SOUNDINGS OF TEMPERATURE AND HUMIDITY IN THE FIELD OF A TROPICAL CYCLONE AND A DISCUSSION OF ITS STRUCTURE.

BY

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Summary.—In connection with the Bay of Bengal storm which crossed the north Madras Coast on 17th November 1933, a series of 10 ascents of sounding balloons carrying meteorographs were made from Madras. The data of temperature and humidity obtained from the records are discussed in the first part of the paper. The storm was preceded by an increase in the thickness of the lower moist layer which is usually present in this season and also by the arrival of warm moist air in the upper atmosphere above 8 gkm. With the continued approach of the storm, the lower moist layer increased in thickness and the lower surface of the upper layer descended. Near the centre of the storm, the two moist columns presumably joined up.

The second part contains a discussion of certain aspects of a tropical cyclone, such as the height to which it extends, the origin of its energy and the probable causes of lowering of pressure near its centre.

Introduction.

In November 1933, a depression formed in the south-east of the Bay of Bengal on the 14th, and following the usual westerly to northwesterly course, developed into a storm on the 16th and crossed the north Madras Coast very near Nellore to its north on the evening of the 17th. It weakened rapidly after entering land and the rainfall area moved into the Deccan and the central parts of the country. The track of the disturbance is shown in *Fig. 1*. In connection with this disturbance a series of sounding

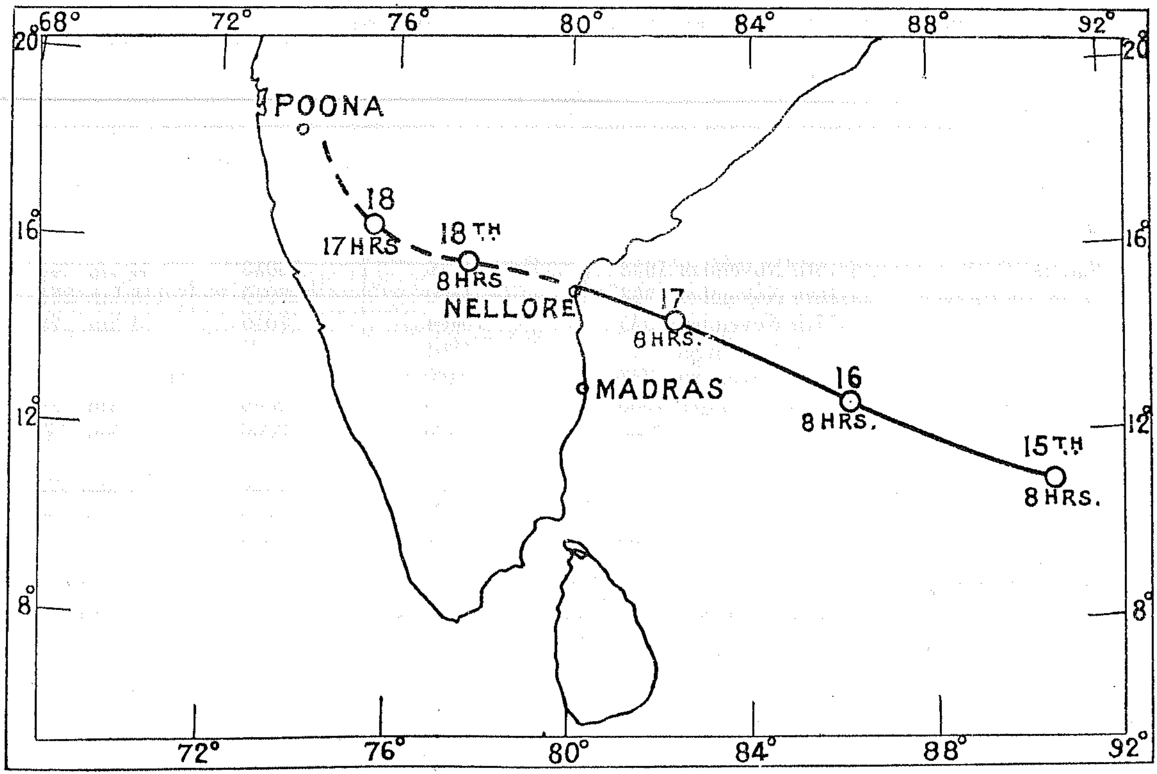

FIG. 1.—THE TRACK OF THE STORM-CENTRE.

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balloon ascents were made at Madras and at Poona during the period 15th to 20th November 1933. In the present paper the results obtained from these ascents are summarised and this is followed by a discussion of the structure of a tropical storm.

The dates and times of ascents of the sounding balloons, the maximum heights reached and the distance and direction of the places of fall from the places of release are given in *Table I*. The positions of the Soundings on the 15th, 16th, 17th and 18th relative to the storm-centre are indicated in *Fig. 2*. It is unfortunate that the instruments sent up from Madras on the evening of the 17th and on the morning of the 18th—the two that were nearest the centre of the storm—were not recovered.

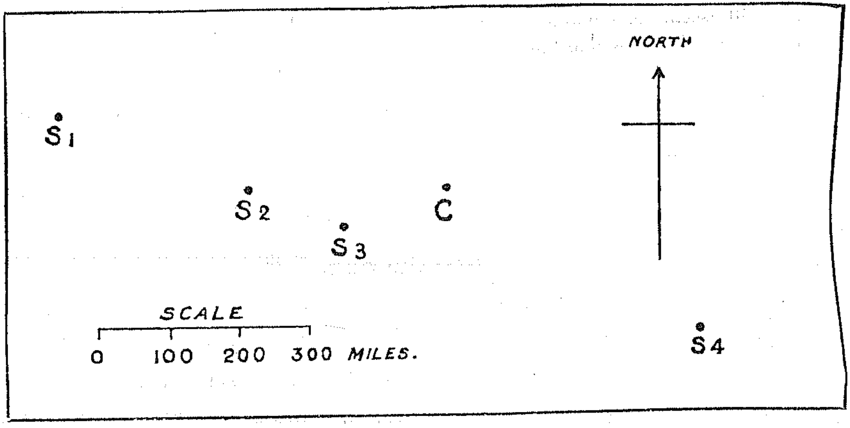

FIG. 2.—POSITIONS OF THE SOUNDINGS (S) ON THE 15TH, 16TH, 17TH AND 18TH RELATIVE TO THE STORM-CENTRE (C).

TABLE 1.

Place.	Date.	Time hrs. I. S. T.	Maximum height (dynamic metres.)	Distance and direction of place of fall.
Madras	15th November 1933	1716	18040	64 km. 246°
	16th November 1933	1800	17040	118 km. 251°
	17th November 1933	0404	17010	94 km. 228°
	17th November 1933	1801	Not recovered.	
	18th November 1933	0400	Do.	
	18th November 1933	1755	18340	115 km. 299°
	19th November 1933	0400	18800	115 km. 299°
Poona	17th November 1933	1727	18440	92 km. 328°
	19th November 1933	0407	18040	43 km. 355°
	20th November 1933	1730	17070	80 km. 49°

The pressures, temperatures, and humidities at various levels obtained from the different ascents are given in the Appendix.

PART I.

Brief description of weather conditions associated with the storm.

Fig. 3 shows the curves of variation of surface pressure, temperature, humidity and vapour pressure at Madras on the 17th and 18th. In the same figure is also shown the rainfall at Madras and the curves of pressure at Nellore. This last curve and the sequence of weather at Nellore make it clear that we are dealing with a fully developed tropical cyclone. Some weather remarks recorded by the Nellore Observer on the 17th are extracted below :—

" From 1430 hrs. very strong squally wind from the north-west of force about 7 commenced, accompanied by rain. At 16 hrs. the wind attained a force of 10, many trees fell down and the rain was heavier. This continued till 1745 hrs. after which there was complete lull. The rain as well as wind stopped and the pressure began to show signs of rising. At 1800 hrs. the wind commenced again, blowing with force of 8—9, from the south in the beginning and from the southeast after half an hour, accompanied by rain. This continued till 0130 hrs. on the 18th."

It is interesting to note that there was considerable dissymmetry in the distribution of rainfall before and after the passage of the storm centre, the amount of rainfall registered at Nellore between 8 hrs. and 17 hrs. on the 17th being 3·17″ while that between 17 hrs. on that day and 3 hrs. on the 18th being only 0·50″. As is evident from *Fig. 2*, there is a corresponding dissymmetry in the Madras rainfall also.*

Upper air conditions over Madras during 15th to 19th.

The height-temperature and height-humidity diagrams of the ascents are given in *Figs. 4 and 5*.

The sounding balloon ascent at Madras on the 15th was made at 1716 hrs. ; at the time of the ascent, the sky was lightly clouded with Cu and Cist. The record shows a large lapse-rate of 9°C/gkm. in the first 1·45 gkm. followed by an isothermal layer with a thickness of about 0·5 gkm. The air had increasing humidity with height in the first 1·4 gkm. and was nearly saturated at the top as shown by one of the curves. The beginning of the inversion marked the boundary between the lower turbulent moistened air and the upper subsiding dry air. Above the inversion, the humidity was 15 to 30 per cent. with indications of a feeble maximum near 4 gkm. The limit of the troposphere was marked by an isothermal layer beginning at 15280 gdm ; the inversion began at 16700 gdm.

On the 16th also, the ascent was made in the evening at 1800 hrs. The cloud at the time of the ascent was Ast 6 and Stcu 4 (mammato-form). Earlier in the day, Cu and Ci were present. The humidity was nearly steady at about 60 per cent. till 1·2 gkm. and thereafter increased rapidly to saturation. The lapse-rate showed a marked decrease at 1·4 gkm. The top of the moist layer was at 2·6 gkm. in one curve and at 2·9 gkm. in the other. A pilot balloon sent up at 1600 hrs. showed a NNWly. to Nly. wind up to 1·2 km. and a NEly. wind at 1·5 and 2 km. The trajectories of air movement show that

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* *See* B. N. Desai and S. Basu, ' Evidence in favour of non-symmetrical structure — Cyclones in Indian Seas ', Gerl. Beitr. Z. Geoph. 1933, 40, 1—10.

the northerly wind was coming direct from North India while the northeasterly above was coming across the Bay. Higher up, there were three significant increases of temperature, one beginning at 4·0 gkm. a second at 8·1 gkm. and a third at 14·0 gkm. The increase of temperature above 8·1 gkm. was accompanied by high humidity. Between the top of the lower moist layer near 2·7 gkm. and the bottom of the upper moist layer beginning at 8·1 gkm. there was thus comparatively smaller humidity. With the increase of temperature and moisture above 8·1 gkm. there was also an increase of lapse-rate between 10 and 13 gkm.

Of the two instruments that were sent up on the 17th, only the one released at 0404 hrs. in the morning was recovered. At the time of the ascent, the sky was overcast with Ast and Stcu and light intermittent drizzle had begun at 0230 hrs.* The important changes noticeable in the upper air conditions since the evening of the 16th are—

(1) The rise of the top of the lower moist layer to 3·7 gkm.

(2) An *increase* of temperature between 1·5 and 2·7 gkm. and a *decrease* between 2·7 and 6·2 gkm.

(3) The lowering of the upper moist layer to 7·0 gkm. and

(4) A large difference in humidity between the ascending and descending curves in the region 5-7 gkm. (It may be remembered that the place of fall of the instrument was 94 km. to the south-west of Madras.)

It will be seen from *Fig. 4* that the increase of thickness of the lower moist layer has broken down the inversion at its top. The decreased temperature between 2·7 and 6·2 gkm. would give rise to instability and seems to be of significance in the mechanism of the cyclone. The low temperature in this region may be due to (1) the cooling of the originally dry air by evaporation of direct precipitation or of particles of moisture brought into it from the region of rainfall by the process of mixing or (2) an *en masse* raising of dry stable air by on-coming monsoon air underneath. Both these processes were probably operative in the present instance ; both would cause an increase of relative humidity, but the former would raise the specific humidity also.

The first registration of upper air conditions after the passage of the depression inland was from a meteorograph sent up at 1755 hrs. on the 18th (*Fig. 5*). There was intermittent rain during the earlier half of the day, but the last spell terminated at 1230 hrs. and there was only some cirrus haze and a few pieces of cumulus at the time of the ascent. A pilot balloon which was sent up at 15 hrs. and reached a height of 1·7 km. showed south-easterly winds. The meteorograph record showed that—

(1) There was a region of small lapse-rate between 1·8 and 3·0 gkm. and an inversion at 3·4 gkm.

(2) High humidity was confined to below 2·2 gkm. and

(3) compared to conditions on the morning of the 17th, the temperatures on this day were lower from 1·5 to 2·6 gkm., higher from 2·7 to 5·2 gkm., and again

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* One feature of the ascent on 17th November 1933 may receive comment here. Appreciable quantities of rain began to fall at Madras only after 7 hrs. on the 17th. The question of what causes the growth of cloud particles into the big drops which constitute rain has been considered by T. Bergeron and he has suggested that the process of aggregation takes place mainly at temperatures below the freezing point. The splitting of drops by air currents will be smaller in the case of solid particles and the decreased vapour pressure over ice as compared to that over water will make the ice particles grow at the expense of the particles of water. It is of interest to note that on the morning of the 17th the top of the lower moist air column had gone up to 3·7 km. where the temperature was only 4°C above the freezing point.

lower above 7·5 gkm. The stratosphere began with an inversion at 16300 dynamic metres.

Isopleths of temperature, potential temperature and equivalent potential temperature obtained from these ascents are drawn in *Figs. 6 (a), (b) and (c).* Regions where the relative humidity was over 80 per cent. are indicated by shading in *Fig. 6 (a).* In these regions, it may be expected that a small ascent would cause the air to follow a saturation adiabat. In the absence of heat exchanges by radiation or by mixing, a mass of air would keep its potential temperature constant so long as it remains unsaturated. The rise of temperature and of potential temperature between 4 and 7 gkm. on the 16th afternoon are to be explained as being due to adiabatic descent of dry continental air. Temperatures and humidities at the high level stations Coonoor and Kodaikanal show that at Coonoor on the mornings of the 16th and 17th and at Kodaikanal on the afternoon of the 16th and on the morning of the 17th the air was exceptionally dry.

Station.	Date.	Time.	D. B.	W. B.	R. H.
					Per cent.
Coonoor (5730 ft.) . . .	15	8 hrs.	62·0	58·8	84
	16	8 hrs.	61·7	50·0	44
	17	8 hrs.	63·0	51·0	43
Kodaikanal (7688 ft.) . .	15	8 hrs.	51·4	51·4	100
	16	8 hrs.	48·9	45·3	77
	16	17 hrs.	52·0	43·0	47
	17	8 hrs.	53·0	42·7	41
	17	17 hrs.	55·3	52·0	80

The rise of potential temperature above 8 gkm. with its attendant rise of humidity requires a different explanation ; the air at these levels is probably the air rising above the heavy rainfall area associated with the storm and carried by the easterly winds prevailing at these levels.

The changes of temperature observed on the 17th morning receive an explanation when we examine the diagram of equivalent potential temperature. Ordinarily in the tropics, owing to the decrease of vapour-pressure with height, the equivalent potential temperature decreases rapidly with elevation. This is especially marked above a " dry " inversion. After reaching a minimum, the E. P. T. again increases, owing mainly to the normal stable stratification of the atmosphere. Air of high E. P. T. near the ground is not generally capable of rising to the region of the same E. P. T. in the higher levels for two reasons : (1) so long as the ascending air is unsaturated, the movement of air is determined not by changes of equivalent potential temperature but by those of potential temperature and (2) when saturated air of limited volume ascends through an environment of dry air, it rapidly becomes unsaturated by the effect of mixing. But when the height of the lower moist layer increases, there comes a stage when the ascent from the lower to the upper level becomes easy. For example, on the 15th evening, the E. P. T. line 340°A was met with at 0·7 gkm. and again at 9·7 gkm. With the approach of the storm, the lower of these two levels went up and the upper one descended. On the

17th morning, the 340° line was found at 3·3 gkm. and again at 7·0 gkm. Moreover the relative humidity in the intervening layer had also increased. The course of changes suggests that later in the day, the equivalent potential temperature in the whole region between 3 to 6 km. was in the neighbourhood of 335°A. The probable trend of lines of flow are indicated by arrows. On the 18th afternoon, conditions somewhat similar to those on the 16th had again established themselves with dry air as low as 2·5 gkm. As the storm passed well to the north of Madras, the real warm sector air is partially missed by confining our attention to Madras upper air data. The defect can to a limited extent be remedied by calling in the aid of observations taken at Poona. The data of the ascents at Poona on the 17th, 19th and 20th show that on the 19th evening, the air of the warm sector had come over the place in the first 5 gkm. (vide *Fig. 9*). By replacing in *Fig. 6* (*c*), the Madras data of the 18th by the Poona data of the 19th, we can obtain a rough east to west section of the storm field along the latitude of Madras as it stood on the 16th afternoon. Such a modified diagram is shown in *Fig. 6* (*d*). Owing to mixing with the previously existing land air near the ground, the Poona data would give too low values of equivalent potential temperature in the first two gkm.

The most important features shown by the diagrams can be summarised as below :—

(1) There is a strong concentration of upward vertical movement in the neighbourhood of the centre of low pressure—the upward movement being predominantly in advance of the storm centre. As has been already mentioned, the rainfall associated with the cyclone was much greater in quantity before the passage of the low-pressure centre than after it.

(2) The warm air rising above the rainfall area and moving with the upper winds acts as a "leader" of the storm. This is shown by the rise of temperature and humidity above 8 gkm. even on the 16th.

(3) There is similarity in vertical structure between the tropical storm and the "occluded" cyclone of temperate latitudes, the dry air taking the place of cold air in the latter.

Two charts showing the detailed distribution of rainfall as recorded on the mornings of the 18th and 19th are given in *Figs. 7* (*a*) *and* (*b*). Upper wind charts and trajectories on the 17th, 18th and 19th are given in *Fig. 8*. The rainfall distributions on the 18th and 19th and the upper wind trajectories show that the dissipation of the storm on entering land was partly if not mainly due to dry land air coming from the south and destroying the humid-labile condition of the feeder-current.

Upper air conditions over Poona on 17th, 19th and 20th.

The cyclone entered land on the evening of the 17th, and on the 19th morning the residual low pressure wave was passing northwards over Poona.

On the 17th, the skies over Poona were clouded with Cist. The sounding balloon ascent on the evening of that day (*Fig. 9*) shows that temperatures were abnormally low from 5 to 15 gkm. The winds were weak northeasterly to easterly and southeasterly up to 6 gkm. and west-south-westerly above. The easterly current was mainly anticyclonic dry air but the increase of humidity above 4 gkm. indicates that between 4 and 6 gkm., moist air was probably beginning to be drawn in. The weather was unsettled on the 18th and light intermittent drizzle occurred during the night and next morning, but there was no measureable rain by 8 hrs. on the 19th. Rain occurred in the afternoon intermittently from 1240 hrs. to 1930 hrs. The sounding balloon ascent on the morning of the 19th showed that since the 17th evening, temperatures had markedly decreased from the ground up to about 4 gkm. and the air was nearly saturated from the surface up to 5 gkm. (in one curve) and nearly dry above. There were inversions or sudden decreases of lapse-rate at 5·4, 7·7 and 12·1 gkm. This is similar to what occurred over Madras on the 16th, but there is no evidence of an upper layer of humidity. On the 20th evening, when the next ascent was made, practically all traces of the depression had disappeared except for some cumulus and moderately strong cumulonimbus. The temperatures at almost all levels were intermediate between those on the 19th and the 17th. There was high humidity from 1 to 3·2 gkm. above which it gradually decreased. The isopleths of temperature, potential temperature and equivalent potential temperature are drawn in *Figs. 10* (*a*), (*b*) *and* (*c*). The comparison of the tephigrams of the ascents at Madras on the morning of the 17th [*Fig. 11* (*a*)] and at Poona on the morning of the 19th [*Fig. 11* (*b*)] is interesting as showing the unstable conditions which prevailed over Madras and the stable conditions over Poona.

Changes of temperature near the tropopause.

At the time of falling pressure, both in the Madras and Poona ascents, there were marked increases of temperature for 2 to 3 gkm. below the original level of the tropopause. At neither place can it be said that there was a lowering of the tropopause although it is possible to interpret the inversion over Madras on the 16th and 17th near 14 gkm. as an incipient conversion of a normal tropopause of tropical latitudes into one of composite type (Type IV).*

PART II.

Some general considerations regarding tropical cyclones.

The characteristics of a tropical cyclone are a region of very strong winds (force about 10 in Beaufort Scale) and rapidly falling barometer round a small area of very weak winds near the centre of lowest pressure. Torrential rainfall is always associated with it, generally on one side of the storm centre. The central area of weak winds has comparatively fine weather and is 10-30 km. in diameter. Many investigators believe that the hurricane winds blow approximately in circles round the central calm region, but all do not share this view.† Recent investigations in India have shown that all tropical cyclones have associated with them an upglide front at which moist air ascends. The front may reach the ground or may be occluded, but the course of weather phenomena leaves little doubt that it exists. Fronts of the same character are found to occur associated with depressions which never develop into full-fledged tropical storms. We have therefore to consider that the storm stage is an incident in the development of a tropical depression which may or may not occur. *Fig. 6* (*c*) shows that in the inner region of a tropical cyclone, there is strong ascent of a well-fed lower moist air stream through

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* Mem. Ind. Met. Dept., Vol. XXVI, part IV, p. 58.

† B. N. Desai and S. Basu, *loc. cit.*

a region unstable for ascending saturated air presumably into an upper current which rapidly carries away the air which feeds into it from below.

We shall now consider two important questions regarding a tropical storm :—

(*a*) How high does it extend and at what level is it deepest ?

(*b*) What is the source of energy of the storm ?

As regards (*a*), we should naturally expect a certain amount of variation from one storm to another. Pilot balloon observations in the vicinity of a storm are naturally scanty, but there is enough material available to show that strong cyclonic circulation exists to a height of more than 4 km. There are a few instances where 6 km. winds are also available (generally only on one side of the storm centre) which show cyclonic circulations. In this particular storm, there was a significant fall of pressure up to 7 gkm. even at a distance of about 100 km. from the storm centre ; the absolute values of pressure-fall were practically the same from the surface up to 4 gkm., but the ratio of the fall of pressure to the mean pressure at the level was greatest at 3 and 4 gkm. Although this gives a general idea of the conditions above a storm, we have to remember that our estimates are subject to certain limitations some of which are practically impossible to overcome. The nearest distance from the centre of the storm at which a balloon was released was 250 km. Owing to the movement of the balloon with the upper winds, the pressures and temperatures do not refer to points on the same vertical nor to the same instant of time. From general considerations, we should expect the tropical storm to have its origin and maximum intensity at the levels of maximum vertical convection. Naturally, this would not be at the ground where both ground friction and the solidity of the earth would prevent the maximum vertical movements being developed. In laboratory examples of tornadoes and in natural small scale cyclones such as dust-devils, an essential condition for formation is super-adiabatic lapse-rate. In the free atmosphere, super-adiabatic lapse-rates for dry air are practically unknown ; but lapse-rates lying between dry adiabatic and saturation adiabatic and with a sufficient supply of moist air underneath are common and can develop to explosion-point.

(*b*) The question of the energy of cyclones has attracted much attention particularly from the point of view of the cyclones of temperate latitudes. Margules investigated the development of kinetic energy in two simple cases, one in which two equal air masses with differing potential temperatures were initially lying side by side, and the other in which one air mass of lower potential temperature was superposed on another of higher potential temperature. He showed that with the temperature contrasts which are usually observable in the atmosphere, the first is much more likely to be the main source of the energy of storms of temperate latitudes. As a variant of the case (2), W. Littwin* investigated the kinetic energy that can be developed by the overturning of an air mass with super-adiabatic lapse-rate of temperature. He showed that if initially a column of air of height 3 km. has a lapse-rate of 12°C/km. then the re-distribution of mass which will be associated with the attainment of equilibrium will be attended with an increase of kinetic energy equivalent to a velocity of 15 m/s. Although instability for vertical movement of *dry* air occurs in the atmosphere only in the neighbourhood of insolated ground, instability for vertical movement of saturated air is fairly common especially under tropical conditions.

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* W. Littwin : quoted in Koschmeider's Dynamische Meteorologie (1933), p. 336.

V. Bjerknes and others* consider that there are two possible ways in which the kinetic energy of cyclones can be generated. One is by the local concentration through wave-motion of pre-existing air-movement. This, although of significance for increasing the kinetic energy, is yet insufficient by itself to account for such large velocities as are observed. The second is by the conversion of the potential energy of the solenoidal field of pressure and density when the pressure is not a function of density alone. They conclude that " the attainment of large velocities in storms depends on the fact that a fast moving air mass can take part in work-generating circulation in a strong solenoidal field ".

D. Brunt† expresses his disagreement with the above view and considers that the term $-2\omega\frac{dF}{dt}$ in the expression for the rate of increase of circulation is the most important one for the growth of large-scale circulations in the atmosphere. ω is the angular velocity of the earth and F is the projection of the area enclosed by a material curve on the equatorial plane of the earth. If an area F′ lies on the horizontal plane at latitude ϕ, $F = F' \sin\phi$. Contraction of a horizontal material curve increases cyclonic circulation while its expansion increases anti-cyclonic circulation. From expressions that have been developed by Lord Rayleigh and D. Brunt, it is easy to calculate the order of velocities which may be expected from the operation of this cause.

If matter be removed from the centre of a circular disc of radius R_0 initially at rest with respect to the earth, and if, after a time, its radius has contracted to R, there would have been generated in the inflowing fluid, a cyclonic velocity whose magnitude at distance r from the centre of the disc is given by

$$v = \frac{R^2{}_0 - R^2}{r}\,\omega \sin\phi$$

$$= \frac{\omega \sin\phi}{r} \times \frac{\text{Quantity of matter removed expressed as area}}{\pi}.$$

Let us suppose that air equivalent to a fall of pressure of 10 mb. or 0·3″ over a circular area of diameter 400 km. is removed from its centre and let this removal take place from a thickness of the atmosphere equivalent to a fall of pressure of 200 mb. The contraction in area will be nearly

$$\pi \times 200^2 \times \frac{10}{200} \text{ sq. km.}$$

and the resulting tangential velocity at a distance of say, 100 km. from the centre will be

$$v = 200^2 \times 10^{10} \times \frac{10}{200} \times \frac{7{\cdot}3 \times 10^{-5}}{100 \times 10^5} \times 1/4 \text{ cm./sec.} = 36 \text{ cm./sec.},$$

where $\sin\phi$ is taken to have a value 1/4.

This mechanism, although of importance in initiating the cyclonic movement, is not apparently directly responsible for the growth of large velocities.

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* V. Bjerknes, J. Bjerknes, H. Solberg and T. Bergeron,: Physikalische Hydrodynamik, 1933, Ch. IV.

† D. Brunt, Physical and Dynamical Meteorology, 1934, p. 177. " It is thus not possible to explain the growth of large-scale horizontal circulations in the atmosphere by the reactions due to the gradients of pressure and density not being parallel to each other."

In tropical cyclones, we have to distinguish between the intense circular vortex of comparatively small diameter and the extensive disturbed field surrounding it. The kinetic energy of the latter probably arises from the annihilation of isobaric-isosteric solenoids which are mainly created by the unstable superposition of unsaturated air over a layer of saturated air. The observed kinetic energy in the inner core can at least qualitatively be accounted for by the pressure field. A velocity of 40 m./s. at a distance of 100 km. from the cyclonic centre would be in equilibrium with a pressure gradient of 21 mb./degree assuming that in a tropical cyclone at such a distance from the centre, the geostrophic component of the wind can be neglected. The main problem is, how is the pressure field produced and maintained ?

A study of the weather charts shows that when a thick moist column of air advances towards higher latitudes in the northern hemisphere the low pressure area is formed in the left hand corner of the advancing moist column. Near the tropical " warm " front, there is a region of very heavy rainfall. Above this area of rainfall, there should be a large and rapid increase of temperature. Calculation shows that one inch of rainfall will liberate a quantity of heat which would be sufficient to raise the temperature of the whole thickness of the atmosphere above a place at sea-level 6°C. The expansion of the air above the region of rainfall will make the air-movement in the upper layers (*Fig. 12*) divergent. We know from the dynamics of a warm front that the cold air in advance of the front will be accelerated towards the left. At the left hand corner of

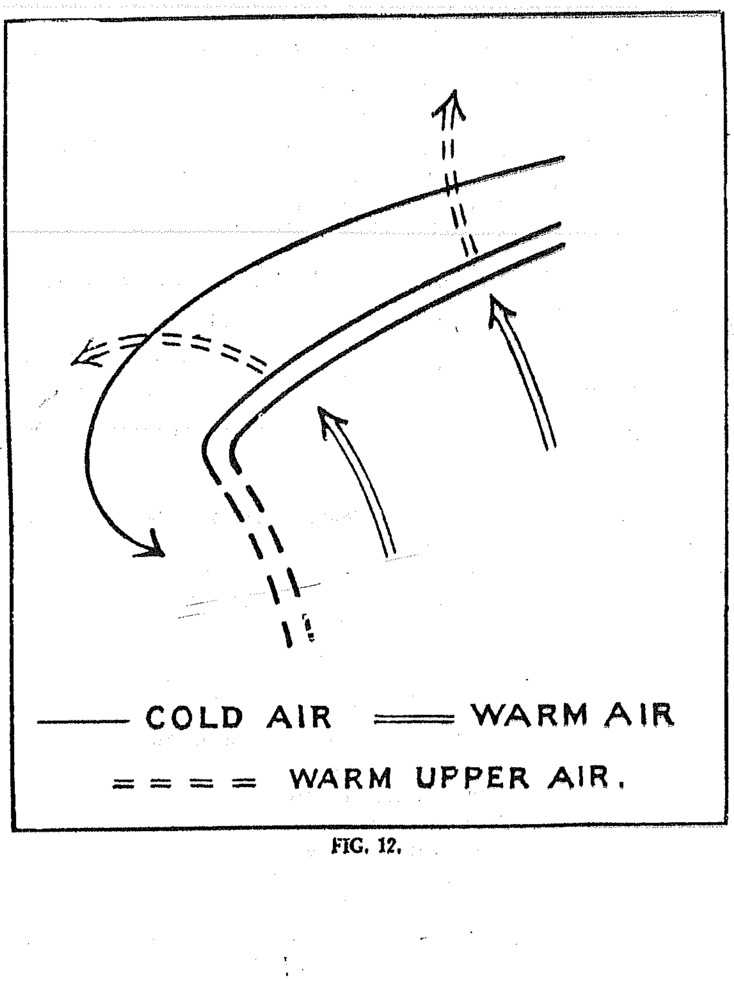

FIG. 12.

the front, there will therefore be formed both in the lower cold air and in the upper warm air a cyclonic whirl. The centrifugal action of the winds will tend to keep the denser air in the upper layers away from the axis and accumulate the warmer air in the central regions of the whirl*. Thus the pressure gradient round the centre will grow. The ultimate lowering of pressure will depend on the excess of temperature inside. In order to produce a lowering of pressure of 2 cm. of mercury in the interior of a depression the mean temperature of the whole atmosphere should rise by about 7°C. If only half the thickness of the atmosphere is involved, the excess of temperature will be 14°C. Most of this rise of temperature will be caused by the latent heat released by rainfall but part may be due to adiabatic descent in the centre of the low. It may be remembered that there is no agency known to us as effective as rainfall for rapidly increasing the temperature of large masses of air.

A lowering of pressure can also be caused by a west to east velocity over the rotating earth or a downward acceleration of the air. The equation governing the pressure lapse in a vertical direction† is given by

$$\frac{dw}{dt} - 2\,\omega\, u \cos\phi = -\frac{1}{\rho}\frac{\delta p}{\delta z} - g, \text{ or}$$

$$-\frac{1}{\rho}\frac{\delta p}{\delta z} = g + \frac{dw}{dt} - 2\,\omega\, u \cos\phi$$

where the positive direction of x is towards the east and that of z vertically upwards. In the static atmosphere, the second and third terms on the right-hand side of the second equation vanish. Let us now consider the relative magnitudes of all the terms in the neighbourhood of a tropical cyclone. As pointed out by Brunt, the effect of the term involving earth's rotation is negligible even when the zonal wind is as much as 100 m/sec., being then only $1{\cdot}4 \cos\phi$ cm/sec^2. If there should be a lowering of pressure due to vertical movement, the acceleration should be downward. It is known that the central region of a tropical storm is often marked by absence of rain and comparatively less cloudy skies. Abnormal dryness is also sometimes experienced in such regions. All these indicate a descending movement of air. We have however no reliable estimate of the magnitude of the downward accelerations. In stormy weather, it is known that sounding balloons with normal rates of ascent of about 5 meters per second are sometimes carried downwards for vertical distances of 5-6 km. If this downward velocity develops within a height of 3 km., the corresponding acceleration will be given by $w^2 = 2\,\frac{dw}{dt}\,h$ or $\frac{dw}{dt}$ will be about 0·4 cm/sec.^{2} An estimate of upward acceleration in hailstorms has been made by Brunt. He has shown that in order to raise a spherical hailstone of radius 3 cm. in an ascending current, a vertical upwards velocity exceeding 55 m/sec. would be required. If this velocity is developed within a distance of 3 km., the acceleration will be 50 cm/sec.^{2} This is by no means negligible compared with g (980 cm/sec.^{2}) and if it extends over a height of the atmosphere corresponding to 1/5 of its total mass, the change of pressure experienced at the earth's surface would be $1/5 \times 50/980 \times 76$ or about 0·8 cm. of mercury. Although sudden rises of pressure of 2 or 3 mm. of mercury are commonly

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* V. Bjerknes, On the Dynamics of the Circular Vortex, etc., Geof. Publ. II, No. 4, Kristiania 1921. p. 43.

† D. Brunt, Physical and Dynamical Meteorology, p. 268.

met with in connection with thunderstorms and hailstorms, and it is possible to explain them as being due to vertical acceleration of air, no exceptional sudden rises of pressure have been noted in the region of torrential rainfall of a tropical cyclone. It would therefore be unreasonable to explain the lowering of pressure in the central region of a tropical storm as being due to a corresponding downward acceleration of air.

The general conclusion of this discussion is that the central vortex of a tropical cyclone is caused by the concentration of warm air in the upper levels in a definite region connected with a tropical up-glide front, heavy rainfall being mainly responsible for the rapid increase of temperature over a limited region.

The storm winds round the cyclone will tend to keep the warm air inside protected against rapid dissipation. The conditions that will help to fill up the vortex are (1) a decrease in the supply of moist air at the front leading to a diminution of rainfall and hence of the supply of warm air in the upper air and (2) inflow of air into the low caused by ground-friction and consequent undergradient winds.

Conclusion.—Apart from theories, the prime necessity for a fuller understanding of tropical cyclones is the collection of more data of temperature, humidity and air movement at as many levels in the atmosphere as possible in the neighbourhood of such cyclones. The east coast of Peninsular India is visited every year by one or more storms coming directly from the sea and both topography and upper winds are favourable for the recovery of a good percentage of sounding balloons. It is hoped that more opportunities will be available for the study of such storms.

The thanks of the author are due to the staff of the Upper Air Section at Poona and to the assistants and observers at Madras for the part they had in the calibration, sending up and the recovery of the instruments and the working out of the records. The help of Mr. K. P. Ramakrishnan, Assistant in the Upper Air Section, Poona, has been specially valuable in the preparation of the paper. His thanks are also due to Dr. C. W. B. Normand, Director General of Observatories for his kind interest in the work.

APPENDIX 1.

Pressures, temperatures and humidities at different levels over Madras.

Madras, 15th November 1933 at 1716 hrs.				Madras, 16th November 1933 at 1800 hrs.				Madras, 17th November 1933 at 0404 hrs.				Madras, 18th November 1933 at 1755 hrs.				Madras, 19th November 1933 at 0400 hrs.			
L gdm	P mb	T °A	U %	L gdm	P mb	T °A	U %	L gdm	P mb	T °A	U %	L gdm	P mb	T °A	U %	L gdm	P mb	T °A	U %
Ground	1008	299·8	60	Ground	1007	298·0	60	Ground	1005	298·0	56	Ground	1012	299·2	88	Ground	1011	295·4	97
500	951	95·0	72													500	953	93·0	..
1000	896	90·2	79	1000	896	93·6	77	1000	894	92·0	92	1000	900	93·0	70	1000	900	91·0	69
1450	850	86·0	61	1450	850	89·8	96	1060	890	91·8	93	1500	850	90·2	72	1500	849	89·4	69
1500	844	86·0	56	1500	845	89·5	96	1500	842	90·2	84	1800	820	87·6	67	2000	798	87·8	23
2000	795	86·0	23	2000	796	87·0	97	1870	810	90·0	85	2000	800	86·6	69	2180	780	87·5	21
2500	748	84·5	21	2500	749	84·4	86	2000	792	88·2	86	2500	753	84·2	30	2500	750	86·0	15
3000	702	82·6	18	2600	740	83·5	79	2500	746	85·2	90	3000	709	84·2	28	3000	706	83·6	15
4000	620	77·4	21	3000	702	83·2	52	3000	701	81·6	95	3470	670	80·6	17	3920	630	79·5	15
4550	580	73·0	23	4000	620	78·0	30	3660	650	77·5	93	4000	627	78·5	15	4000	624	78·8	25
5000	547	70·4	22	4750	565	75·8	32	4000	620	76·0	82	5000	552	72·5	18	5000	550	71·5	34
6000	480	64·2	19	5000	549	74·0	32	5000	547	71·4	65	6000	485	66·6	22	6000	483	65·5	32
7000	420	57·0	21	6000	482	67·0	40	5110	540	70·8	59	7000	424	60·5	19	6700	440	62·0	30
8000	366	50·2	27	7000	422	58·4	53	6000	480	66·6	64	7440	400	57·6	15	7000	423	60·2	30
9000	318	42·8	29	8000	369	51·0	79	7000	420	60·0	91	8000	370	52·5	21	8000	368	52·4	31
10000	275	34·8	26	8070	365	50·4	83	7130	415	59·6	91	9000	322	44·0	22	9000	320	44·4	31
11000	236	26·8	25	9000	320	46·0	85	8000	368	53·8	88	10000	279	36·0	16	10000	277	36·4	29
12000	203	18·5	25	10000	278	39·6	85	9000	320	46·2	85	11000	240	26·6	15	11000	237	27·0	30
13000	172	10·4		11000	240	31·2	84	10000	277	38·2	82	12000	205	18·4	16	12000	204	20·0	30
14000	145	01·2		12000	205	21·6	83	11000	239	29·8	79	13000	175	09·6		13000	174	10·8	
15000	122	194·8		13000	174	12·0		12000	204	21·4	76	14000	147	00·0		14000	147	02·0	
15280	116	93·2		14000	147·5	02·8		13000	174·5	12·0		14700	130	194·7		15000	123	194·0	
16000	102	92·7		14220	142	02·8		13600	158	07·2		15000	123	92·5		15520	112	92·0	
16700	90	93·5		15000	124·5	197·4		14000	147·5	04·6		16000	102	87·5		16000	103	94·0	
17000	85·5	95·6		15730	109	192		14440	137	02·6		16300	97	86·5		17000	86	96·5	
18000	71·5	02·8		16000	104	192		15000	124	196·7		17000	86	91·8		17780	75	200·1	
				17000	86·5	195·8		15200	120	94·7		18000	71·3	97·0					
								16000	104	92·5									
								16200	100	93·0									
								17000	87	202·0									

APPENDIX 2.

Pressures, temperatures and humidities at different levels over Poona.

Poona, 17th November 1933 at 1727 hrs.				Poona, 19th November 1933 at 0407 hrs.				Poona, 20th November 1933 at 1730 hrs.			
L gdm	P mb	T °A	U %	L gdm	P mb	T °A	U %	L gdm	P mb	T °A	U %
Ground	948	299·9	48	Ground	949	293·1	87	Ground	950	300·7	64
1000	898			1000	898	88·5	100	1000	900	294·2	86
1440	852	90·2	43	1500	846	87·2	99	1500	849	90·0	100
1500	846	90·0	42	2000	797	85·0	97	1670	832	88·4	100
1780	820	89·0	41	2500	750	82·4	99	2000	800	86·4	100
2000	798	88·2	36	3000	705	80·4	92	2500	752	83·9	97
2500	751	85·0	32	3020	704	80·0	91	3000	708	81·2	97
3000	707	83·2	34	3650	650	77·4	78	4000	624	76·0	73
4000	624	77·0	43	4000	622	76·0	80	4450	590	73·6	57
5000	550	69·2	53	5000	548	70·0	69	5000	550	70·0	46
6000	482	62·6	55	5400	520	67·2	39	5760	497	64·0	39
7000	422	55·8	52	6000	481	66·4	25	6000	482	63·0	37
8000	367	48·0	51	7000	421	57·2	24	7000	422	56·5	30
9000	318	39·8	51	7600	388	51·2	22	8000	367	48·7	30
10000	275	32·0	52	8000	367	50·4	20	9000	319	40·8	29
10630	250	27·8	54	9000	319	42·0	19	10000	275	32·6	28
11000	236	25·0	53	9280	306	39·4	18	10120	270	31·8	28
12000	201	14·8	52	9700	288	37·2	19	11000	236	24·6	28
13000	171	06·8		10000	275	34·4	19	12000	202	15·6	28
14000	144	198·3		11000	236	25·0	20	12050	200	15·2	
14880	123	92·4		12000	202	16·6	21	13000	172	08·4	
15000	121	92·4		12130	198	15·4		13400	160	05·0	
15280	115	93·5		13000	172	11·5		14000	145	01·2	
16000	101	91·3		13050	171	11·4		14700	128	195·0	
16020	100	91·5		14000	146	04·6		15000	122	93·1	
16700	89	94·5		15000	122·5	197·7		15580	109	91·3	
17000	85	94·8		16000	102	93·2		16000	101·5	94·0	
17900	72	95·3		16720	90	91·5		16600	91	94·4	
18000	71	95·6		17000	86	92·7		17000	85	96·7	
18440	65	200·4		18000	71·6	96·8					

MGIPC—M—VIII-3-185—20-4-36—380.

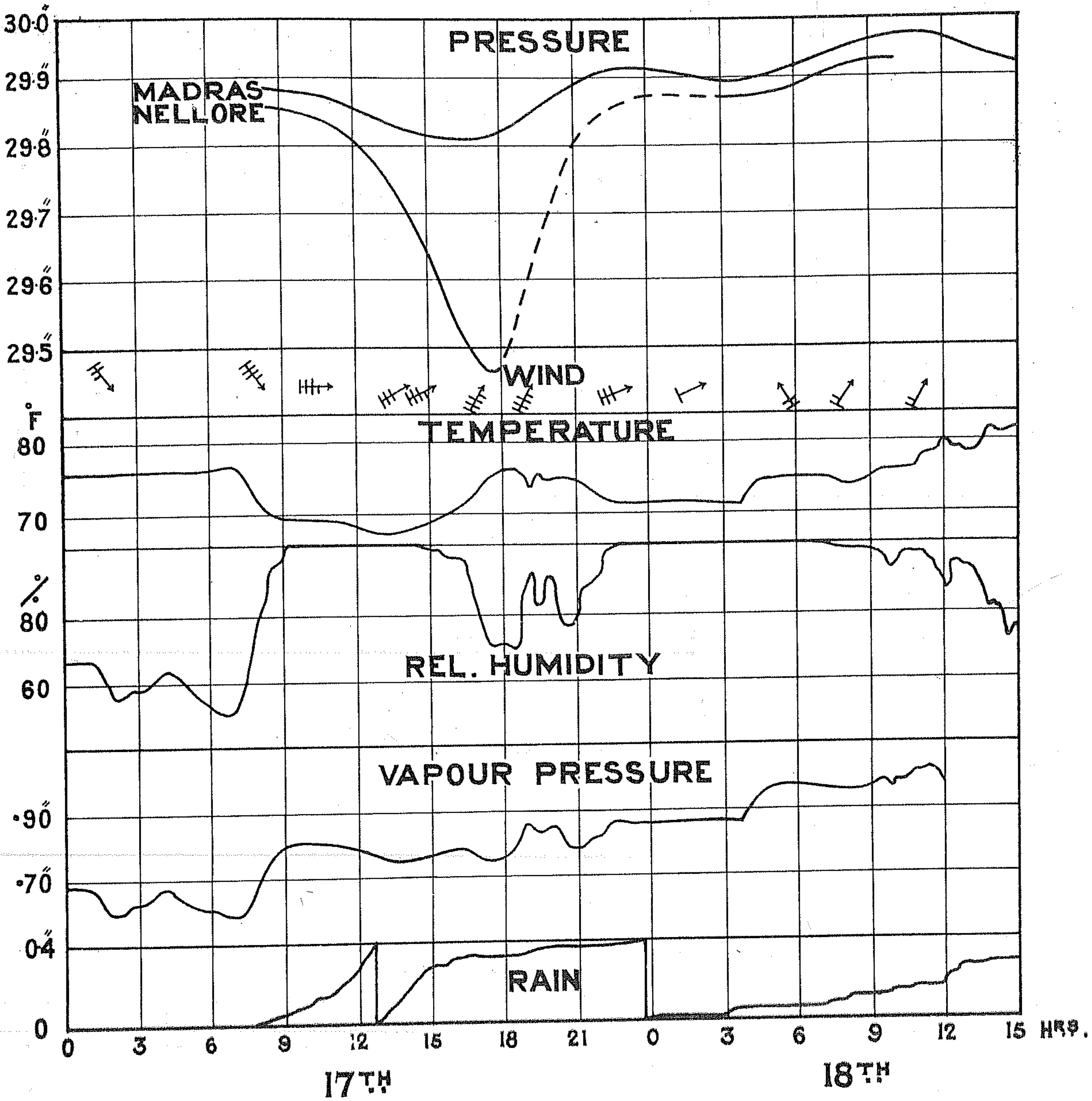


Fig. 3. Variation of the meteorological elements at Madras and pressure at Nellore on the 17th and 18th November, 1933.

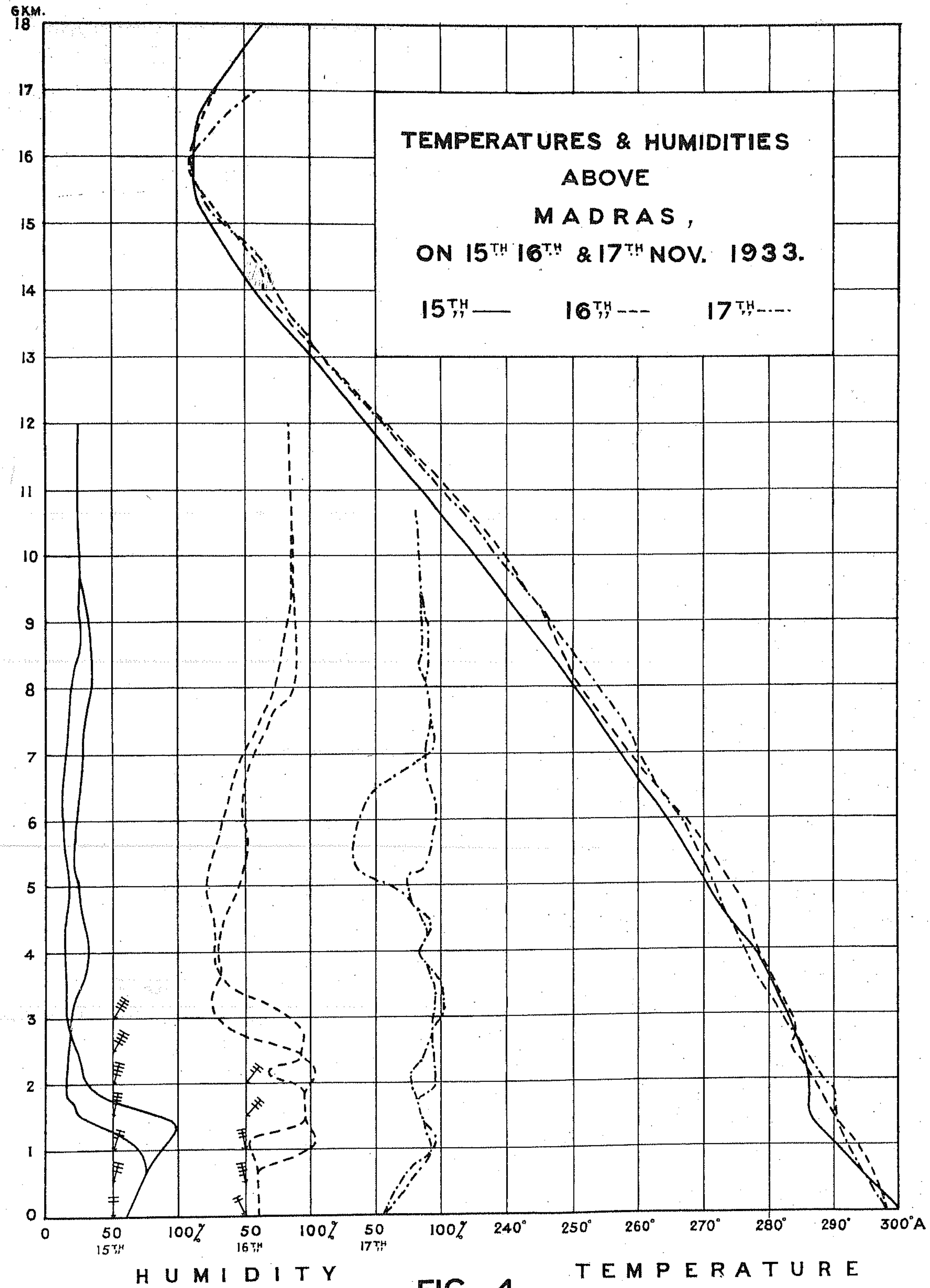

TEMPERATURES & HUMIDITIES
ABOVE
MADRAS,
ON 15TH 16TH & 17TH NOV. 1933.
15TH ——
16TH - - -
17TH -·-·-
6KM.
18
17
16
15
14
13
12
11
10
9
8
7
6
5
4
3
2
1
0
0
50
15TH
100%
50
16TH
100%
50
17TH
100%
240°
250°
260°
270°
280°
290°
300°A
HUMIDITY
TEMPERATURE

FIG. 4.

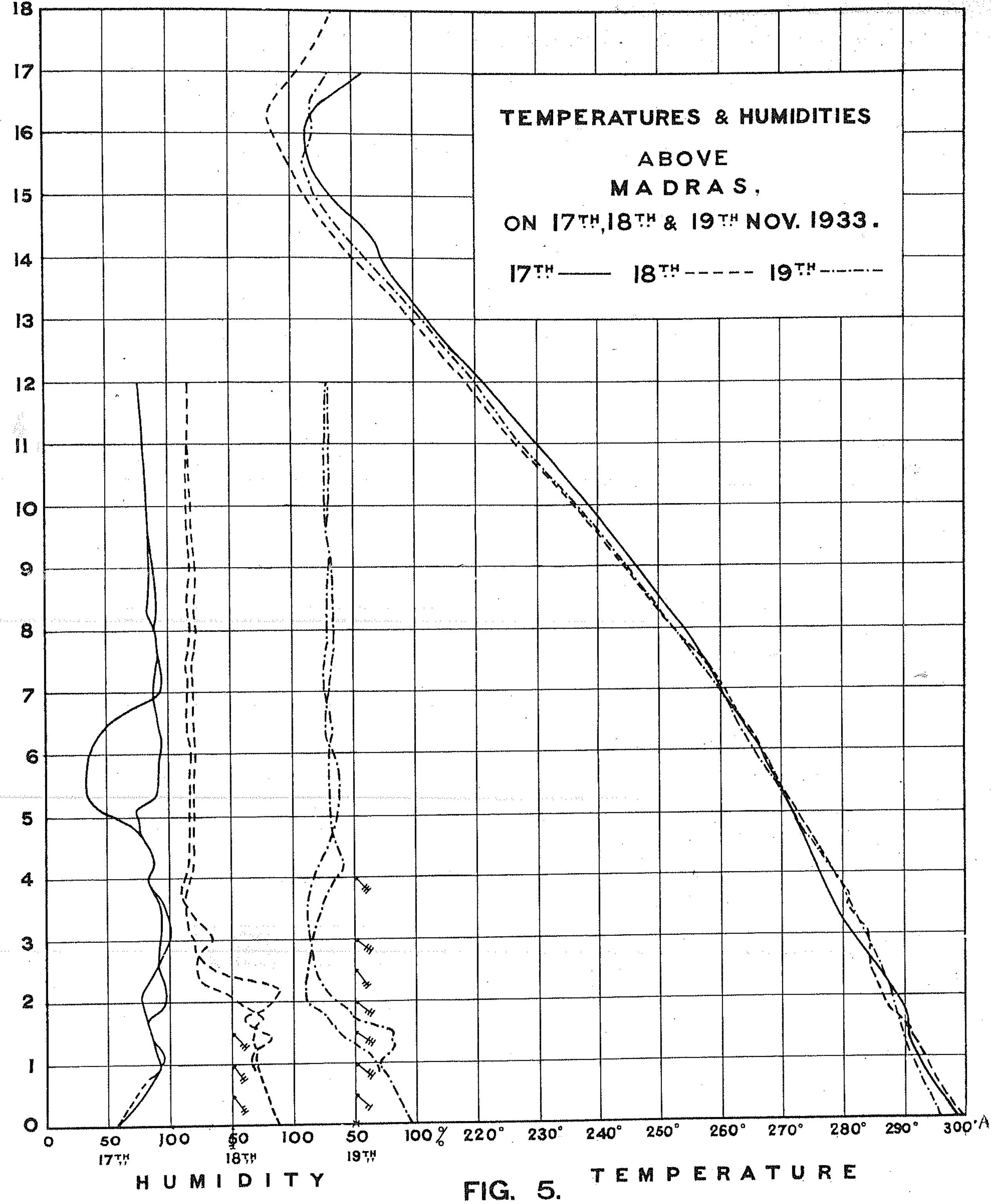

TEMPERATURES & HUMIDITIES
ABOVE
MADRAS,
ON 17TH, 18TH & 19TH NOV. 1933.
17TH ——— 18TH - - - - - 19TH —·—·—
GKM.
18
17
16
15
14
13
12
11
10
9
8
7
6
5
4
3
2
1
0
0
50
17TH
100
50
18TH
100
50
19TH
100%
HUMIDITY
220°
230°
240°
250°
260°
270°
280°
290°
300°A
TEMPERATURE

FIG. 5.

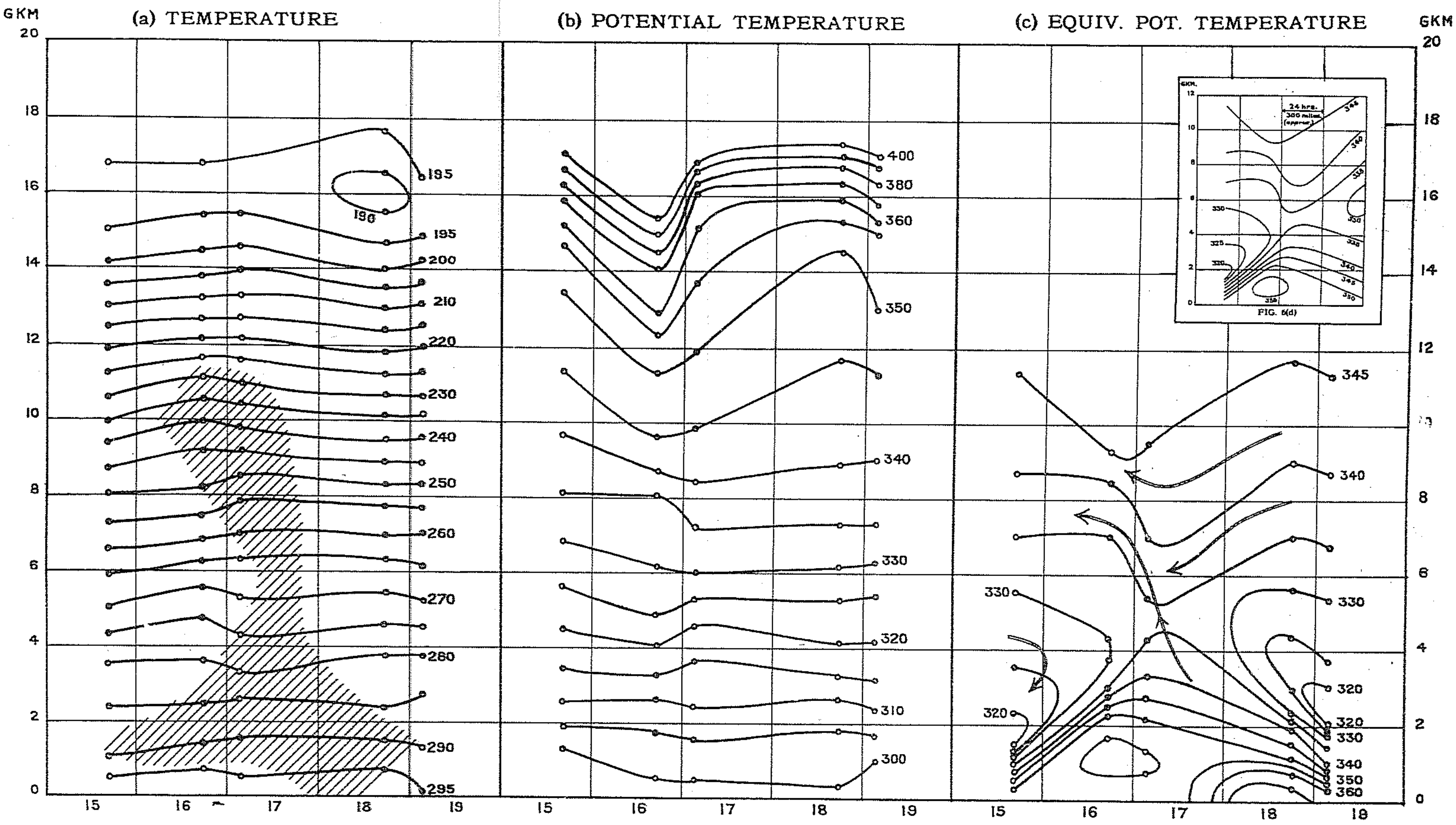
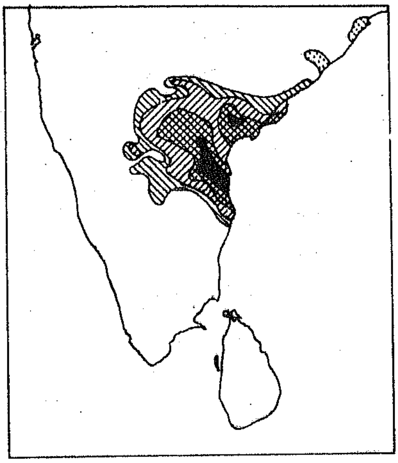


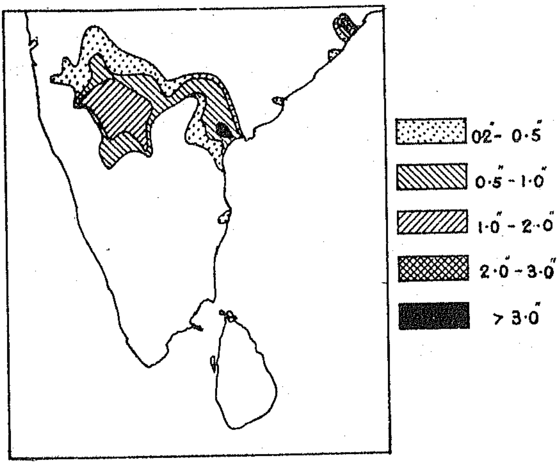
Fig. 6. Isopleths of temperature, potential temperature and equivalent potential temperature drawn from the ascents at Madras.

Inset: Isopleths of eq. pot. temp. modified by partial substitution of Poona data.



RAINFALL RECORDED AT 8 HOURS ON 18-11-1933.

Fig. 7(a)



RAINFALL RECORDED AT 8 HOURS ON 19-11-1933.

Fig. 7(b)

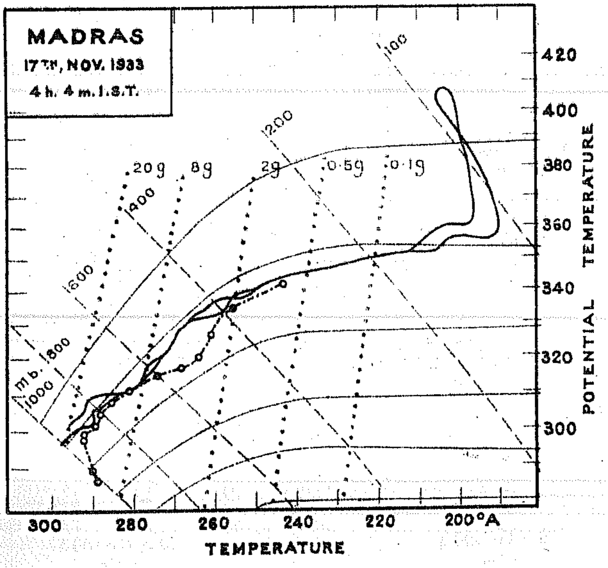


Fig. 11 a

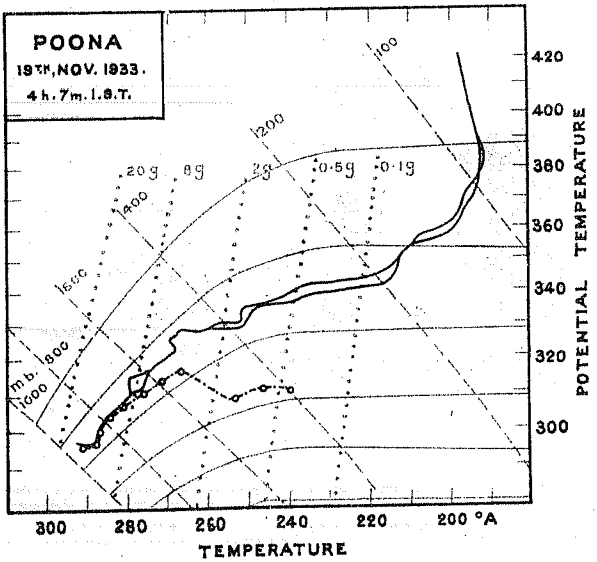
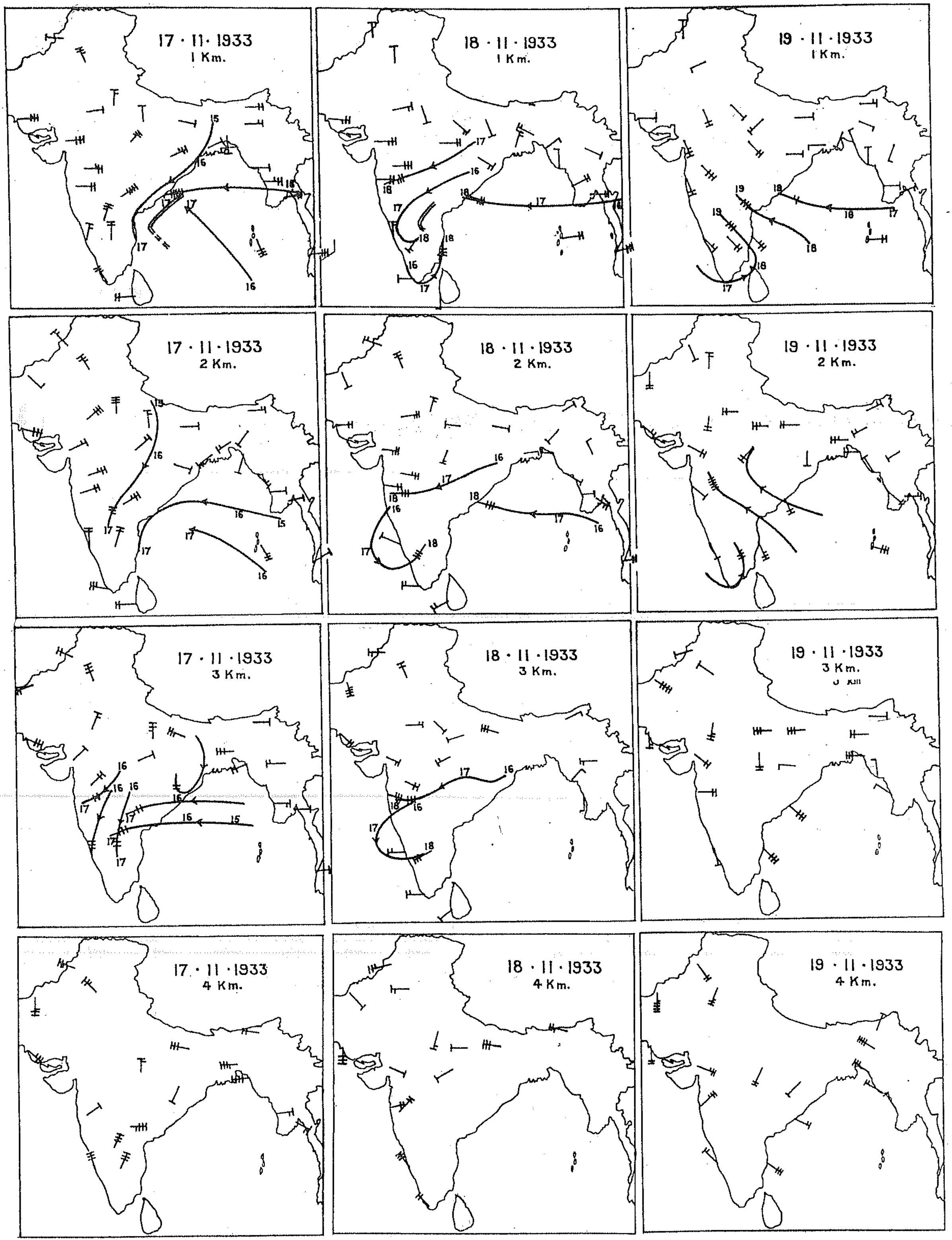


Fig. 11 b



17 · 11 · 1933
1 Km.

18 · 11 · 1933
1 Km.

19 · 11 · 1933
1 Km.

17 · 11 · 1933
2 Km.

18 · 11 · 1933
2 Km.

19 · 11 · 1933
2 Km.

17 · 11 · 1933
3 Km.

18 · 11 · 1933
3 Km.

19 · 11 · 1933
3 Km.

17 · 11 · 1933
4 Km.

18 · 11 · 1933
4 Km.

19 · 11 · 1933
4 Km.

Fig. 8. Upper winds and (selected) trajectories of air movement on 17th. 18th and 19th.

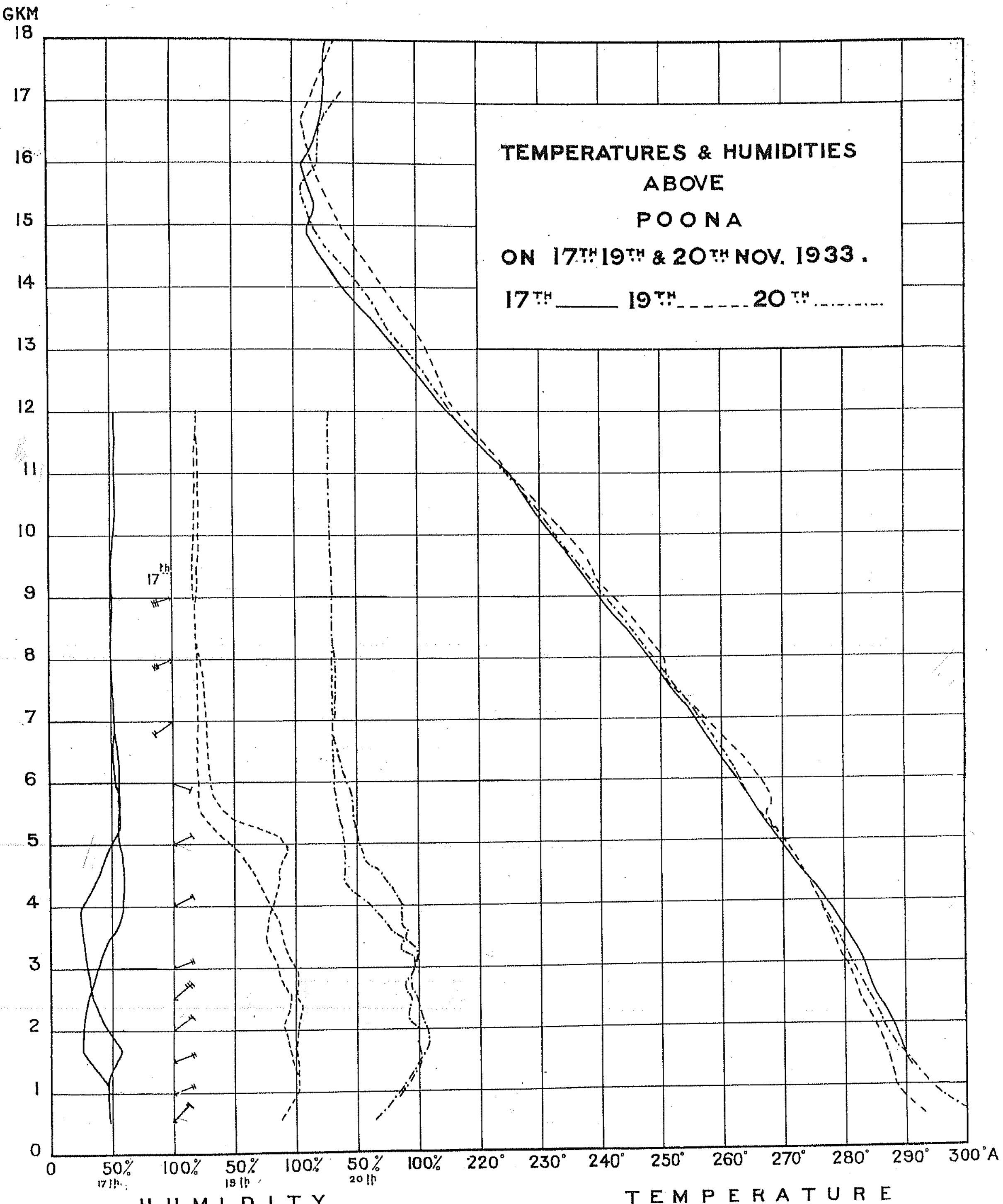
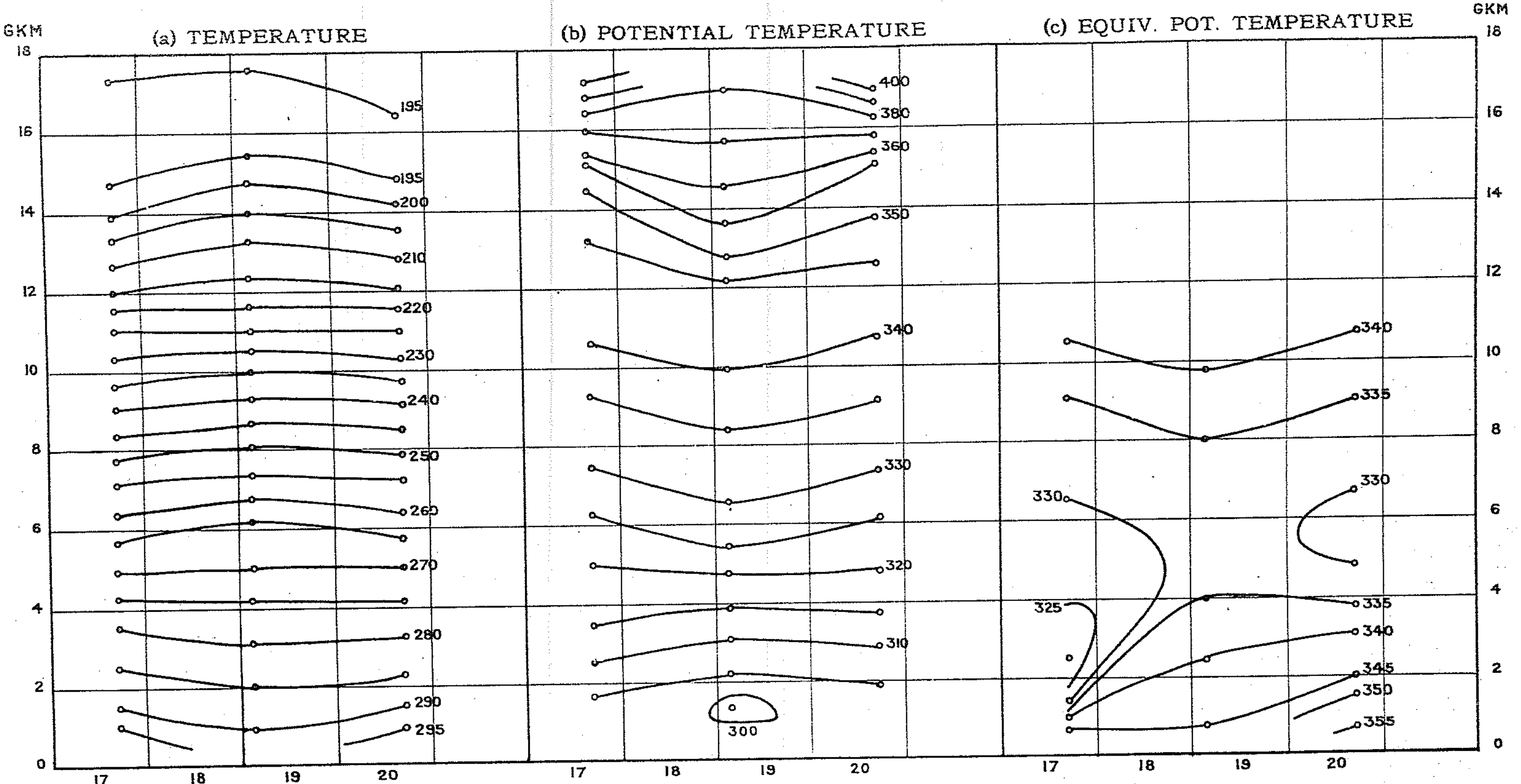

GKM
0
1
2
3
4
5
6
7
8
9
10
11
12
13
14
15
16
17
18
TEMPERATURES & HUMIDITIES
ABOVE
POONA
ON 17TH 19TH & 20TH NOV. 1933.
17TH ——— 19TH - - - - - 20TH -·-·-·-
17th
0
50%
17th
100%
50%
19th
100%
50%
20th
100%
220°
230°
240°
250°
260°
270°
280°
290°
300°A
HUMIDITY
TEMPERATURE

FIG. 9.


(a) TEMPERATURE

(b) POTENTIAL TEMPERATURE

(c) EQUIV. POT. TEMPERATURE

Fig. 10. Isopleths of temperature, potential temperature and equivalent potential temperature drawn from the Poona ascents