PHILOSOPHICAL TRANSACTIONS.

I. *The Electric Field of Overhead Thunderclouds.*

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[PLATES 1–6.]

CONTENTS.

1. *Introduction.*

In a previous paper* I drew attention to the fact that, owing to the peculiar geographical position of Bombay, almost all the "heat" thunderstorms† which form during the pre-monsoon and the post-monsoon periods over the hills to the east of the Colaba Observatory, between the sea coast and the Western Ghats, develop a westerly movement and pass over the station. When the air has attained a certain state in regard to its moisture content and lapse-rate, these thunderstorms are initiated by the strong instability produced through the heating of the surface layers over the hills by intense insolation. Their westerly movement was explained by means of the schematic diagram given in fig. 4 of the paper mentioned above. There is no definite evidence whether the "trigger action" is caused by a kind of katabatic flow down the Western Ghats advancing as a wedge, but such an assumption would not be inconsistent with this schematic diagram. A second class of thunderstorms of the usual "line-squall" type form on the discontinuous fronts associated with the temporary or

* 'Quart. J. R. Met. Soc.,' vol. 56, p. 305 (1930) referred to in the text as the first paper.

† There is probably no fundamental difference in the mechanism of "heat" and "line-squall" thunderstorms, but there is some advantage in retaining the names to distinguish those which invariably form in the afternoon over land areas from those which may form over sea as well as land and at any time during day or night.

permanent advance of the monsoon or a fresh advance after a break, and some of these also pass over the Colaba Observatory. During the passage of these thunderclouds overhead valuable opportunities are obtained for recording the changes in the electric field and the charges of raindrops falling from the different parts of the clouds. From these observations important conclusions can be drawn regarding the distribution of charges in such clouds.

In the paper referred to above the field changes produced by eighteen thunderclouds which passed over the Observatory in 1929 were studied. During the discussion of the paper at the Royal Meteorological Society, several of the speakers emphasised the need of a more detailed observation of these thunderclouds. But, before these views were expressed, preparations were in progress for a more elaborate investigation of the electricity of these thunderstorms. A photographic electrograph* was received in May, 1930 from the Cambridge Instrument Company, Ltd., and immediately installed in a small isolated building (old Milne seismograph room) in an open part of the Observatory compound. The radium collector was exposed through a hole in the wall at a height of 150 cm. above the ground and at various distances from the wall according to the needs of the case. Although the exposure was not as good as in the open space near the sea coast, this room had to be chosen temporarily because it was a dark room and very convenient for a photographic instrument. For comparative purposes, two Benndorf electrographs, joined to a Kew type double-nozzle water dropper, and ionium collector respectively were installed in the open space near the sea coast, as described in the first paper, and also maintained in continuous action.†

An apparatus for recording charges of raindrops was set up in exactly the same form as described by SIMPSON; ‡ but, instead of a corrugated iron hut, a small cylindrical masonry building 8 feet in diameter with a hemispherical wooden dome with its highest point 9 feet above the floor level, constructed many years ago for a small equatorial telescope and now lying vacant, was used for the purpose. The dome was completely covered with galvanized iron sheets, and these were properly earthed. A cylindrical funnel with a trap arrangement for receiving the drops splashing on the sides in exactly the same manner as described in SIMPSON's paper was fixed in the central part of the dome. The insulated receiver for the drops, which fall through the central part of the funnel without striking the sides, the recording of the charge acquired every two minutes by a Benndorf self-recording electrometer, the arrangement for momentarily earthing the receiving vessel every two minutes, the measurement of the raindrops passing through the receiver by a tilting bucket rain-gauge, and all other details were exactly as described in SIMPSON's paper.§

* 'J. Sci. Inst.,' vol. 5, p. 145 (1928).

† The photographic electrograph was removed to a small building near the sea coast in April, 1931.

‡ 'Phil. Trans.,' A, vol. 209, p. 379 (1909).

§ The capacity of the receiving system was 260 cm., and the diameter of the opening through which rain fell into the receiver was 15·4 cm.

Arrangement was also made for recording the sudden changes in the field produced by lightning discharges by three different methods. Professor C. T. R. WILSON's method, which requires the use of an exposed metal sphere and capillary electrometer, did not prove very successful owing to certain defects in the electrometers made locally in accordance with his specifications.* Three electrometers were tried, but each one failed to work at the critical time. After two or three displacements produced by lightning discharges the meniscus would not return exactly to its original position and would thus cause a gradual shift of "zero" in one direction. This was apparently due to imperfect cleaning of the capillary tubes before they were filled up and to the non-uniformity of the bore.

The following two methods were also tried :—

(1) The usual potentiometer circuit† was arranged with a thermionic valve, having its filament earthed, and the fluctuations in the plate current caused by imposing the potential of an exposed metal sphere on the grid were recorded by a galvanometer on a quick-run photographic paper.

(2) A small metal sphere was exposed at a short distance from the wall, in exactly the same manner as the spiral radium collector of the photographic electrograph, and its potential was recorded by a Dolezalek electrometer in a similar manner to method (1), except that a quick-run photographic paper was used instead of the ordinary slow-moving one.

Both methods involve the use of suspended system for recording purposes. Although the first method permits the use of a "dead beat" or "ballistic" galvanometer for recording the sudden changes produced in the field by lightning discharges, in practice the maintenance of the "equilibrium" of the potentiometer circuit or a constant "zero" of the galvanometer presents serious difficulties. Capacity effects and also the variation of battery current produced an unstable balance, and the method, therefore, did not prove very useful for continuous recording purposes. The second method is undoubtedly very simple, but its disadvantages are that the suspended system is not aperiodic. Thus when the exposed sphere is kept at a considerable distance away from the wall and at a considerable height above the ground, the records are lost owing to the speck of light going outside the photographic paper during periods of intense field ; alternately, when it is kept too close to the hole in the wall, lightning discharges produce too small a displacement on the record, except when the most active region of the cloud is overhead. In spite of these defects it will be seen from the records reproduced in this paper and their discussion that the information obtained is very valuable.

The thunderstorm activity in the year 1930 was considerably less than that in the year 1929. Only eight thunderclouds passed over the Observatory, but during the

* 'Proc. Roy. Soc.,' A, vol. 92, p. 564 (1916).

† 'Nature,' vol. 124, p. 91 (1929) ; 'J. Franklin Inst.,' pp. 287–384, March (1930) ; 'C. R. Acad. Sci.,' vol. 178, pp. 1480–1482, 2171–2173 (1924).

pre-monsoon months of 1931 five more storms passed over the station. Continuous records of the changes produced in the electric field during the passage overhead of these thunderclouds were obtained with all the electrographs. Continuous records of the charges of raindrops were also obtained for all the thunderclouds with the exception of the one on June 25, 1930, on which date the charge recorder was under experimental tests. Owing to experimental difficulties, quick-run records of the sudden changes in the field produced by lightning discharges could be obtained for seven thunderstorms only.

The changes in the electric field produced by the eight thunderclouds of 1930 and the five pre-monsoon thunderclouds of 1931, during their passage overhead, are very similar to those described in the first paper and find a natural explanation on the basis of the " breaking-drop " theory. The charges of raindrops and the sudden changes in the field produced by lightning flashes also appear to be consistent with this view.

In the Benndorf electrograms published in the first paper the extremes of the field changes were mostly lost. In the present series of experiments the radium collector of the photographic electrograph, which was exposed under normal conditions with its farthest end at a horizontal distance of 110 cm. away from the wall and at a height of 150 cm. above the ground surface, was dragged in immediately after the onset of a storm so that the farthest end of the spiral was about 5 cm. away from the plane of the wall. With this modification, in spite of the intense field, a potential within the range of the photographic paper was picked up by the collector and all the fluctuations in the field were faithfully recorded.

In order to determine the increase in the " reduction factor," when the collector is dragged in and placed at various distances from the wall, points were obtained on the photographic paper by placing the collector at the various distances in cyclical order (as shown in fig. 1). When the collector is placed in the normal position with its farther end at 110 cm. away from the wall, the reduction factor obtained by taking observations in an open field varies from 4 to 5. This large multiplying factor is due to the presence

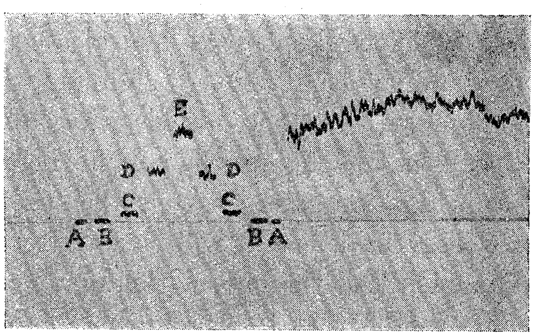


Fig. 1.—Showing the relative scale values for different positions of the collector (photographic electrograph). Length of radium spiral collector, 7 cm.; diameter, 1·5 cm. A, A. Collector earthed. B, B. End of collector 5 cm. from wall (O-position). C, C. End of collector 12 cm. from wall. D, D. End of collector 62 cm. from wall. E. End of collector 110 cm. from wall (normal position).

of low trees and buildings of height about 20 feet at a distance of about 100 feet from the collector. The length of the radium-coated spiral is 7 cm. and the question arose whether the collector picked up the potential of the point coinciding with the farther end, or the nearer end, or the mean point of the spiral from the wall. Observations of deflections obtained by placing the collector at various distances from the wall show that the ratio of the deflections agrees best with the corresponding ratio of distances, if it is assumed that the collector takes up the potential of the point coinciding with its mean point. When, however, the collector is placed very close to the wall, the ratio of the deflections does not show definite relationship with the ratio of the distances of the mean point or of any other point. This can also be seen from the deflections given in fig. 1. The ratio of the mean displacement for the " E " position to that for the " D " position is 1·84, while the ratio of the distances of the farther end is 1·94, of the nearer end 1·77, and of the mean point 1·83. The ratio of the mean deflection for the " E " position to that for the " C " position is 9·67. In this case the ratio of the distances of the farther end is 9·2 and shows closest agreement. The ratio of the distances of the nearer end is 20·6 and is too large, and even the ratio of the distances of the mid-point, which is 12·6, is also too large. The deflection in " B " or " zero " position is extremely small, but measurement by means of a microscope gives the ratio of the mean deflection in the " E " position to that in the " B " position to be of the order 100. In this case a part of the collector was actually inside the hole in the wall and very little meaning can therefore be attached to the ratio of the distances of the mid-point, which comes to be about 73·7. The " B " position is, however, the most important one, for the collector was invariably dragged into this position during the passage of the thunderclouds in order to secure the records. In a case like this it would appear desirable to use the observed ratio of the deflections rather than the ratio of the distances for the determination of the scale values. Since the ratio of the deflections is found to be of the order 100, the scale value for the " B " or " zero " position has been obtained in all the tabulations by multiplying the scale values for " A " position by 100.*

The electrograms obtained with the Benndorf electrometer during the passage of thunderclouds were very similar to those given by the photographic electrograph, except that as the former gave only two-minute marks, they failed to record the very quick fluctuations in the field. The electrograms reproduced in figs. 2 to 9 of this paper were obtained with the photographic electrograph.

2. *Overhead thunderclouds of unitary type.*

The following table gives the essential particulars relating to the thirteen thunderclouds which passed over the Observatory in 1930–31 :—

* After the photographic electrograph was removed to the building near the sea coast, the reduction factor was only 1·3 when the farther end of the spiral was 100 cm. from the wall.

TABLE I.

Serial No.	Date.	Type.	Time taken to pass overhead.	Total rainfall during the period.
	1930.			inches
1	June 13 ...	Line-squall, unitary type ...	From 13 h. to 16 h. ... (Fringe passed over station)	Dry
2	June 25 ...	Line-squall, unitary type ...	From 5 h. to 11 h.	2·3
3	Sept. 6 ...	Heat thunderstorm, unitary type	From 15 h. to 23 h. ...	4·12
4	Sept. 7 ...	Heat thunderstorm, unitary type	From 17 h. to 22 h. ...	0·17
5	Oct. 6 ...	Heat thunderstorm, double type	From 16 h. 40 m. to 22 h. 30 m.	1·45
6	Oct. 9 ...	Heat thunderstorm, unitary type	From 17 h. 30 m. to 21 h. 30 m. (Fringe passed over station)	Dry
7	Oct. 11 ...	Heat thunderstorm, unitary type	From 17 h. to 20 h. ...	0·18
8	Oct. 28 ...	Heat thunderstorm, double type	From 16 h. 30 m. to 19 h. ...	0·47
	1931.			
9	April 2 ...	Line-squall, unitary type ...	From 2 h. to 5 h.	0·01
10	June 13 ...	Line-squall, unitary type ...	From 7 h. to 16 h.	0·27
11	June 14 ...	Line-squall, double type ...	From 2 h. 30 m. to 16 h. 30 m.	2·08
12	June 21 ...	Line-squall, unitary type ...	From 8 h. to 13 h.	0·17
13	June 28 ...	Line-squall, unitary type ...	From 7 h. to 13 h. 30 m. ...	1·60

The distinction between " unitary type " and " double type " has been fully explained in the first paper. A thundercloud of unitary type invariably causes a single disturbance in the meteorological records. It is a compact mass of cloud and in a few cases, when it has come overhead, the horizon has been found to remain clear all round. The meteorological changes associated with a thunderstorm of double type indicate the passage of two distinct disturbances of unitary type in succession. They invariably have two distinct periods of heavy rainfall. When the front part of a thundercloud of unitary type comes overhead, the potential gradient becomes generally intensely negative, when the central part comes overhead it becomes intensely positive, and when the rear part comes overhead it becomes again strongly negative. The field reverts to normal positive after the cloud has passed away. The front part of a cloud of this type has, therefore, in general a charge of negative electricity, the central part a charge of positive electricity, and the rear a charge of negative electricity. This, as explained in the first paper, is in perfect agreement with the " breaking-drop " theory, which suggests that the positive electricity is concentrated in the region where the ascending current is strong, while the negative electricity spreads throughout the cloud, front, above and the rear. In thunderclouds of double type the sequence of changes in the field is repeated as if two thunderclouds of unitary type, or a composite thundercloud with two distinct regions of ascending current, have passed over in succession.

During periods of heavy rainfall the electric field undergoes very violent and rapid fluctuations. This finds a natural explanation according to the "breaking-drop" theory. For, according to this theory, while the quantity of negative electricity remains more or less constant in a thundercloud, the quantity of positive electricity must undergo tremendous and rapid changes. Sometimes the whole of the positive charge would fall out of the cloud with the rain, and at other times would be highly increased owing to the concentration due to the increased vertical current. During light rainfall fluctuations occur in the field, but they are much less rapid. This is what one would expect, as, normally, light rainfall would be associated with comparatively weak vertical current, a slow removal of charge and a slow regeneration. Besides the above, extremely quick fluctuations occur in the field; these are due to lightning discharges.

In order to test the theory that the fluctuations in the field, excluding the extremely quick ones produced by lightning discharges, are really due to loss of charge by rainfall and regeneration by increased vertical current, it is necessary to analyse a large number of thunderstorm records of all types and examine in detail whether the meteorological factors and, in particular, the sign of charge brought down by raindrops at the time when a particular fluctuation occurred would actually support such a view.

The five pre-monsoon line-squall thunderclouds, which passed over the Observatory on June 25, 1930, April 2, 1931 and June 13, 21 and 28, 1931, present more or less similar features. They were all of unitary type. While the changes produced in the electric field during the passage of each of these thunderstorms could be divided broadly into three distinct stages, namely—a front negative field, a central positive field and a rear negative field, fluctuations in the field occurred in any or all of the stages. That they were due either to loss of charge by rainfall or a regeneration of charge by increased activity was, in the case of every fluctuation, corroborated by the actual sign of charge brought down by raindrops after the fluctuation occurred. The intensity of the field at any time is apparently determined by the relative importance of the two processes, namely, removal of charge and its regeneration. Occasionally a kind of counter-balance is attained between the two processes, with the result that the field neither becomes intensely positive nor intensely negative, but remains of moderate value of either sign or undergoes a slow periodic variation about the zero line.

Since all the above-mentioned thunderclouds showed essentially the same features, we need discuss only one of them. We choose the storm of June 21, 1931, specially because, during its passage over the Observatory, very violent lightning discharges occurred in rapid succession, and the quick-run record of the field changes produced by these lightning discharges shows many important features. The electrogram, the record showing the charges* of raindrops, and the meteorograms obtained during the passage of this storm have been reproduced in fig. 2 (Plate 1). This storm, which was associated with a temporary advance of the monsoon, came over the station from the south-west in a diffused form at about 7 hrs., but the main thundercloud came overhead shortly before 9 hrs. It will be seen that during the passage of the front part of the cloud, the field became intensely negative (marked LM on the electrogram) and the raindrops brought down mostly an excess of negative charge. During the passage of the central part of the cloud, marked MN on the electrogram, the raindrops brought down generally an excess of positive charge. In the beginning of this stage the field became positive, but owing to loss of charge and a kind of balance having been obtained between loss and generation the field became negative and continued to remain negative during the period marked PQ on the electrogram. The very violent and extremely quick changes seen in this portion of the electrogram are due to lightning discharges ; these discharges, therefore, originated in the central region of positive charge ; they will be discussed later on. The increased rainfall at the end of the period suggests increased activity, which apparently made the field become positive again. During the passage of the rear part of the cloud, marked NR on the electrogram, the field became negative, and the raindrops brought down an excess of negative charge. The intermediate positive field is due to the cloud having acquired an excess of positive charge, owing to heavy loss of negative charge and generation of positive charge by a process which will be presently explained. That there was a real excess of positive charge at this time is confirmed by the charge record.

The "heat" thunderstorm of September 7, 1930, during its passage overhead, produced certain remarkable periodic fluctuations in the electric field which call for explanation. This thunderstorm developed over the hills on the mainland to the east of the Observatory in the afternoon and passed over it between 17 hrs. and 23 hrs. The electrogram, the record showing the charges of drops, and the associated meteorograms have been reproduced in fig. 3 (Plate 2). The meteorological records suggest the passage of a single disturbance. It was therefore a thunderstorm of unitary type. This thundercloud was peculiar in the sense that it had a fairly widespread and preponderating region of positive charge. The region of negative charge was apparently above that of positive charge, so that it was generally incapable of making the electric field negative except when considerable loss of positive charge was caused by rainfall.

Immediately after the onset of the storm the radium collector was dragged in so that the end of the spiral was just 5 cm. outside the hole in the wall. When this was done the speck of light came to the position marked "A" in fig. 3. During the passage

* The rain-charge curve has been obtained by joining the deflection points given by the electrometer every two minutes. The ordinates of the curve therefore represent in electrostatic units the charge which has been given to the receiver (capacity 260 cm.) every two minutes by rain which has fallen into it through an aperture 15·4 cm. in diameter.

of the front part of the cloud the field was purely positive, and the charge record shows that positively charged rain was falling at the time. The value of the gradient during this time was, however, comparatively low, not exceeding 2,000 V/M. This comparatively low value, which continued until 19 hrs. 45 mins., was apparently due to a kind of balance having been obtained between the loss of charge due to rainfall and regeneration. Thereafter the loss exceeded the regeneration and the gradient became negative, reaching a minimum value of 22,000 V/M. Soon after this the rainfall became more intense owing apparently to a stronger vertical current, which caused an increase in the concentration of positive charge. The field therefore reverted to positive at about 20 hrs. 15 mins. and attained a maximum value of about 21,000 V/M. The removal of charge by rain caused the field to become negative again, and increased concentration of charge to revert once again to positive. All this time positive rain was falling. But when the rear part of the cloud came overhead the charge carried by the drops became negative.

The final reversion of the field to positive was apparently due to the removal of a large amount of negative charge by rain, which was even then falling almost as intensely as before.

It is necessary to emphasise here one point regarding the charges of drops. The air current is not only continually carrying from the active region negative charge to the rear part of the cloud, but at the same time it is also carrying from that region a certain number of suspended drops, which are broken fragments of larger drops and are positively charged. On the whole, however, considerably more negative charge is carried than positive. There is also another process which might bring in the presence of both positively and negatively charged drops in the rear part of the cloud. Breaking of drops and consequently a certain amount of separation of charge will occur in all those parts of the cloud wherever rain is falling, though on a very small scale compared with that in the central region. Indeed, SIMPSON* has remarked: "It should be noticed that it is not necessary for the air to have passed through the region where the vertical velocity exceeds 8 metres a second for electricity to be separated and for the air to receive a negative charge and the rain a positive charge. Breaking of drops takes place in all parts of the air stream where rain is falling, and the relative velocity between the downward-moving rain and upward-moving air always produces a separation of the positive and negative electricity." Owing to the comparatively weak vertical current in the rear part of the cloud, it is probable that the electricity separated in this way is unimportant compared with that carried there by the air current from the most active region. Whatever be their relative importance, there must be a certain amount of fluctuation in the process of permeation of charges and also in the process of generation of charges by breaking of drops in the rear part of the cloud, in consequence of the fluctuations in the air current and the separation of charges in the active region.

* 'Proc. Roy. Soc.,' A, vol. 114, p. 376 (1927).

The mere fact that the recorder showed a negative charge during the passage of the rear part of the cloud does not necessarily mean that all the drops brought down negative charge. The result merely means that both positive and negative drops were falling, but the total charge carried by negative drops which fell in two minutes on the receiver exceeded the total charge carried by positive drops. As a matter of fact, the observations of SCHWEND,* who measured the charges of individual drops, indicate the presence of both positively and negatively charged drops. If, therefore, as a consequence of the removal by raindrops of the excess of negative charge and also a generation of positive charge by breaking of drops, which goes on at the same time in the rear part of the cloud which is overhead, the field becomes positive, there must then be in that part of the cloud an excess of positive charge, and the raindrops must also bring with them an excess of positive charge. This is exactly what is shown by the charge record for the thunderstorm of September 7. An excess of positive charge in the rear part of the cloud cannot, however, continue long, for not only are the raindrops removing this excess, but an increased activity in the central region of the cloud is bringing in a fresh accumulation of negative charge. We therefore get again an excess of negative charge, and thus the excess charge fluctuates between positive and negative. The oscillations in the latter part of the above-mentioned charge record and the corresponding oscillations in the potential gradient illustrate this process.

The heat thunderstorm of September 6, 1930, is interesting in many respects. It was a thunderstorm of the unitary type, but it caused very heavy rainfall during its passage over the Observatory, about 4 inches being recorded in nearly $2\frac{1}{2}$ hours. The electrogram, the record showing the charges of raindrops, and the meteorogram have all been reproduced in fig. 4 (Plate 3). The storm developed over the hills to the east of the Observatory and came over the station in a more or less diffused form at about 14 hrs., a light shower immediately commenced, but this part of the cloud did not cause much electrical disturbance. This condition continued for nearly a couple of hours, and the raindrops brought down mostly an excess of positive charge. The main thundercloud came over the station shortly after 16 hrs. The field immediately became intensely negative and the speck of light went off the scale. The speck was brought back on the photographic paper at the time shown by " A " on the record, by drawing in the collector to the " O " position, with its end 5 cm. away from the wall. At this time heavy rainfall commenced and continued with remarkably uniform intensity for over 2 hours. It is clear from the charge record that this period of heavy rainfall can be divided into three distinct stages. During the first stage, or when the front part of the cloud was passing over the station, the raindrops brought down an excess of negative charge ; during the second stage, when the central part of the cloud was passing overhead, the drops brought down an excess of positive charge ; while during the third stage, when the rear of the cloud was passing overhead, the drops brought down an excess of

* 'Jahresbericht der Kantonalen Lehrenstalt in Samen,' 1921–22.

negative charge. The oscillations in the latter part of the electric field are due to causes which have already been explained.

Terrific peals of thunder and vivid lightning flashes occurred in quick succession during the passage of the portion of the cloud marked PQ on the electrogram. A close examination of the oscillations that occurred in the electrogram during this period, as well as those in the portion PQ of the electrogram of June 21, 1931 (fig. 2), suggest that they can be divided into distinct classes :—

(1) Broad oscillations having generally large amplitudes and periods varying from about 5 minutes to half an hour.

(2) Superposed on the above there are very quick and violent fluctuations, so quick and violent that, in most cases, the details have been lost, and only the extremes of the excursions have been recorded.

The broad fluctuations are, as already explained, due to the loss of charge, either positive or negative, by rainfall and the regeneration of charge in the cloud owing to increased activity. It is interesting to note that, in spite of the rapid removal of charge by heavy rainfall, the field frequently became positive when the central part of the cloud was passing overhead and positively charged rain was falling, as it ought to be, according to the " breaking-drop " theory.

Eye observations indicate that a near lightning discharge gives a sudden kick to the needle of the electrometer, and so confirms the fact that very quick and violent superposed oscillations are due to lightning discharges. The quick-run records, which will be discussed later on, definitely show that these violent movements are due to near lightning discharges. Some small but sudden movements can also be seen in other parts of the record, and particularly in the portion LM. These are due to distant lightning discharges which had originated in a part of the cloud which was not then overhead.

It will be seen from the subsequent discussion of thunder-lightning intervals that during the passage of the thunderstorm of September 7 (fig. 3), the lightning discharges did not originate very near the station. They did not therefore produce any conspicuous fluctuations in the electric field ; the minor but very quick fluctuations seen on the peaks of the electrogram on that date were due to these distant discharges.

I now proceed to analyse the " heat " thunderstorm of unitary type which passed over the Observatory on October 11, 1930. The electrogram, the record for the charges of the raindrops and the meteorograms obtained during the passage of this thunderstorm, have been reproduced in fig. 5 (Plate 1). This thunderstorm, like the previous two, formed over the hills to the east of the Observatory. At about 16 hrs., when the thundercloud was advancing towards the station but did not come quite over it, there was a slight increase in the positive gradient, but when the front part of the cloud came overhead the field became immediately intensely negative. The rainfall throughout this storm was light ; it commenced at about 17 hrs. 10 mins. ; the charge record shows that for nearly an hour mostly positively charged rain fell. This period coincided with the central part of the cloud. In spite of rapid removal of charge the field often tended to become positive.

When the rear part of the cloud came overhead at about 18 hrs. 20 mins., the field remained intensely negative for nearly an hour. During this period mostly negatively charged rain fell. The loss of negative charge and to a certain extent generation of positive charge by the process already explained led the rear part of the cloud to acquire an excess of positive charge and the field to become positive. That the cloud had really an excess of positive charge is confirmed by the fact that during the period the rain-drops mostly brought down positive charge.

Lightning discharges occurred overhead in rapid succession during the period shown by P and Q on the electrogram. These caused violent and very quick changes in the record. In fact, they were so quick that it is difficult to count their number and some left no impression on the photographic paper. The quick-run record obtained for this thunderstorm enables us to distinguish the sudden displacement caused by each lightning discharge and shows that there were in all about 150 such displacements during the period. The extremely quick fluctuations in the portions LM and SR of the electrogram are also due to lightning discharges.

3. *Overhead thunderclouds of " double type."*

The " heat " thunderstorm which passed over the Observatory on October 6, 1930, is one of " double type." The electrogram, the records for the charges of raindrops and the associated meteorological changes have all been reproduced in fig. 6 (Plate 4). The wind records, both direction and velocity, suggest the passage of two distinct disturbances, the first between 16 hrs. 30 mins. and 18 hrs. 30 mins., and the second between 19 hrs. and 22 hrs. 30 mins. This is supported by both the pressure and temperature records. The pluviogram shows two distinct periods of heavy rainfall associated with the two disturbances. We had, therefore, in this case two distinct thunderclouds passing over the station one after the other.

We see from the electrogram that, in the first thundercloud, the front part had a positive charge and the rear a negative charge. This is confirmed by the charge record. The heavy rain which occurred for about 20 minutes during the passage of the most active region of this thundercloud brought down positive charge and made the field become negative. During the passage of the rear part of the cloud the raindrops brought down negative charge. Similarly, during the passage of the front part of the second thundercloud, the raindrops brought down positive charge. The oscillations, almost sinuous in character, which occurred in the electrogram during the passage of the rear part of this cloud, are very similar to those of fig. 3 and are due to the same cause.

During the passage of the central part of this second thundercloud there were terrific lightning discharges, all within the cloud, and peals of thunder. The very quick and violent fluctuations that occur in the portion PQ of the electrogram are due to these near lightning discharges. The extremely quick fluctuations, but of much smaller amplitude, seen in the other parts of the electrogram are due to more distant lightning discharges.

It will be clear from this electrogram, as well as the electrograms previously given and those to be given hereafter, that the amplitude of the extremely quick fluctuations due to lightning discharges occurring during the passage overhead of the central part* of the cloud is considerably greater than that due to lightning discharges occurring during the passage of the front or the rear of the cloud. In those electrograms where this feature is not shown in a marked degree the centre of the cloud did not actually pass overhead, but followed a northerly or southerly path. The first thundercloud of the thunderstorm of double type under discussion is a specific instance. This cloud did not show this feature and its centre apparently did not pass directly overhead. The second thundercloud was more severe than the first; the wind during its passage attained a velocity of 50 miles per hour. If the activity of a thundercloud can be taken to be an indication of the path followed by the centre of the storm, then the meteorological records certainly support the view that the centre of the second thundercloud came much nearer to the station than that of the first. A similar argument would suggest that the centre of the thunderstorm of September 7 (fig. 3) followed a northerly or a southerly track and would thus explain its comparative inactivity, which we have already noticed.

Another interesting " heat " thunderstorm of double type passed over the Observatory on October 28, 1930. The electrogram, the record for the charges of raindrops, as well as the records showing the meteorological changes obtained during the passage of this storm, have been reproduced in fig. 7 (Plate 2). The Dines record shows the passage of two distinct disturbances, the first between 16 hrs. 40 mins. and 17 hrs. 40 mins., and the second between 18 hrs. and 19 hrs. This is broadly confirmed by the pressure and temperature records. There are also two distinct periods of heavy rainfall associated with the passage of the two component thunderclouds.

We see from the electrogram that during the passage of the front part of the first thundercloud the field became intensely negative. A sharp shower occurred during the passage of the central part of this cloud, and the charge record shows that the raindrops brought down positive charge. The field was generally positive. The light drizzle which followed the sharp shower also brought down mostly positive charge. When, however, the rear part of the cloud came overhead, the field became negative and the drops were negatively charged. The electrogram shows further that when the front part of the second thundercloud came overhead the field became positive. The heavy rainfall which occurred during the passage of this part removed the positive charge and made the field become negative for a time. When the rear part of the

* This portion has been marked PQ in all the electrograms.

cloud came overhead the field again became negative and the raindrops brought down negative charge.

Unlike that of October 6, the first thundercloud in this storm was more active and passed more nearly overhead than the second. We had consequently during the passage of the central part of the first thundercloud extremely quick and violent fluctuations in the electric field due to lightning discharges, all originating in the most active region. These are seen in the portion marked PQ on the electrogram.

The " line-squall " thunderstorm of double type recorded on June 14, 1931, presented essentially similar features.

SIMPSON pointed out in his paper* on the mechanism of a thunderstorm that, according to the " breaking-drop " theory, the heavy rain of a thunderstorm should not generally fall to the ground immediately below its most active region. He remarks (*loc. cit.*, p. 378) : " The region in which this process of drop breaking and recombining is large is indicated in the diagram by a dotted curve which starts from the surface, where the vertical velocity is 8 metres a second, and is shown to extend to a height of about 4 kilometres. All the time the water is within this region it is being transferred to the left, where the vertical currents are smaller, and finally it is able to escape and fall to the ground to the left of the region of maximum activity." If water can be transferred by air current to the rear of the most active region, we must also postulate the possibility of water being transferred to its front, for, in the front the stream lines, as has been indicated in figs. 3 and 4 of the first paper, bend forward and the vertical current is comparatively weak. The two thunderclouds of October 28 would clearly support such a view. In the case of the first thundercloud we had first a heavy rainfall and as soon as this decreased the most active region, marked PQ on the electrogram, came overhead. Similarly, before the most active region of the second thundercloud of this thunderstorm came overhead, a heavy rainfall occurred which was positively charged.

For another conspicuous example we may refer to the second thundercloud of the thunderstorm of double type of October 6, 1930 (fig. 6). The most active region of this thundercloud was overhead during the period marked PQ on the electrogram. This was preceded by heavy rainfall, which was positively charged. In other words, the water was carried to the front part of the cloud by the air current. The first thundercloud of the above thunderstorm also shows essentially the same features. The heavy rainfall occurred during the passage of the front part of the cloud and was positively charged. A fourth example is furnished by the thunderstorm of October 11, 1930 (fig. 5). We see from the pluviogram given in this figure that the most intense rainfall preceded the passage overhead of the most active region of the cloud, and the charge record shows that this was positively charged, but in the thunderstorm of September 7 (fig. 3) the comparatively more intense rain fell from the rear of the most active region.

Although rainfall generally decreases in intensity during the passage overhead of

* ' Proc. Roy. Soc.,' A, vol. 114, pp. 376–401 (1927).

the most active region of a thundercloud, it does not cease altogether. The charge brought down by rain during the passage of this region appears to follow a certain definite law; generally it is most intensely positive when the centre of the region is overhead and decreases on either side to zero or to negative value. Considering first the thunderstorm of October 28 (fig. 7), when the centre of the most active region of the first thundercloud was overhead, the intensity of charge brought down by raindrops reached a maximum value and was indicated by the peak C_1 in the charge record. The intensity of charge decreased in this case to negative value on either side. Again, when the centre of the most active region of the second thundercloud came overhead, we got the peak C_2 in the charge record. The intensity of charge decreased to zero in the front part of the region and to negative value in the rear. Similarly, in the case of the thunderstorm of October 6 (fig. 6), we had the peak C_1 in the charge record when the centre of the most active region of the first thundercloud was overhead. In this case also the intensity of charge decreased to zero in the front part of the region and to a negative value in the rear. When the centre of the most active region of the second thundercloud was overhead the peak C_2 in the charge record was not marked, but its intensity decreased to negative value in the rear of the region.

On October 11, when the centre of the most active region of the thunderstorm of unitary type was overhead, we got the peak C in the charge record (fig. 5), and the intensity of the charge decreased to slightly negative value on either side. With the unitary thunderstorm of September 6 (fig. 4) the peak C occurred in the charge record, when the centre of the most active region was overhead, and again the intensity of the charge decreased on both sides to well-marked negative values. Similarly, on September 7, the peak C_1 occurred in the charge record (fig. 3), when the centre of the most active region came overhead. It will, however, be seen from the subsequent discussion of the thunder-lightning intervals for this thunderstorm that the region where lightning originated came nearest to the station at the time coinciding with the peak C_2 (not C_1) on the charge record. The reason for this appears to be that the next portion of the cloud was negatively charged and lightning discharges must occur between contiguous positive and negative charges.

The charge record is a time picture and not an instantaneous picture of the sign and magnitude of the charge of raindrops which had fallen from different parts of the cloud. During the interval the sign and intensity of charges in the different parts of the cloud have undergone many changes. If, however, we consider that the record represents, even roughly, the instantaneous state of the charges in the different parts of that longitudinal section of the cloud which has moved overhead, we can readily find an explanation on the basis of the "breaking-drop" theory as to why the intensity of charge has the maximum positive value in the centre of the most active region and rapidly decreases on either side to negative values. For, according to this theory (SIMPSON, *loc. cit.*, p. 379), in the centre of this region the drops are all highly charged with positive electricity, and as we approach the border of the region on either side we get a mixture of both positively and negatively charged drops, but, on the whole, positively charged drops preponderate. Just outside the region of separation the density of negative charge is greatest. In some cases the negative charge may be obliterated on the side where the heavy rainfall of the region has drifted ; an example of this is shown in the second thundercloud of October 6 (fig. 6).

4. *Thunderclouds whose fringes only passed over station.*

Careful observations showed that the centres of the two thunderstorms, recorded on June 13 and October 9, 1930, did not pass overhead. The first one was associated with a weak advance of the monsoon and was a " line-squall " thundercloud (fig. 3 of the first paper). It was observed to advance from the west over the sea and move towards the mainland along a track lying to the south of the Observatory. The northern fringe only of this cloud passed over the Observatory. From 13 hrs. 30 mins. to 15 hrs. 30 mins., when the northern fringe was passing overhead, the cloud amount varied from 7 to 8 ; the southern sky was fully covered with cumulus and cumulo-nimbus clouds right up to the horizon, but the northern sky, particularly near the horizon, was mostly clear. Thunder was heard for about an hour, beginning from 14 hrs., at long intervals, but no lightning was observed. During the passage of the cloud it was apparently raining 10 or 15 miles south of the station, but no rainfall was recorded at the station.

The electrogram and the associated meteorograms obtained during the passage of the above-mentioned thundercloud have been reproduced in fig. 8 (Plate 4).

In the first few records obtained with the photographic electrograph the time increased from right to left. The electrogram given in fig. 8 is one of those. The meteorograms have also consequently been plotted with the time increasing from right to left. This fact should be borne in mind when comparing this record with the other records in this paper.

During the passage overhead of the northern fringe of the thundercloud the electrogram showed two distinct changes. When the front part of the fringe came overhead the field became strongly negative, but the intensity of the field was only a small fraction of that attained in those cases in which the centres of the clouds passed overhead. During the passage of the rear part of the fringe the field became highly positive, but here, too, the intensity was much smaller than that attained in the case of thunderclouds whose centres passed overhead. This is exactly what one would expect, for in this case the fringe only, in which the density of charge was a small fraction of that in the most active region, passed over the station. The field changed from negative to positive with great suddenness, suggesting that there was a sharp transition between the regions of positive and negative charges even in the fringe.

The " heat " thunderstorm of October 9, 1930, whose southern fringe passed over the station, produced changes in the electric field which were very nearly opposite to those described above. As usual, this thunderstorm developed over the hills to the east of the Observatory, but moved from east to west along a track lying to the north of Bombay. During its passage the thundercloud (cumulo-nimbus and nimbus, amount about 8) covered up the whole of the northern sky, but the southern sky, particularly near the horizon, was clear. This thundercloud caused no rainfall at Colaba, but observations suggested that rain was falling north of the station 8 or 10 miles away. This was confirmed by information received subsequently from the northern suburbs of the city.

The electrogram and the associated meteorograms obtained during the passage of the above-mentioned thunderstorm have been reproduced in fig. 9 (Plate 5). The front part of the southern fringe of the thundercloud, during its passage over the Observatory, produced a large increase in the positive gradient, and attained a maximum value in the form of a sharp peak. This slowly changed to negative when the rear part of the fringe came overhead. The negative gradient reached the lowest value in the form of a sharp peak, slowly shifted towards positive, but again became highly negative before reverting to the normal positive. In the fringe of this cloud the regions of positive and negative charges were not as sharply separated from one another as in the previous one.

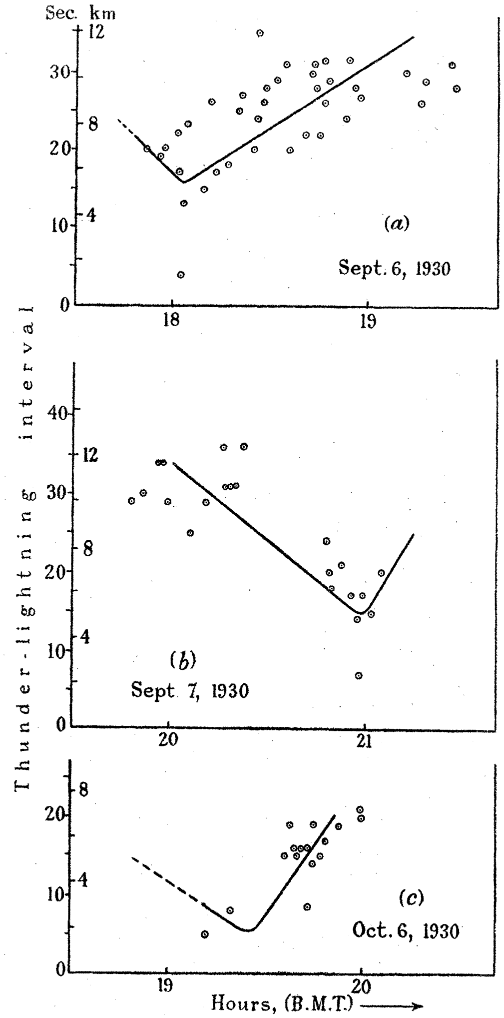


FIG. 10.—Showing relationship of thunder-lightning intervals with movements of thunderclouds overhead.

5. *Thunder-lightning intervals.*

Owing to the great attention which had necessarily to be given during the passage of thunderclouds to the large number of self-recording instruments which were maintained in continuous action, it was not possible to take observations of the intervals between thunder and lightning for all the thunderstorms. Furthermore, the observations were sometimes rendered very difficult during the hours of daylight. A fairly large number of observations of this interval were, however, taken during the passage of some of the thunderstorms. These intervals have been plotted against time in fig. 10 for the thunderstorms of September 6, 7, and October 6, 1930. The vertical axis gives the intervals in seconds and the corresponding calculated distances in kilometres of the places where thunder originated, on the assumption that it travelled with the velocity of explosive sound,* namely, 340 metres per second. The horizontal axis gives the time at which lightning was observed.

Although there is considerable scatter and the number of observations is to a certain extent insufficient, yet all the three curves† show similar tendencies, namely, a gradual approach of the place of origin of thunder to the observing station, and after reaching a minimum distance of about 2 to 5 km., a gradual receding away from the station.

It is seen from fig. 10 (*a*) that on September 6 the region of positive charge, or the central part of the cloud, where usually the lightning originates, came nearest to the station at about 18 hrs., and the electrogram and the charge record given in fig. 4 show that this is also the time when the most active region of the cloud was overhead. The time also coincided with the middle of the period of heavy rainfall which lasted for about $2\frac{1}{2}$ hours.

Fig. 10 (*b*) shows that on September 7 the thunder-lightning interval reached a minimum at about 21 hrs. It will be seen from the electrogram given in fig. 3 that this time coincided with the peak C_2 on the charge record. This was at the extreme rear end of the region of the cloud, which took about $2\frac{1}{2}$ hours to pass over the Observatory and from which positively charged rain was falling. Beyond that region the cloud was negatively charged and the raindrops brought down negative charge. Fig. 10 (*b*) would thus suggest that the lightning discharges apparently originated near the region of the cloud corresponding to the peak C_2 on the charge record and extended towards the contiguous region of negative charge. This is what we should expect. For, if a cloud has an extensive region of positive charge, the lightning discharges must naturally originate at that end of the region which adjoins the region of negative charge.

From fig. 10 (*c*) we see that, on October 6, the centre of the thundercloud apparently came overhead at about 19 hrs. 30 mins. This thunderstorm is one of double type, and a reference to the electrogram given in fig. 6 at once shows that at this time the region of the cloud which gave the portion PQ on the electrogram was overhead. It has already been explained that the extremely quick and violent fluctuations seen in the portion PQ of the electrogram are due to near lightning discharges. And now the thunder-lightning interval record confirms the fact that the most active region of the cloud was nearest to the station at the time.

A comparative study of (*a*), (*b*) and (*c*) of fig. 10 suggests that the most active region of the thundercloud came nearer the station on October 6 than on September 6 or 7. This is supported by the fact that the lightning discharges produced more violent changes in the electrogram of October 6, during the passage overhead of the most active region of the cloud, than on the other two occasions.

* Recent observations of the sounds produced by explosion suggest a velocity of about 340 metres per second, *vide* F. J. W. WHIPPLE, 'Solar and Terrestrial Relationships,' International Research Council, Second Report, pp. 114–125; also GUTENBERG, 'Z. Geophysik,' vol. 2, p. 105 (1926).

† These curves have been drawn so as to lie evenly about the observational points. Theoretically, the curves should be hyperbolas on the assumption of uniform movements of the clouds. They are in fact very flat hyperbolas almost coinciding with the asymptotes.

It will thus be clear that the thunder-lightning intervals generally support the conclusions made regarding the position and movements of the most active region of these thunderclouds from a study of the electrograms, the charge records, and the pluviograms.

6. *The quick-run records of changes in the electric field.*

As already explained, the changes in the electric field produced by lightning discharges were obtained by an arrangement similar to that used in the photographic electrograph except that the " radium collector " was replaced by a small metal sphere having a diameter of about 8 cm., and a quick-run photographic arrangement was used, the driving clock producing a movement of 0·5 cm. per minute or more in the photographic paper, according to the needs of the case.

Experiments made in an artificial field between two large parallel plates show that an exposed metal sphere takes up a very small fraction (5 to 10 per cent.) of the true potential at any point, but it takes up this potential almost instantaneously. The great advantage of the method is that we get an open-scale picture of the changes in the electric field and we can identify this picture with the corresponding portion of the ordinary electrogram obtained with the radium collector. Since an ordinary Dolezalek electrometer is used for recording purposes, there is no uncertainty about the action of the electrometer or difficulty in the interpretation of the record. The uncertainty due to rectification of current, which has been assigned by some investigators to the capillary electrometer, does not attach to the present method. The sudden change produced in the field by a lightning discharge is found to give a " kick " to the electrometer needle, which is thus set into free vibrations. The initial deflection of the electrometer needle is almost proportional to the " kick " given to it. It thus represents correctly the " sudden change " both in sign and magnitude. The initial displacement may be either small or large according to the distance of the place of origin of the lightning discharge, but it is invariably followed by rapidly decreasing free oscillations of the needle, unless two lightning discharges have occurred in quick succession. This feature enables us in most cases to identify readily the sudden changes produced by lightning discharges.

I shall first describe the quick-run record from 17 hrs. 30 mins. to 18 hrs. 35 mins. obtained during the passage of the first thundercloud of October 6, 1930. This record has been reproduced in fig. 11 (Plate 6).

It is readily seen that this record represents on an open scale the portion marked LM on the electrogram of October 6 (fig. 6). The electrometer was connected with the metal sphere at about 17 hrs. 32 mins. and disconnected at 18 hrs. 35 mins. It is important to notice that although the open-scale record given in fig. 11 agrees with the portion marked LM in fig. 6 in the broad features, all the changes seen therein have not been proportionately magnified. This is apparently due to the fact that, although an exposed metal sphere picks up a certain fraction of the true potential, that fraction is never definite. The fraction apparently depends on the state of the surrounding air and also on the leakage of the insulating system. With good insulation the fraction varies from 5 to 10 per cent.

I have already remarked that the centre of the first thundercloud of October 6 did not pass exactly overhead, and as the whole sky was covered with cloud it is difficult to say whether the centre followed a northerly or southerly track. But since rainfall of about 0·4 inch was recorded during the passage of the thundercloud, the centre apparently did not move very far north or south of the station.

I have numbered the most conspicuous changes produced in the above record (fig. 11) by lightning discharges serially by the figures 1 to 18, omitting a few insignificant ones. Each of these changes is of the nature of a sudden kick, which either tended to increase or decrease the negative gradient. The oscillations produced in the needle as a result of the kick are just faintly visible. It will be seen that the discharges 1, 2 and 3 increased the negative gradient, the discharges 4, 5 and 6 decreased the negative gradient, while the remaining discharges 7 to 18 all increased the negative gradient.

According to WILSON, SCHONLAND and CRAIB,* the sign of the sudden changes produced in the potential gradient by the passage of lightning discharges is more often positive than negative, *i.e.*, the greater number cause a sudden increase of a previously existing positive potential gradient, or a *diminution* or *reversal* of a previously existing *negative gradient*. It will be shown later that the signs of the sudden changes produced by lightning discharges photographed at Bombay do satisfy collectively this law. In the case under discussion, however, the signs of the sudden changes clearly do not satisfy the law, for the greater number of discharges have caused an increase, not diminution, in the previously existing negative gradient. There is, however, no difficulty in explaining these changes in accordance with the "breaking-drop" theory.

Since according to the "breaking-drop" theory the positive charge is concentrated in the central region, while the negative charge spreads throughout the cloud, and since it has on the whole an excess of negative charge, let us represent the distribution of charges in the cloud by five equal spheres, A, B, C, D, E, as shown in fig. 12 (*cf.* figs.

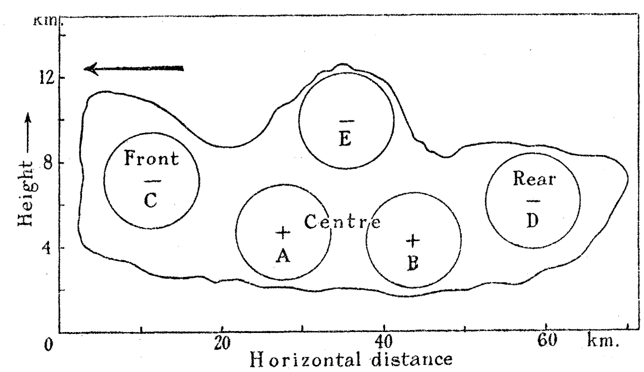


FIG. 12.

* 'Phil. Trans.,' A, vol. 222, p. 73 (1920); 'Proc. Roy. Soc.,' A, vol. 114, p. 229 (1927); 'Proc. Roy. Soc.,' A, vol. 118, p. 233 (1928).

3 and 4 of the first paper), each comprising an equal amount of charge. The two spheres A and B represent the central and lower positive charge, C the front negative charge, D the rear negative charge, and E the upper negative charge. The ratio of the total negative charge to the total positive charge is 3 : 2. Since during the period the lightning discharges given in fig. 11 occurred, the field at the station was negative, we assume that the distances of these charges from the station were such that the cloud on the whole produced a negative potential gradient.

In no thundercloud, which passed over Bombay, was a lightning discharge observed to take place between the cloud and the ground. We would therefore exclude in the present discussion the possibility of such discharges. A lightning discharge can in the circumstances extend from A to any of the directions AC or AE, or from B to any of the directions BD or BE, or both types may occur simultaneously, assuming that a discharge will always occur between contiguous positive and negative charges, and neutralise equal amounts of opposite charges.

Let us denote the five charges by Q_A, Q_B, Q_C, Q_D and Q_E, and assume that they are all equal. If H_A, H_B, H_C, H_D and H_E denote their elevations and L_A, L_B, L_C, L_D and L_E, the horizontal distances of their centres from the station, then the potential gradient F at the station is approximately given by

$$F = \frac{2Q_A}{H_A^2\left(1+\frac{L_A^2}{H_A^2}\right)^{3/2}} + \frac{2Q_B}{H_B^2\left(1+\frac{L_B^2}{H_B^2}\right)^{3/2}} - \frac{2Q_C}{H_C^2\left(1+\frac{L_C^2}{H_C^2}\right)^{3/2}} - \frac{2Q_D}{H_D^2\left(1+\frac{L_D^2}{H_D^2}\right)^{3/2}} - \frac{2Q_E}{H_E^2\left(1+\frac{L_E^2}{H_E^2}\right)^{3/2}}, \quad \ldots (1)$$

where

$$Q_A = Q_B = Q_C = Q_D = Q_E. \quad \ldots (2)$$

The electrogram in fig. 6 shows that at the period the lightning discharges given in fig. 11 occurred, the rear part of the first thundercloud was almost overhead. We can therefore take

$$L_D = 0 \quad \ldots (3)$$

and

$$L_B < L_A < L_C \quad \ldots (4)$$

Let us now denote the five terms in (1), without regard to sign, by

$$[Q_A],\quad [Q_B],\quad [Q_C],\quad [Q_D] \text{ and } [Q_E].$$

Then, when the rear part of the cloud is overhead, the following inequalities will hold in general :—

$$[Q_D] > [Q_B] > [Q_A] > [Q_E] > [Q_C]. \quad \ldots (5)$$

In this we assume that the height of the charge Q_E is so great as to make $[Q_E]$ less than $[Q_A]$, but not less than $[Q_C]$. This will in general be true when the rear part of the cloud is overhead.

We have further, since the cloud on the whole produced a negative potential gradient at the station, the following inequality :—

$$[Q_C] + [Q_D] + [Q_E] > [Q_A] + [Q_B] \quad \ldots\ldots\ldots\ldots (6)$$

In view of the inequalities (5) and (6), we can readily deduce the laws of the sudden changes in the field, when lightning discharges occur between Q_A and Q_C or Q_A and Q_E, or between Q_B and Q_D or Q_B and Q_E :—

(1) When the lightning discharges occur between Q_A and Q_C and they are neutralized, the inequality (6) is *increased.* The negative potential gradient is therefore increased.

(2) When the discharge occurs between Q_A and Q_E, the inequality (6) is *increased.* The negative potential gradient is therefore increased.

(3) When the discharge occurs between Q_B and Q_D, the inequality (6) is *decreased.* The negative potential gradient in this case undergoes a diminution.

(4) When the discharge occurs between Q_B and Q_E, the inequality (6) is *increased.* In this case, therefore, the negative potential gradient is increased.

We thus see that in three out of the four cases the negative potential gradient will undergo a sudden increase during a lightning discharge. It is therefore not surprising that in fig. 11, out of 18 lightning discharges, 15 caused a sudden increase in the negative potential gradient. It is clear that the discharge between Q_B and Q_D, which causes a diminution in the negative potential gradient, affects the charges in the part of the cloud which is overhead at the time. Such a discharge will therefore generally cause a more intense change in the field than the other types of discharges. We see, indeed, from the record that the sudden changes 4, 5, 6 are generally more intense than the rest. It is interesting to note the sequence of the sudden changes produced in this record. The fact that a number of sudden changes more or less similar in character and of the same sign occur in succession does apparently suggest a kind of persistency in the manner in which lightning discharges occur. If a lightning discharge occurs between one part of the cloud and another, the next few lightning discharges will occur between the same two parts of the cloud, in a more or less similar manner.

I will now proceed to discuss the quick-run record obtained during the passage of the thunderstorm of October 28, 1930. This record has been reproduced in fig. 13 (Plate 6). From the times of beginning and ending of the quick-run record and also from the broad changes in the potential gradient, we can easily identify this record with the portion marked LM in the electrogram of October 28, 1930 (fig. 7).

The thunderstorm is one of double type. The quick-run record comprises the changes in the field produced by the rear of the first thundercloud and by a large part of the second thundercloud. The sudden changes produced by lightning discharges have been numbered 1 to 27, omitting a few insignificant ones.

The potential gradient was positive during the period marked ST in fig. 13. All the sudden changes due to lightning discharges 1 to 14, during the period, caused a decrease in the positive potential gradient. This is easily explained. During this period the field was positive and consequently the following inequality was satisfied :—

$$[Q_A] + [Q_B] > [Q_C] + [Q_D] + [Q_E] \quad \ldots \ldots \ldots \ldots (7)$$

The region of positive charge had, during this period, a preponderating influence over the field at the station. This region was either overhead or very nearly overhead. Each of the terms $[Q_A]$ and $[Q_B]$ was therefore individually greater than any of the terms $[Q_C]$, $[Q_D]$ and $[Q_E]$. A lightning discharge will mean the obliteration of one of the terms $[Q_A]$ and $[Q_B]$ and one of the terms $[Q_C]$, $[Q_D]$ and $[Q_E]$. This is equivalent to taking away a bigger quantity from the left-hand side of inequality (7) and a smaller quantity from the right-hand side. The inequality (7) will therefore decrease. Consequently, the positive gradient must undergo a decrease. For exactly the same reason the two sudden displacements due to lightning discharges reproduced on the margin of fig. 2 caused a diminution of the positive gradient.

The negative gradient recorded during the period marked TU in fig. 13 is due, as already explained, to loss of positive charge by rainfall. The region of positive charge was still overhead. In this case there are two possibilities :—

(1) The loss of positive charge may be very small. If so, $[Q_A]$ will remain greater than $[Q_C]$ and $[Q_E]$, and $[Q_B]$ greater than $[Q_D]$ and $[Q_E]$.

(2) The loss of positive charge may be very great. When this is the case, $[Q_A]$ will become less than $[Q_C]$, and $[Q_B]$ less than $[Q_D]$, but they may or may not become less than $[Q_E]$.

Since the field as a whole is negative, we have

$$[Q_C] + [Q_D] + [Q_E] > [Q_A] + [Q_B] \quad \ldots \ldots \ldots \ldots (8)$$

When condition (1) is satisfied, lightning discharges of all kinds will increase the above inequality. The negative gradient will therefore be increased by each lightning discharge. When condition (2) is satisfied, a discharge between Q_A and Q_C or between Q_B and Q_D will cause a diminution of the above inequality, and therefore a diminution of the negative gradient. A discharge between Q_A or Q_B and Q_E may either cause an increase or decrease in the negative gradient according to the intensity of Q_A or Q_B. In the early part of the portion of electric field under discussion the loss of positive charge was not great, and consequently the discharges 15 and 16 caused an increase in the negative gradient. Subsequently, however, when the loss of charge became great, the discharges 16 to 21 caused a diminution of the negative gradient.

In consequence of the regeneration of charge, the field became generally positive during the period marked UV in fig. 13. The lightning discharges, 22, 23, 24, 25, 26 and 27, which occurred during this interval, caused very violent changes in the field. The sudden displacement in the speck of light caused by lightning discharge No. 22 is about nine times greater than that caused by discharge No. 14. Apparently the region where the above-mentioned lightning discharges originated was nearest to the station at the time. Since the region of positive charge was still overhead, the preceding discussion is applicable, and we therefore find that all these lightning discharges either caused a decrease in the positive or an increase in the negative gradient.

It is clear from figs. 12 and 13 that the sign and magnitude of the " steady " field as recorded by the electrometer are not affected by the sudden changes produced by lightning discharges.

Neither of the above two quick-run records represents a case in which violent fluctuations have occurred in the field in rapid succession owing to lightning discharges. I have therefore given in fig. 14 (Plate 3) the quick-run record corresponding to the portion marked PQ, of the electrogram of June 21, 1931 (fig. 2).

The sudden changes produced in the field have been numbered 1 to 57. Most of the lightning discharges caused a diminution of the negative gradient. In this case, therefore, the WILSON law is satisfied, but there is no difficulty in explaining the changes on the basis of the " breaking-drop " theory. During this period the most active region, or the region of positive charge, was overhead, but the field was negative owing to very heavy loss of positive charge by rainfall. The term $[Q_A]$ was therefore less than $[Q_C]$ and the term $[Q_B]$ less than $[Q_D]$. A lightning discharge between Q_A and Q_C or between Q_B and Q_D would consequently decrease the inequality

$$[Q_C] + [Q_D] + [Q_E] > [Q_A] + [Q_B],$$

for negative gradient. The loss of positive charge was probably not so great as to make $[Q_A]$ and $[Q_B]$ less than $[Q_E]$. For, if that was so, a lightning discharge between Q_A or Q_B and Q_E would cause a diminution of the above inequality. We would therefore get in all types of discharges a diminution of the negative gradient. We see, however, that although in most cases the lightning discharges caused a diminution of the negative gradient, there were some, namely, Nos. 40, 42, 43, 47, 49, 51 and 53, which caused an increase in the negative gradient. These discharges all occurred during the passage of the rear end of the most active region. At that time there was a rapid accumulation of positive charge, for, soon afterwards, the field became positive. As a consequence of this the term $[Q_A]$ became probably greater than $[Q_C]$, or the term $[Q_B]$ became greater than $[Q_D]$, and both of them certainly became greater than $[Q_E]$. Lightning discharges between any two regions for which this relationship became true made the inequality

$$[Q_C] + [Q_D] + [Q_E] > [Q_A] + [Q_B]$$

still greater and thus increased the negative gradient.

7. *Some General Remarks.*

(*a*) *Wilson's law relating to the sign of sudden changes in the field produced by lightning discharges.*—An analysis of the sign of the sudden changes in the electric field produced by lightning discharges during the passage of thunderclouds overhead, for which photographic records were obtained, gives the following results :—

I.	Total number of lightning discharges which caused increase in the positive gradient	51
II.	Total number of lightning discharges which caused decrease in the positive gradient	70
III.	Total number of lightning discharges which caused increase in the negative gradient	39
IV.	Total number of lightning discharges which caused decrease in the negative gradient	180

The value of the ratio, $\frac{\text{type I} + \text{type IV}}{\text{type II} + \text{type III}}$, is $2 \cdot 1$. It is thus clear that the greater number of lightning discharges caused a sudden increase of a previously existing positive gradient or a diminution of a previously existing negative gradient. The sudden changes in the electric field produced by lightning discharges in the few thunderclouds which have been discussed in this paper, therefore, satisfy WILSON's law, which has been confirmed by various investigators. Although collectively they satisfy WILSON's law, each individual " sudden change " finds a perfectly natural explanation from the " breaking-drop " theory.

(*b*) *Electricity of thunderstorm rain.*—Unless a thundercloud has moved overhead, it is not possible to obtain even approximately from the record at a single station the total positive and the total negative charges which have been carried to the ground by rainfall from the cloud as a whole in a given time or during the period of its existence. It is not therefore known how far the results regarding the relative proportion of positively and negatively charged rain obtained by various investigators from experiments with non-thunderstorm rain as well as rain associated with thunderstorms, which may or may not have passed overhead, are applicable to a thundercloud considered as a whole.

When, however, it is definitely known that a thundercloud has travelled overhead with more or less uniform velocity, we can approximately calculate these quantities. In Table II is given, for nine thunderclouds, certain data relating to the charges carried down by rain during their passage overhead. For each individual storm the average charge per cubic centimetre of rain during each separate period of positive and negative rain was calculated. The figures so obtained for the entire period taken by a storm to pass overhead have been used to obtain the average values of charge per cubic centimetre of rain.

The average charge per cubic centimetre of rain and the maximum charge per cubic

TABLE II.

Date of storm.	Total rainfall in centimetres.	Positively charged rain.			Negatively charged rain.		
		Amount in centimetres.	Average charge per cubic centimetre of rain in els. units.	Maximum charge per cubic centimetre of rain in els. units.	Amount in centimetres.	Average charge per cubic centimetre of rain in els. units.	Maximum charge per cubic centimetre of rain in els. units.
1930.							
Sept. 6 ...	10·67	4·50	0·02*	5·6	6·17	0·03†	2·1
Sept. 7 ...	0·55	0·35	0·20	8·9	0·20	0·16	1·7
Oct. 6 ...	3·45	3·30	0·02*	13·7	0·15	0·40	13·1
Oct. 11 ...	0·48	0·35	0·20	8·6	0·13	0·12	2·2
Oct. 28 ...	1·19	0·99	0·04*	5·4	0·20	0·20	6·4
1931.							
June 13 ...	0·69	0·33	0·10	3·2	0·36	0·06†	3·1
June 14 ...	5·28	0·68	0·15	5·7	4·60	0·03†	6·2
June 21 ...	0·43	0·05	0·60	7·2	0·38	0·14	7·1
June 28 ...	4·06	1·07	0·02*	3·2	2·99	0·07†	2·4
Mean ...	2·98	1·29	0·15	6·8	1·69	0·13	4·9

* Low values due to heavy rainfall associated with positive charge.

† Low values due to heavy rainfall associated with negative charge.

centimetre of rain are roughly of the same order as determined by other investigators from the records for non-thunderstorm rain as well as rain associated with thunderstorms, which may or may not have passed overhead. In some thunderstorms the amount of positively charged rain was greater than that of negatively charged rain, while in others it was less. Taking the average of the nine storms, we see that the amount of negatively charged rain was greater than that of positively charged rain, but the amount of average positive charge per cubic centimetre of rain was very nearly equal to that of average negative charge per cubic centimetre of rain. On the average, therefore, each square centimetre of ground received 0·22 els. unit of negative charge and 0·19 els. unit of positive charge during the passage of a thundercloud. The "heat" thunderstorm, which develops on the mainland to the east of the Observatory, covers an area which is limited by the coast line and the Western Ghats. Considering this fact and assuming that the average life of a storm is double the average time taken by it to pass over the station, we shall probably not be far out if we estimate that an area of about (100 km.)^2 receives charge at the rate given above. We thus obtain the result that on the average each thunderstorm transfers to the ground a total positive charge of about 6×10^3 coulombs and a total negative charge of about 7×10^3 coulombs. The number of overhead thunderclouds from which this result is deduced is very small. Should further observations of thunderstorms moving overhead confirm the above

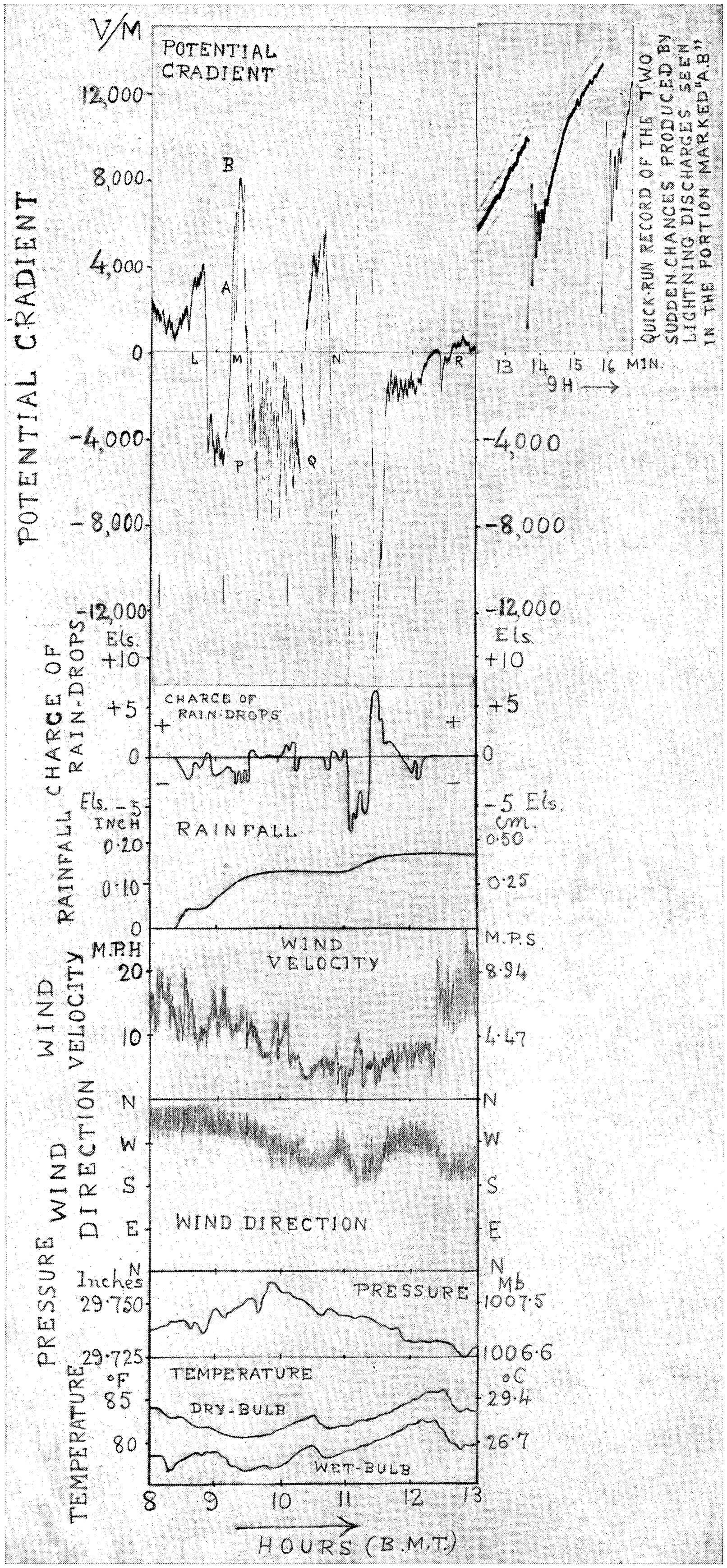


Fig. 2.—Line-squall thunderstorm of June 21, 1931. (Unitary type.)

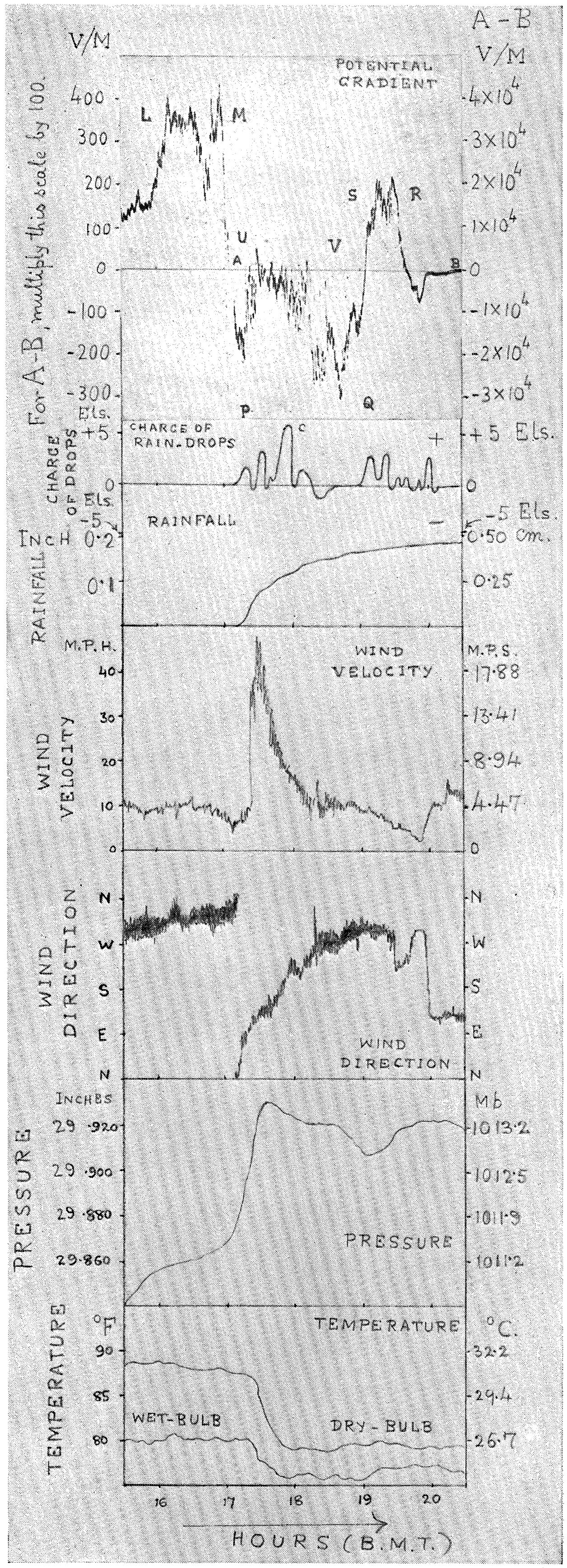


Fig. 5.—Heat thunderstorm of October 11, 1930. (Unitary type.)

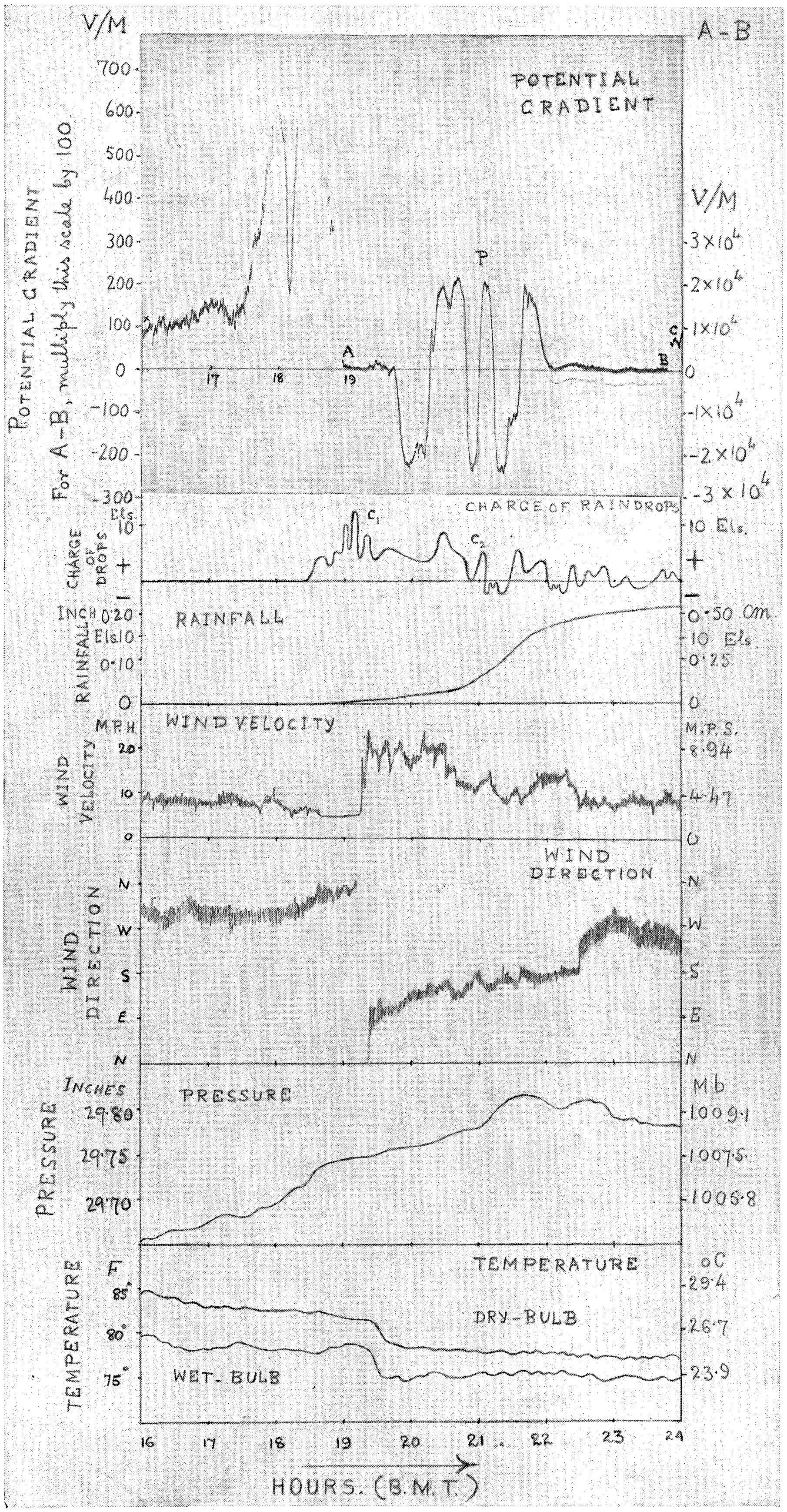


FIG. 3.—Heat thunderstorm of September 7, 1930. (Unitary type.)

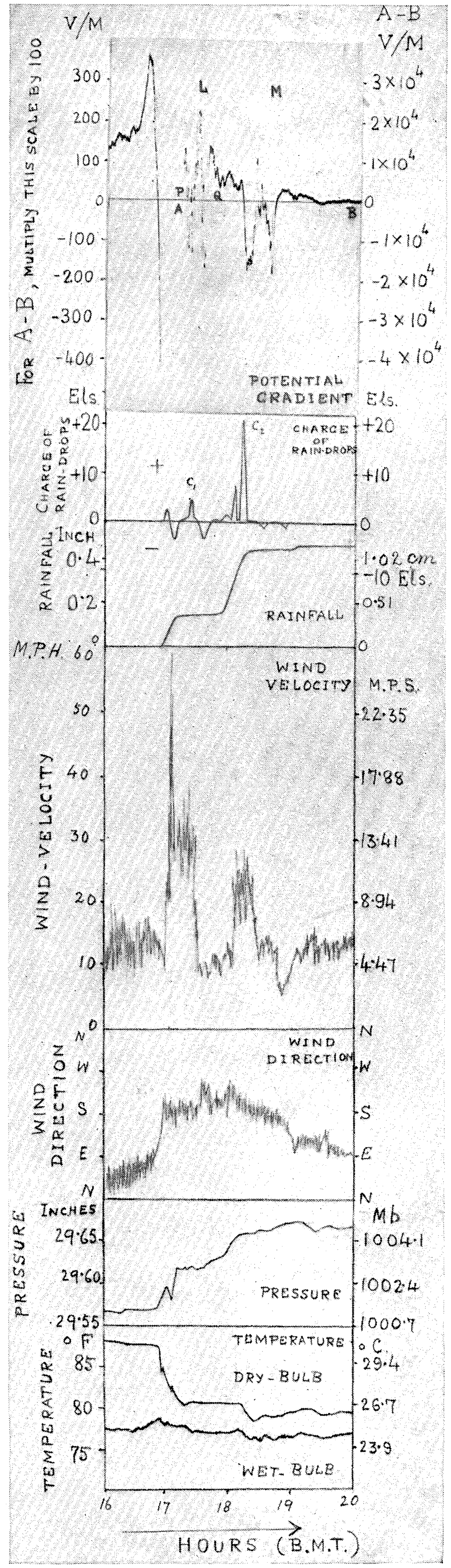


FIG. 7.—Heat thunderstorm of October 28, 1930. (Double type.)

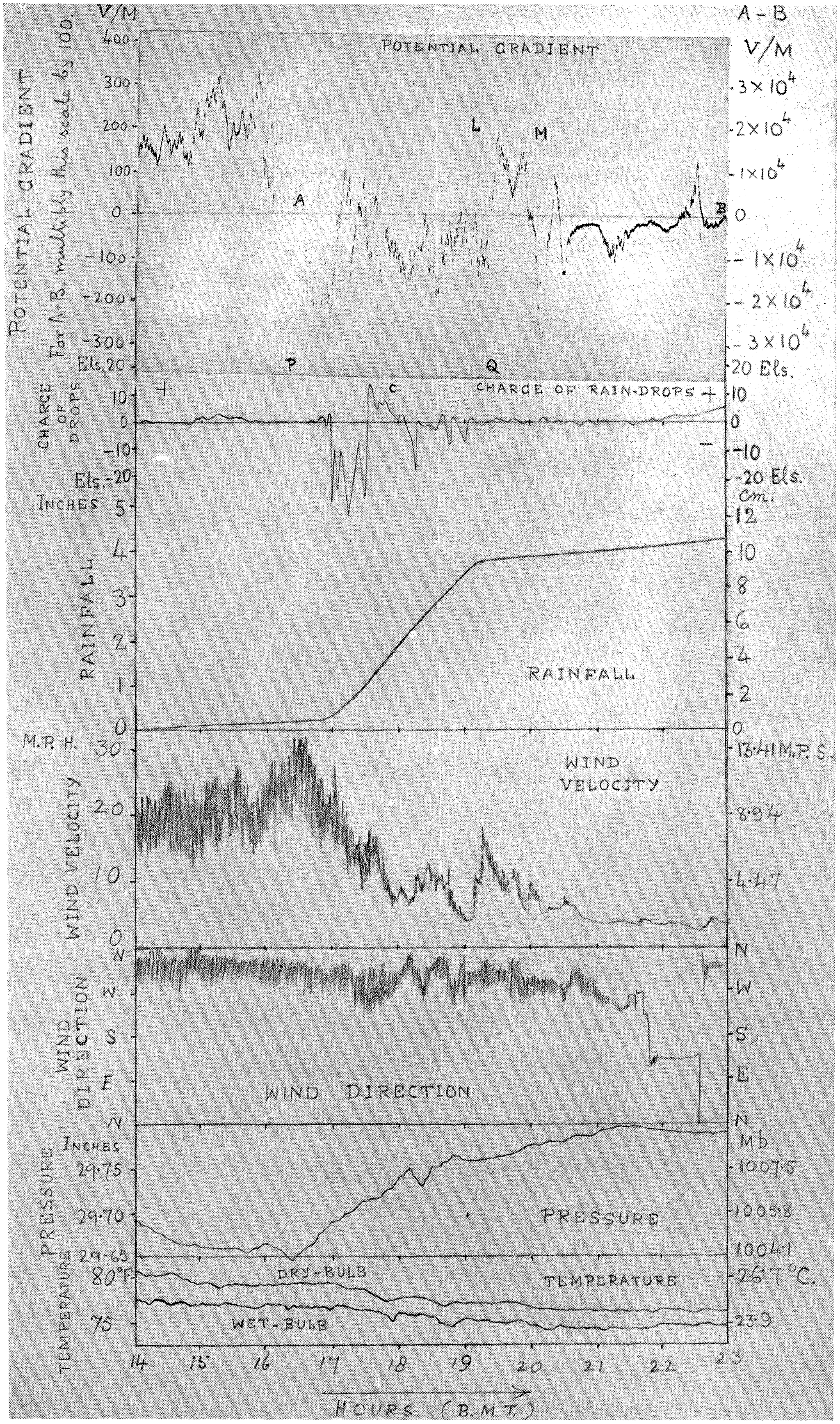


FIG. 4.—Heat thunderstorm of September 6, 1930. (Unitary type.)

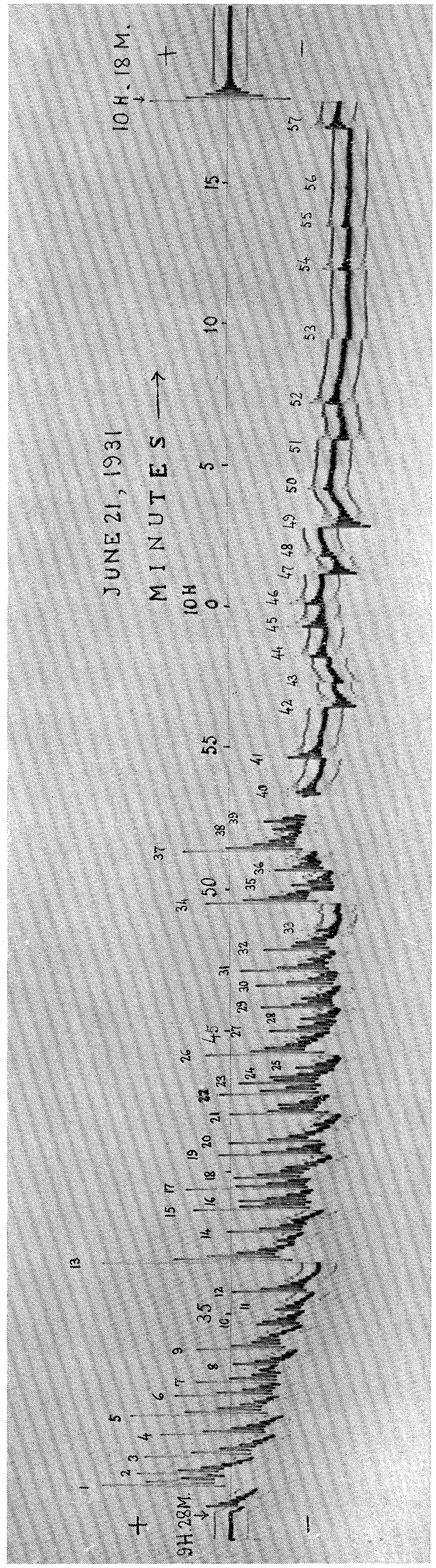


FIG. 14.—Electrogram showing violent fluctuations in the electric field due to lightning discharges occurring in rapid succession on June 21, 1931. (Collecting sphere placed 50 cm. from wall and 175 cm. above ground, quadrant potentials + 1 and − 1 volt.)

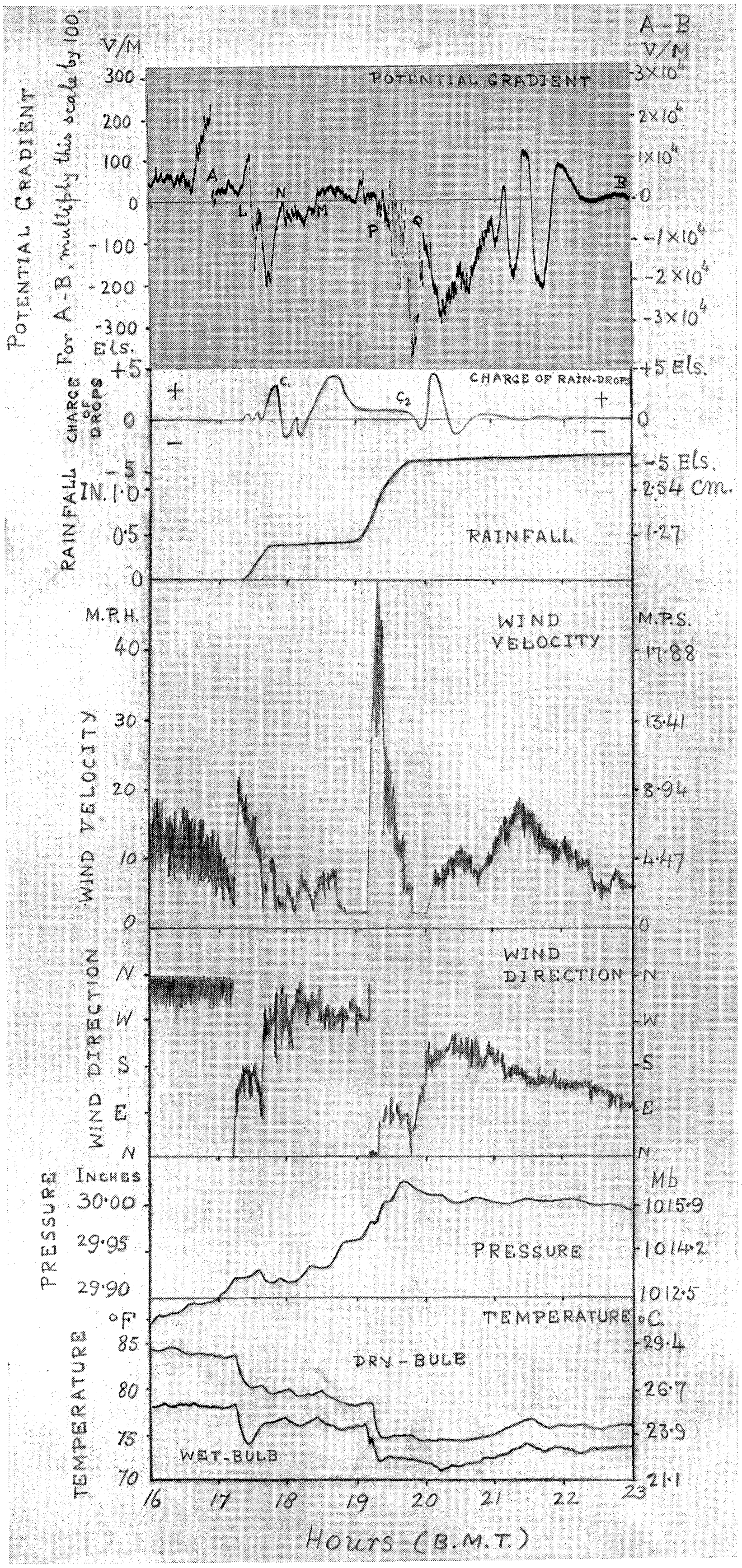


Fig. 6.—Heat thunderstorm of October 6, 1930. (Double type.)

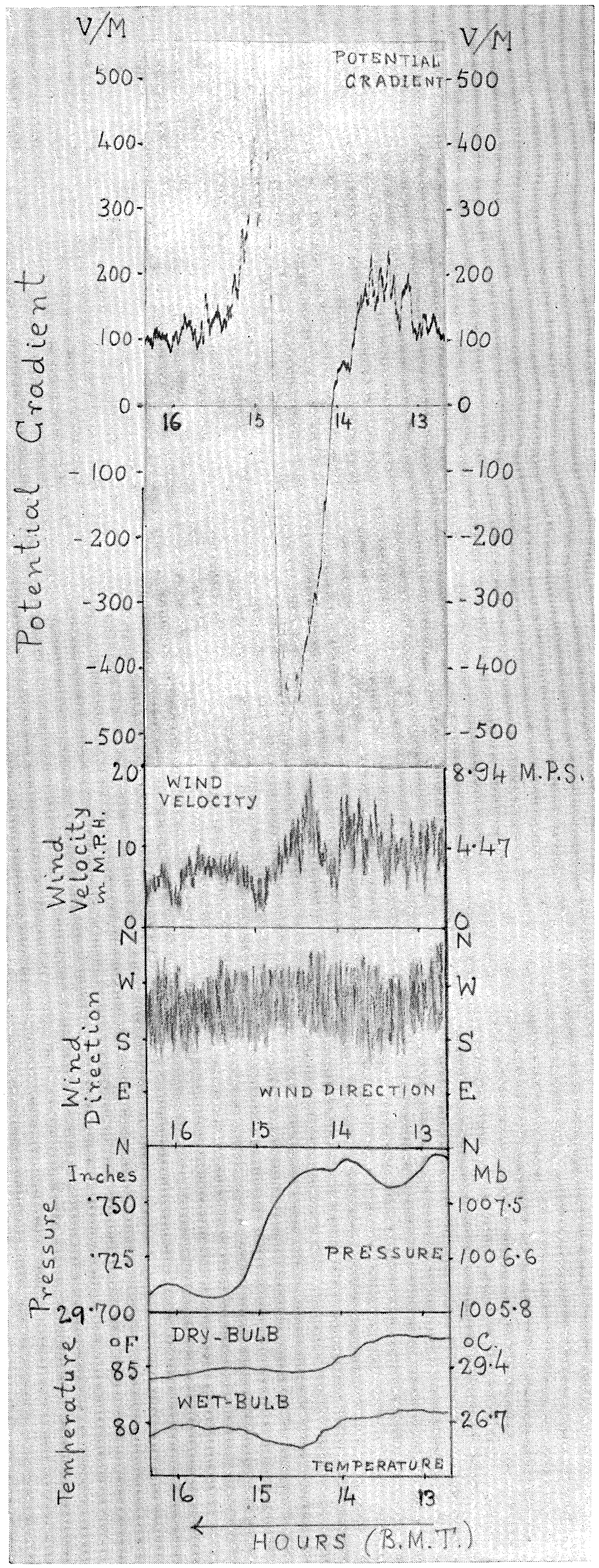


Fig. 8.—Thunderstorm of June 13, 1930. (Line-squall. Northern fringe passed over station. (No rainfall at station.)

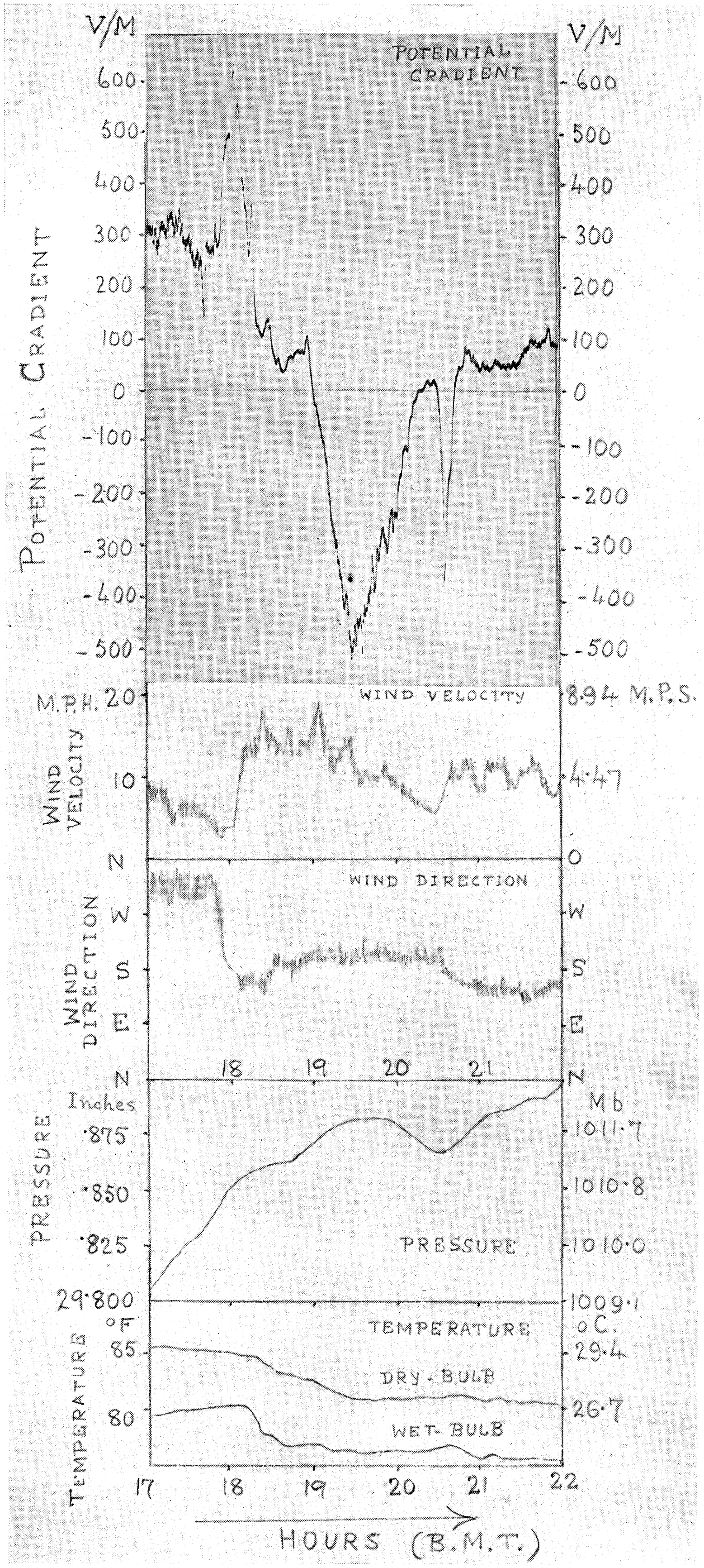


Fig. 9.—Heat thunderstorm of October 9, 1930. Southern fringe only passed over Bombay. (No rainfall at station.)

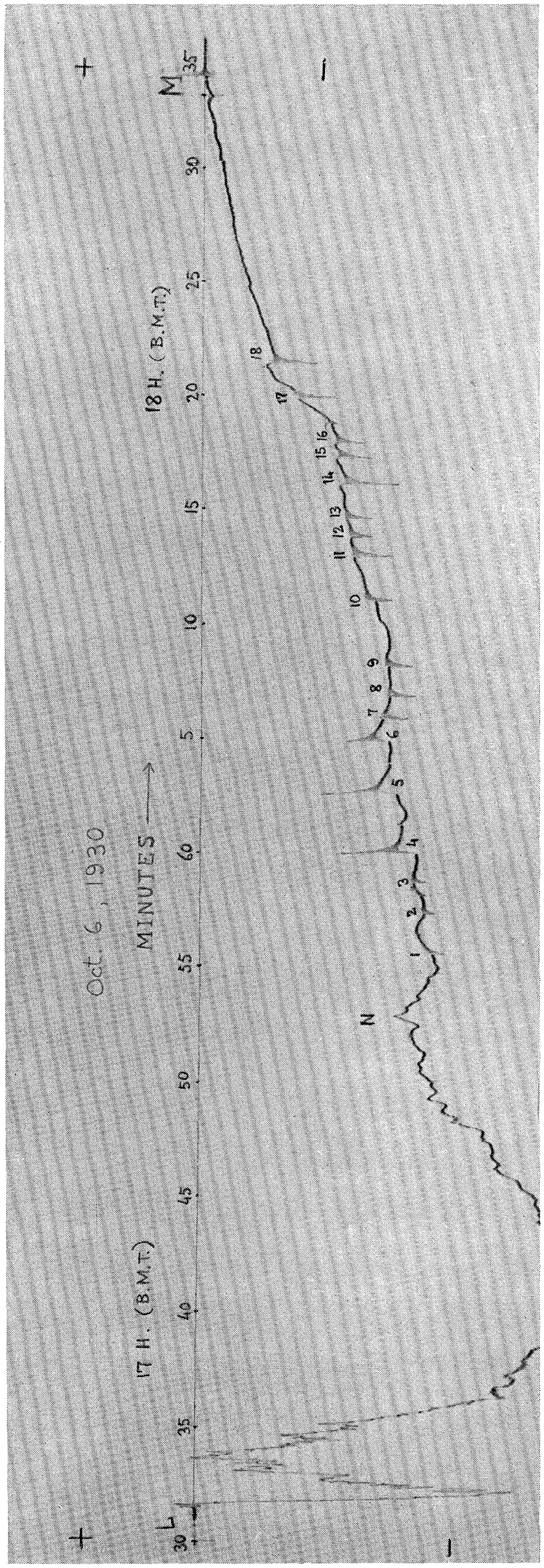


FIG. 11.—Electrogram showing the sudden changes in the electric field produced by lightning discharges on October 6, 1930. (Collecting sphere placed 94·5 cm. from wall, 138 cm. above ground, quadrant potentials + 2 and — 2 volts.)

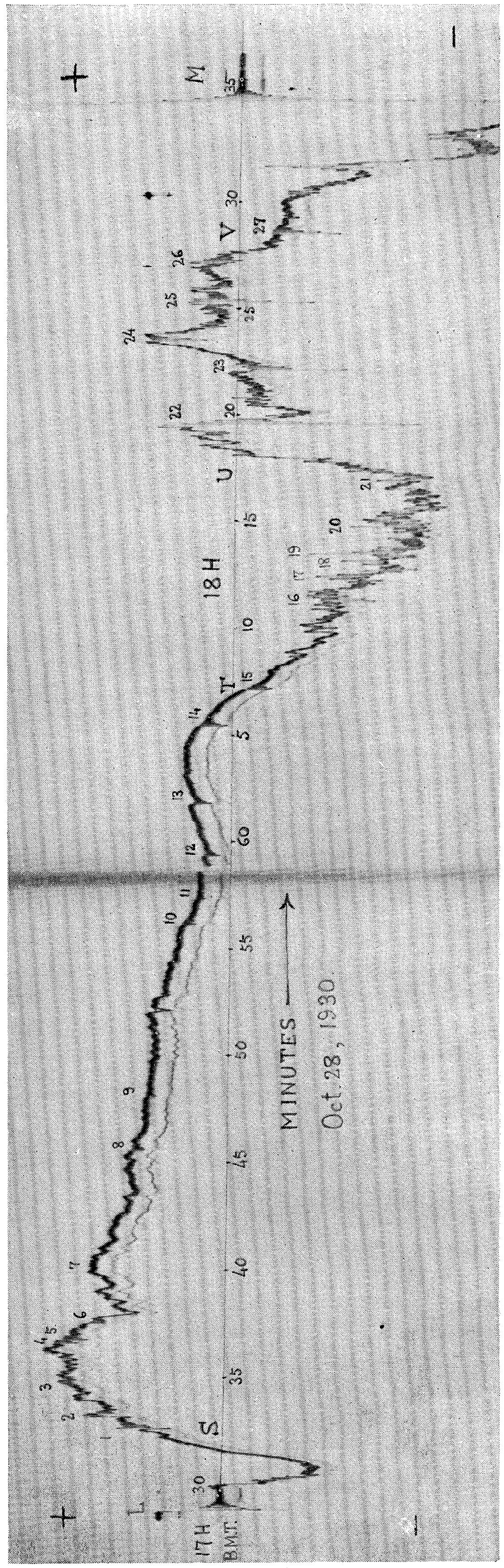


FIG. 13.—Electrogram showing the sudden changes in the electric field produced by lightning discharges on October 28, 1930. (Collecting sphere placed 94·5 cm. from wall, 138 cm. above ground, quadrant potentials + 2 and — 2 volts.)

result, the excess negative charge which is transferred to the ground by rain would probably be found to play an important part in the replenishment of the earth's charge.

8. *Summary.*

The heat thunderstorms which form over the hills to the east of the Colaba Observatory, between the sea coast and the Western Ghats, during the pre-monsoon and the post-monsoon months, develop a westerly movement and invariably pass over the station. Some of the line-squall thunderstorms which form on the discontinuous front associated with a temporary or permanent advance of the monsoon, also pass over the Observatory. These thunderstorms can be divided into two distinct types, namely, "unitary type" and "double type." In a previous paper* the changes in the electric field produced by eighteen such thunderstorms during their passage over the Observatory in 1929, were discussed. In 1930–31 a more elaborate investigation was made. In addition to two Benndorf electrographs, a photographic electrograph was installed and kept in continuous action. Continuous records were obtained by SIMPSON's method of the charges brought down by rain from the different parts of the clouds. Quick-run records were also obtained of the sudden changes in the field produced by lightning discharges.

Thirteen thunderclouds passed over the Observatory in 1930–31, ten of which were of "unitary type" and three of "double type." A detailed discussion has been given in this paper with the help of the fuller materials now available of all the changes produced in the electric field during the passage of these thunderclouds over the station. The results given in the first paper that a thundercloud of unitary type has in general a charge of negative electricity in its front, a charge of positive electricity in the centre, and a charge of negative electricity in the rear, are confirmed by these further observations. In thunderclouds of double type this sequence of changes is repeated, as if two thunderclouds of unitary type had passed over in succession. It is shown in the paper that the changes in the electric field produced on account of the different parts of the cloud coming overhead, the sign of the charges brought down by rain, and the sudden changes in the field produced by lightning discharges all find a natural explanation on the basis of the "breaking-drop" theory. Fluctuations in the field which occur during rainfall are explained as being due to removal of charge by raindrops, and increased concentration owing to increased vertical current, and this is confirmed by the actual sign of charge brought down by raindrops. The "sudden changes" satisfy collectively WILSON's law. An average thundercloud transfers to the ground by rainfall 6×10^3 coulombs of positive electricity and 7×10^3 coulombs of negative electricity; the excess negative electricity probably plays an important part in the replenishment of the earth's charge.

My thanks are due to Mr. N. CHATTERJEE, M.Sc., and Mr. P. A. SALVI, B.A., for their assistance in helping to take the observations described in this paper.

* 'Quart. J. R. Met. Soc.,' vol. 56, pp. 305–334 (1930).

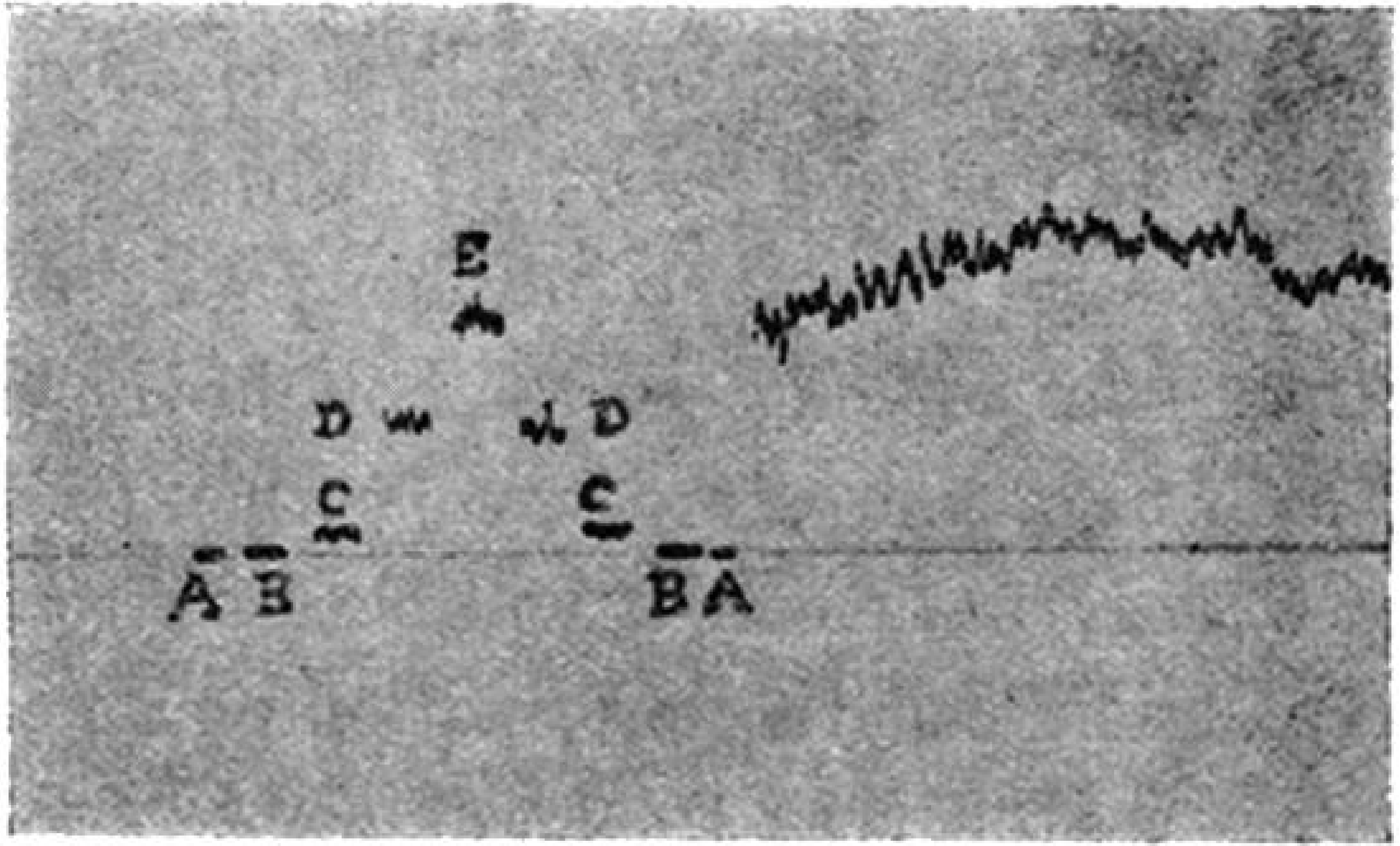


FIG. 1.—Showing the relative scale values for different positions of the collector (photographic electrograph). Length of radium spiral collector, 7 cm.; diameter, 1·5 cm. A, A. Collector earthed. B, B. End of collector 5 cm. from wall (O-position). C, C. End of collector 12 cm. from wall. D, D. End of collector 62 cm. from wall. E. End of collector 110 cm. from wall (normal position).

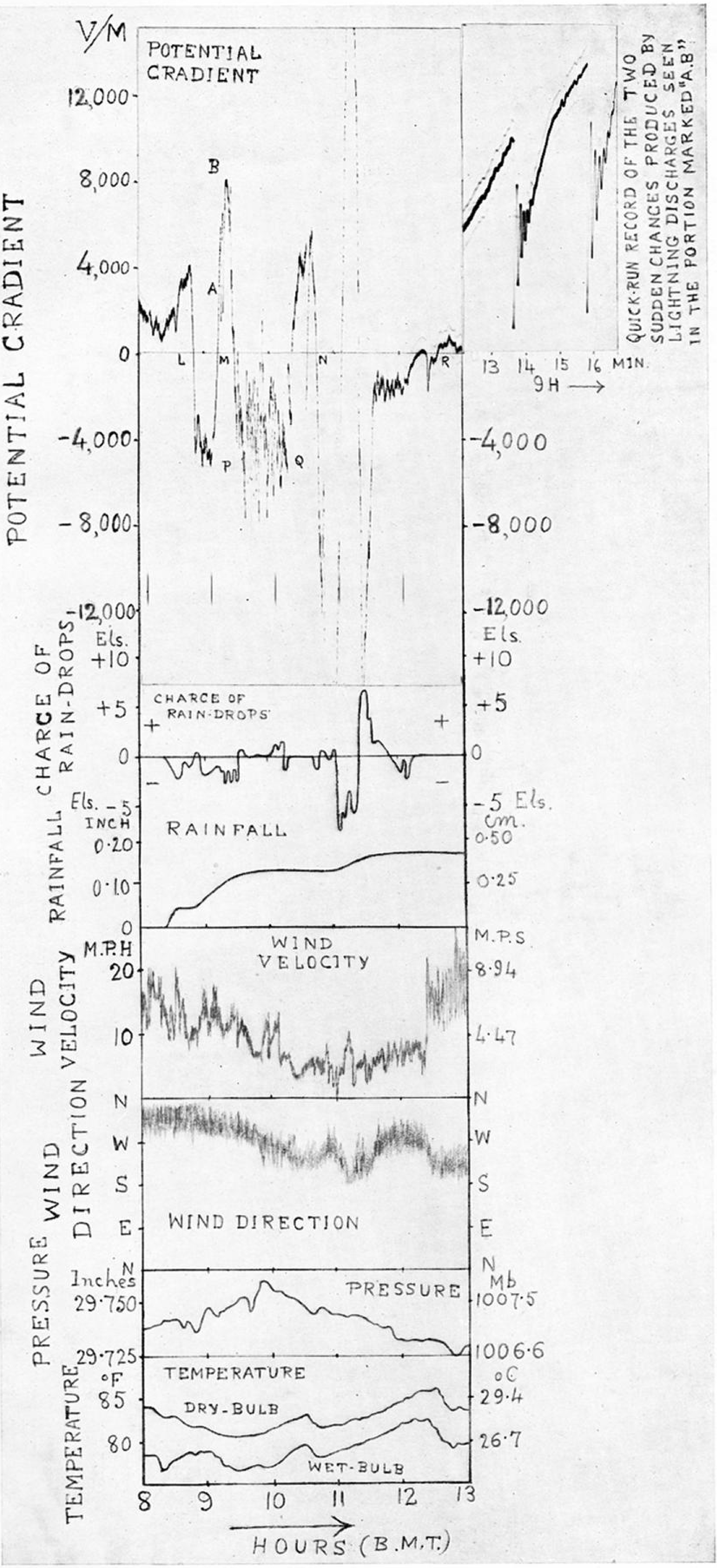


Fig. 2.—Line-squall thunderstorm of June 21, 1931. (Unitary type.)

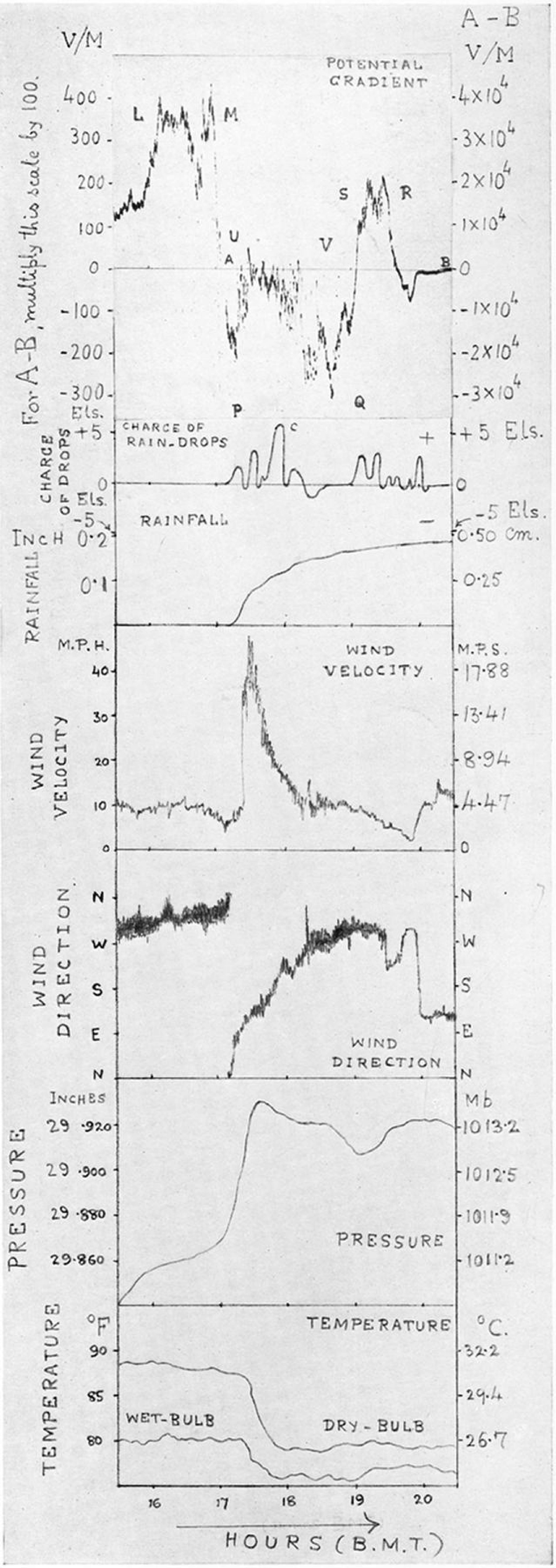


FIG. 5.—Heat thunderstorm of October 11, 1930. (Unitary type.)

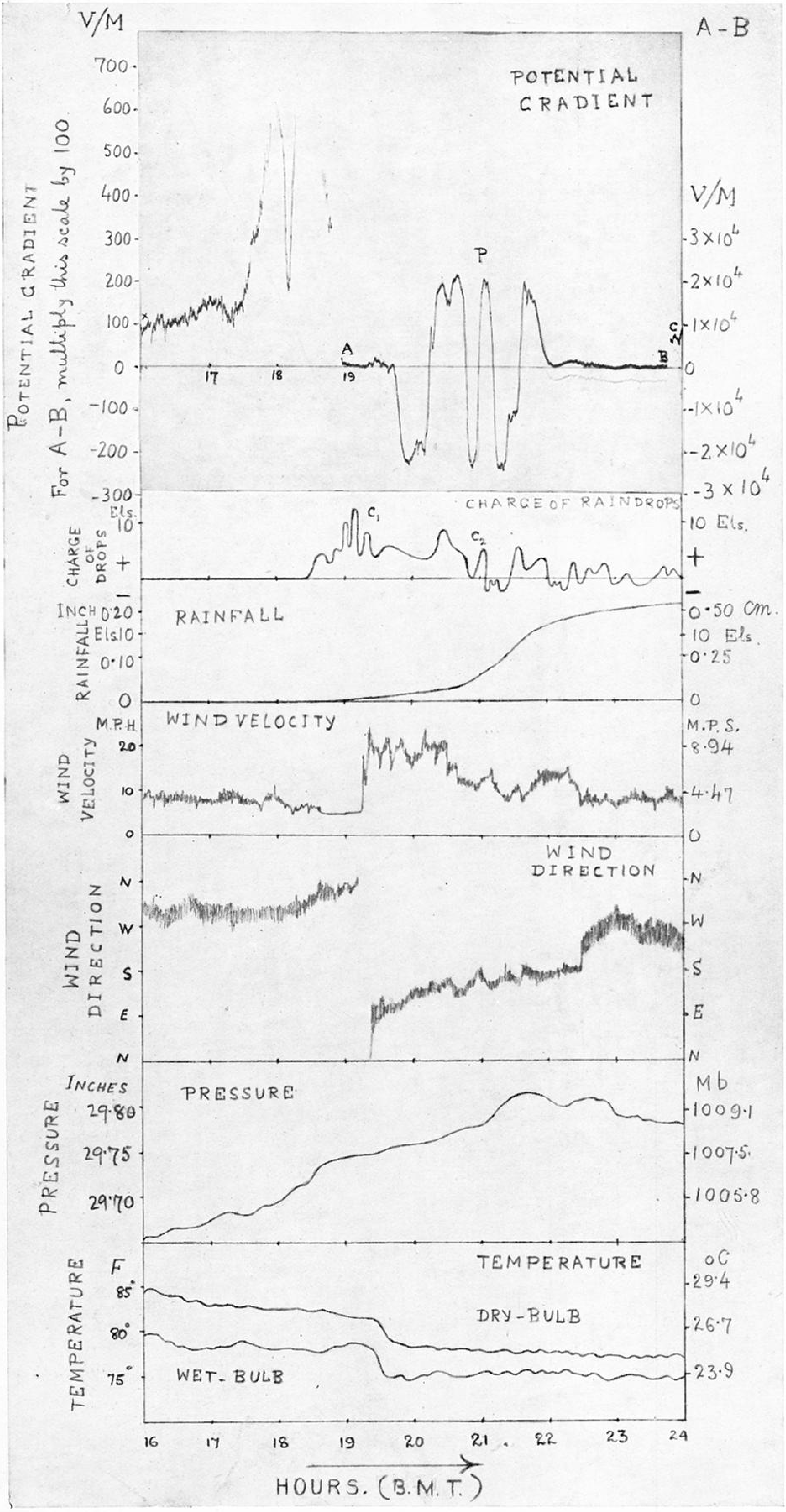


Fig. 3.—Heat thunderstorm of September 7, 1930. (Unitary type.)

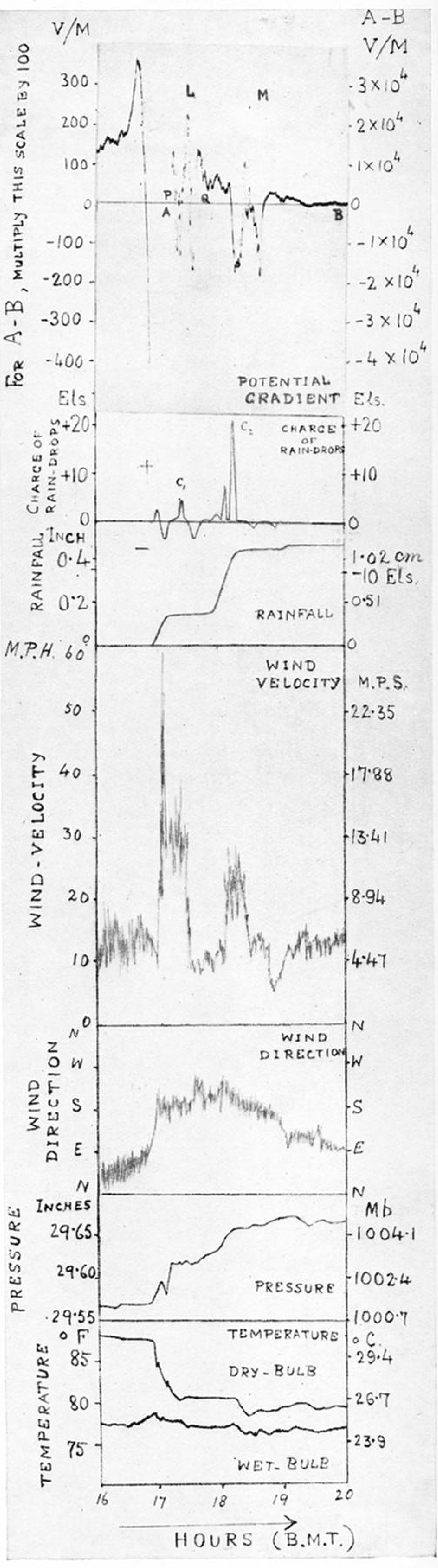


FIG. 7.—Heat thunderstorm of October 28, 1930. (Double type.)

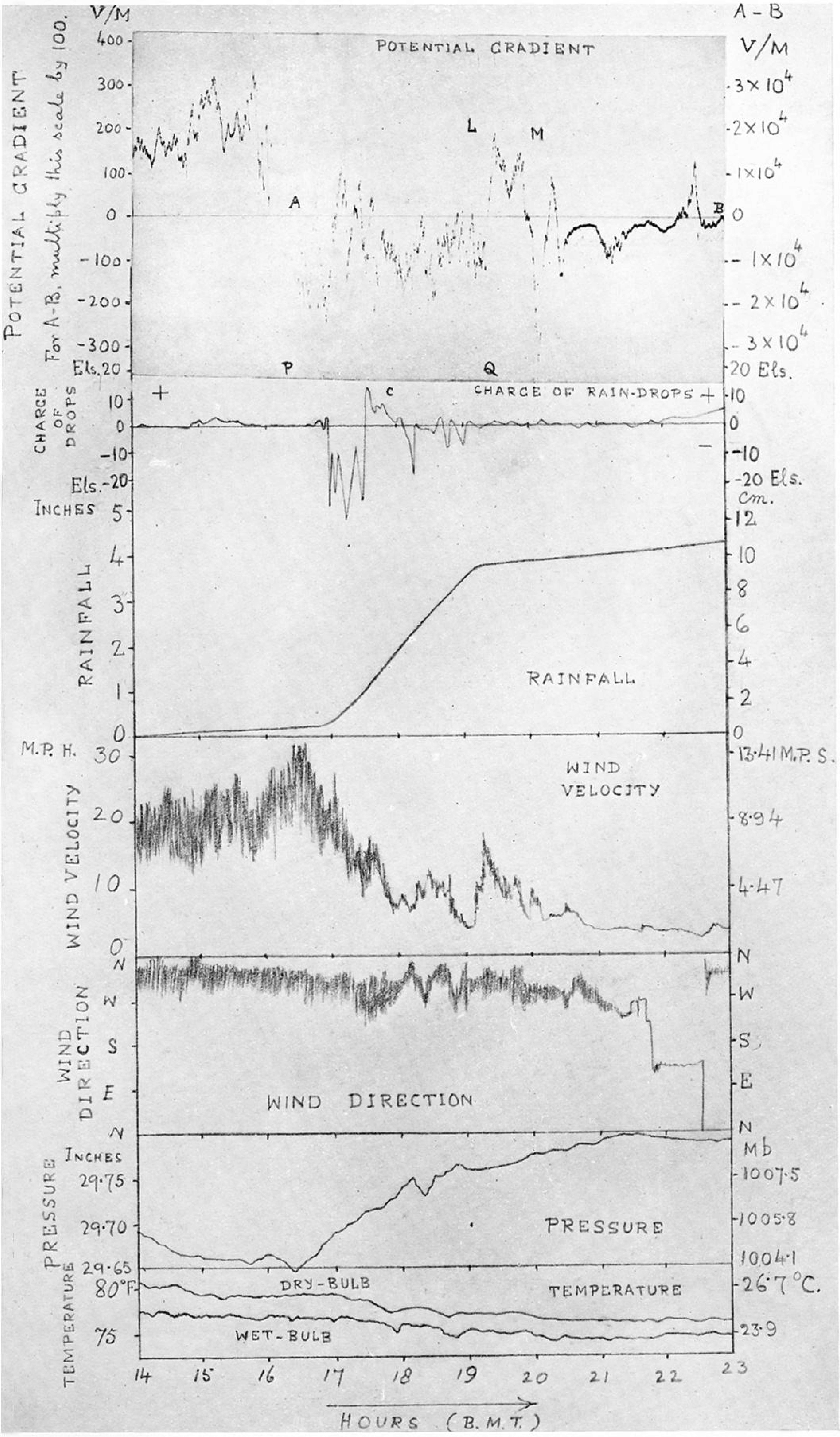
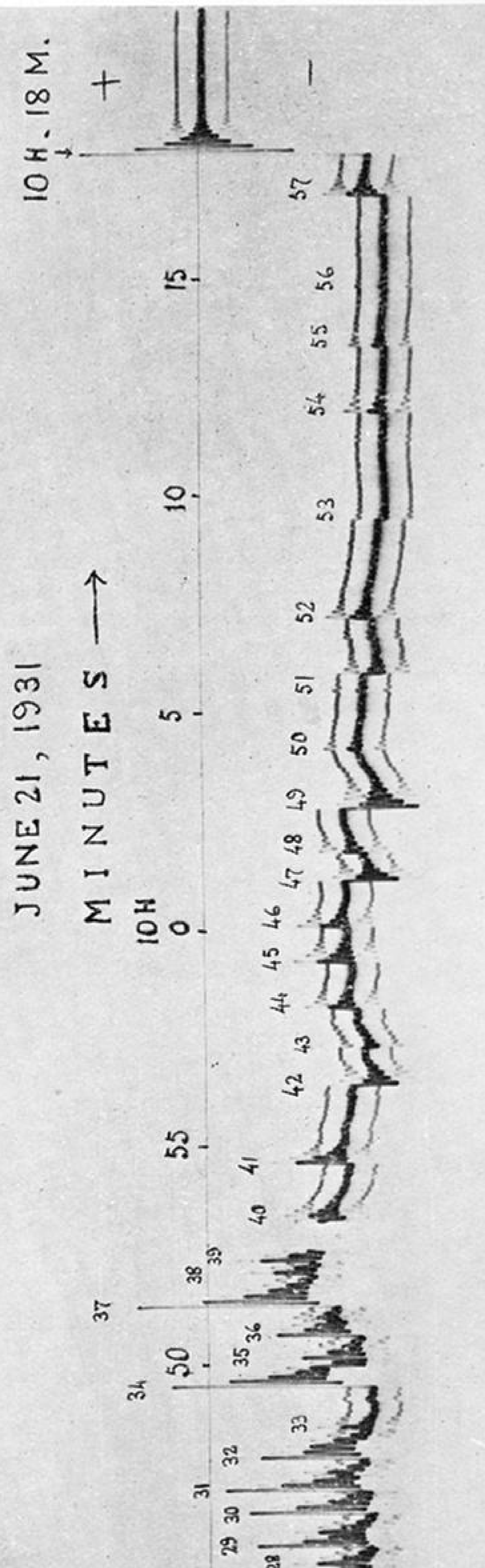


FIG. 4.—Heat thunderstorm of September 6, 1930. (Unitary type.)



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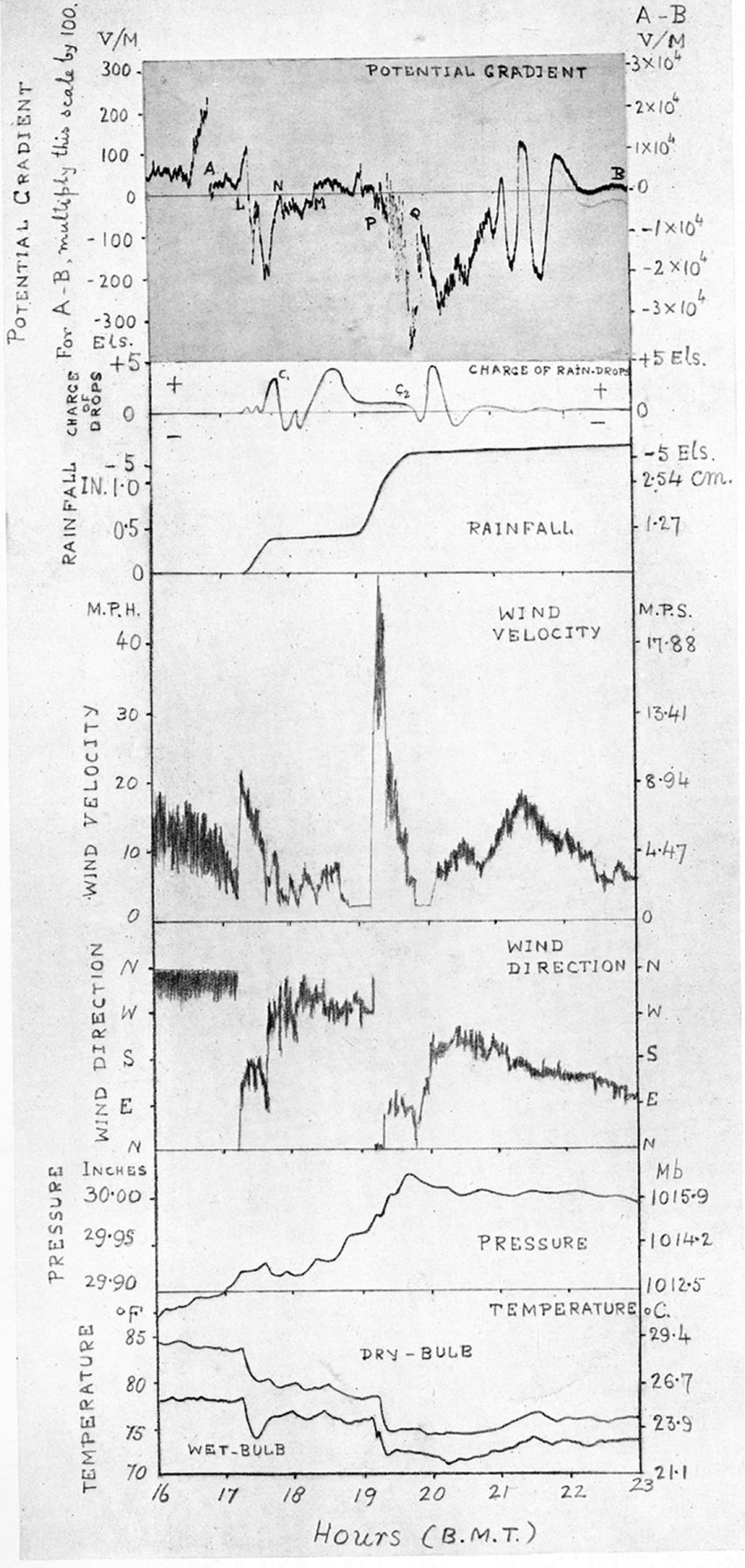


FIG. 6.—Heat thunderstorm of October 6, 1930. (Double type.)

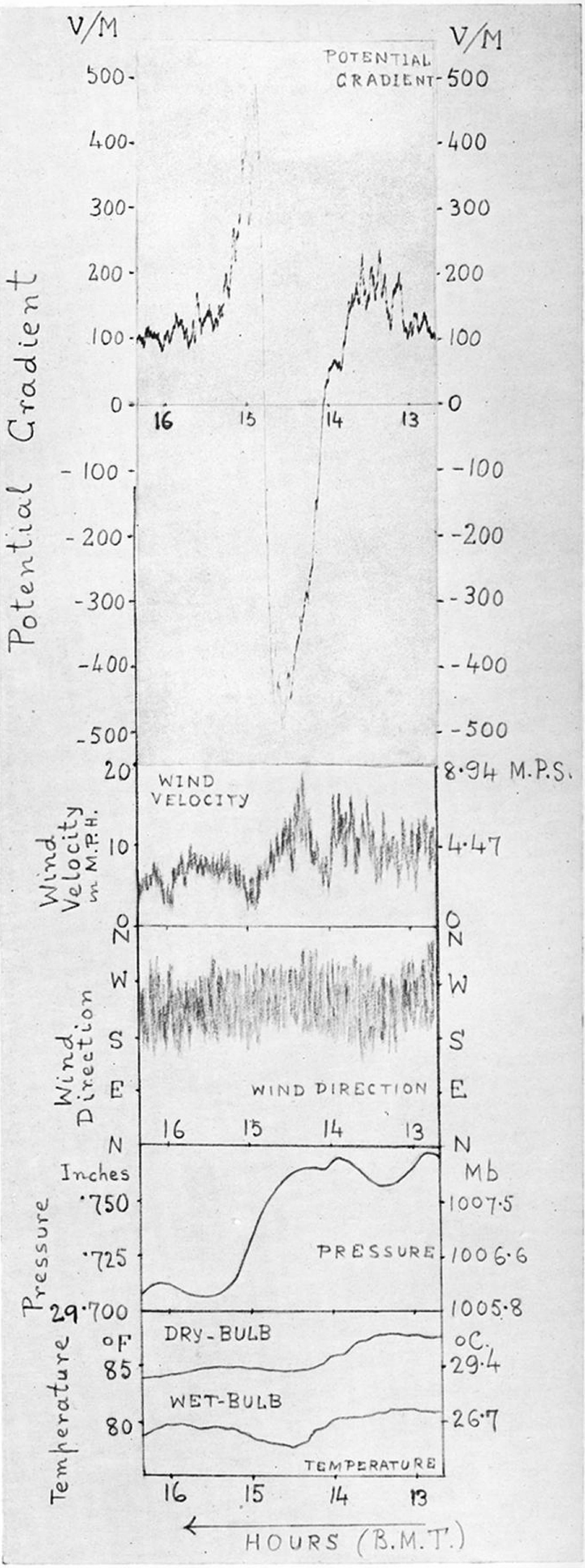


FIG. 8.—Thunderstorm of June 13, 1930. (Line-squall.) Northern fringe passed over station. (No rainfall at station.)

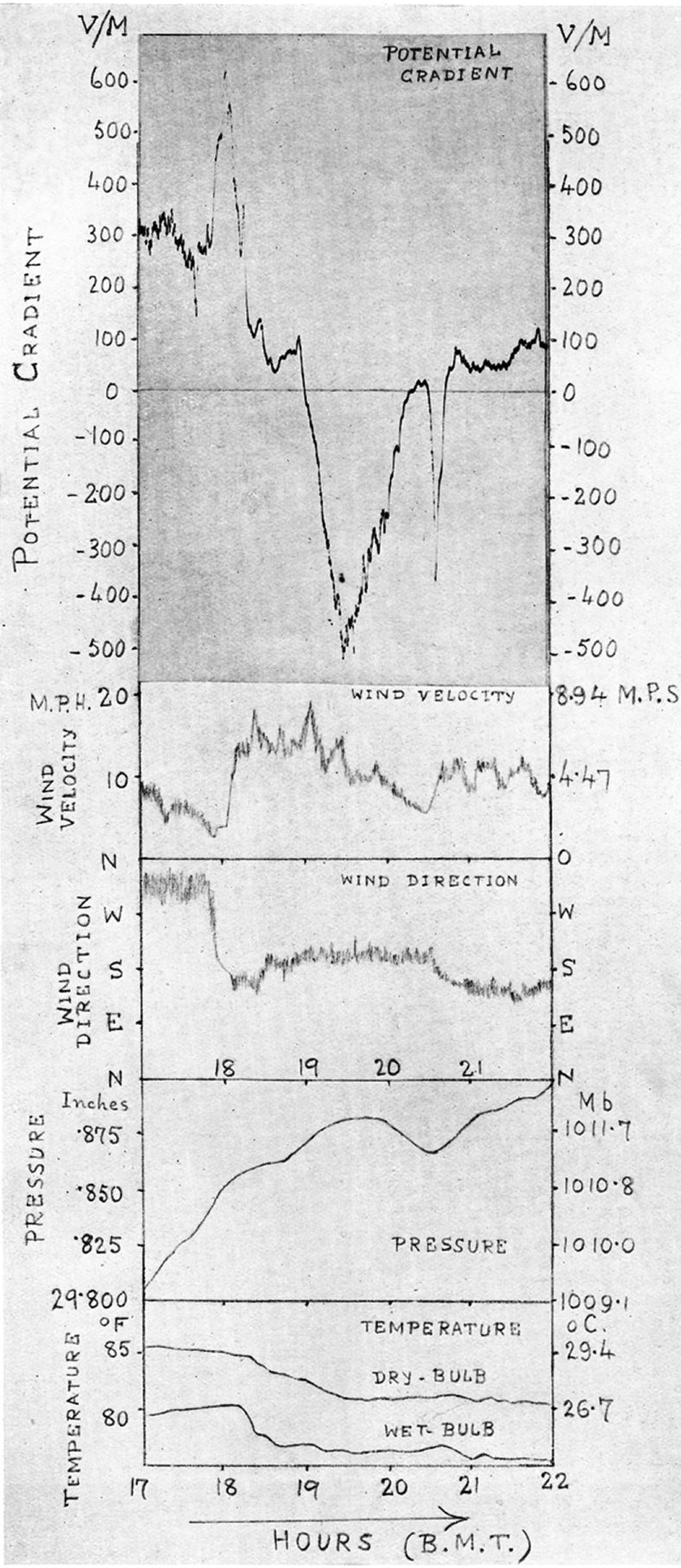
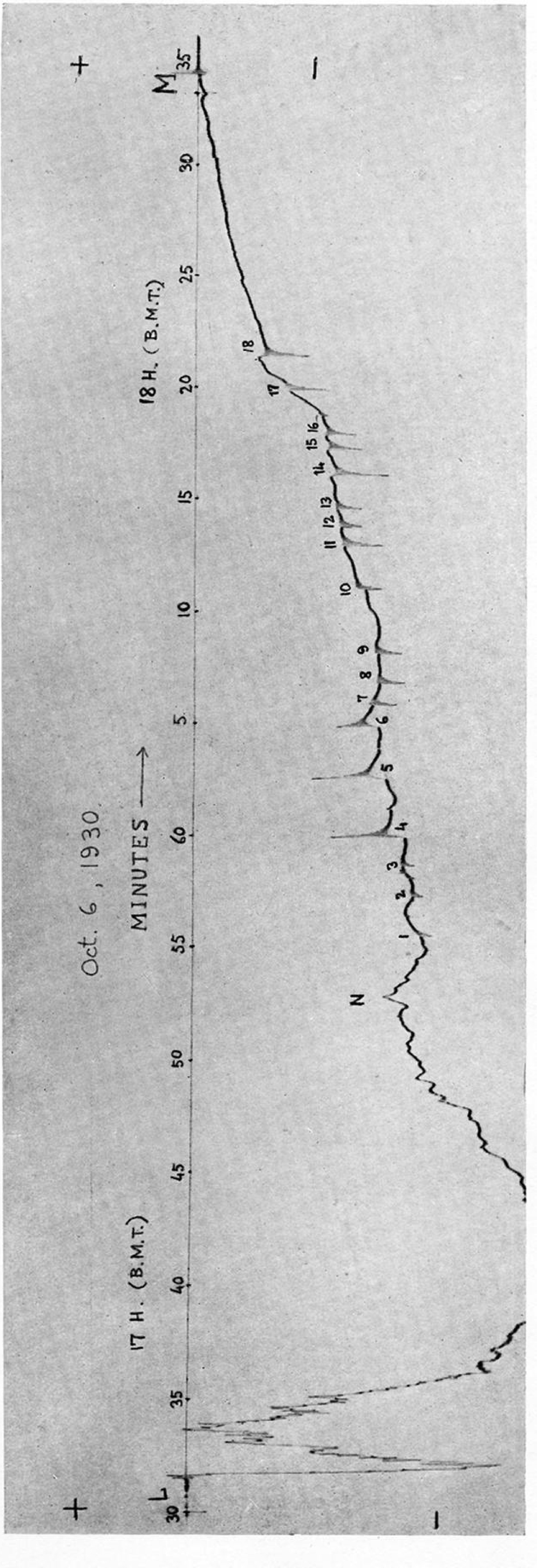


Fig. 9.—Heat thunderstorm of October 9, 1930. Southern fringe only passed over Bombay. (No rainfall at station.)



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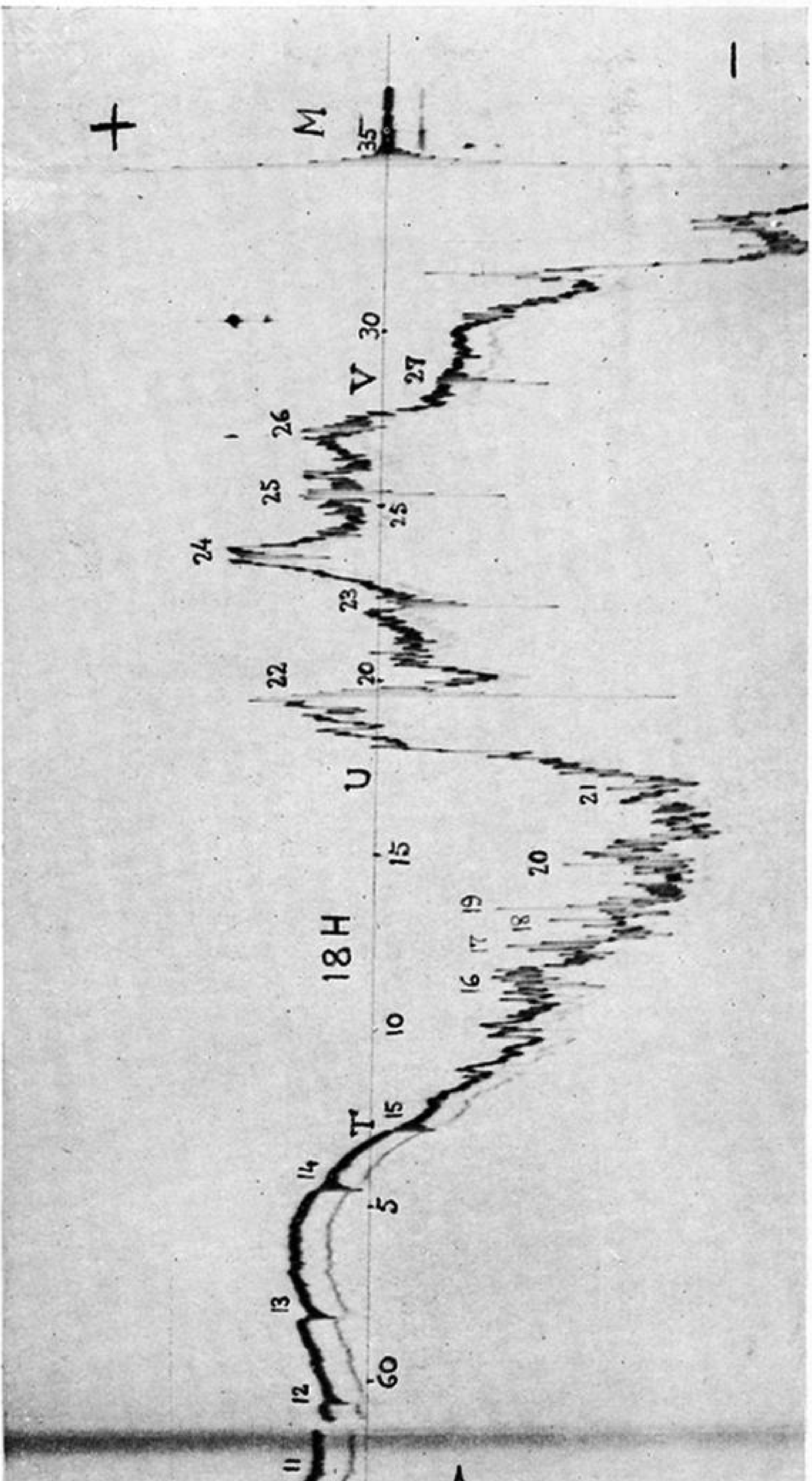

FIG. 13.—Electrogram showing the sudden changes in the electric field produced by lightning discharges on October 28, 1930. (Collecting sphere placed 94·5 cm. from wall, 138 cm. above ground, quadrant potentials + 2 and — 2 volts.)