an annual mean of 39×10^{-18} ohm^{-1} cm.$^{-1}$ when all hours were represented, so we may take this figure as being the final mean which would have been obtained if the observations with the Wilson apparatus had been made at all hours. It is considerably lower than the values obtained at other stations; most measurements of the conductivity for positive electricity exceed 100×10^{-18} ohm^{-1} cm.$^{-1}$, but at Potsdam the mean value is about 53×10^{-18} ohm^{-1} cm.$^{-1}$ The low value of the mean at Kew is no doubt due to the frequent pollution of the air at a site so near to such a large city as London. In this connexion it is of interest to mention that H. L. Wright (16), who has examined statistically the effect of Aitken nuclei and dust particles on conductivity at Kew, finds that the coarse particles (such as are measured by the Owens dust counter) can be at least as effective as nuclei in reducing the conductivity.

§ 8—SUMMARY

Observations of atmospheric electricity were commenced at Kew Observatory in 1843. A brief historical sketch of the early experiments is given and this leads on to a description of the improvements in the methods of observation which have been introduced during more recent years.

The changes mainly concern the exposure of the apparatus for obtaining absolute values of the electrical elements. An underground laboratory is now used for observations over a flat plane. The results of comparisons of various exposures used in potential-gradient measurements are discussed, and these results are applied to the data which have accumulated since the end of last century in order to make them comparable with measurements now being obtained under improved conditions.

For the measurement of the air-earth current and the conductivity the Wilson method is used, and numerous experiments have been made in order to determine what factors govern the apparent diminution of conductivity which occurs when the apparatus is used on a stand above ground level. The results of the experiments enable corrections to be applied to the old observations making them comparable with measurements made at ground level.

The main features of the variations shown by the revised values of the potential gradient, air-earth current and conductivity are discussed. The final means of the three elements for the period 1910 to 1931 are as follows:

Potential gradient	.. ..	363 volts per metre.
Air-earth current	.. ..	104×10^{-18} amp. cm.$^{-2}$
Positive conductivity	.. ..	39×10^{-18} ohm^{-1} cm.$^{-1}$

These values refer to the air at ground level at a site which is a very good approximation to a flat plane.

ACKNOWLEDGMENTS

In conclusion I should like to express my warmest thanks to Dr. F. J. W. Whipple, Superintendent of Kew Observatory, for his kind help and criticism; to Mr. E. Boxall, who has for many years been responsible for the tabulation of the electrograph records; and to Dr. H. M. Tickell for his assistance in the computation of the revised data. I am also indebted to Mr. L. C. Burridge for most of the photographs with which the paper is illustrated.

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