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THE AIR-EARTH CURRENT AT KEW OBSERVATORY

Some Results obtained with a New Automatic Recorder

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THE AIR-EARTH CURRENT AT KEW OBSERVATORY

SOME RESULTS OBTAINED WITH A NEW AUTOMATIC RECORDER

§ 1—INTRODUCTION

It is well known that in fine weather a current of electricity is always flowing from the air into the ground. The origin of this current and the factors which control its variations constitute one of the most important problems of atmospheric electricity and any additions to our somewhat scanty knowledge concerning the nature of the variations of the current may bring us nearer to a satisfactory solution of the problem. The present research was started with the idea of obtaining some such additional information.

Direct measurements of the air-earth current have not been very numerous. The first reliable determinations were made by C. T. R. Wilson (1)* at Cambridge in 1906. Wilson's method was adopted at Kew Observatory in 1909 and from then up to the present time observations have been made at 15h. G.M.T. on fine days. The results have been published annually (2).

Few attempts have been made to obtain continuous direct records of the air-earth current. The most successful was that of G. C. Simpson (3) at Simla. The disadvantage of Simpson's method was that the record gave the charge brought down by the air-earth current plus any induced charge produced by changes in the earth's field which may have occurred during the period of measurement. It was necessary, therefore, to allow for field changes by applying corrections obtained from a simultaneous potential-gradient record.

The first object of the present investigation was to devise a method of recording the current which would require no corrections for field changes. A device was needed which would automatically compensate the field changes and so leave us with a record of the air-earth current alone. Having obtained satisfactory records the second object was to see how the magnitude of the current varied with other conditions.

§ 2—DESCRIPTION OF THE APPARATUS

In the direct method of measuring air-earth current a flat conducting surface, preferably level with the ground, is isolated and exposed to the earth's electric field. The charge which flows into the surface in a known time is measured by some form of electrometer. In Wilson's apparatus the effects of field changes are eliminated by shielding the conductor from the earth's field at the beginning and end of the measurement. The process of shielding and unshielding is also used for measuring the strength of the field at the time. In designing a recording apparatus it was thought that it would be more satisfactory if some other method of allowing for field changes could be used. The method adopted was to use a quadrant electrometer differentially such that the charge brought down by the current and any induced charge due to field changes were collected on one pair of quadrants whilst the other pair of quadrants collected the induced charge only. The electrometer deflexion was then a measure of the charge due to the current.

* The numbers in brackets refer to the bibliography on p. 22.

The apparatus is shown diagrammatically in Fig. 1. The test-plate TP, made of a sheet of duralumin 91 cm. square and 0·2 cm. thick is supported on a sulphur insulator B in a shallow concrete pit. The plate is arranged to be flush with the ground ; the air gap round the plate is 3 cm. across while the depth of the pit is 12 cm. The lay-out of the recording apparatus which is installed in a hut 10 m. away from the test plate, is shown in Fig. 2. An insulated connexion runs from the test plate in a covered trough to one pair of quadrants of a Dolezalek electrometer E_1. The second pair of quadrants of this electrometer is connected to one side of a parallel-plate condenser C, the other side of which is attached to a potential-gradient collecting system consisting of an insulated rod projecting through the side of the hut and carrying a radio-active collector R. The collecting system is connected to the needle of a second Dolezalek electrometer E_2. Both electrometers are arranged to record photographically on the same drum D. By means of electromagnetic keys K worked from a contact clock both pairs of quadrants of the electrometer E_1 are earthed for one minute at regular intervals (every ten minutes).

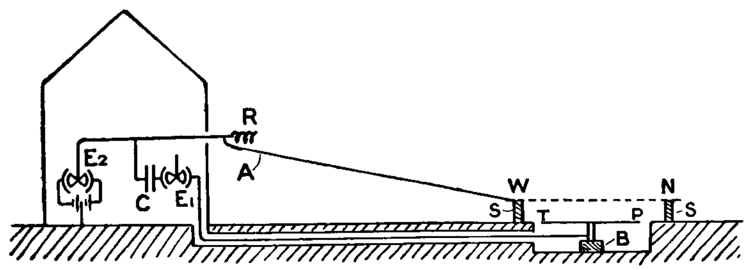

FIG. 1.—DIAGRAM OF APPARATUS FOR RECORDING AIR-EARTH CURRENT AND POTENTIAL GRADIENT.

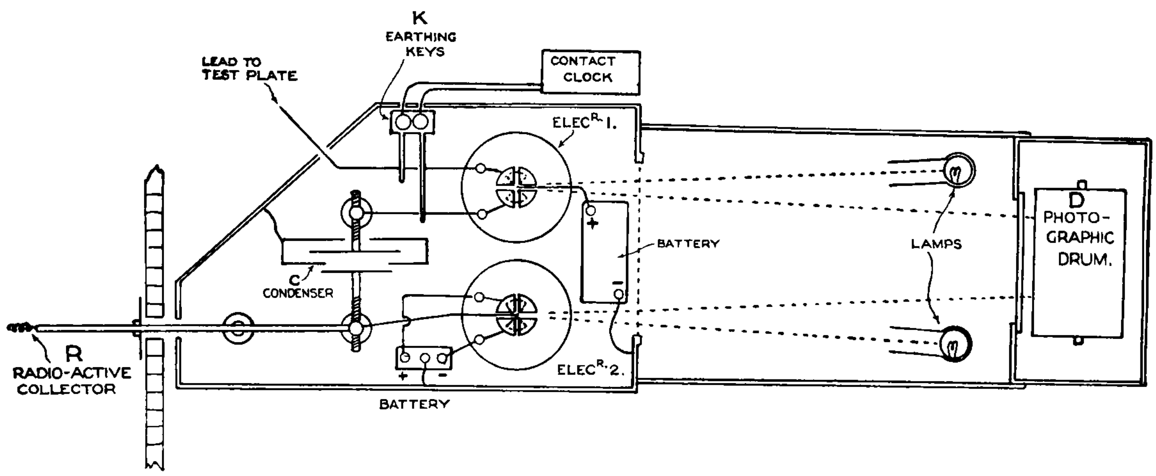

FIG. 2.—PLAN OF RECORDING APPARATUS.

In Fig. 1 the test plate is shewn to be covered with a wire net WN supported on insulators SS and connected by a wire to the potential-gradient collecting system. The purpose of this arrangement will be explained later, but for the moment we will assume that the net and its connecting wire are absent. The working of the apparatus is then as follows. After the radio-active collector has picked up the potential of the air at its position the quadrants of electrometer E_1 are earthed momentarily. Any subsequent changes in the potential gradient will produce charges on the electrometer E_1 ; on one side by induction on the test plate and on the other by induction across the condenser C. If, then, the capacity of C is suitably adjusted the two effects can be made to cancel each other. When such a balance is attained the rate of deflexion of the electrometer E_1 is proportional to the current flowing into the test plate.

In the original arrangement the correct adjustment of the condenser was obtained in the following way. The test plate was screened from the earth's field by an earthed metal cover and initially the test plate and collecting system were earthed. On insulating the whole system the needle of electrometer E_1 gradually deflected as the collector picked up and the corresponding charge accumulated on one pair of quadrants. When the full potential was reached the cover was removed from the test plate so that the plate immediately obtained a charge corresponding to the full field above it, thus causing the needle to move back in the opposite direction. These operations were repeated with various distances between the plates of the condenser C until the second deflexion exactly balanced the first. To facilitate the procedure the plates of the condenser were mounted on threaded spindles giving comparatively fine adjustment.

A record obtained with the apparatus in its original form is shewn in Fig. 7 (Plate III). The lower trace represents the potential gradient as recorded by the electrometer E_2. Since the quadrants of the electrometer E_1 are insulated for nine minutes and then automatically earthed for one minute the upper trace consists of a series of lines all starting from zero. The mean slope of each line is a measure of the average value of the air-earth current during an interval of nine minutes.

§ 3—MODIFIED SYSTEM

In Fig. 7 (Plate III) it will be observed that the sloping lines of the record of the air-earth current are by no means straight. Superimposed on them are irregular oscillations. The effect is most pronounced between 16h. and 21h. when the wind was very light. On all days when the potential gradient was not very steady the superimposed oscillations on the current record were so great that it was impossible to make any satisfactory measurements; the effect was at its worst in foggy weather. At first it was thought that the effect was due to bad adjustment of the compensation system but careful tests shewed that this was not the case. Also it seemed unlikely that the oscillations represented genuine fluctuations in the current. After a number of experiments the conclusion was reached that the effect was due mainly to the fact that whereas field changes over the test plate instantaneously alter the potential of one half of the electrometer E_1, the corresponding changes of potential of the other half have a small lag depending on the efficiency of the radio-active collector and the capacity of the collecting system. On this account compensation is not completely effective when the field changes are rapid.

There appeared to be no satisfactory way of speeding up the collector system to any appreciable extent except by greatly reducing its capacity, and other considerations prevented this. The alternative was to smooth out the rapid changes which occur over the test plate. This was done by fitting the wire net WN (Fig. 1) at a suitable height above the plate and connecting this net to the radio-active collector. The height of the net is regulated by the reduction factor connecting the voltage of the collecting system with the potential gradient over the test plate. This factor was ascertained by measuring the gradient with a stretched-wire system at one metre above the plate and comparing the measurements with simultaneous records of the collector. From several determinations it was found that for 100 volts recorded by the collector the gradient over the plate was 8·3 volts per cm. The net was therefore arranged to be at a height of 100/8·3 *i.e.*, 12·1 cm. above the plate; the collector then maintained the net at the same average potential as that of the air at the level of the net but any rapid fluctuations of the potential were smoothed out. The results obtained in this manner were a vast improvement, the current records being much less irregular, as can be seen in Fig. 8 (Plate III). That the apparatus would not work satisfactorily without this modification was, of course, somewhat of a disappointment, but it is considered that the presence of the net does not appreciably affect the conditions above the test plate. On days of steady potential gradient, for instance, removal of the net shewed no discontinuity in the magnitude of the current.

The net itself consisted of ordinary galvanised iron wire of 1-inch mesh fitted to a light wooden frame 120 cm. square. A further advantage of having the net was to render easier the adjustment of compensation. It was now only necessary to apply a voltage to the collector system (with net attached) and observe the deflexion of the electrometer E_1. The process was repeated with various adjustments of the condenser until no deflexion occurred on applying (or removing) the voltage.

§ 4—METHODS OF INSULATION

Owing to the large number of insulators required to support the various parts of the apparatus great difficulty was at first experienced in maintaining satisfactory insulation. In view of the importance of having good insulation in this work, some details of the methods of overcoming the difficulties may not be out of place. The trouble was nearly always due to condensation of moisture on the insulating surfaces or on spider webs. The supports were made of sulphur, suitably shielded from dust and light, and in order to prevent condensation on the sulphur, electric heating was employed. The test-plate insulator was kept warm by two 20-watt lamps attached to the side of the insulator case. One 20-watt lamp placed inside the recorder cabinet was found sufficient to warm the inside insulators which include the amber on the electrometers and the sulphur supports of the condenser plates and the collector rod.

When the wire net was fitted above the test plate the insulation problem became still more difficult, since four more outside insulators were necessary to support the net. It was found impossible to prevent condensation on these insulators by using calcium chloride so electrical heating was finally resorted to. A diagram showing the construction of the net insulators is given in Fig 3 The sulphur S which fills an inner container has a rod R embedded in it which slides into a tube T in the ground. The rod carries a cylinder C which protects the inner container. A heating coil H of 30 S.W.G. eureka wire with a total resistance of about 75 ohms is wound round this cylinder and the coil is covered with tin foil so as to shield the insulator from stray fields caused by variations in the heating current. An outer container P acts as a protection against rain. The heating coils are wired in series and are included in the lamp circuit, the three 20-watt lamps being in parallel with each other. In the summer it was found that the warm interior of the insulators proved an attraction for earwigs. These were kept out by fitting small moats M filled with paraffin oil round the bases of the insulators.

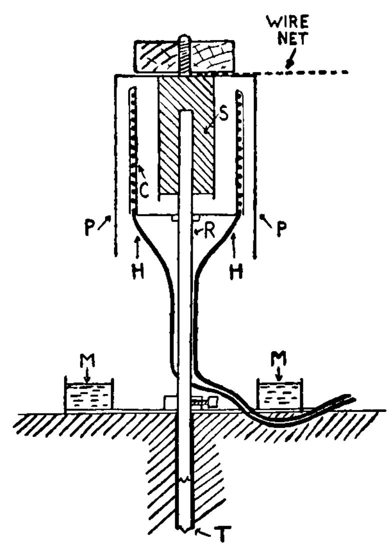

FIG. 3.—INSULATOR FOR SUPPORTING WIRE NET.

Although the warming arrangements were a satisfactory way of keeping the sulphur surfaces in a dry condition it was difficult to guard against condensation on spider webs, especially on the webs produced by small wind-blown spiders. By smearing the ground surrounding the test plate with " tree-tanglefoot," a compound which remains sticky for weeks, insects were prevented from bridging the gap between the ground and the test plate. The greatest trouble occurred with the wire connecting the plate to the recorder in the hut. This wire was held taut in a shallow trench. It was practically impossible to keep spiders away from the trench and from the place where the wire entered the hut. As a final resort the wire was replaced by lead-covered cable. This defeated the spiders but it had the disadvantage of increasing the capacity of the system very considerably (necessitating a much more sensitive electrometer suspension) and also it always showed an appreciable leak. The rate of leak, however, was practically constant in all weather and it was thought better to put up with this and apply a correction for the leak rather than have very good insulation on some days and very bad leaks on other days, which is what occurred before the lead-covered cable was introduced.

Rough insulation tests on both electrometer systems were made every morning at the time of changing the photographic paper and occasionally precise measurements were made to see that the rate of leak of the lead-covered cable did not vary appreciably.

§ 5—CALIBRATION AND REDUCTION OF RECORDS

The method of reduction of the records of potential gradient is similar to that usually employed. Calibration of the electrometer was done once a month with a battery of standard cells. The reduction factor for obtaining the potential gradient was measured occasionally. The scale value employed was such that 1 cm. on the record is equivalent to about 25 volts on the collector and the net. Since the net is at a height of 12·1 cm. (to correspond to the reduction factor), 1 cm. on the potential-gradient record is equivalent to about 205 volts per metre above the test plate.

From the record of air-earth current the magnitude of the current is obtained by the formula $i=Cv/At$, where i is the current per unit area, C is the capacity of the test-plate system, A is the area of the plate and v is the change of potential recorded in t seconds. If C and v are in electrostatic units, i is in these units. The current is usually expressed in practical units, so the potential is measured in volts and C is converted to farads. If k is the scale value of the electrometer in volts per division and d is the deflexion recorded in t seconds the formula becomes

$$i=\frac{C.\ \ k.\ \ d}{A.\ \ t.\ \ 9{\cdot}10^{11}} \qquad \ldots \qquad \ldots \qquad \ldots \qquad (1)$$

The capacity C was determined by measuring the induced charge $A\sigma$ produced on the test plate when a known field F was applied between the net and the plate, the relation $F=4\pi\sigma$ being used. In making this measurement it was, of course, necessary to put an earthed screen between the plates of the compensating condenser. The capacity was also checked by means of a standard condenser. The value obtained was 3850 cm.; (before the lead-covered cable was introduced the capacity was 440 cm.).

In determining the scale value, k, of the electrometer E_1 it is important to remember that when records are being taken both pairs of quadrants are insulated. In such circumstances the mutual capacity between the quadrants is sufficient to decrease appreciably the sensitivity below that obtained when the electrometer is used in the normal manner, *i.e.*, with one pair of quadrants earthed. Calibrations were therefore carried out by applying known voltages to the test plate immediately after both pairs of quadrants had been earthed momentarily and then insulated. During the calibration the wire net and the outer plate of the compensating condenser were kept at earth potential. A very fine phosphor-bronze suspension was used on electrometer E_1, with 130 volts on the needle. The sensitivity was such that one cm. on the record (at 100 cm. from the electrometer) was equivalent to about 0·09 volts on the test plate. The area, A, of the plate being 8,360 cm.^{2} and the time interval, t, between successive earth marks being 540 sec., the calibration factor given by formula (1) is obtained:

$$i=\frac{3850 \times 0{\cdot}09 \times d}{8360 \times 540 \times 9 \times 10^{11}}$$

$$\text{or } i = 85d \times 10^{-18} \text{ amp. cm.}^{-2},$$

where d is the deflexion in cm. reached in 540 sec. The scale value, k, was measured once a month and the factor was altered if necessary.

The largest fine-weather current recorded was about 230×10^{-18} amp. cm.$^{-2}$. With a current of this magnitude the potential acquired by the test plate at the end of nine minutes was about 0·25 volt. Such a small difference from earth potential would cause no appreciable distortion of the field above the test plate.

§ 6—CORRECTION FOR INSULATION LEAK

It has been mentioned that the lead-covered cable connecting the test plate to the electrometer caused an appreciable but fairly constant leak. Actual measurements gave values of the insulation resistance of the test-plate system varying from 5 to 7 $\times 10^{11}$ ohms, the mean being $6{\cdot}1 \times 10^{11}$ ohms. To find the effect of the leak the formula (1) connecting the current and the voltage acquired by the test plate in time t is modified as follows. The rate of increase of charge (neglecting that due to field changes) is:

$$C\ dv/dt = iA - v/R,$$

where R is the insulation resistance. From this equation we get

$$v = iAR\ (1 - e^{-t/CR}).$$

The corrected current, i, is given by

$$i = \frac{v}{AR\ (1 - e^{-t/CR})},$$

whereas if the leak is neglected we have

$$i' = vC/At,$$

hence

$$\frac{i'}{i} = \frac{CR}{t}\ (1 - e^{-t/CR}).$$

Using the measured values of R it is found that the ratio i'/i varies from 0·88 to 0·91. The correction which must be added to the measured values of the current ranges from 9 to 12 per cent. These are extreme values and for the sake of simplicity a correction for 10 per cent has been applied throughout. Although the correction is a large one, this procedure of adopting the same correction throughout is not likely to introduce an error exceeding $\pm$ 2 per cent.

§ 7—CORRECTION FOR VOLTA EFFECT

It was noticed that the electrometer E_1 showed an appreciable rate of deflexion when the wire net over the test plate was kept earthed and also when the plate was covered with an earthed metal box. A long series of experiments was necessary before the causes of this effect could be traced. Since the charging-up was practically eliminated when the test plate was removed, apparently only a negligible part of the effect was associated with the insulators, the leads or the apparatus inside the hut. (Actually small deflexions were obtained when one side or the other of the electrometer E_1 was kept earthed, but when both sides were insulated these small effects balanced out). The bulk of the effect was therefore thought to be due to some process occurring at the test plate. This was confirmed by making measurements with a sensitive Lindemann electrometer attached directly to the test plate, the rest of the apparatus being disconnected. It was found that the charging-up could be eliminated by keeping the net at a potential of from 3·5 to 5 volts or alternatively by charging the test plate initially to a potential of 1·2 volts. The rate of charging was directly proportional to the conductivity of the air at the time and it was in the same direction as that produced by the normal air-earth current. It appeared therefore that potential gradients existed above (and below) the test plate and that they were of sufficient size to cause an appreciable current to flow into the plate.

One source of these gradients was found to be Volta differences of potential between the plate and the net and also between the plate and the lining of the pit (tin foil was used after these tests were started). These Volta differences were measured in the laboratory and it was found that the wire net showed a potential of +0·97 volt with respect to the plate while the tin-foil lining was at a potential of about +0·5 volt. The additive effect of these potential differences is sufficient to account for about 30 per cent of the charging-up.

A second cause was found in the fact that the wire net was not of sufficiently small mesh to cut off completely the earth's field above it. Some experiments with artificial fields showed that the field which penetrated to the distance (12·1 cm.) at which the plate was situated amounted to 2·8 per cent of that above the net. Thus with an average potential gradient of 300 volts per metre the field between the net and the plate was such that the net was virtually at a potential of +1 volt with respect to the plate. A field of this order would account for roughly 25 per cent of the charging-up.

The remaining part of the charging-up is probably due to an excess of positive ions attracted to the net by virtue of the negative charge on the upper surface when the net is at earth potential.

In applying corrections it should be realized that the second and third causes are only effective when the potential of the net is considerably different from that of the air at the height of the net ; when the apparatus is recording, no appreciable difference exists. On the other hand the first cause, Volta differences of potential, must be allowed for, since in the ideal arrangement there should be no potential difference between the test plate and its surroundings when these are earthed. It was shown that the potential difference below the plate is effective as well as that above it, there being sufficient air flow underneath the plate to supply ions for a current. The full effect of Volta differences is then equivalent to a potential of +1·5 volts at the height of the net i.e. a field of +0·12 volts per cm. on one side of the plate.

If i = recorded current (corrected for leak),
i_T = true current,
λ = recorded conductivity,
λ_T = true conductivity,
F = recorded field in volts per cm.,

then $$i_T = \frac{iF}{F + 0{\cdot}12}$$

and $$\lambda_T = \frac{i}{F + 0{\cdot}12} = \frac{\lambda F}{F + 0{\cdot}12}.$$

It was necessary, therefore, to apply different corrections for different potential gradients. This was done in the case of monthly mean values but not for individual values except when these were required for purposes of comparison. For the average strength of field, about 3 volts per cm., the correction for Volta differences amounts to —4 per cent.

§ 8—DIRECT COMPARISONS OF RECORDS WITH EYE READINGS OF OTHER APPARATUS

The values of the air-earth current and potential gradient obtained from the recorder do not apply to an open site. The presence of two huts and two tall trees near the test plate causes the field over the plate to be appreciably less than that over level open ground.

Numerous observations, 41 in all, of potential gradient in the paddock* enable us to obtain a reduction factor for converting the values of the gradient over the test plate to those corresponding to the more open site. These comparisons extended over a year and the monthly mean exposure factors varied from 0·73 to 0·81 but there was no systematic seasonal variation. The final mean of 0·77 was adopted as the factor by which the gradient over the test plate must be divided in order to obtain the value corresponding to the open paddock site. It is reasonable to apply this same factor to the recorded values of the current if there is no appreciable difference in the conductivity at the two sites.

On 75 days comparisons were made between the conductivity obtained from the records and that obtained by eye observations with a Wilson apparatus (1). The test plate of the latter was arranged to be almost at ground level in the paddock,

* These observations were made on the same site as those recorded by R. E. Watson (4). The underground laboratory has been made where the pit used by Watson was excavated.

the electrometer being in the underground chamber the roof of which is about 20 cm. above the general level of the ground. The individual comparisons showed variations which were sometimes considerably larger than could be explained by experimental errors and it appeared as if local difference in conductivity sometimes occurred. The monthly means of the ratios of the conductivities at the two sites are given in Table I.

TABLE I.—COMPARISONS WITH WILSON APPARATUS

	Aug.	Sept.	Oct.	Nov.	Dec.	Jan.	Feb.	Mar.	Apr.	May
No. of obs.	9	8	4	9	10	3	8	11	5	8
Recorded λ / Wilson λ	1·01	0·99	0·95	1·00	0·92	0·90	0·90	1·04	1·04	0·96

The lowest ratios occur in the winter months when the conductivity is very small. No satisfactory explanation has been found to account for this; it is difficult to believe that it is associated with the small distortion of the field produced in the neighbourhood of the test plate by the presence of obstructions. The mean ratios of the conductivities, obtained from all the comparisons, is 0·98. On the whole, therefore, the agreement may be considered very satisfactory. It should be strongly emphasized here that these comparisons with the Wilson instrument, an instrument of totally different nature and with entirely independent constants, show that the recorder does really give the absolute current flowing from the air to the earth at the particular site. The presence of the wire net has no appreciable disturbing effect on the measurements of the current. The only factor that need be applied to the recorded values is that which allows for the fact that the test-plate site is not free from obstructions, such as huts and trees, which distort the field in the neighbourhood. The factor determined by means of the potential-gradient comparisons referred to above enables us to obtain values of the current which are applicable to an open site comparatively free from obstacles. Use has been made of this factor in discussing the annual means.

§ 9—ANALYSIS OF THE RECORDS

A considerable number of records were obtained during the period January 1929 to May 1930 and although many of them showed interesting features, these records were not suitable for detailed investigation owing to difficulties in obtaining complete compensation before the wire net was adopted and to numerous failures of insulation. Soon after the introduction of the wire net and the improvements to the insulators, good records were obtained with comparatively few breaks. A systematic analysis has been carried out on twelve months' records commencing June 1930.

The main part of the analysis concerns the results obtained at times when the electrical conditions were not disturbed by rain or thunderstorms. All negative currents were omitted, together with abnormally excessive positive currents. Measurements recorded in foggy conditions, when the range of visibility was less than one kilometre, were excluded, since on several such occasions a downward flow of negative electricity was recorded and it was thought to be due to the settling out of charged water droplets and not to ionic conduction. The effects associated with foggy conditions are treated separately.

In tabulating the air-earth current and potential gradient for undisturbed conditions, hourly means centring at the exact hours were obtained. The tabulations were not restricted to complete days of 24 hours, otherwise the numbers of observations would have been insufficient for obtaining representative monthly means. On the average the monthly means of hourly values were derived from 15 hourly means, but this number varied considerably from month to month. Although there were fewer breaks in the potential-gradient records, these records

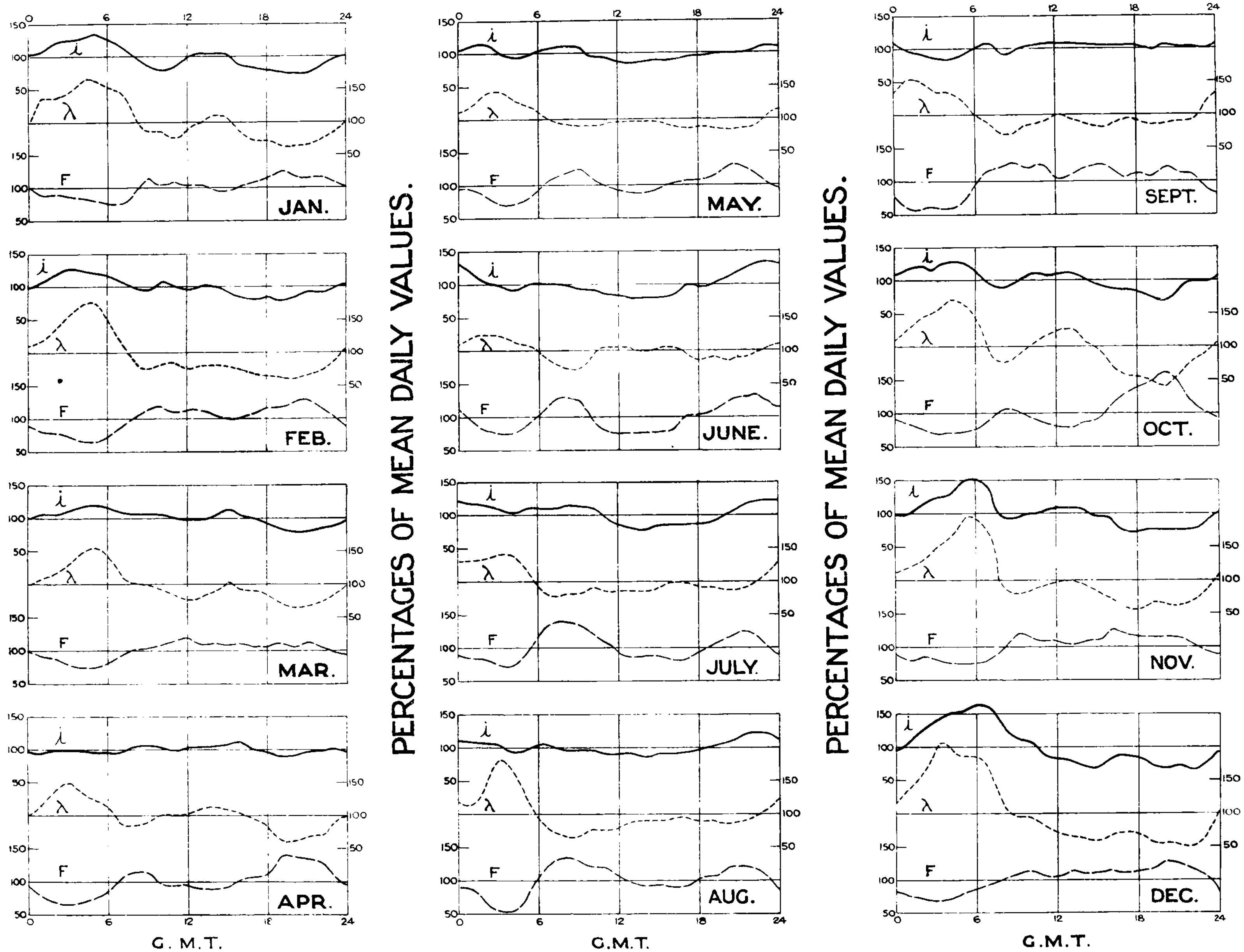

Fig. 5. MONTHLY CURVES OF DIURNAL VARIATION OF AIR-EARTH CURRENT (i), CONDUCTIVITY (λ) AND POTENTIAL GRADIENT (F) AT KEW OBSERVATORY.

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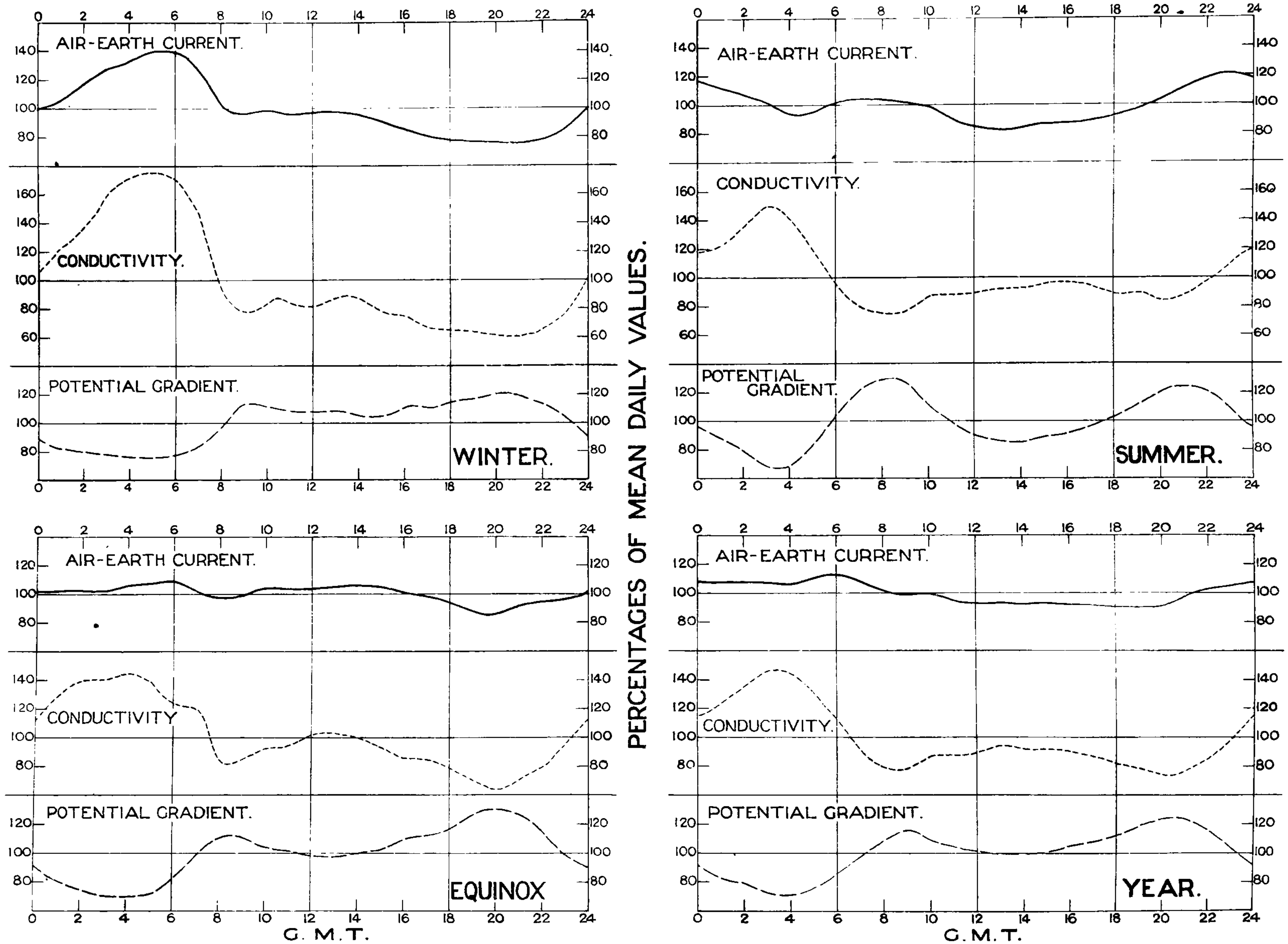

Fig. 6. SEASONAL AND ANNUAL CURVES OF DIURNAL VARIATION OF ELECTRICAL ELEMENTS AT KEW OBSERVATORY.

were read only when the current could be measured. The corrections which have been discussed were applied to the monthly means of air-earth current. It should be remembered that the recorded potential gradient is the gradient between the test plate and the wire net, but as the net is maintained at the mean potential of the air at the same level by the collector, the recorded potential gradient may be taken as the natural potential gradient over the test plate. The correct height of the net having been determined to correspond with the adopted position of the collector, care was taken to see that no alteration occurred, otherwise an abnormal field would have been produced over the test plate.

Mean values of the conductivity were obtained by dividing the monthly means of the hourly values of the current by the corresponding means of the potential gradient.

In Tables II, III and IV, are given the mean hourly values of air-earth current, conductivity and potential gradient respectively for the months, seasons and year. Maximum values are printed in heavy type and minimum values in italics. 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. In obtaining seasonal and annual means equal weight has been given to each month. The hourly means given in the tables have been corrected for the effects of insulation leak and Volta difference of potential. It should be emphasized that the data given in these tables refer to undisturbed conditions, i.e. to what are usually known as " quiet day " conditions.

Curves showing the annual variations of the three elements are shown in Fig.4. in which the monthly means are expressed as percentages of the annual means. The daily variations, expressed as percentages of the means for the months, seasons or year, are shown in Figs. 5 and 6 (Plates I and II).

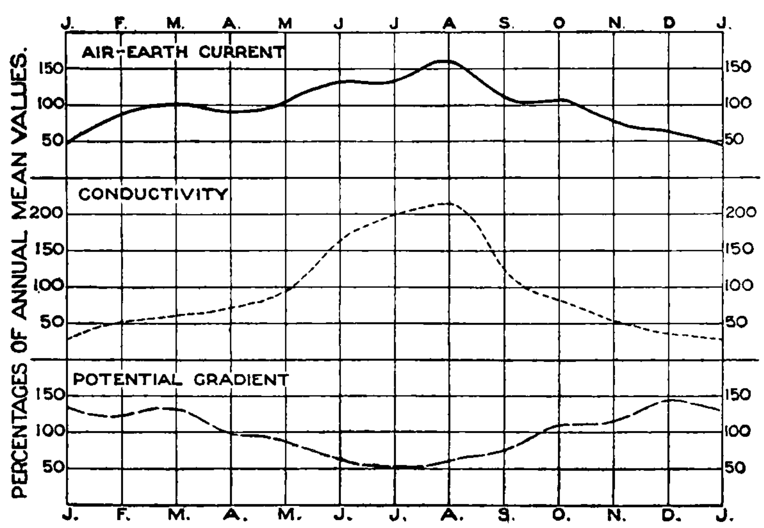

FIG. 4.—ANNUAL VARIATION OF ELECTRICAL ELEMENTS AT KEW OBSERVATORY (JUNE, 1930—MAY, 1931).

§ 10—ANNUAL MEANS

The means for the year given in Tables II, III and IV are reproduced below together with the corresponding values for the more open paddock site, these values being obtained by applying the exposure factors which were derived from the direct comparisons.

Exposure	Potential gradient v./m.	Conductivity ohm^{-1} cm.$^{-1}$ $\times 10^{-18}$	Current amp. cm.$^{-2}$ $\times 10^{-18}$
Recorder test-plate site	281 ..	39 ..	86
Converted to open paddock site ..	365 ..	39 ..	112

TABLE II.—AIR-EARTH CURRENT: HOURLY

Month and Season	Hour 0	G.M.T. 1	2	3	4	5	6	7	8	9	10	11
1931												
Jan.	42	50	51	50	54	**55**	50	46	40	34	32	34
Feb.	68	69	77	**85**	83	82	78	71	67	62	72	67
Mar.	83	91	88	95	101	103	**104**	92	91	91	90	86
Apr.	73	72	75	75	75	72	75	72	80	81	79	75
May	97	102	**104**	91	84	86	95	96	100	100	86	84
1930												
June	149	132	115	112	98	111	118	116	114	105	106	94
July	**137**	129	125	119	111	122	119	119	128	122	125	103
Aug.	152	150	144	148	126	129	144	142	136	131	135	128
Sept.	102	89	84	81	76	80	90	**104**	84	91	100	101
Oct.	99	104	112	104	**120**	115	111	87	80	88	95	99
Nov.	65	63	72	80	81	97	**98**	89	55	60	63	66
Dec.	52	57	66	76	83	82	**91**	85	66	60	59	48
Year	93	92	93	93	91	95	**98**	93	87	85	87	82
Winter	57	60	67	73	75	**79**	**79**	73	57	54	57	54
Equinox	89	89	90	89	93	93	**95**	89	84	88	91	90
Summer	134	128	122	117	105	112	119	118	119	115	113	102

TABLE III.—CONDUCTIVITY: HOURLY

Month and Season	Hour 0	G.M.T. 1	2	3	4	5	6	7	8	9	10	11
1931												
Jan.	11	15	15	16	**18**	**18**	17	16	12	8	9	8
Feb.	23	25	28	33	36	**37**	31	24	19	16	18	18
Mar.	23	26	27	31	35	**37**	34	27	24	24	22	21
Apr.	29	34	39	**43**	39	36	33	25	25	26	30	29
May	41	44	50	**52**	46	44	40	35	34	32	32	33
1930												
June	73	80	**82**	**82**	73	72	66	54	50	47	62	70
July	102	102	101	107	**108**	90	69	58	61	60	69	63
Aug.	102	96	121	**154**	142	105	79	63	57	58	66	61
Sept.	62	**72**	71	63	64	59	46	42	34	34	41	39
Oct.	34	40	46	48	**54**	52	46	31	24	27	32	36
Nov.	23	25	27	31	34	**40**	**40**	36	18	16	18	19
Dec.	16	19	22	**28**	**28**	25	26	23	16	13	13	11
Year	45	48	52	**57**	56	51	44	36	31	30	34	34
Winter	18	21	23	27	29	**30**	29	25	16	13	15	14
Equinox	37	43	46	46	**48**	46	40	41	27	28	31	31
Summer	79	81	89	**99**	92	78	63	53	51	49	57	57

MEANS (UNIT—Amp. cm.$^{-2}$ × 10^{-18})

12	13	14	15	16	17	18	19	20	21	22	23	Mean.
39	43	42	42	33	33	32	32	31	*30*	35	37	40
64	66	67	60	55	*53*	56	*53*	55	60	60	64	66
82	83	88	101	89	87	78	71	*65*	67	72	73	86
78	78	80	80	**85**	76	72	*68*	*68*	75	72	78	76
80	*77*	78	82	80	84	87	88	91	92	95	101	90
95	*89*	91	99	97	114	106	118	122	138	147	**154**	114
87	87	*84*	96	92	93	97	110	112	126	135	134	113
124	128	*117*	127	124	126	133	140	144	160	166	**167**	138
102	100	101	98	96	98	101	90	99	96	96	93	94
97	102	96	87	81	78	79	75	*62*	81	93	90	93
71	69	69	60	63	46	*44*	50	46	47	47	55	65
44	44	39	37	47	46	46	39	36	40	*35*	40	55
80	81	79	81	79	*78*	*78*	*78*	*78*	84	88	91	86
55	55	54	50	49	45	45	44	*42*	44	44	49	57
90	91	91	91	88	85	83	76	**74**	80	83	83	87
97	95	*93*	101	98	104	106	114	117	129	136	**139**	114

MEANS (UNIT—Ohm^{-1} cm.$^{-1}$ × 10^{-18})

12	13	14	15	16	17	18	19	20	21	22	23	Mean
10	11	12	12	9	8	8	7	7	7	8	9	11
16	17	18	17	16	15	14	14	*13*	14	15	18	21
18	20	21	25	21	22	20	17	*16*	*16*	18	20	24
30	32	33	32	30	26	24	*18*	*18*	20	20	26	29
34	35	35	34	31	31	32	31	*28*	29	32	39	36
69	68	65	71	70	63	56	60	57	60	63	70	66
65	67	64	73	76	75	70	70	66	68	75	85	77
67	76	75	76	81	81	75	76	71	76	80	90	85
48	44	42	38	38	45	43	40	39	41	42	53	47
39	41	35	31	23	19	18	16	*12*	18	25	28	32
20	21	19	17	15	*12*	*12*	14	13	13	14	18	21
10	9	9	8	10	10	10	8	7	8	7	9	14
35	37	36	36	35	34	32	31	*29*	31	33	39	39
14	15	15	13	13	11	11	11	*10*	11	11	13	17
34	34	33	31	28	28	26	23	*21*	24	26	32	33
59	61	60	63	65	63	58	59	55	58	63	71	66

TABLE IV.—POTENTIAL GRADIENT (OVER THE TEST PLATE):

Month and Season	Hour. 0	G.M.T. 1	2	3	4	5	6	7	8	9	10	11
1931												
Jan.	375	325	330	320	305	300	*285*	*285*	330	420	375	405
Feb.	300	275	270	255	230	*225*	250	295	345	385	405	375
Mar.	370	345	330	300	290	*280*	305	340	385	385	410	420
Apr.	255	210	190	*175*	190	200	225	285	315	315	260	255
May	240	230	210	*175*	185	195	240	280	295	315	265	250
1930												
June	205	165	140	135	135	155	180	215	230	220	170	135
July	135	125	125	110	*105*	135	170	205	**210**	205	180	165
Aug.	150	155	120	95	*90*	125	185	225	**235**	225	205	210
Sept.	165	125	*120*	125	*120*	135	195	245	250	**265**	245	260
Oct.	290	260	245	*215*	225	220	240	280	335	330	300	275
Nov.	285	250	270	260	*240*	*240*	245	250	305	385	360	350
Dec.	335	310	300	*275*	290	325	345	370	400	445	465	435
Year	259	231	221	203	*200*	211	239	273	303	325	303	295
Winter	324	290	293	277	*266*	273	281	300	345	409	401	391
Equinox	270	235	221	*204*	206	209	241	287	321	324	304	303
Summer	183	169	149	*129*	*129*	153	194	231	**243**	241	205	190

For the purposes of indirect comparisons, earlier observations made at Kew Observatory (1) may be quoted, but in order to eliminate differences in exposure it is necessary to apply factors which have been determined recently. The annual mean potential gradient for selected quiet days is available for the years 1910 to 1930 and the average for the 21 years is 323 volts per metre. This refers to a control station which is not so well exposed as the paddock site. R. E. Watson (4) obtained the factor 1·13 connecting these two sites and when this is applied the 21 years' average becomes 366 volts per metre. Our corresponding value given above is almost the same as this, so the year as a whole was apparently a normal one so far as potential gradient is concerned.

Measurements of the conductivity and the air-earth current by means of the Wilson apparatus have been carried out at Kew Observatory (1) as a routine procedure at 15h. on all fine days. From an analysis of 22 years' observations (1909 to 1930), mean values of the conductivity and the current of 35×10^{-18} ohm^{-1} cm.$^{-1}$ and 77×10^{-18} amp. cm.$^{-2}$ have been obtained. Several adjustments are necessary to make these means comparable with our values for the paddock site. Tables II and III show that an increase of five per cent should be made to obtain means referring to all hours instead of to 15h. only. A still larger correction is necessary to correct for diminished value obtained when the Wilson apparatus is used on a tripod instead of at ground level. R. E. Watson (4) has investigated this point and further experiments are in progress. For the present purpose we may take Watson's factor 1·2 for the ratio of the apparent conductivity at ground level to that over the tripod. A third correction is necessary in the case of the current, for the published values are obtained by multiplying the conductivity measured with the Wilson apparatus by the mean potential gradient at 15h. which, as has already been stated, requires a factor of 1·13 to make it correspond to the paddock site. When all these adjustments are applied to the 22 years' means we obtain the values 44×10^{-18} ohm^{-1}cm.$^{-1}$ for the conductivity and 110×10^{-18} amp. cm.$^{-2}$ for the current. The final means obtained from the recording apparatus are in satisfactory agreement with these values. It is anticipated that in future routine

HOURLY MEANS (UNIT—Volts per Metre)

12	13	14	15	16	17	18	19	20	21	22	23	Mean
385	390	355	345	370	395	415	**465**	420	415	430	400	368
390	380	365	345	345	365	400	380	425	**435**	400	360	341
450	410	425	405	420	390	400	420	395	420	400	365	377
260	245	240	250	280	290	295	**375**	370	370	360	300	272
230	225	220	245	260	270	270	280	**325**	**325**	300	260	253
135	130	140	140	140	180	190	195	215	230	**235**	220	177
135	130	130	130	120	125	140	160	170	185	180	155	151
185	170	155	170	155	155	175	185	205	210	205	185	174
215	230	240	255	250	215	235	225	255	235	225	175	208
250	250	275	280	350	405	440	470	**505**	460	365	325	316
350	325	355	350	**415**	375	380	360	360	370	325	300	321
425	485	440	455	470	455	465	475	**525**	505	480	435	413
284	281	278	281	298	302	317	333	**347**	**347**	325	290	281
387	395	379	374	400	397	415	420	**433**	431	409	374	361
294	284	295	297	325	325	343	373	**381**	371	337	291	293
171	164	161	171	169	183	194	205	229	237	230	205	189

observations with the Wilson apparatus at Kew Observatory will be carried out at ground level at the more open site; this will eliminate the necessity for applying such large factors to allow for the effects due to excessive distortion of the field. Some preliminary measurements in this manner have been made by R. E. Watson (4). He obtained a mean value of 94×10^{-18} amp. cm.$^{-2}$; this value refers to the summer daytime when, as Table II indicates, the current is about the minimum. Had the observations been representative of all hours a value very close to our final mean would have been obtained.

§ 11—THE ANNUAL VARIATION OF THE AIR-EARTH CURRENT

The monthly mean values of the electrical elements, expressed as percentages of the annual means, are plotted in Fig. 4. The potential-gradient curve follows the usual form, with a maximum about midwinter and a minimum about midsummer; the total range of variation is about 100 per cent of the annual mean. The maxima of both the current and the conductivity occur in summer, but about one month later than the minimum of the gradient. The variation of the conductivity is extremely large, the range being 190 per cent of the annual mean. It was not anticipated that the variation of the current would be very marked but it is actually larger than that of the potential gradient; the range is 110 per cent.

Mention has been made of the 22 years' observations of current made with the Wilson apparatus at Kew Observatory. The mean annual variation derived from these observations shows a somewhat different form. There are two maxima, a principal one at the end of the summer and a weak secondary one in the spring; a strongly marked minimum occurs in the winter and a weak minimum, which does not fall below the annual mean, occurs just before midsummer. As has been pointed out these data refer to observations made at 15h. G.M.T. and it will be seen that the recorded values for 15h., given in Table II, show the same sort of double oscillation. It is clear that the values observed at 15h. are not representative of the mean values for the day, especially in summer.

The annual variation of air-earth current has been deduced at a few other stations from records of conductivity and potential gradient. The results are not strictly comparable with those recorded in the present paper but may be quoted; the main features are summarised in Table V. This table also includes results obtained at Munich and at the mountain observatory on the Zugspitz from observations by Wilson's method of the current received on an exposed plate.

TABLE V.—AIR-EARTH CURRENT: ANNUAL VARIATION AT VARIOUS STATIONS

Station		Times of observations G.M.T.	Observation period (years)	Month of Max.	Month of Min.	Percentage range of variation	Character of variation.
Kew ..	..	All hours	1	Aug.	Jan.	110	Unlike potential gradient.
Potsdam	(5)	,,	10	Jan.	June-Aug.	37	Like potential gradient
Pawlowsk	(6)	,,	4	—	—	40	Irregular.
Davos	(7)	,,	1	Feb.	June	37	Like potential gradient.
Munich	(8)	12h.	1	Jan.	July	94	Like potential gradient.
Tortosa	(9)	11h.	5	Jan.	June	44	Like potential gradient.
Val Joyeux	(10)	9h., 13h., 17h.	6	Aug.	Jan.	50	Unlike potential gradient.
Zugspitz	(11)	8h., 13h., 20h.	1	—	—	14	Irregular.
Oceans	(12)	various	not continuous	—	—	small	No marked variation.

It would be unsafe to draw any definite conclusions from these few results especially in view of the fact that in only four cases are they derived from observations at all hours. Where the variation is well marked it has a single period but the maximum may fall either in winter or in summer, this apparently depending on whether the potential gradient or the conductivity is the dominating factor. The range of variation is largest at Kew, where pollution is comparatively great, and smallest over the oceans and at Zugspitz (a high-altitude station), where pollution is almost absent.

§ 12—DIURNAL VARIATION

The diurnal variation of the three electrical elements is shown in Fig. 5 (Plate I), which gives the monthly mean curves, and also in Fig. 6 (Plate II), in which the curves are based on seasonal and annual means. So far as potential gradient is concerned there is little to add to the very full discussion by C. Chree (13) on the variation of this element at Kew; the variation follows the usual form shown at land stations, there being two distinct maxima and minima. The double oscillation is unusually prominent at Kew, however. It will be seen that the daily variation of conductivity is very closely related to that of potential gradient but the changes are in the opposite direction. The conductivity curves are, in fact, almost exact mirror images of the potential-gradient curves; the proportional range of variation is greater in the case of the conductivity. The characteristic changes of these two elements are closely associated with atmospheric pollution, which also shows a double oscillation. The connexion between pollution and potential gradient has been studied by C. Chree and R. E. Watson (14) and by F. J. W. Whipple (15), who attributes to G. C. Simpson an explanation of the double oscillation of pollution as resulting from a combination of two effects—the variation in the rate of production of pollution and the variation in the stability of the atmosphere.

When we turn to the diurnal variation of the air-earth current we find that the most striking feature is the seasonal change in the type of variation; Fig. 6 (Plate II) shows this clearly. In the winter the current follows the conductivity very closely, there being a very prominent maximum at about 5h. and a fairly strong minimum at 20h. The percentage ranges of variation are 64 for the current and 110 for the conductivity, both being larger than the range of the potential gradient which is 44 per cent. In summer, on the other hand, the changes in current are not at all similar to those of conductivity but bear much more resemblance to those of potential gradient. The principal maximum and minimum are at 23h. and 13h. respectively while the range is 23 per cent. For conductivity and potential gradient the summer ranges are 72 and 53 per cent respectively. In the equinoctial and annual curves of the daily variation of the current the changes are small and somewhat irregular. This, presumably, is because the opposing effects of summer and winter almost annul each other ; it cannot, therefore, be regarded as evidence of an automatic adjustment between potential gradient and conductivity, such as to maintain an almost constant air-earth current. Typical fair-weather records for summer and winter conditions are reproduced in Figs. 8 and 9 (Plates III and IV).

These features of the variation of the air-earth current at Kew have been discussed by F. J. W. Whipple in a paper on the circulation of electricity through the atmosphere which he read at the 1931 meeting of the British Association in London and which will be published shortly. F. J. W. Whipple suggests that the fluctuations in current at a place like Kew are governed partly by the potential difference between the Kennelly-Heaviside conducting layer of the upper atmosphere and the ground and partly by the resistance of the air column in between. The resistance of the air is subject to large variations in winter owing to the effects of pollution and it then becomes the dominating factor. In summer, on the other hand, the resistance of the air column is much less variable and there is a greater tendency for the air-earth current to follow the changes in the potential of the upper conducting layer rather than changes in resistance (or, of course, conductivity). Where pollution is almost absent the resistance of the air column should remain comparatively steady and we should expect the connexion between the changes in current and those of the potential difference between the Kennelly-Heaviside layer and the ground to be very close. This idea is supported by observations which have been made over the sea. A rough estimate of the diurnal variation of air-earth current at sea was obtained from a few series of simultaneous measurements of potential gradient and conductivity which were made on board the *Carnegie* during the period 1918-1921 ; the results have been discussed by S. P. Mauchly (12). It was found that the conductivity has only a weak variation through the day and that the current is very similar to the potential gradient both as to the general nature of its daily variation, which consists of a single oscillation, and also as to its progression according to universal time, the maximum occurring at about 19h. G.M.T. and the minimum at 4h. G.M.T. It seems very probable, therefore, that at sea the variation of both air-earth current and potential gradient are determined almost wholly by the changes in the potential of the upper conducting layer but that over land the local effects of pollution may overwhelm this world-wide effect.

Before leaving the question of diurnal variation of current the few results which have been deduced at other land stations from records of conductivity and potential gradient should be mentioned. Data which are based on measurements made at all hours for a year or more are available for Potsdam (5), Davos (7) and Pawlowsk (6). There is a certain amount of agreement among these stations and Kew as to the summer type of variation ; in every case the minimum occurs between noon and 14h. G.M.T. and the maximum during the night. At Pawlowsk the summer variation is very definitely a single oscillation, with a large range of 119 per cent ; at Potsdam there is a tendency for a double oscillation to occur. As regards the daily variation of current in winter there is not very close agreement between the stations. The prominent maximum which occurs at Kew at 5h. is not evident at the other stations where the maximum tends rather to fall in the evening or night. There is no close correspondence as to the time of minimum in winter. The winter variation is greatest at Davos where the range is 80 per cent. One further result which may be quoted is that of G. C. Simpson (3) who, from continuous records of the current entering an exposed plate, on ten days in November 1909 at Simla, found a resemblance between the daily variations of current and potential gradient ; a minimum occurred at about 2h. G.M.T., and a maximum at about 15h. ; there was a secondary maximum at 7h. The only definite conclusion that can be drawn from the results for these few places is that the general similarity in the fluctuations of current in summer supports the view that a world-wide cause is operating but that in winter this factor is masked by the effects of local conditions. It is clear that further observations, preferably direct, of air-earth current at suitably selected places are urgently needed.

§ 13—THE AIR-EARTH CURRENT DURING FOG

It has been mentioned that in the main analysis of the records, occasions of fog were omitted. These have been made the subject of a separate examination and some interesting results have been noted. In selecting occasions of fog the usual criterion of visibility less than one kilometre has been taken. For periods between the hours at which meteorological observations are made, interpolation of visibility estimates has been necessary, but this has been facilitated by making use of the records of air pollution given by the Owens automatic filter and of records of relative humidity.

The general effect of fog on electrical conditions is as follows. The resistance of the air is increased owing to the diminution in the number of small ions. This diminution is brought about by the absorption of the small ions by the nuclei of condensation, the numbers of which are increased in fog. The increased resistance causes the potential gradient to assume high positive values as a rule, whilst the air-earth current is considerably reduced, often nearly to zero. These effects are noticeable on many of the records. There is, however, a further effect associated with fogs which is of a surprising nature and which has apparently escaped notice hitherto. It takes the form of a reversal in the sign of the charge entering the ground and the surprising fact is that the reversal, which usually persists for several hours, is not, as a rule, accompanied by a corresponding change in the sign of the potential gradient. Before proceeding to a general discussion of this phenomenon some individual cases will first be considered.

Some records showing negative charging of the test plate during fog are reproduced in Figs. 10-16 (Plates IV to VII), and the following notes supplement the information included in the records :—

FIG. 10 (Plate IV). This is a good example of the effect during very high positive gradient. The normal air-earth current started decreasing as the fog began to form and reversal took place as the gradient was rising. When the fog was thickest the negative current reached a maximum value of about -400×10^{-18}amp. cm.^{2} and the potential gradient reached 1,800 volts per metre. A rapid fall in the gradient was accompanied by a decrease in the negative current but the latter increased again later. Then as the gradient started its drift back to normal the current became zero and soon afterwards increased suddenly to its normal positive value ; during this period the fog was apparently decreasing but there is no information as to whether it thinned suddenly at the time when the current increased so quickly. The record points to some correspondence between the potential gradient and the negative current but this is not borne out in every case. A trace of precipitation was found in the standard rain-gauge after the fog but it was interpreted as melted hoar frost. The relative humidity was between 98 and 100 per cent during the whole foggy period.

FIG. 11 (Plate V). On this occasion the negative effect did not become well marked until about two hours after the fog reached its greatest intensity. There was no close correspondence between the potential gradient and the current ; the gradient did not reach its maximum until after the current had changed back to the positive direction. The relative humidity was about 98 per cent and a rainfall chronograph recorded that an extremely small amount of moisture, of the order of 0·075 mm., was precipitated during the fog at about the time the current was negative.

FIG. 12 (Plate V). In this case the negative current occurred when the fog was thickest and the high potential gradient lagged behind a little. The very large negative current which occurred at 7h. after the fog had cleared was due to a small amount of snow; apart from this no precipitation was recorded. The relative humidity during the fog was 98 per cent.

FIG. 13 (Plate VI). On this occasion evening ground fog, reported as being wet, followed a misty day. During the night, as the fog intensified, a strong negative current suddenly started and persisted for nearly twelve hours. While the potential gradient was at its maximum, between 1h. and 3h., the rate of negative charging was so great that the light spot failed to register. During this period about 0·1 mm. of precipitation was recorded and it was interpreted as very fine drizzle. The air was saturated during the fog. It will be noticed that the negative current remained quite large after the potential gradient had fallen to its more normal value. The current reverted to the positive sign when the fog cleared suddenly just after the next day's record was started. It will be noticed that negative current was also recorded between 15h. and 17h.; this is the only occasion on which the effect definitely occurred in the absence of fog (or rain). There was, however, slight mist at the time and it is significant that the onset of the negative current was accompanied by a fairly sudden increase in relative humidity from 88 to 93 per cent and that as the negative effect diminished the humidity fell to 74 per cent.

FIG. 14 (Plate VI). This is the only case in which fog was accompanied by a negative potential gradient of long duration. The fog was at its thickest at about 19h. but the gradient, which had not been excessively high, did not reverse until three hours later; the current became negative at the same time and it persisted negative for an hour after the gradient had climbed to a high positive value. No precipitation was recorded and the relative humidity was between 95 and 98 per cent. It is of interest to mention that a second potential gradient recorder 100 metres away showed exactly the same fluctuations of gradient. On the other hand, although fog also occurred at the same time at the Royal Observatory, Greenwich, which is 22 km. away, the potential gradient record there was very different; there was no negative gradient at all, but from 21h. and to 0h. large oscillations between about +150 to +1,000 volts per metre occurred.

FIG. 15 (Plate VII). This is a more recent record of some interest as it shows a small negative gradient for a short time as the fog thickened, followed by a very rapid rise to a high positive value. A small negative current accompanied the negative potential; large negative current occurred while the gradient was at its maximum positive values. Although fog was present during the whole of the time covered by the record the effects produced between 19h. 30m. and 0h. 30m. are totally different from those which were recorded during the rest of the time. It is noteworthy that some abnormalities were also shown by an ionisation recorder which was being run experimentally at the time; the ratio of the negative to positive conductivity and also the ratio of the numbers of negative to positive large ions increased greatly during the thick fog. These ratios suddenly returned to more normal values at 0h. 30m. No precipitation was recorded during the fog; the air was saturated from about 21h. onwards.

FIG. 16 (Plate VII). This record is included as being more typical of the usual effects of fog in increasing the potential gradient and decreasing the air-earth current but causing no reversals. The relative humidity was about 75 per cent when the fog began to form and 98 per cent after 5h. when the fog was thickest.

A few remarks as to the frequency of occurrence of the negative current in fog may now be given. Bad visibility was unusually prevalent during the winter of 1930-31; there were about 32 distinct periods of fog and in 10 of these the negative charging effect was well developed. When hourly readings of the air-earth current during foggy conditions were tabulated it was found that 25 per cent of all the hourly values were negative. The phenomenon usually occurred during the night or early morning and rarely during the afternoon. It appeared to be associated with the denser fogs as can be seen from Table VI which gives the frequency of occurrence of negative values of the current with different visibilities; the occasions are limited to those hours at which visibility observations are normally made, viz: 7, 9, 13, 15, 18 and 21h. G.M.T.

TABLE VI.—FREQUENCY OF NEGATIVE CURRENT WITH DIFFERENT VISIBILITIES

Visibility (metres)	Total number of hours	Number in which current was negative	Percentage frequency of negative current
< 25	10	7	70
25 to 50	18	7	40
50 to 100	14	3	20
100 to 200	21	2	10
200 to 500	25	2	8
>500	350	1	< 1

The average negative current was about -80×10^{-18} amp. cm.$^{-2}$, but this was greatly exceeded on a number of occasions. The largest effects occurred at midnight, the mean negative current at this hour being -190×10^{-18} amp. cm.$^{-2}$. When all the negative values were excluded the average current in foggy conditions was $+22 \times 10^{-18}$ amp. cm.$^{-2}$ and the total positive charge brought down during all the fogs was $+2{\cdot}3 \times 10^{-11}$ coulomb cm.$^{-2}$ The total charge brought down by the negative current was $-2{\cdot}8 \times 10^{-11}$ coulomb cm.$^{-2}$; the effect was therefore more than sufficient to counterbalance the positive current in fog.

It is evident that the negative charge carried to the ground in fog is due to the settling out of charged water droplets, i.e. to very fine drizzle of such an extreme type as to be barely recognizable in the ordinary way. The deposition of water on exposed surfaces is a frequent occurrence in fogs which are associated with high relative humidity and in all of the cases in which negative charging occurred the relative humidity was very high (96 to 100 per cent). In some cases a sensitive rain recorder did register the precipitation of small amounts of moisture of less than 0·1 mm. but such small quantities might have been dew or melted hoar frost. In one case (Fig. 13, Plate VI) the precipitation developed into ordinary drizzle for a short time. Experiments showed that the negative charging was not caused by drops, such as dew falling from the wire net; any charge carried to the plate by such drops was much too small to account for the effect and moreover it was positive rather than negative.

A rough estimate of the charge associated with the extreme type of precipitation that appears to occur in fog has been obtained by making one or two assumptions. The records show that the negative charge brought down is about 3×10^{-7} E.S.U. per cm.^{2} per sec. If we take the rate of precipitation as being 0·1 mm. in five hours the charge per cc. of water is $-0{\cdot}5$ E.S.U. This is considerably larger than the value, 0·12 E.S.U. per cm.^{3}, which McClelland and Nolan (16) found in the case of " fine " rain; they found that the charge was always negative. G. C. Simpson's (17) measurements showed that the more feeble the rain the greater is the charge per unit volume.

If we assume the radii of the fog droplets to be 2×10^{-3}cm., this being roughly the size at which they begin to gravitate, then the charge on each droplet works out at 17×10^{-9} E.S.U. or 35 electron units. Wigand and Frankenberger (18) measured the charges on droplets in a number of fogs and obtained values between 60*e* and 2,200*e* for dry persistent fogs, but in cases where coagulation set in and the fog was definitely wet the charges varied between 4*e* and 60*e*; in many cases, however, the charges were positive.

Whilst it is concluded that the negative current in fog is carried by water droplets no satisfactory explanation has so far been obtained as to the process by which the droplets become charged. A complete explanation has to take into account the fact that the effect can occur in a negative as well as in a positive potential gradient. A clue has been suggested by the fact that a point-discharge apparatus similar to that used by Wormell (19), has sometimes recorded a small negative discharge from the point in fogs. In sufficiently high potential gradients this process may occur at the tops of such objects as trees. Before suggesting a complete theory it is hoped to make some further observations and experiments on the problem.

§ 14—SUMMARY

An apparatus for obtaining continuous records of air-earth current and potential gradient is described in detail. The chief feature is the method of compensating for changes in the earth's field and so obtaining a record from which the air-earth current is derived by a direct measurement. Comparisons with the Wilson apparatus, an eye-reading instrument of entirely different type, showed that the new apparatus gives reliable records of the air-earth current. The results obtained from an analysis of one year's records are discussed and the main conclusions are as follows :—

(1) In undisturbed conditions the annual mean of the air-earth current at Kew is 112×10^{-18} amp. cm.$^{-2}$ This value refers to an open site.

(2) The annual variation of the air-earth current is opposite to that of the potential gradient, there being a maximum in summer and a minimum in winter. The proportional ranges are roughly the same.

(3) In winter the daily fluctuations of current and conductivity are very much alike. In summer, on the other hand, there is more resemblance between the diurnal variation of the current and that of the potential gradient.

(4) The air-earth current is usually very small in fog but in dense fogs large negative currents are often recorded. These currents are thought to be due to charges brought down by very small water droplets. The effect is usually accompanied by high potential gradient but in one case a prolonged negative gradient was recorded.

ACKNOWLEDGMENTS

I am greatly indebted to Dr. R. E. Watson who made the preliminary experiments and set up the apparatus in its original form. The idea of providing automatic compensation of field changes by means of the condenser, which is the main feature of the apparatus used in this investigation, is due to Dr. G. C. Simpson, C.B., F.R.S., Director of the Meteorological Office, and I wish to express my thanks to him for this and other useful suggestions. I am also indebted to Dr. F. J. W. Whipple, Superintendent of Kew Observatory, who initiated this investigation as part of a programme for obtaining continuous records of all the atmospheric-electrical elements.

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1929, NOVEMBER 20, 12h. 45m. to 21, 9h. 47m.

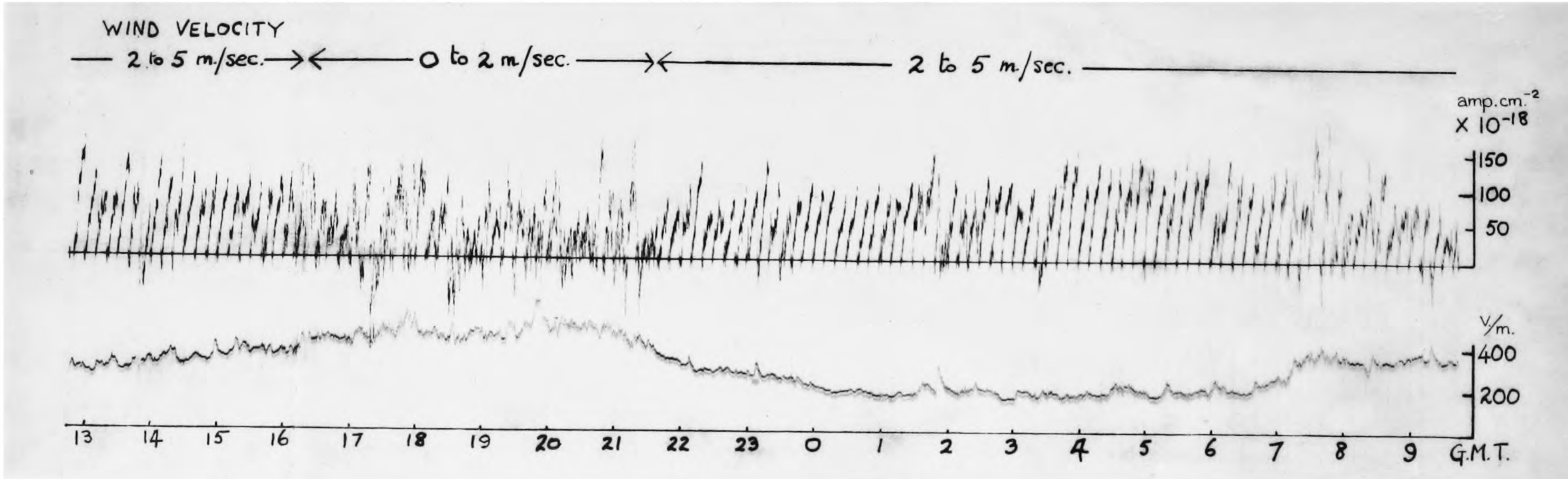

Fig. 7- Record obtained before wire net was introduced.

1931, MAY 8, 9h. 28m. to 9, 9h. 25m.

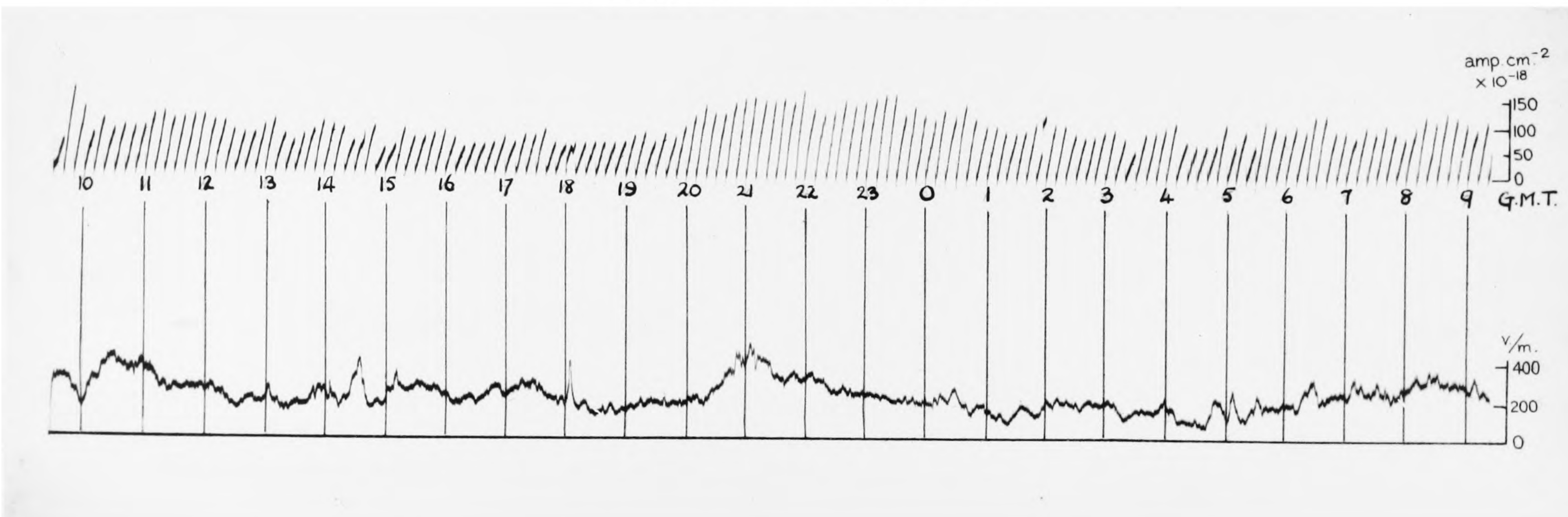

Fig. 8—Record obtained in fair weather in summer.

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1931, FEBRUARY 22, 9h. 46m. to 23, 9h. 37m.

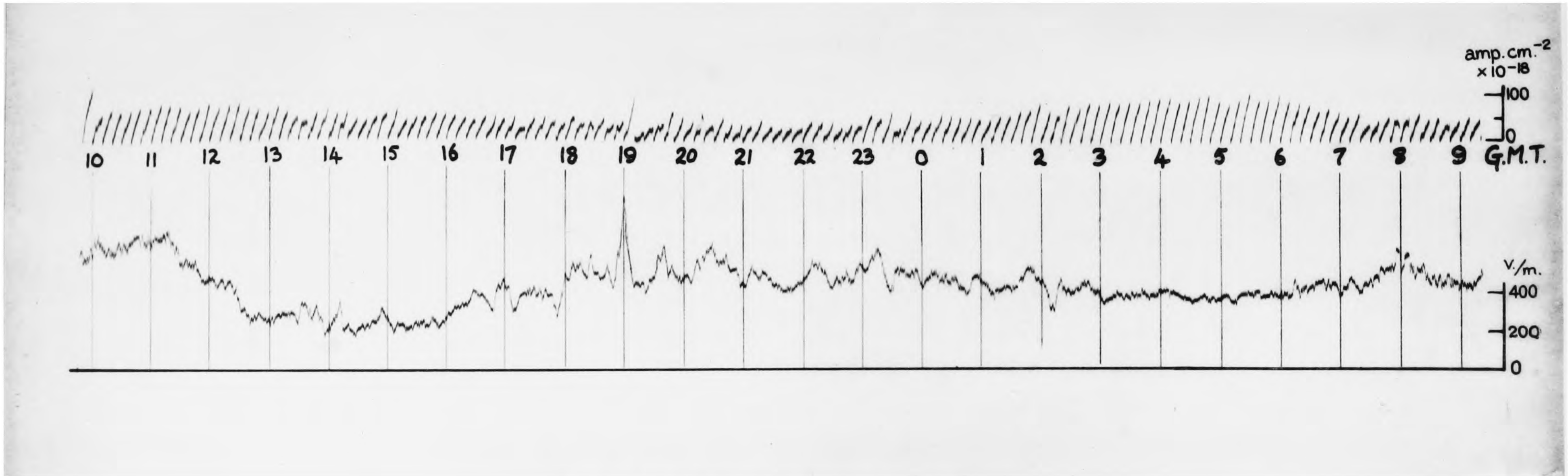

Fig. 9—Record obtained in fair weather in winter.

1931, FEBRUARY 7, 9h. 33m. to 8, 10h. 7m.

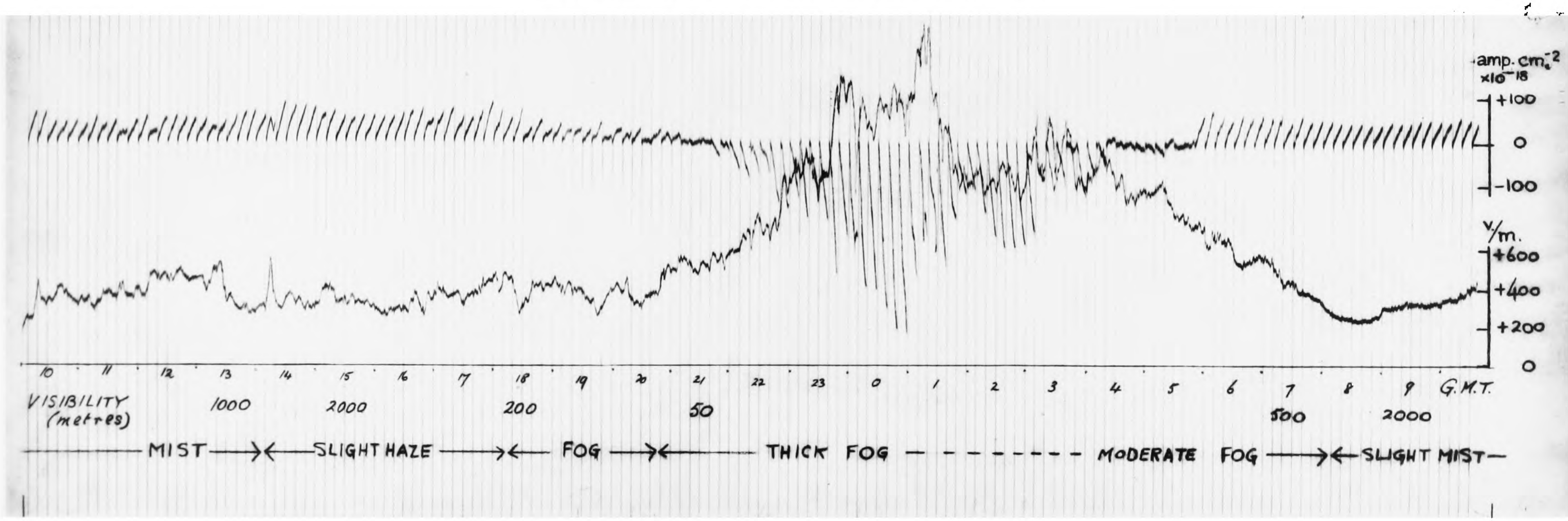

Fig. 10—Record showing negative current associated with fog.

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1930, DECEMBER 17, 9h. 46m. to 18, 9h. 35m.

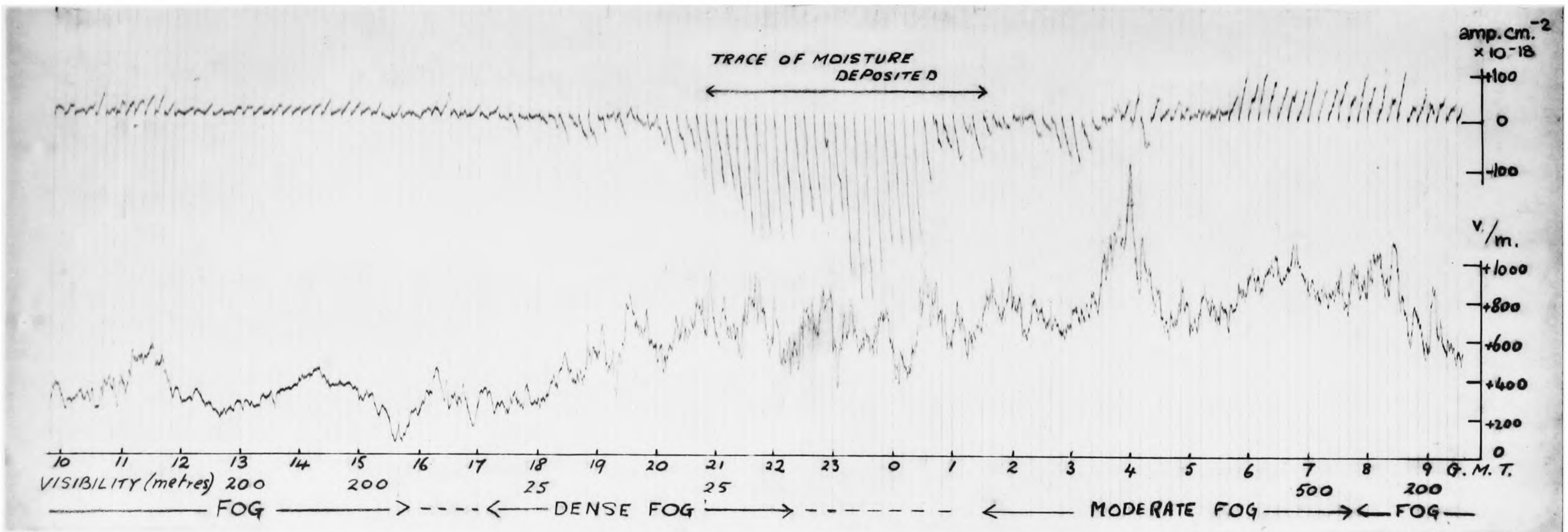

Fig. 11—Record showing negative current associated with fog.

1931, JANUARY 8, 9h. 58m. to 9, 9h. 42m.

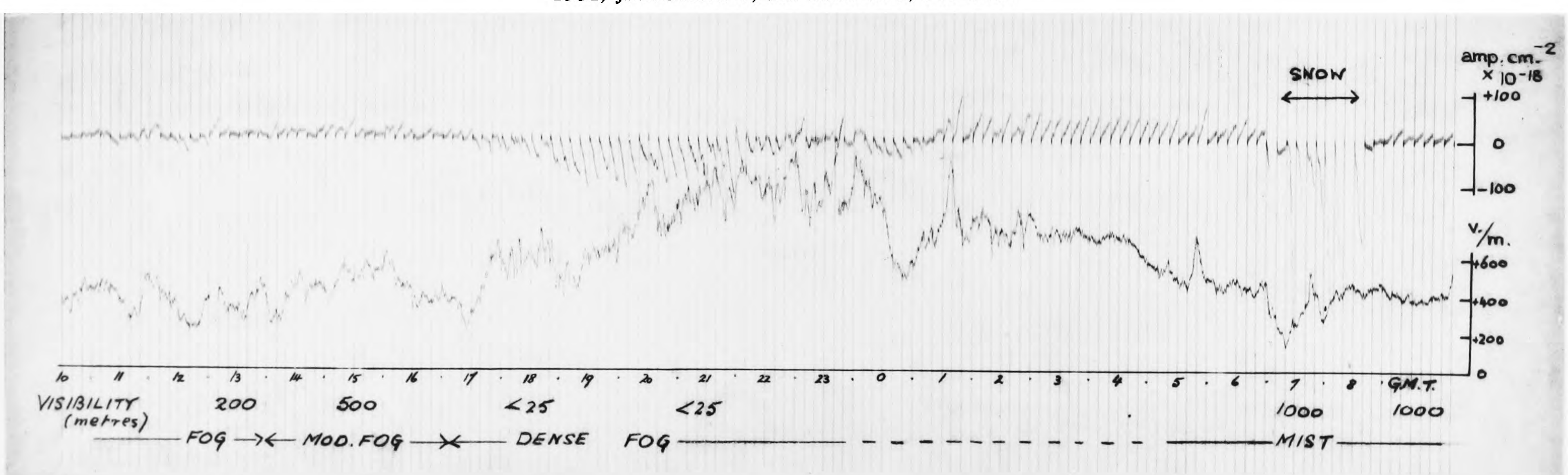

Fig. 12—Record showing negative current associated with fog.

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1931, JANUARY 20, 9h. 44m. to 21, 9h. 36m.

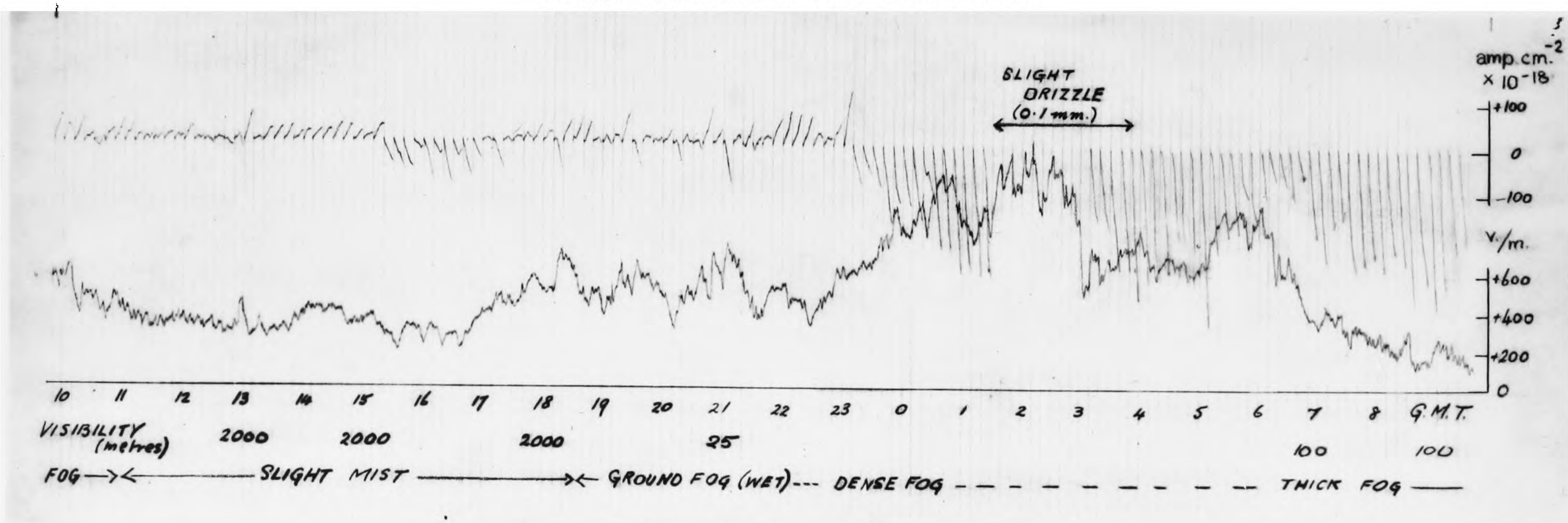

Fig. 13—Record showing negative current associated with fog.

1930, DECEMBER 4, 9h. 36m. to 5, 9h. 35m.

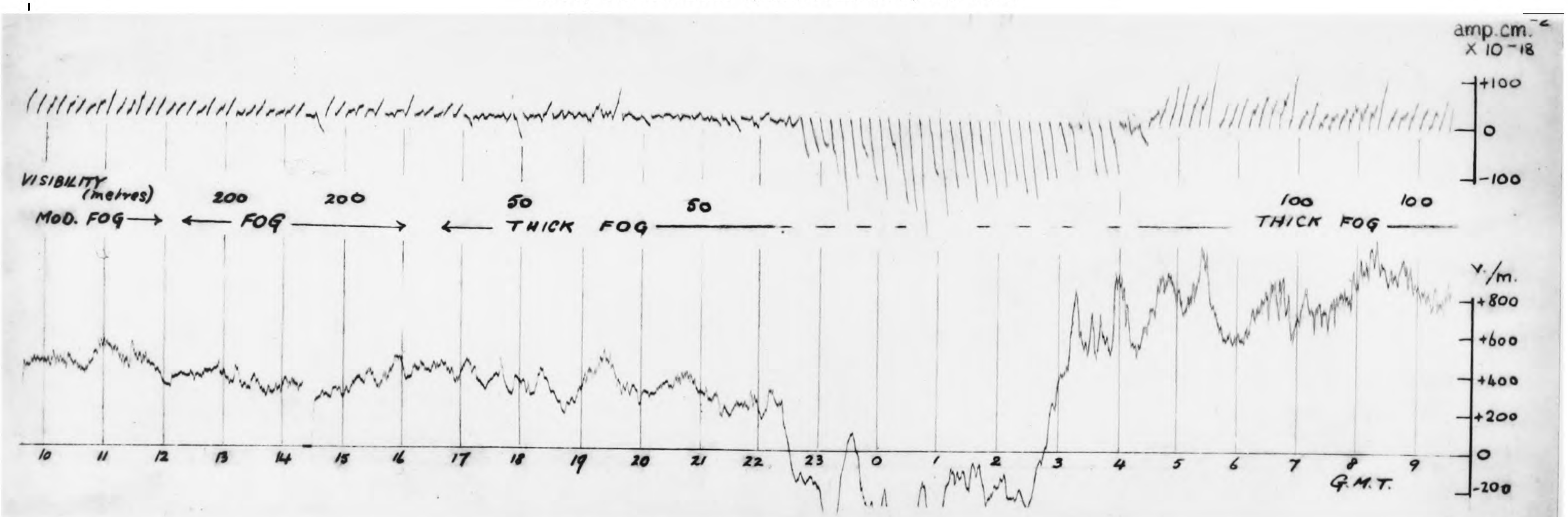

Fig. 14—Record showing negative current associated with fog.

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1931, OCTOBER 27, 14h. 54m. to 28, 10h. 4m.

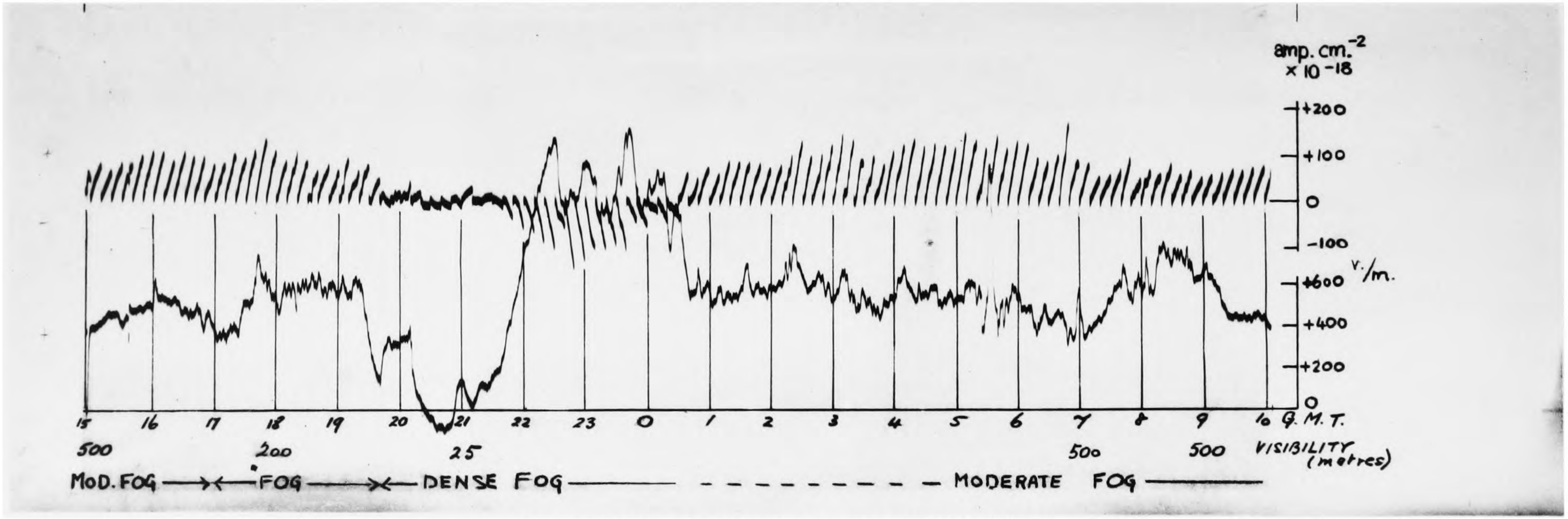

Fig. 15—Record showing negative current associated with fog.

1931, JANUARY 9, 9h. 45m. to 10, 9h. 44m.

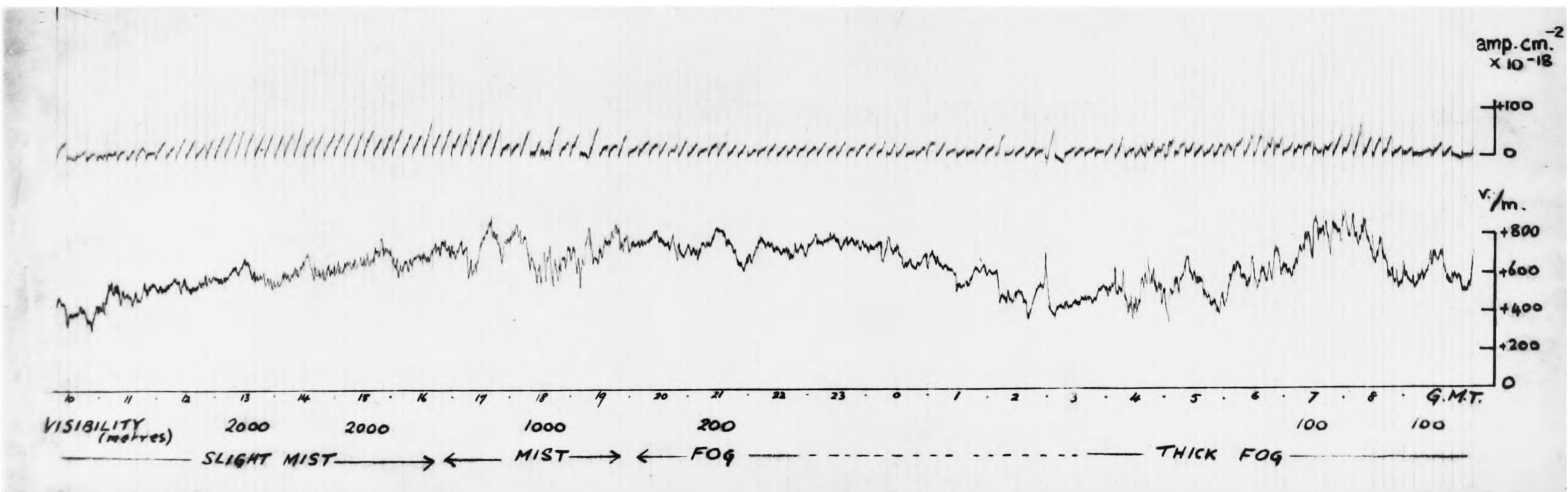

Fig. 16—Record showing decrease in positive, but no reversal, in fog.

Collotype by Waterlow & Sons Limited, London, Dunstable & Watford.