THE INDIAN SOUTHWEST MONSOON AND THE STRUCTURE OF DEPRESSIONS ASSOCIATED WITH IT.

BY

K. R. Ramanathan, M.A., D.Sc.

AND

K. P. Ramakrishnan, B.A.

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Introduction.

In a previous paper on the structure of two pre-monsoon storms in the Bay of Bengal[1] one of the authors and Mr. H. C. Banerjee have shown that surface-heated continental air entering the north-west of the Bay of Bengal, when it meets monsoon air, forms a " dry warm front " at which the continental air ascends over the monsoon air in the lower layers. It was also pointed out that owing to the difference in the lapse-rate between the two air masses, the dry warm front would, at levels higher than 3 km., transform itself into a " cold front ". Strong winds, heavy swell and fierce rain-squalls are experienced before this front within the monsoon air mass.

In the present paper, the general upper air circulation before and during the south-west monsoon with the attendant distribution of temperatures in the free atmosphere as far as can be gathered from the available data is discussed, followed by an analysis of two storms of the monsoon period. The principal features of the analysis are the use made of upper winds in tracing the sources of air supply and of detailed rainfall charts to elucidate the nature of the " fronts ". The rôle of the old monsoon air, as compared with that of surface-heated continental air in the storms which form at the head of the Bay in this season, is brought out.

A very good early summary of the mechanism of the south-west monsoon is contained in the Imperial Gazetteer of India, prepared out of material gathered by Sir John Eliot.[2] The subject has subsequently been discussed by various authors, notably by Simpson,[3] Harwood[4] and recently Wagner.[5] Some aspects of the question have also been considered by S. C. Roy and A. K. Roy[6] and by H. C. Banerjee and one of us.[7]

According to Simpson, the primary cause of the monsoon is the relatively high temperature and correspondingly low pressure over the land in the northern hemisphere during the summer. The air in the South Indian Ocean, under the influence of the

[1] K. R. Ramanathan and H. C. Banerjee: Ind. Met. Dept. Sc. Notes, Vol. IV, No. 34, 1931.

[2] The Imperial Gazetteer of India: Vol. I, Ch. III, 1907.

[3] G. C. Simpson, " The South-west Monsoon ": Q. J. R. Met. Soc., Vol. 47, p. 151, 1921.

[4] W. A. Harwood, " Upper air movement in the Indian Monsoons, etc.": Mem. Ind. Met. Dept., Vol. XXIV, Part 8, p. 249, 1921.

[5] A. Wagner, Zur Aerologie des Indischen Monsuns: Ger. Beitr. z. Geophy., Bd. 30, p. 196, 1931.

[6] S. C. Roy and A. K. Roy, " Structure and Movement of Cyclones in the Indian Seas ": Beitr. zur Physik der freien Atmosph., Bd. 16, p. 224, 1930.

[7] H. C. Banerjee and K. R. Ramanathan, " Upper Air Circulation over India and the neighbourhood, etc.": Ind. Met. Dept. Sc. Notes, Vol. III, No. 21, 1930.

(Memoirs of the India Met. Dept., Vol. XXVI, Part II.)

Mem. Ind. Met. Dept 26(2), 13-36, 1933.

pressure distribution and of the rotation of the earth, moves to the north-west in the southern hemisphere and to the north-east in the northern. The moist air with its long sea-travel is caught by the mountain system of India and the rainfall is determined by the ranges of mountains in and around India. The small rainfall in the north-west of India is explained by Simpson as being due to the arrangement of the neighbouring mountains and the prevalence of a dry upper wind and the high temperature. Simpson does not discuss the depressions of the monsoon season and their importance as agencies responsible for precipitation over a considerable part of the country. Harwood discusses the circulation in the upper levels and the manner in which the air brought into India by the lower monsoon currents is disposed of. He concludes that of this air :—

(*a*) " Part crosses the Himalayas and the mountains of north-east India and is then lost sight of but may be presumed to continue as part of the circulation round the Asiatic ' low '.

(*b*) Part rises and passes first westwards and then northwards round the western side of a high pressure area in the upper levels over north India.

(*c*) Part rises and passes westwards, subsequently descending to rejoin the lower monsoon current over the Arabian Sea ; and

(*d*) Part rises and passes first westwards and then southwards in the same way as the anti-monsoon postulated by Blanford and Eliot."

Harwood does not consider the distribution of rainfall or the causes which give rise to it.

Wagner,[5] in an important paper, has emphasised the view that the south-west monsoon represents a stationary system of cyclonic disturbances reaching up to the average height of the Himalayas between two air-masses, one continental belonging to the W. winds of the middle latitudes and the other maritime. He considers that the continental air is warmer than the monsoon air at the surface and up to 1 km. and colder above and that a considerable part of the monsoon precipitation in and south of the Gangetic plain is due to cyclonic convergence. Wagner's stream-lines are drawn with mean wind data for the months June, July and August. For heights above 3 kms., the data of one single year, 1928, have been used for 13 stations. As Wagner himself points out, June cannot be considered a representative monsoon month for a considerable part of north India. The present paper contains a discussion of average monthly upper air stream-lines and temperatures before and during the monsoon * and an analysis of two typical monsoon depressions during the months June and July, 1930.

We shall first examine the mean monthly stream-lines (at 1, 2, 3, 4, 6 and 8 km.) and isotherms (as far as can be made out from the available data) at different heights in the months May, June and July.

SECTION I.

Normal wind and temperature distribution in May, June and July.

Wind-roses at a number of pilot balloon stations and approximate isobars at 0·5, 1, 2 and 3 km. have been published in the departmental Scientific Note, Vol. 1, No. 8. Up-to-date average upper wind velocities for different levels have also been recently calculated, utilising data at more stations—and the charts for May prepared with them are reproduced in *Figures 1-6*. In drawing conclusions, these average stream-lines should be

[5] A. Wagner, *Loc. cit.*

* A more detailed study of the mean monthly stream-lines and the general circulation in the Indian area is in progress.

considered along with charts of wind-roses both of pilot balloon winds and of cloud movement. They bring out the following facts :—

May.

At 0·5 and 1 km. the winds are westerly to north-westerly over most of the Arabian Sea and the whole of India west of a line running from Cape Camorin to between Allahabad and Patna ; east of this line the winds are westerly to south-westerly. While over the north Indian plains, the air is surface-heated continental air, further south it should be considered as maritime continental air, the length of sea travel increasing both in the Arabian Sea and the Bay of Bengal with decrease of latitude and increase of longitude. At 2 km. the north-westerly continental current extends much further towards the south-east, the line of separation between continental and maritime air lying now in the Bay of Bengal between east Ceylon and south of the Pegu Coast in Burma. Although the mean wind at Port Blair is weak, this is due more to the variability of the wind direction than to general weakness of wind, both westerlies to south-westerlies and easterlies and south-easterlies being common. The region of separation of continental and maritime air at 2 km. coincides more or less with the region where storms originate or strengthen in the Bay of Bengal.[8] The maritime air pushes itself farthest northwards in the east of the Bay of Bengal. The normal winds at 2, 3, 4 and 6 km. indicate that while the continental air at 3 km. pushes itself further southward than at 2 km., at 4 and 6 km. it is pushed backward towards the north by maritime air. This is in agreement with the scheme sketched out in *Fig. 27* of " Scientific Notes ", Vol. IV, No. 34.

Some light is thrown on the mechanism of the change of wind with height by considering the distribution of temperature in the upper air. In *Figs. 19-21* are shown the monthly mean temperatures at 2, 3, 4 km. in May, June and July at a number of stations, the values being based on results of sounding balloon ascents, aeroplane ascents and mountain observations. Sounding balloon ascents were made at about the time of sunset, aeroplane data refer to forenoon hours (9 to 12 hours) and mountain observations to 8 hours local time. The number of observations and period over which they extend are also different. The isotherms that have been drawn can therefore be considered only as tentative. They have, however, an internal consistency which justifies our drawing general conclusions. In May the isotherms at 2 km. have a great similarity to the isotherms at the surface. At 3 km. there seems to be little difference of temperature between the different parts of India with the possible exception that N. E. India may be slightly cooler by 1° or 2°. The southing of winds in the Bay of Bengal, Burma and N. E. India is obviously due to the low pressure at the surface in the Deccan and the central parts of the country caused by the heating of the land area. The marked change in the wind circulation at 2 and 3 km. compared with that at 1 km. indicates a greater decrease of pressure with height and a correspondingly lower temperature in the Bay than in the Peninsula and the corresponding northward extension of maritime air in the Bay of Bengal above 2 km. is therefore a consequence primarily of the differential heating of the Peninsula and the Bay.

June.

The main points of difference in the wind system of June (*Figs. 7-12*) at 1 and 2 km. as compared with that of May are the more marked westing and strengthening of winds

[8] C. W. B. Normand, " Storm Tracks in the Bay of Bengal ", Ind. Met. Dept., 1925.

in the Arabian Sea and the Peninsula and their increased southing and strengthening in the Bay of Bengal and Burma. The approximate line of meeting of surface-heated land air and of fresh sea air at 2 km. in the Bay of Bengal has naturally got shifted northwards and the Arakan hills have exerted their influence in rendering the line of discontinuity in the Bay nearly south to north. The weakness of wind at Aden at this level with the contrasted winds at 1 and 3 km. indicates a level of transition at about 2 km. At 3 km. the winds in South India and the Bay of Bengal have weakened and those in the north of the Peninsula, on the Mekran Coast and at Aden have acquired a more northerly character. While caution is necessary in interpreting the former result as there will be a tendency to miss out days of stronger wind owing to the absence of pilot balloon information, we may be practically certain about the latter, as a comparison of the number of observations will show. The winds at 4 km. are more or less similar to those at 3 km. and both of these show that the winds of northerly origin overspread those of more southerly origin in the middle of the Peninsula. The winds at 6 km. are very weak in the south of the Peninsula and have no defined direction. This is also borne out by observations of middle cloud. The advance of southerly to south-easterly current in Bengal at 6 km. over the north-westerly current at 4 km. shows that the former stream now behaves as warmer air. The resultant movement, however, is weak. At 8 km. the general upper easterly circulation has set in over the south and the ridge of high pressure separating the easterly and westerly circulations now lies over a latitude of about 22° North showing a northward shift of more than 10° since May. It will be noticed that except for the first 2 km. the winds in the Arabian Sea are from a northerly direction, those in Burma and a great part of the Bay of Bengal are from the south.

Considering the distribution of temperature, while in May at 2 km. the decrease of temperature towards the north persists in the Gangetic Valley, the gradient being roughly perpendicular to the Himalayas, it has become much weaker in June (*Fig. 20*). The region of highest temperature has also got shifted from the central parts of the country north-westwards to Rajputana and Sind. The horizontal temperature gradients at 2 km. have become generally weaker. The level of approximate equality of temperature in different parts of the country is in this month at about 4 km.

July.

As representing conditions at the time when India is under the full sway of the monsoon, the distribution of winds and temperature in July are particularly interesting (*Figs. 13-18*).

The main point of difference in the wind systems at 1 and 2 km. between June and July is the incursion of south-easterly winds in the Gangetic Valley right up to the Punjab Hills. With the turning round of the maritime winds along the Himalayas towards the north-west the continental air sector at 2 km. becomes very much restricted in area and in the region between Gujarat and Orissa to some extent loses its individuality owing to the supply of moisture from below and sideways from both south and north-east; it becomes the mixed monsoon air of S. C. Roy and A. K. Roy. The southern boundary of this region is extremely indefinite.* Pure continental air exists only to the west of Rajputana. It is worthy of note that the wind at Aden is in this month from the west-

* Wagner says that the surface of separation between the continental air and the SW monsoon air is sharply pronounced at 2 and 3 km. This difference is due to his averaging the data for June, July and August.

south-west unlike the weak north-easterly of the previous month. At 3 and 4 km. " the continental air " has spread over a larger area in the Peninsula. In the south of the Peninsula the air is probably purely of maritime origin but in the middle of the Peninsula, there should be a high frequency of occasions when the air at these levels is of continental origin. Comparing the wind directions at the pilot balloon stations in Baluchistan, Persia and Arabia at 2, 3 and 4 km. it appears that the continental air pushes farthest into the Arabian Sea at 3 km.

Even at 4 km. the air supply over the north and west Arabian Sea has begun to be replenished by air over the Gangetic Valley, while at 6 km. the easterlies are in full sway over North India and the winds are very weak in the Peninsula. The contrast of conditions at 6 km. between June and July is very striking, the line of separation between continental and maritime air which lay over the north Bay of Bengal having been displaced to the Punjab and Kashmir. At 8 km. the system of circulation has again assumed a simple form similar to that in June, but with the high pressure ridge displaced northwards by another 8°.

The upper air temperatures (*Fig. 21*) show that the region of highest temperature at 2 and 3 km. is now Baluchistan and Persia. The air over South India is definitely cooler than that over North India as will be seen from a comparison of temperatures at Agra, Hyderabad and Kodaikanal. This is shown more conspicuously by the mean monthly tephigrams and dew-point temperature diagrams for July of the air over Hyderabad and Agra obtained from results of sounding balloon ascents (*Fig. 22*). The upper air data of individual days also, whenever they are available, bear this out.

The increase of temperature of the air in going from the Peninsula to North India is due to the following causes. When the moist air reaches the Western Ghats as a cold air mass at the surface orographic precipitation results, causing an increase of temperature above the low-cloud level and a decrease below. The Deccan Tableland which is swept by the westerly subsiding winds is generally free from heavy rain and the air, even right down to the surface, gets warmed by insolation. On entering the Bay of Bengal, more moisture is picked up and with renewed precipitation on the Burmese Coast the upper air gets warmed up further. The easterly current over the Gangetic Plain is, above 6 km., part of the general easterly circulation, but this stream is fed from the south by air rising over the Bay and Burma and by a similar addition from the east by the air rising over the region of the Chinese monsoon. Absorption of solar radiation by the water vapour in the atmosphere with the long hours of sunshine and the sun practically overhead at noon is also an important cause of increasing the temperature. While the easterly current is generally not fully saturated, it has a larger amount of moisture throughout its thickness, and owing to the high temperature, the absolute amount of moisture held is large. Old monsoon air may therefore be expected to behave as a warm air mass when compared with fresh monsoon air.

It will also show a similar behaviour towards surface-heated continental air above a level which may vary from 2 to 4 km.

SECTION II.

We shall now examine in some detail the air movement and precipitation connected with two depressions during the monsoon of 1930. Short general descriptions of these have been published in Part C of the India Weather Review for 1930.

It may be mentioned at the outset that the upper air trajectories at different levels have been drawn with the aid of winds obtained from pilot balloon observations. The observations are made twice daily, once in the morning and once in the afternoon at North Indian Stations and only in the morning at stations in the Deccan. In times of disturbed weather, however, single flight stations also take two observations a day. The trajectories have been drawn giving due consideration to the general wind field. It has been assumed that the level of the air does not change during its travel; this is obviously not correct, but owing to the absence of data which will enable us to fix the isentropic surfaces' no better method is available.

The depression during the period 27th June to 4th July, 1930.

The upper winds over the Indian area on the morning of the 27th June 1930 had a remarkably simple structure. In the Indian Peninsula, approximately south of latitude 21°, the winds were westerly up to at least 3 km., while north of this latitude they were practically easterly over most of north India and the Mekran Coast. On the Arakan Coast in Burma, the winds were south-south-easterly to south-easterly up to 2 km. and tended to become easterly at higher levels. The winds at 1, 2 and 3 km. are shown in *Figure 23.*

The following points are noteworthy :—

(1) At 1 km. the wind at Rangoon is WSW, while at Akyab and Chittagong it is SSE. This is due to the Arakan Yomas and the Chin Hills deflecting the westerly current northward. There is a similar though weaker tendency at Ahmedabad, due to the effect of the Central Indian plateau and the Aravalli hills.

(2) In Gujarat, Sind and the Mekran Coasts the strength of the easterly winds generally increased with height up to 6 km. The easterly current at Agra extended up to 20 km.

This system of wind circulation was associated with abnormal excess of pressure north of a line running approximately from Lat. 25° N., Long. 65° E. to Lat. 17° N., Long. 95° E.

Ships' observations in the Arabian Sea show that on the 27th morning strong south-westerly or west-south-westerly winds extended up to about 20° N.

An extraordinary strengthening of upper winds took place in the Deccan between the 26th and the 27th. This is well brought out from the wind data of Hyderabad.

TABLE 1.

Date and time.		Height above sea level in km.						
		1·0	1·5	2·0	2·5	3·0	4·0	5·0
26th June, 1930 (07-13)	Direction	265°	290°	290°	315°	335°	290°	295°
	Vel. m. p. s.	13·0	14·0	10·5	3·0	2·0	5·0	6·0
27th June, 1930 (06-55)	Direction	260°	265°	280°	280°	280°	..	..
	Vel. m. p. s.	19·5	18·5	18·0	15·5	14·5	..	..

Directions are in degrees from north in a clock-wise direction and velocities in metres per second.

This rapid strengthening of wind produced a short-lived shallow low-pressure area between the Satpuras and the Vindhyas near Latitude 22° N., Long. 76° E. and a ridge of high pressure down the Peninsula. All along the line of separation of westerly and easterly wind-systems, there was this tendency for the formation of cyclonic vortices, but further development took place in places where orographical features were favourable for the continuous creation of cyclonic vorticity and contrasted air masses could converge. The morning weather chart of 28th June 1930 shows the development of a low pressure area in the north-east corner of the Arabian Sea off Kathiawar (*Fig. 24a*). (In these weather charts, winds over land at 0·5 km. above sea level obtained from pilot balloon ascents are shown by full-lined arrows.) Surface winds over the sea and high level stations are also shown by continuous arrows, and those at ground level (at a few representative stations) by discontinuous ones. From *Fig. 24a* and the accompanying chart of upper air trajectories (*Fig. 24b*) it will be seen that while at 1 km. the south-westerly winds were deflected northwards and then westwards into Gujarat, lower Sind and the Mekran Coast, winds at 2 km. and above over Karachi and Gwador had a northerly land origin. The upper winds at Karachi and Gwador on the morning of 28th June 1930 are given in *Table 2.*

TABLE 2.

Place.	Date and time.		Height in km. above sea level. 0·5	1·0	1·5	2·0	2·5	3·0
Karachi .	28th June, 1930 (06-23)	Direction .	70	105	110	95	80	70
		Vel. m. p. s. .	5·5	5·0	9·0	13·0	13·5	15·0
Gwador .	28th June, 1930 (07-09)	Direction .	185	80	360	35	40	35
		Vel. m. p. s. .	4·0	9·0	9·0	13·0	20·0	24·0

The surface temperatures at Karachi and in Gujarat were of the order of 84° F. while further north in north-west India, they varied from 94° to 100° F. The over-running of the moist south-westerly winds by the drier and warmer (at the surface) land air such as is indicated by the backing of the winds at Karachi and Gwador can only lead to a strong inversion of the type usually observed at Karachi in this season. It is only when the monsoon air is sufficiently thick that the difference of lapse rates between the monsoon air and the dry land air can lead to the disappearance of the inversion and, under favourable conditions of air movement, cause instability.

The southward deflection of air currents at 1 and 2 km. at Sambalpur and Waltair is a necessary consequence of the northward forced movement of air on the Burma Coast. In *Fig. 24b* is also given the areas of general rainfall during the *next* 24 hours. In determining these areas, use has been made of the rainfall data of all raingauge stations* in the country. Areas which had a general rainfall of 4″ and over in 24 hours are shaded black, those with rainfall between 2″ and 4″ by vertical hatching and those with falls between 2″ and 0·5″ by dots. Areas with scattered light falls have not been marked. The

* There are about 3,300 stations in India and Burma registering rainfall.

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moderately heavy rainfall during the next 24 hours was confined to the coastal strip on the west coast of the Peninsula and to a small area on the Orissa coast. Rainfall was practically confined to south of Lat. 24° N. The two regions of comparative freedom from rainfall, one in the west Central Provinces and the other in west Bengal and Orissa, were regions of divergence. Places which reported thunder or lightning are also marked in the figure.

On the 29th morning, the Arabian Sea depression had moved north-westwards and another depression had also developed in the Bay of Bengal near Lat. 19° N., Long. 86½° E. (*Fig. 25a*). The simple upper wind system of the 27th morning had become very much disturbed. The principal new feature was an incursion of northerly to north-westerly upper winds in the North-West Frontier Province and the Punjab. In connection with the Bay depression the transitional zone between about Lat. 19° N., Long. 86° E. and Lat. 23° N., Long. 80° E., was being contracted to a front, the thickness of the current from the Arabian Sea increasing with decrease of latitude. At this front, the north-easterly deflected or old monsoon air was meeting the westerly to north-westerly Arabian Sea monsoon current broadside on. The upper winds at Jubbulpore and the rainfall during the next 24 hours (*Fig. 25b*) show that at this place the old monsoon air at 2 to 4 km. was passing over fresh monsoon air. The area of heavy rainfall on the Northern Circars and Orissa Coast was due to convergence of the very fast monsoon current with the northerly deflected monsoon current, aided by the action of the hills near the Circars Coast in stemming the main monsoon current. It will be noticed that there was a patch of precipitation in Rajputana on and to the west of the Aravallis which was obviously due to the deflected Arabian Sea current overrun by easterly winds. A new feature is the area of precipitation in the south-east Punjab and the west United Provinces with locally heavy falls. The trajectories show that this was due to the obstruction set up against the easterly current by a north-westerly and northerly current in the Punjab which was specially marked at 2 to 4 km. and whose onset should be considered as induced by the rapid deflection of the easterly current round the low pressure areas in the Bay of Bengal and the Arabian Sea. Practically all rainfall north of Lat. 20° N. was attended with thunder or lightning.

On the 30th morning, the storm in the Bay had concentrated without any appreciable movement (*Figs. 26a* and *26b*). The up-glide surface associated with it shows little displacement since the previous morning. Some extracts from the logs of S. S. Badarpur and S. S. Mathura are reproduced in *Tables 3* and *4* below, which show that the front extended out to sea and that no particularly severe weather was experienced near the centre of low pressure. They also show clearly the nature of weather experienced in the neighbourhood of such a front.

TABLE 3.

Log of S. S. Badarpur.

Date.	Time (Hrs.)	Lat. (N.) ° ′	Long. (E.) ° ′	Bar. (Inches.)	Air Temp. (°F.)	Cloud.	Wind (Beaufort scale).	Weather Remarks.
29th June, 1930	4	14 05	81 31	29·58	82	St 10	WSW 3	Overcast with drizzling rain.
	8	14 38	82 07	·60	83	St 10	WNW 5	Overcast.
	12	15 12	82 43	·55	83	St 10	WNW 6	Overcast with frequent light rain squalls.
	16	15 46	83 19	·43	80	Nb 10	W/N 6/7	Hard squalls with light rain but clear intervals.
	20	16 20	83 55	·40	82	St 10	W 7	Fierce squalls with heavy rain but clear intervals.
	24	16 54	84 31	·35	81	Ci-St, St, Nb } 10	W/S 7	Frequent fierce squalls getting harder and intervals decreasing. No rain or lightning.
30th June, 1930	4	17 28	85 07	·25	80	Nb, St } 10	WSW 8	Squalls almost continuous. Wind increasing to gale force. Some light rain in squalls but horizon clear in intervals.
	8	18 01	85 43	·24	80	Do.	SW/W 6	Similar weather continued till 06-30 when the first heavy rain fell during a squall. Heavy rain continued but wind ceased off a bit.
	10	..	..	·18	81	Ci-Cu, Nb, St } 9	SW/W 6	Frequent heavy rain continued, but squalls less frequent. Small patches of blue sky appeared at 10.

TABLE 3—*contd.*

Log of S. S. Badarpur.

Date.	Time (Hrs.)	Lat. (N.)	Long. (E.)	Bar. (Inches.)	Air Temp. (°F.)	Cloud.	Wind. (Beaufort scale).		Weather Remarks.
		° ′	° ′						
30th June, 1930 —*contd.*	12	18 35	86 19	29·16	81	Ci-Cu, S-Cu, St-Nb } 10	SW	6	10-30 to 11-45 continuous and heavy rain. 12-00 sky clearing.
	14	..	..	·14	82	Ci-Cu, St-Cu } 7/8	SW	6	Occasional light rain showers. Weather rapidly clearing and becoming fine and clear, but barometer still falling.
	17	..	..	·14	84	Ci-Cu, Nb, Cu } 6	S	5/4	Short hard rain squall at 17 hours. Passing showers before.
	18	..	..	·17	83	..	SSE	4	Fine and clear.
	20	18 44	87 22	·22	83	Cu-Nb, Nb-S } 5	SE	6	Sky clear overhead but heavy rain lying down southward.

The ship must have passed nearest the centre at about 10 hours on the 30th. Note the mildness of weather on the eastern and northern sides and absence of thunder or lightning even on the night of the 29th. The transition from south-westerly to south-easterly wind was rapid and although attended with a short rain squall, was not attended with very severe weather. Between 20 and 24 hours it was fine and clear with occasional light rain squalls.

TABLE 4.

Log of S. S. Mathura.

Date.	Time. (Hrs.)	Lat. (N.)	Long. (E.)	Bar. (Inches.)	Air Temp. (°F.)	Wind (Beaufort scale).	Weather Remarks.
		° ′	° ′				
30th June, 1930	8	17 21	84 54	29·30	80	W/S 6	Heavy rain.
	12	17 56	85 34	·21	81	WSW 6/7	Rain squalls.
	14	18 18	85 56	·10	81	SSW 5	
	15	18 29	86 08	·07	82	NW/N 3	
	16	18 37	86 16	·07	82	N 3	
	17	18 45	86 24	·05	84	SW 2	
	18	18 53	86 32	·07	84	SW 3	
	20	19 08	86 48	·13	83	E 4	Dull.
	22	19 32	87 02	·23	83	ESE 5	
	24	20 06	87 13	·20	83	SE 5	Frequent rain squalls.

The ship passed very near the centre of the storm at about 17 hours. Note the increase of temperature near the " calm " centre and the heavy rain in the south-west.

The upper air trajectories in *Fig. 26b* show that at this "warm" front, the participating air masses were the fresh monsoon air and deflected monsoon air mixed with air from Siam and Indo-China. The directions of the air currents, the variation of wind with height at Jubbulpore and the distribution of rainfall during the next 24 hours all bear out this conclusion. At such a surface, with the orientation existing at 8 hours on 30th June 1930 the warm air will, as is well-known, be accelerated north-westwards and the cold air south-eastwards. Naturally, the tendency will be for the depression to move north-westwards. The heavy rainfall area from Raipur to Calingapatam can with confidence be extended out to sea up to Lat. 18½° N., Long. 86° E. Jubbulpore and Waltair winds are given below in *Table 5.*

TABLE 5.

Place, date and time.		Height above sea-level.						
Jubbulpore.		0·6 km.	0·9 km.	1·5 km.	2·0 km.	3·0 km.	4·0 km.	4·5 km.
30th June 1930 (06-43) .	Direction .	285°	335°	70°	65°	80°	65°	60°
	Vel. m. p. s.	6·0	6·0	5·0	6·5	12·0	12·5	[13·0
Waltair.		0·5 km.	1·0 km.	1·5 km.				
30th June 1930 (08-41) .	Direction .	270°	310°	340°	..	..	..	..
	Vel. m. p. s. .	13·0	9·0	11·5	..	..	..	..

The upper air trajectories also make it clear that the heavy rainfall on the Gujarat Coast was due to the deflected monsoon air rising over the fresh monsoon air from the Arabian Sea. It may be noted that the latitude at which heavy rainfall commenced on the Arabian Sea Coast was about the same as that at which it ended in the east Central Provinces. On the morning of the 1st July, the Arabian Sea depression had entered land and was being dissipated (*Fig. 27a*); this helped to divert the monsoon air that was feeding into this depression to flow eastward. In *Fig. 27b* is also drawn with the help of pilot balloon winds and movements of low clouds, the line of separation at 2 km. between the Arabian Sea monsoon air and the deflected monsoon air. The position of this line with respect to the area of heavy rainfall during the next 24 hours shows that the rainfall was mainly in the fresh monsoon air sector. The importance of convergence of deep fresh monsoon air and old monsoon air for producing heavy and extensive precipitation is again evident. The entry of old monsoon air up to 2 km. on the Mekran Coast with pure continental air above caused extension of precipitation into that area.

The surface chart on 2nd July 1930 (*Fig. 28a*) shows an interposition of a north-westerly current between the north-easterly deflected monsoon current and the westerly fresh monsoon current. The deflected monsoon air was ascending over the intervening shallow north-westerly air and as is evident from *Fig. 28b* heavy precipitation began where the fresh monsoon air of sufficient thickness (more than 2 km.) was encountered. The low cloud directions at Neemuch, Hoshangabad, Amraoti and Jagdalpur were westerly while at Saugor and Raipur, they were northerly. At Chanda, it was southerly. Surface temperatures were lowest in the region of westerly currents. It is noteworthy that the north-easterly current at Sambalpur (Lat. 21° 28′ N., Long. 84° 01′ E.) did not cause heavy rainfall further south-west where it met the monsoon current ; this was due to the facts (1) that the fresh monsoon current was deflected south-eastwards owing to the action of the front between Hoshangabad and Chanda and could not therefore form an effective obstacle in the path of the north-easterly deflected monsoon current and (2) that the Arabian Sea current had already had its moisture decreased in its lower layers and increased in its upper layers owing to the heavy rainfall within it on the previous day and had thus become similar in properties to old monsoon air. The effect of the front is well seen in the pilot balloon winds at Hyderabad and Waltair which were very strong WNW to NW at 1·5 and 2 km, *Table 6.*

TABLE 6.

Place, date and time.		Height above sea-level in km.				
		0·5	1·0	1·5	2·0	2·5
Hyderabad.						
2nd July, 1930 (07-20)	Direction .	..	215	295	300	..
	Vel. m. p. s. .	..	22·0	27·0	30·0	..
Waltair.						
2nd July, 1930 (14-50)	Direction .	265	270	290	300	305
	Vel. m. p. s. .	15·0	12·0	21·5	17·0	23·0

The air from Bengal having been deflected south-westward, NW Indian air began to be drawn in above 2 km. into Rajputana and Central India as shown by the upper wind trajectories at Ajmer and Agra (*Fig. 28b*). Comparison of the heavy rainfall chart with a contour map shows that the very heavy rainfall in the Central Provinces was concentrated in the Narbada Valley and in the Purna and Wardha valleys respectively. The divergence of south-westerly winds in north Bombay and Gujarat, one branch going up the Narbada valley and the other to the angle formed between the Aravallis and the west Central Indian Hills, is of frequent occurrence during the monsoon ; the heavy rainfall area in Central India was due to the convergence of the south-westerly and northerly winds at the Central Indian Hills. In the surface chart of 3rd July 1930 (*Fig. 29a*), the temperature of air at the surface reduced to sea level assuming a uniform lapse-rate of 6° C. per km. has also been shown, as an example. The higher temperature of the north-easterly air and the marked cooling of the shallow north-westerly current within the area of rainfall are evident. The double branch of the area of heavy rainfall during the next 24 hours (*Fig. 29b*) is accounted for by the influence of the Aravallis and Central Indian Hills in promoting convergence and deflecting the monsoon current. Owing to the absence of upper wind information, it is not possible to be definite about what took place at the heavy rainfall area in Gujarat, but presumably a moist surface layer not less than 2 km. thick had superposed on it drier north-westerly air at 3 and 4 km. and higher still north-easterly old monsoon air. Limited instability between the top of the fresh monsoon air and bottom of the old monsoon air would then occur, the source of supply of moisture for the heavy rainfall being mainly the fresh monsoon air at the surface. The low temperatures of both dry and wet bulbs at the surface after rainfall would be caused by mixing with air of less specific humidity at levels above 2 km.

On the 4th morning, the low pressure area was diffuse with centre between Jhansi and Gwalior (*Fig. 30*). The front between the fresh monsoon air and deflected monsoon air had disappeared. By next morning the depression had become still more diffuse and moved north-eastwards between Mainpuri and Cawnpore where it broke up. It is not, however, necessary to pursue the matter further. The distribution of reduced wet bulb temperature (reduced to mean sea level on the assumption that it follows the curve of saturation adiabatic)—*Fig. 31*—shows that the old monsoon air had a greater heat content at the surface.

SECTION III.

The depression of the period 13th to 23rd July, 1930.

Following the decay of the monsoon depression on the eastern side of the Aravalli between the 10th and the 11th July 1930, practically the whole of the Deccan became filled with air of continental origin at 2 and 3 km. on the 13th (*Fig. 32*). As Upper Burma and north-east India were also under the influence of westerly winds of either land origin or air which though originally coming from the sea had for some days lain over land, the rainfall over the country was confined to afternoon instability showers usually attended with thunder. The only exceptions were the Arakan and Pegu Coasts in Burma where maritime winds of 2 to 3 km. thickness were causing moderately heavy precipitation along the coastal strip. The same figure shows the areas of general rainfall during the next 24 hours.

14th July, 1930.

On the morning of the 14th the upper wind directions above 2 km. at Madras, Hyderabad and Waltair showed a marked change from some north-westerly to a westerly or west-south-westerly direction. The following table gives the directions and velocities of upper winds at Madras, Hyderabad and Waltair on the dates 13th to 17th.

TABLE 7.

Date.	Time.		Height in km.						
			0·5	1·0	2·0	3·0	4·0	5·0	6·0
Madras.	Hrs.								
13th July, 1930 .	07 14	Direction .	280	325	315	330	305	..	..
		Vel. m. p. s. .	10·5	6·5	4·5	6·5	4·5	..	..
14th July, 1930 .	07 53	Direction .	285	305	260	255	225	250	240
		Vel. m. p. s. .	10·0	7·0	6·5	6·5	6·0	5·0	7·0
15th July, 1930 .	07 21	Direction .	280	300	270	270	..	..	..
		Vel. m. p. s. .	6·5	8·5	6·5	9·5	..	..	..
16th July, 1930 .	07 58	Direction .	275	295	290	280	280	..	..
		Vel. m. p. s. .	12·0	14·0	7·5	11·0	11·0	..	..
17th July, 1930 .	07 45	Direction .	260	275	300	295	..	..	..
		Vel. m. p. s. .	17·0	19·5	10·5	9·0	..	..	..

TABLE 7—*contd.*

Date.	Time.		Height in km.						
				1·0	2·0	3·0	4·0	5·0	6·0
Hyderabad.	Hrs.		(0·76 km.)						
13th July, 1930	07 17	Direction	295	310	310	..	..	..	..
		Vel. m. p. s.	13·5	15·0	12·5	..	..	..	..
14th July, 1930	07 47	Direction	280	290	285	250	..	..	..
		Vel. m. p. s.	7·0	11·5	11·5	10·5	..	..	..
15th July, 1930	07 34	Direction	280	295	295	280	..	..	..
		Vel. m. p. s.	11·0	14·0	14·0	10·0	..	..	..
16th July, 1930	07 28	Direction	270	270	290	290	..	..	..
		Vel. m. p. s.	14·0	15·0	21·5	16·5	..	..	..
17th July, 1930	08 39	Direction	255	260	..	..	..	..	..
		Vel. m. p. s.	11·5	14·5	..	..	..	..	..
Waltair.	Hrs.		(0·5 km.)						
13th July, 1930	07 26	Direction	280	320	305	300	..	..	..
		Vel. m. p. s.	6·0	7·0	12·0	14·0	..	..	..
14th July, 1930	14 40	Direction	260	285	295	270	270	..	..
		Vel. m. p. s.	6·0	8·0	17·0	15·5	14·0	..	..
15th July, 1930	14 52	Direction	260	280	275	275	..	..	..
		Vel. m. p. s.	8·0	10·0	19·0	9·0	..	..	..
16th July, 1930	15 04	Direction	270	290	295	295	..	..	..
		Vel. m. p. s.	11·0	15·5	17·0	14·0	..	..	..
17th July, 1930	14 52	Direction	270	280	295	..	..	..	..
		Vel. m. p. s.	13·5	12·0	22·0	..	..	..	..

The trajectories of air at 2 km. reaching Akyab and Rangoon (*Fig. 33b*) make it strikingly evident that there was a strong horizontal velocity gradient off the Arakan Coast favourable for the formation of a cyclonic vortex. *Figures 33a* and *33b* also show that the region of rain and squalls in the Bay was where the accelerated air, south-westerly at the surface and westerly above, was flowing into an area previously filled with old monsoon air. It is instructive to note that there was not any large rainfall on the west coast of India on any day from the 9th to the 14th, and that although on the 14th the direction of the north-westerly air overrunning the Deccan changed to west or west-south-west, the trajectories do not suggest particularly low latitudes as origin for these currents.

15th July, 1930.

On the morning of this day, the area of squally weather had moved northward (*Fig. 34a*) and the monsoon air had begun to feed into the low over the head of the Bay. The trajectories at 2 km. of this day's morning (*Fig. 34b*) and of the previous two days show that the monsoon air was still meeting old monsoon air which had been for many days in regions where instability showers were of daily occurrence. Air from Assam and Upper Burma was being drawn in as can be seen from the trajectories of air at 2 and 3 km. at Patna and Dacca. The monsoon air was definitely cooler at the surface. A remarkable change happened in the upper winds of North-West India between the morning and the afternoon of the 15th. The winds at 2, 3 and 4 kms. which were weak and southerly in Rajputana and the west United Provinces became westerly and increased in strength. The distribution of rainfall recorded on the 16th morning and shown in *Fig. 34b* shows heavy falls on the Arakan Coast. Though the rainfall was frontal in character, it was very much influenced by orography. This is also true of the rainfall distribution in Orissa and Bihar.

16th July, 1930.

With the forced north-westerly movement of the moist air of the monsoon parallel to the Arakan Hills the depression intensified into a storm and on the morning of the 16th its centre lay a few miles north of Cox's Bazaar. The worst weather in the Bay was experienced to the south of the front marked in *Fig. 35a*. Continuous heavy rainfall occurred in the neighbourhood of the storm centre and preceded it as the monsoon current moved north-westwards under the influence of the Chin and Lushai Hills. There was also fairly concentrated heavy rainfall to the east of the Chota Nagpur Hills attended with thunder. The scattered nature of this heavy rainfall and the fact that the 2 km. wind supply at Dacca and Calcutta on the morning of the 16th were from Upper Burma travelling comparatively slowly, *Fig. 35b*, show that the falls in south-west and Central Bengal were not due to fresh monsoon air being brought in, but rather due to old monsoon air at 2 km. and above moving southward over a moister layer of local origin. It will be noticed that upper air from NW India had not begun to take part in the depression. Further west in the United Provinces and the Central Provinces, air at lower levels from the North Arabian Sea was meeting old air and causing moderately heavy precipitation attended with thunderstorms.

At 8 hours on the 16th, surface temperatures in the monsoon sector in the Bay and in Burma Coast were of the order of 78—80° F., in south Bengal 82° F. and in north Bengal 88° F.

17th July, 1930.

So far, the rainfall in Bengal was due to the overrunning of the normally moist surface layers of south Bengal by the north-easterly old monsoon air from north Burma and Assam. With the advent of a fresh air stream from the Bay of Bengal parallel to the Chin and Lushai Hills, the old monsoon air had an opportunity of meeting fresh monsoon air further to the north-east and the trajectories and rainfall drawn in *Fig. 36b* show how the heavy rainfall occurred within the monsoon air sector where the upper old monsoon air had the first opportunity of climbing it. This is a feature repeatedly made evident by these charts.

The persistent occurrence of heavy rainfall in the plains of SW Bengal to the east of the Orissa Hills is a consequence of orography which is well worthy of note.

18th July, 1930.

Both on the 17th and the 18th, three more or less distinct sectors can be recognised, (1) Monsoon Air Sector, (2) Assam Air Sector and (3) North-Westerly Air Sector. Of these (2) and (3) had little contrast (*cf.* upper winds at Allahabad and Patna) and on the 18th, with the curving round under the influence of the hills, (1) was losing its individuality. The influence exercised by the Khasi Hills in deflecting the moist cold monsoon stream is shown by the shape and position of the area of heavy rainfall during the next 24 hours (*Fig. 37b*). The old continental air from the Punjab and the air from Assam were tending to surround the monsoon air.

19th July, 1930.

No fresh monsoon air was being drawn into Bengal (*Figs. 38a* and *38b*). The area over which rain was falling at 8 hours in the morning of the 19th was practically where heavy falls had occurred during the previous 24 hours and the surface air was cooler than in the surrounding area. The upper air trajectories at Chittagong and Calcutta show that the air supply at 2 km. was old continental air with little difference in properties from the old monsoon air. At 0·5 and 1 km. it was either from north Bay or from the west. The weak front between the north-east and north-west Indian air streams was running from near the centre of the depression in a north-westerly direction to between Delhi and Agra.

To the south of Lat. 23° N., fresh westerly air from Arabian Sea was advancing eastward as shown by the 2 km. trajectory at Jubbulpore on the 18th morning and at Sambalpur on the 19th.

Heavy rainfall occurred during the next 24 hours at the following two areas: (1) At the Chota Nagpur Hills where moist air was first projected against the hill on the southern side in the lower layers followed by old monsoon air from the north-east. The orography, the backing of the hills by moist westerly air not less than 2 km. in thickness, and the incidence of upper north-easterly current over an intervening area of shallow north-westerly current were all contributory to this heavy rainfall.[5] (2) At the Vindhya Hills, where the westerly monsoon current advancing along the Narbadha valley and up to the Vindhyas was met by the north-westerly continental air current.

It is interesting to note that these two areas of heavy rainfall show themselves distinctly separate and that in the first case, the rainfall area is continued most markedly in a north-easterly direction while in the latter, it progresses in a north-westerly direction.

20th July, 1930.

The upper air observations on this day show that the surface of separation between the easterly and north-westerly air currents on the northern side of the depression was sloping upward towards the south-west (*Figs. 39a* and *39b*). As on the previous day, the heavy rainfall area during the subsequent 24 hours could be approximately divided into two—one in which the north-easterly and the other in which the north-westerly upper current was operative. As usual, these currents became effective in causing heavy rainfall only where the monsoon current exceeded a certain limiting thickness. On the 20th morning alto-stratus clouds (10) at Hoshangabad and alto-cumulus clouds (4) at Khandwa (both in the monsoon sector) were coming from the west. It will be useful here to summarise the weather at a few stations near which the centre of the depression passed.

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TABLE 8.

(The symbols for weather remarks are the same as in the India Weather Message Code, 1931.)

Date. 1930.	Time. Hrs.	Pressure. Ins.	Temperature °F. D. B.	Temperature °F. W. B.	Wind.	Low or middle cloud with direction.	Rain in previous 24 hours.	Weather Remarks.
Jubbulpore (Lat. 23° 10′ N., Long. 79° 59′ E.)								
19th July .	8	29·55	76·8	75·2	..	SK 10 NW	0·95″	r 5 to 8 hrs. Shower 15 hrs.
	17	·40	..	..	..	AK 8 NE	..	d 20 hrs. to 4 hrs. on 20th July.
20th July .	8	·44	75·4	75·0	NW 1	N 10 NW	2·21″	rr 10 to 16 hrs., r with T, L and strong wind at night.
	17	·29	74·2	74·0	WNW 3	N 10 SW	..	
21st July .	8	·37	75·4	73·8	SSE 2	SK 10 S	9·95″	d 5 to 7 hrs. and 10 hrs.
	17	·36	79·2	74·2	WSW 1	AK 8 SW	..	
Saugor (Lat. 23° 50′ N., Long. 78° 50′ E.)								
20th July .	8	·50	72·4	71·9	WNW 1	N 10 NW	1·82″	r T 1 to 7 hrs. rr° 7-30 to 20 hrs.
	17	·34	75·9	75·1	WNW 3	N 10 W	..	rr 20 to 3 hrs. on 21st.
21st July .	8	·31	73·9	73·3	ENE 2	N 10 NE	4·42″	d° 3 to 10 hrs., 15 to 19 and 23 to 3 hrs. on 22nd.
	17	·32	75·0	73·1	SW 3	N 8 SW	..	
22nd July .	8	·47	72·6	71·1	SSW 1	N 10 SW	0·05″	d° 7 to 8-30 hrs.
Neemuch (Lat. 24° 27′ N., Long. 74° 52′ E.)								
20th July .	8	·57	83·5	78·5	W 2	N 1 ? SK 3	0·13″	
	17	·43	78·0	76·0	W 3	N 2 ?	..	r 20-15 to 20-45 hrs. and 21 to 4-30 hrs. on 21st.
21st July .	8	·46	80·0	77·0	NW 2	N 2 ?	2·27″	r 10-30 to 10-45 hrs., T 19-10 to 19-15 hrs., r 18-10 to 21-05 hrs. Surface wind changed from E to W at about 18 hrs.
	17	·33	78·0	76·5	NE 4	N 2 SW	..	
22nd July .	8	·39	74·5	73·0	SW 3	N 1 SW SK 3 ?	2·72″	
	17	·35	78·0	75·0	SW 3	N 1 SW SK 1 ?	..	Light shower at 19 hrs.
Mount Abu (Lat. 24° 36′ N., Long. 72° 43′ E.)*								
21st July .	8	26·34	66·7	66·7	WSW 3	N ?	0·00″	Fog whole day, d at 15 hrs., rr from 22-30 hrs.
	17	·24	69·7	66·7	W 2	N W	..	
22nd July .	8	·24	69·7	69·7	NE 2	N NE	3·90″	rr till 6 hrs., r° 12 to 15 hrs., T at 17 hrs.
	17	·17	71·3	69·7	N 2	KN N ?	..	
23rd July .	8	·26	68·7	67·9	SE 2	..	0·76″	

* Pressures at Mount Abu are reduced to 1 km. above sea level.

TABLE 8—*contd.*

Date. 1930.	Time. Hrs.	Pressure. Ins.	Temperature °F. D. B.	Temperature °F. W. B.	Wind.	Low or middle cloud with direction.	Rain in previous 24 hours.	Weather Remarks.
Ahmedabad (Lat. 23° 02′ N., Long. 72° 38′ E.)								
21st July .	8	29·55	81·6	77·1	WSW 2	AS	0·11″	Shower at 16 hrs., rr from 17-30 hrs.
	17	·44	83·3	79·7	Calm	N SW	..	
22nd July .	8	·46	75·6	75·2	SW 3	N	2·65″	rr till 11 hrs., dd from 16-55 hrs.
	17	·39	78·5	77·5	WSW 2	N	..	
23rd July .	8	·46	76·5	75·8	SSW 2	N SW	0·32″	dd throughout day. Overcast.
	17	·46	77·7	76·7	SW 3	FrN SW	..	
Rajkot (Lat. 22° 18′ N., Long. 70° 56′ E.)								
21st July .	8	29·56	82·0	76·5	WSW 6	K 5 SW	0·00″	d° from 22 hrs.
	17	·45	87·0	75·5	WSW 6	N 10 SW	..	
22nd July .	8	·47	76·0	75·0	WSW 4	N 10 SW	3·76″	rr 3 to 9 hrs., r 9 to 17 hrs. and rr 17 to 24 hrs.
	17	·40	75·5	74·5	SSW 4	N 10 SW	..	
23rd July .	8	·46	75·5	74·5	SW 5	S 10 SW	11·36″	rr 0 to 4 hrs., d 4 to 9 hrs., d occasionally 9 to 17 hrs., d° 17 to 20 hrs.
	17	·42	81·5	77·5	SSW 5	N 10 SW	..	
Hyderabad (Sind) (Lat. 25° 23′ N., Long. 68° 24′ E.)								
22nd July .	8	29·41	84·8	81·0	Calm	N 7	0·14″	T, L previous night, 21-30 to 22-30 hrs.
	17	·32	82·2	77·8	NNW 6	KN 6	..	≡S≡ 16-40 to 17-00 hrs. rain.
23rd July .	8	·37	84·2	80·0	N 3	N	0·44″	Showers 15 to 15-40 hrs., d 21 to 24 hrs.
	17	·35	83·4	81·6	NW 1	KN	..	
24th July .	8	·53	81·6	79·4	SE 1	N	0·32″	d 0 to 5 hrs.

N.B.—Rainfall is not entered against 17 hrs. in the above Table, as rainfall was measured only once a day at 8 hrs.

At Saugor, on the morning of the 20th the temperatures of both wet and dry bulbs were comparatively low, as some showery rain accompanied by thunder had already occurred. The continuous rainfall during the day time of the 20th should be considered as warm-front rain due to the ascent of north-easterly air over the rain-cooled north-westerly. The heavy continuous rainfall on the night of the same date occurred after the westerly thicker monsoon current had arrived. On the morning of the 21st the nimbus direction was from NE and it changed later to SW. The weather at Jubbulpore on the night of the 20th, with heavy rain, strong wind and thunderstorm, and the changes of low cloud direction on the 20th and 21st suggest that the advance of the southerly or south-westerly air immediately on the eastern side of the low was in the nature of a cold front.

The behaviour of upper winds and the nature of weather experienced at Agra between the 19th and 22nd are interesting as showing the relative qualities of the north-westerly, easterly, and south-easterly air currents. Some pilot balloon trajectories on these dates are reproduced in *Fig. 43.* As will be seen from the trajectory at 6 hours on the 20th the easterly old monsoon current had come up that time at levels above 1·3 km. over Agra. There was a thunderstorm at Agra at about 15 hours on the 20th attended by a rapid fall of both dry and wet bulb temperatures (*Fig. 44*). Momentarily, the surface wind changed from N to SE and later became NW. The easterly air first came in as a moist current above 1 km ; and the instability was due to the large lapse-rate near the ground and the supply of moisture above 1 km. Once instability rain has cooled the northerly air mass and thus removed the effect of surface heating, it behaves as cold air with respect to the old monsoon air. The large fall of temperature of both dry and wet bulbs after the rainfall was obviously due to the comparative dryness of the pre-existing air. The easterly old monsoon air (*see* trajectory of 21st at 6 hours) was replaced by comparatively fresher and cooler south-easterly monsoon air by the morning of the 22nd. The fall of temperature at 23 hours on the night of the 21st may be noted.

21st July, 1930.

The warm-front between the easterly and north-westerly streams was well-developed on this day (*Figs. 40a* and *40b*). The upper wind directions at Ajmer, Lat. 26° 27′ N., Long. 74° 44′ E., on the 20th and 21st are given below :—

TABLE 9.

Date.	Time.		Height in km.							
			0·6	1·0	1·5	2·0	2·5	3·0	3·5	4·0
20th July .	16 05	Direction .	275	270	310	320	340	340	25	30
		Vel. m. p. s.	6·5	8·0	7·0	7·5	4·0	4·5	4·0	4·0
21st July .	00 16	Direction .	290	310	360	80	55	..	..	..
		Vel. m. p. s.	8·0	8·0	6·0	5·0	4·5	..	..	..

At Kotah (Lat. 25° 10′ N., Long. 75° 52′ E.) on the morning of the 21st, both strato-cumulus and alto-stratus clouds were coming from the north-east.

From the weather records at Ahmedabad and Rajkot given in *Table 9,* it will be seen that the rainfall at both those places was of the continuous warm-front type such as occurred at Saugor on the night of the 20th. Both dry and wet bulb temperatures at Mount Abu on the morning of the 22nd were higher than those on the previous days though a rainfall of 3·9″ had occurred during the preceding 24 hours. The rainfalls in Sind and Rajputana, however, were of the thunderstorm type. These suggest that, in Kathiawar, north-westerly dry upper air was not coming into conflict with monsoon air, the shallow west-north-westerly winds at Karachi and Ajmer notwithstanding. On this day, another feeble depression was developing in the north-west corner of the Bay with a feeble warm-front along a line running to the north-west from Balasore. The fact that rain was falling at places where the wind was westerly or south-westerly shows that the easterly current was ascending. It is important to notice that there was no north-westerly fresh continental air involved in the formation of this new depression.

22nd July, 1930.

The chart (*Fig. 41a*) shows that the Aravallis had the effect of concentrating the warm-front rain on itself and preventing it from extending westwards. North-easterly warm air had already arrived at Mount Abu and at upper levels it must have progressed further to the south-west. *Fig. 41b* shows that the heavy rainfall in Kathiawar occurred at the surface of convergence of this air with the fresh monsoon current. The heavy falls in Sind along the Indus were due partly to the orographic effect of the hills west of the river. The pre-existing presence of moisture at the lower levels of the Indus delta causing a cool surface layer which is usually about 1·5 km. thick at Karachi in this season was also a contributory cause. It will be noticed that the rainfall in Sind and Rajputana was mostly of thunderstorm type and this is what is to be expected considering that the previous air supply over the region was from Baluchistan and that it was into this that a moist supply of air was injected at levels of 1 and 2 km.

23rd July, 1930.

On the previous day, the depression was partly on the eastern side of the Aravallis and partly on the western side. This morning, it had entirely crossed over to the west with a front running in an east-south-easterly direction from Karachi (*Figs. 42a* and *42b*). The easterly deflected monsoon air had arrived at Quetta and, as showing the contrast between the old continental air and the easterly old monsoon air, the aeroplane temperatures and humidities obtained on this day and the previous and succeeding days at Quetta are given in *Fig. 45*. The comparative coolness and moistness of the monsoon air are evident.

It is not necessary to pursue the progress of the depressions further except to say that it was dissipated on the Baluchistan and Mekran Hills on the 24th.

In *Fig. 46* are shown in one consolidated diagram the positions of the centres of low pressure at 8 hours on each day from the 17th to the 23rd and the areas of heavy rainfall in every successive 24 hours. It shows the unsymmetrical nature of the distribution of heavy rainfall about the low pressure centre and the remarkable manner in which it is concentrated in the fresh monsoon sector in front of the lines where old monsoon or continental air attacks it.

The study of upper air conditions and of individual depressions during the monsoon leads to the following general conclusions.

(1) The formation of monsoon depressions in July and August is generally preceded by an acceleration of the monsoon air in the Deccan especially at 2 and 3 km.

(2) The Burmese mountains help to deflect this current northward and roll it up into a vortex.

(3) The air masses that initially meet are the accelerated monsoon air and old monsoon air.

(4) When near the Burma Coast, the old monsoon air is often mixed with air from Upper Burma and Siam, especially at levels above 2 km. The latter may be expected to be similar in properties to old monsoon air coming as it does from the region of rainfall of the Chinese monsoon.

(5) Squally weather and heavy rainfall occur within the monsoon sector adjacent to the place where either the old monsoon air from NE India or continental air from NW India meets monsoon air of more than 2 km. thickness ; in addition to frontal action adiabatic expansion due to large hori-

zontal gradients of pressure is an important cause of producing rainfall within the humid monsoon air mass travelling partially across the isobars towards the centre of low pressure.

(6) The main front is formed between fresh monsoon air and old monsoon air in which the former behaves as a cold air mass and the latter as a warm air mass. Fronts also form between the fresh or old monsoon air and surface heated continental air. In this case the continental air is generally warmer up to about 3 km. and colder above.

(7) Depressions retain their strength so long as there is a good supply of fresh monsoon and old monsoon air.

(8) When depressions move into Rajputana owing to the gradual replacement of old monsoon air by surface heated continental air the monsoon air rapidly gets desiccated and the depression dies down.

(9) The entry of monsoon air into Rajputana, Sind and the-N.-W. Frontier Province causes fall of temperature and increase of humidity between 1 and 3 km. and is invariably accompanied by thunderstorms.

Some general remarks regarding the properties of continental and maritime air masses involved in the storms of the Indian Seas.

A comparison of the places of origin of storms in the Indian seas and the stream lines of upper winds at 2 and 3 km. shows that storms generally originate or strengthen at places where there is the best chance for air from land to meet sufficiently deep maritime air at an angle. The atmospheric effects that will ensue as a result of the coming together of these air masses will obviously depend on their properties as regards temperature and humidity and on the circumstances of their movement. The properties of land air over India, especially over North India, change considerably during the course of the year. During winter the continental air that drains into the Bay of Bengal is cooler and drier than the maritime air that enters the south of the Bay from the east and in the storms that form in this season, the continental air behaves as cold air mass and the maritime air as warm air mass at all levels from the surface up to at least 6 or 8 km.[9] Conditions are partially altered in the pre-monsoon months, April, May and part of June. Owing to the differential heating of land and sea, the air over land has in its lower layers a higher temperature than that over sea, but as this is accompanied by a larger lapse-rate near the ground, the temperature conditions get reversed at higher levels. In the storms of this season, therefore, the continental air behaves as " warm air " at the surface and as " cold air " at higher levels, generally above 2 or 3 km. There is a still further change in the air over the major portion of North India during the monsoon months July and August. Except in North-West India, the air over North India is generally old monsoon air—that is air which for the most part originally came into the country as fresh monsoon air but whose temperature and moisture content in its higher layers have been increased owing to precipitation and insolation. Although at the surface the relative humidity of this air is smaller than that of fresh monsoon air, in consequence of its higher

[9] K. R. Ramanathan and A. A. Narayana Iyer: Ind. Met. Dept., Sc. Notes, Vol. III, No. 18, 1930; and S. Mal and B. N. Desai: Ind. Met. Dept., Sc. Notes, Vol. IV, No. 39, 1931.

temperature the absolute humidity is higher. If therefore extensive cloud formation can occur in this air mass below the level at which its temperature would otherwise become equal to that of the fresh monsoon air, the old monsoon air would acquire above the condensation level a lapse-rate approaching that of saturation adiabatic and behave as a warm air mass with respect to fresh monsoon air. Indeed, it is known from the results of sounding balloon ascents at Agra that, during July and August, the height-temperature curve there follows closely the curve of saturation adiabatic and that even between 2 and 4 kms. the lapse-rate is only 4·5°C. km.[10] This picture, however, of old monsoon air ascending over fresh monsoon air at a warm-front in the depressions of the monsoon season is too simple. There is often intercalated between the fresh and old monsoon airs a comparatively drier air stream of surface-heated continental air from NW India. The continental air behaves at levels of 2—4 km.*

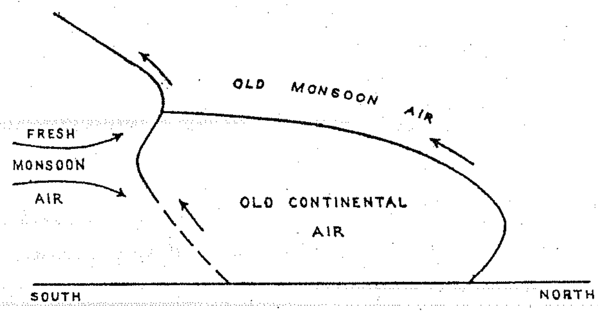


FIG. 47. SCHEMATIC DIAGRAM SHOWING STRUCTURE OF MONSOON DEPRESSION WHEN OVER CENTRAL INDIA.

as cold air with respect to old monsoon air, and if rain has already fallen within it, at lower levels also. We have no definite information as to the level to which high humidity extends in the fresh monsoon stream or the level at which the continental air would begin to behave as cold air mass towards fresh monsoon air, but it may be expected to be higher than in the case of old monsoon air. A vertical section of the composite front such as often forms over Central India in connection with monsoon depressions is shown in *Fig. 47*. It is obvious that more extended upper air observations of both temperature and humidity are much needed for the elucidation of many important points.

We wish to acknowledge our thanks to Mr. A. Narayanan for his help in the preparation of normal wind data for the stream-line diagrams and to Messrs. S. S. Kohli and L. V. Joshi for help in the preparation of detailed rainfall maps.

Our thanks are also due to Mr. S. Basu and Dr. S. C. Roy for their helpful criticisms.

[10] K. R. Ramanathan, " Sounding Balloon Ascents at Agra ", Mem. Ind. Met. Dep., Vol. 25, Part 5, 1930.

* As already remarked, this height is liable to variation depending on the recent history of the continental air mass.

Explanation of symbols used in the charts of weather at 8 hrs. and of history of upper air movements.

(a) *Weather charts.*

Wind velocity.

The number of feathers in the wind arrows represents the Beaufort number of the wind, *e.g.*,

Beaufort No. 1

„ „ 2

„ „ 3

„ „ 4

Winds at 0·5 Km. at pilot balloon stations, at surface at hill stations of nearly 0·5 Km. height, and at sea are represented by full arrows; those at surface at plain stations by broken arrows.

Fronts.

Well marked front.

Diffuse front.

Region where rain was falling at the time of observations.

(b) *Upper air movement charts.*

Trajectories of air movement at

1 Km.

2 Km.

3 Km.

4 Km.

Amount of rain in next 24 hrs.

<0·5″

0·5″-2·0″

2·0″-4·0″

>4·0″

Remarks about weather during next 24 hrs.

T Thunder

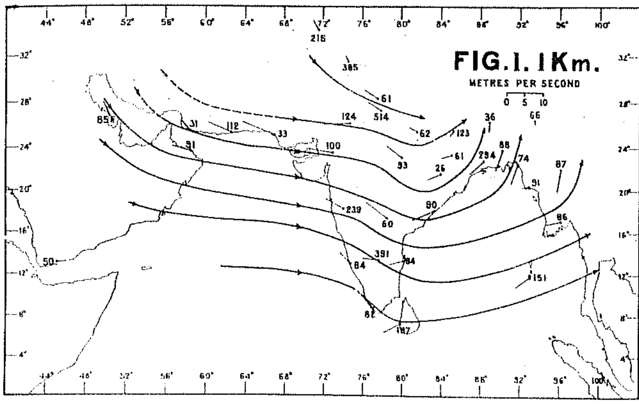
Lightning.

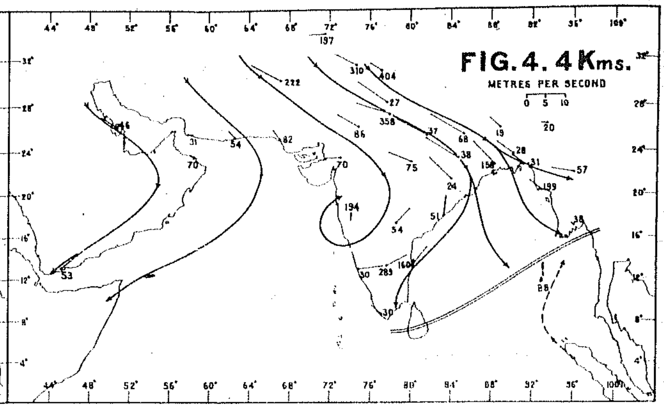
Thunderstorm.

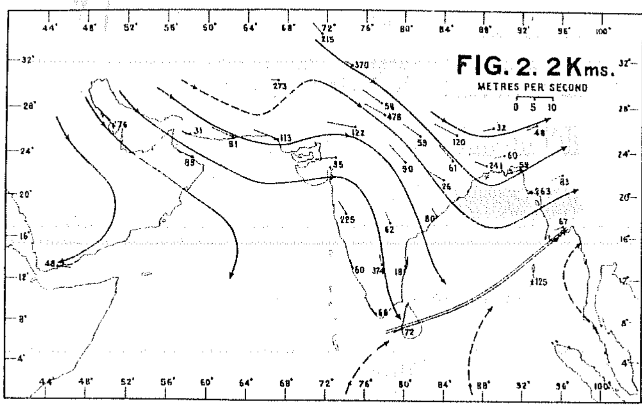
N.B.—Positions of fronts at 2 Km. are marked on these charts on a few days.

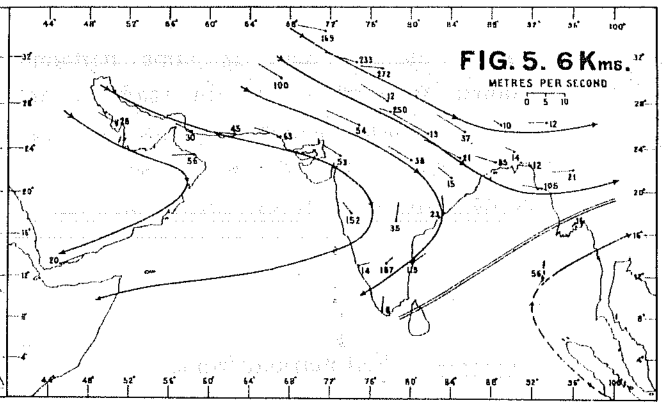
MGIPC—M 4-9-33—350.

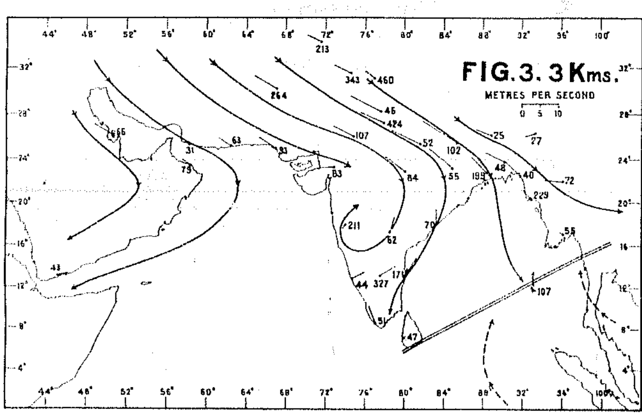
NORMAL WINDS AND STREAM LINES OVER INDIA IN MAY

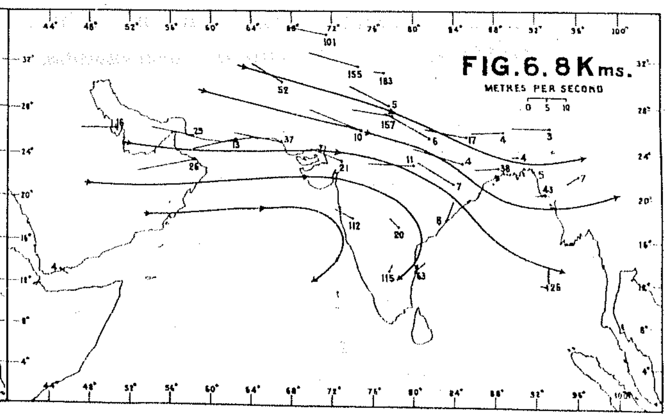












NORMAL WINDS AND STREAM LINES OVER INDIA IN JUNE

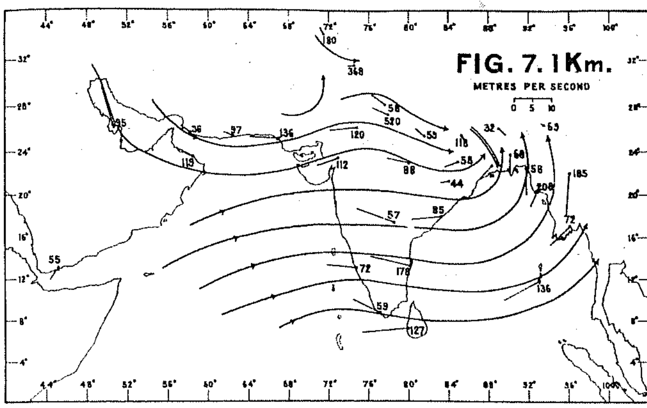


FIG. 7. 1Km.

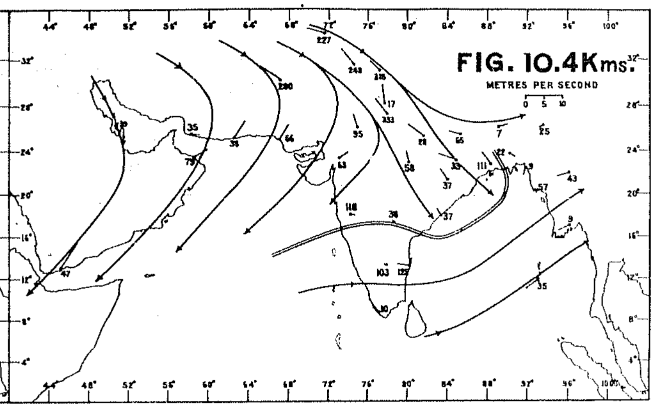


FIG. 10. 4Kms.

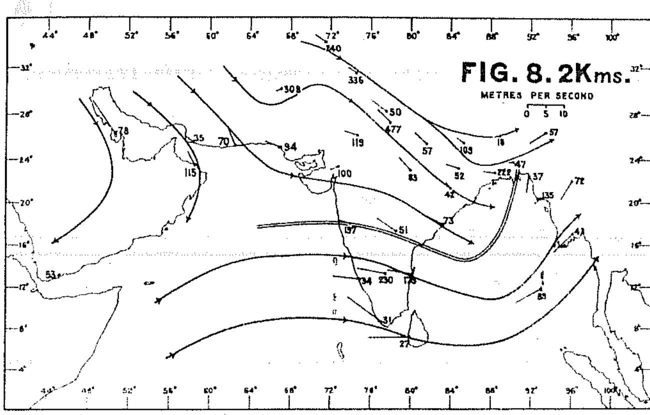


FIG. 8. 2Kms.

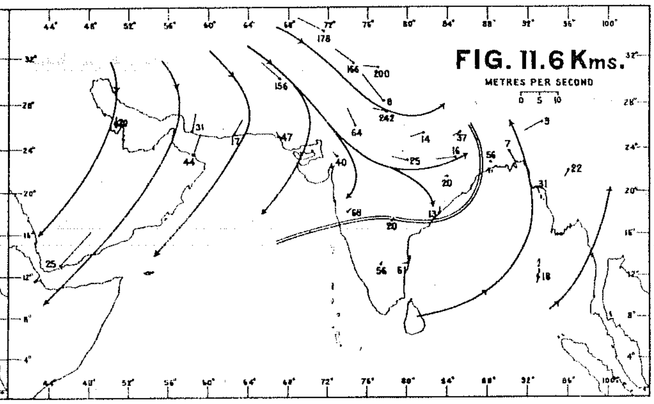


FIG. 11. 6 Kms.

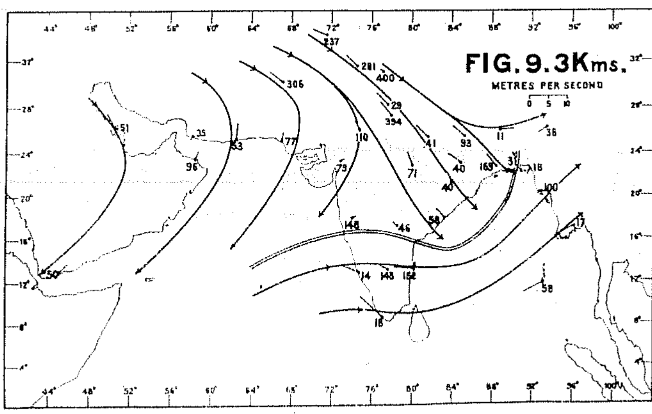


FIG. 9. 3Kms.

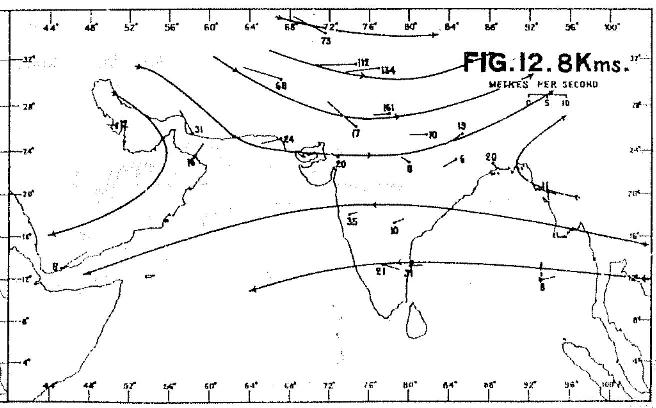


FIG. 12. 8Kms.

NORMAL WINDS AND STREAM LINES OVER INDIA IN JULY

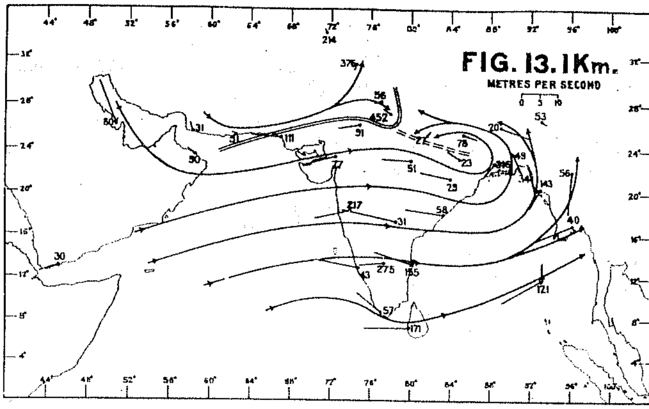


FIG. 13. 1 Km.

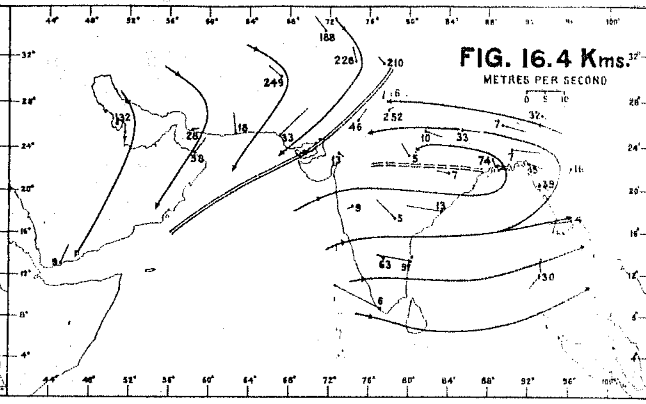


FIG. 16. 4 Kms.

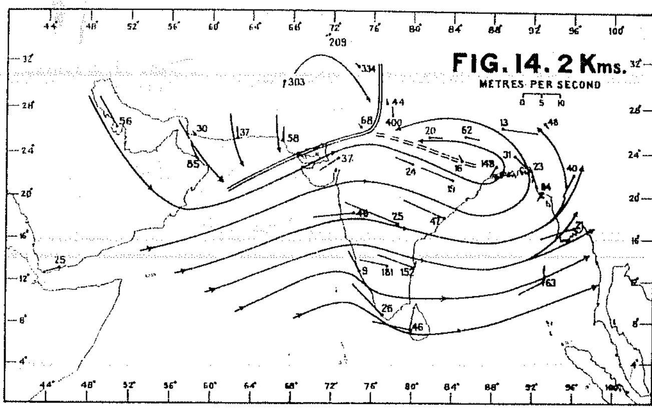


FIG. 14. 2 Kms.

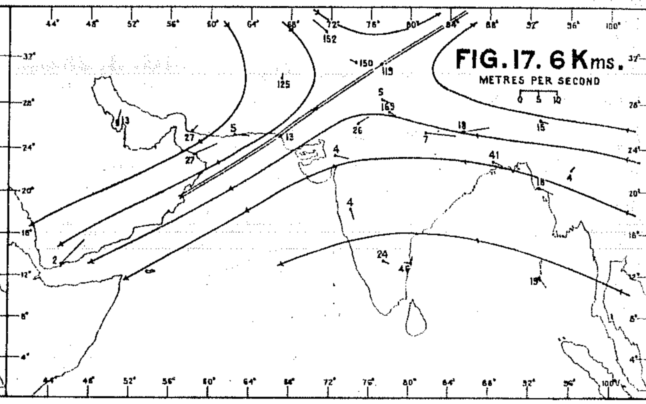


FIG. 17. 6 Kms.

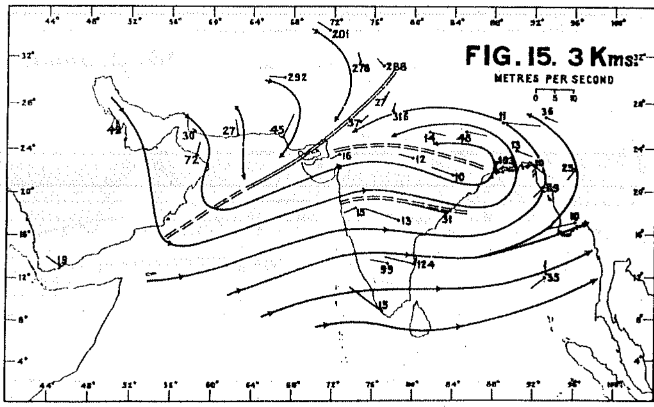


FIG. 15. 3 Kms.

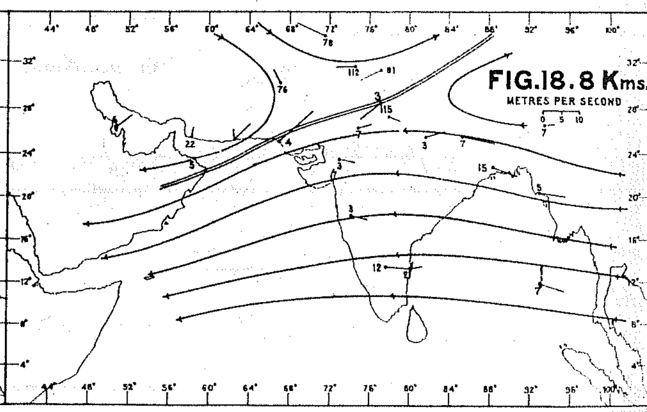


FIG. 18. 8 Kms.

G.P.Z.O. Poona, 1933.

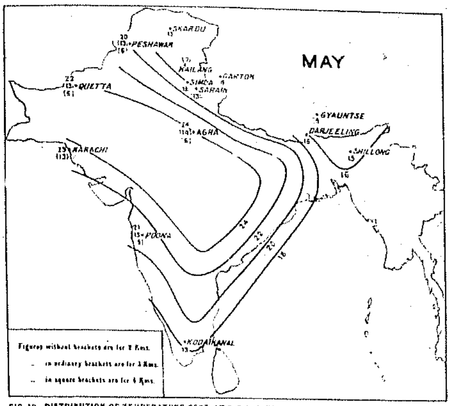


FIG. 19. DISTRIBUTION OF TEMPERATURE [°C] AT 2, 3 & 4 KMS OVER INDIA AND ITS NEIGHBOURHOOD. (ISOTHERMS REFER TO 2 KMS.)

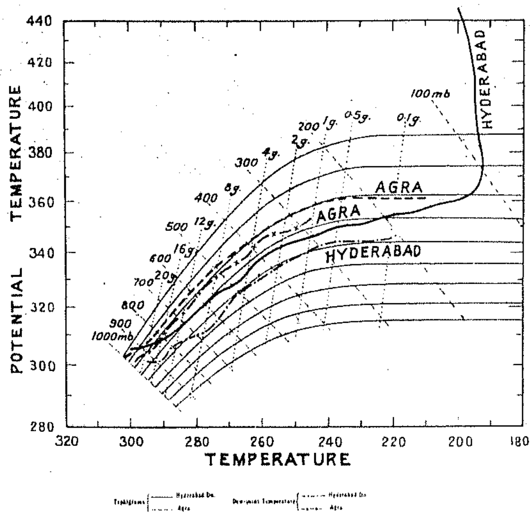


FIG. 22. TEPHIGRAMS AND DEW-POINT TEMPERATURE DIAGRAMS REPRESENTING MEAN CONDITIONS OVER AGRA AND HYDERABAD (DECCAN) IN JULY.

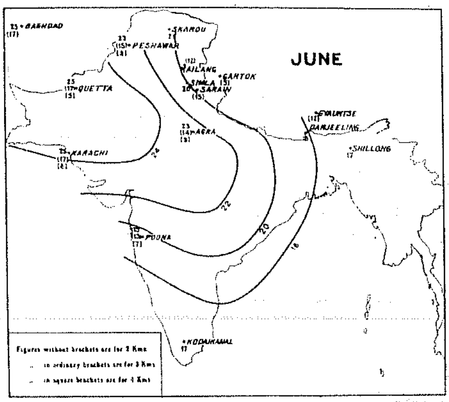


FIG. 20. DISTRIBUTION OF TEMPERATURE [°C] AT 2, 3 & 4 KMS OVER INDIA AND ITS NEIGHBOURHOOD. (ISOTHERMS REFER TO 2 KMS.)

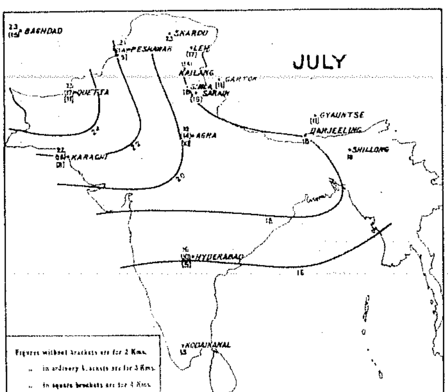
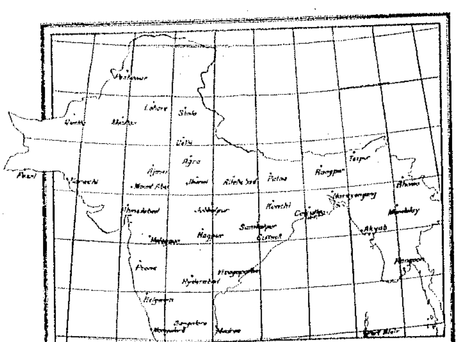


FIG. 21. DISTRIBUTION OF TEMPERATURE [°C] AT 2, 3 & 4 KMS OVER INDIA AND ITS NEIGHBOURHOOD. (ISOTHERMS REFER TO 2 KMS.)



MAP SHOWING THE POSITIONS OF SELECTED METEOROLOGICAL STATIONS.

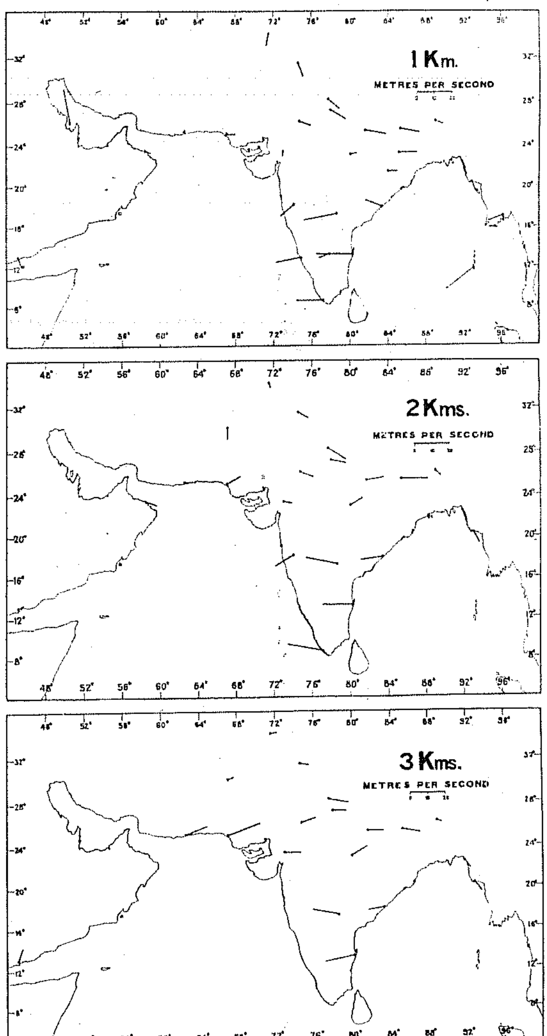


FIG. 23. UPPER WINDS AT 1, 2 AND 3 KMS. ON THE MORNING OF 27-6-1930.

G.P.Z.O. POONA, 1933.

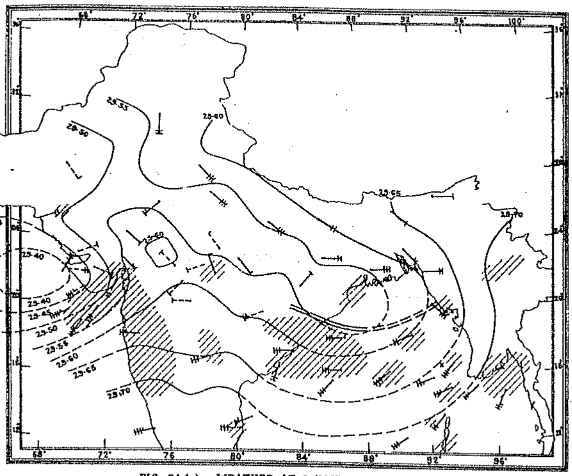


FIG. 24 (a). WEATHER AT 8 HOURS ON 28-6-1930.

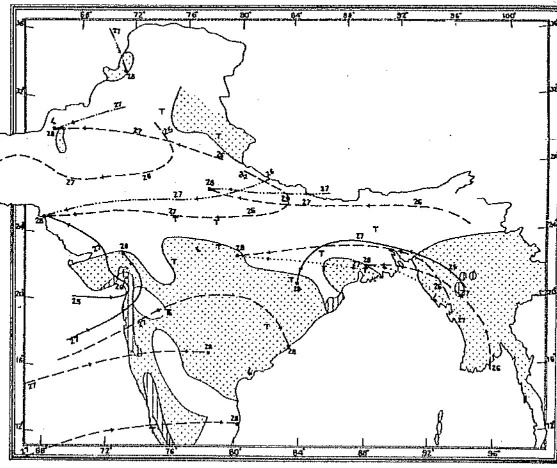


FIG. 24 (b). HISTORY OF UPPER AIR MOVEMENT AT 8 HOURS ON 28-6-1930 AND RAINFALL DURING NEXT 24 HOURS.

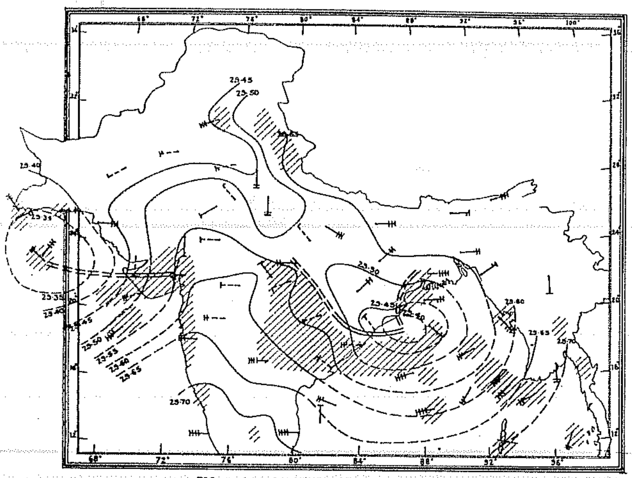


FIG. 25 (a). WEATHER AT 8 HOURS ON 29-6-1930.

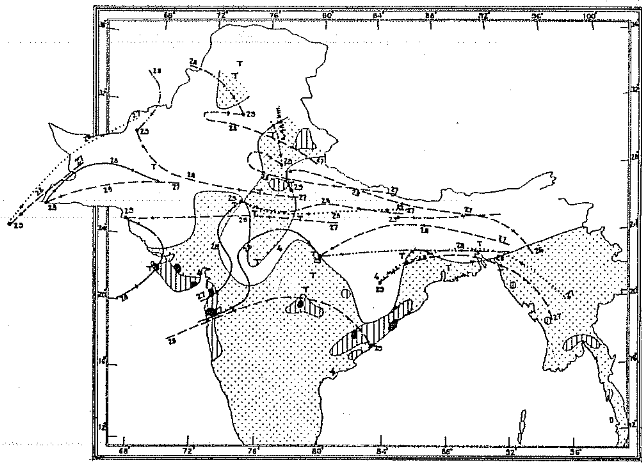


FIG. 25 (b). HISTORY OF UPPER AIR MOVEMENT AT 8 HOURS ON 29-6-1930 AND RAINFALL DURING NEXT 24 HOURS.

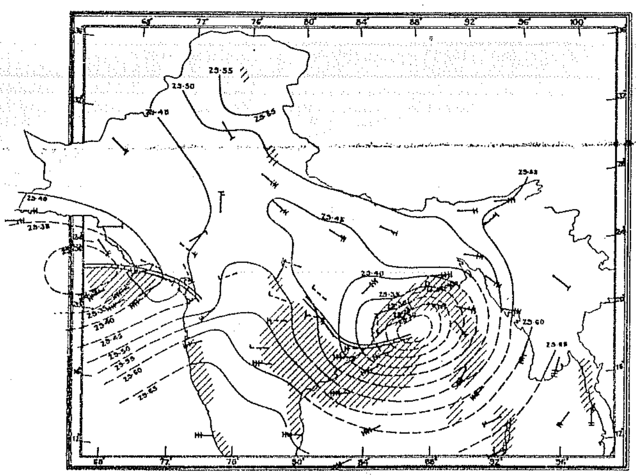


FIG. 26 (a). WEATHER AT 8 HOURS ON 30-6-1930.

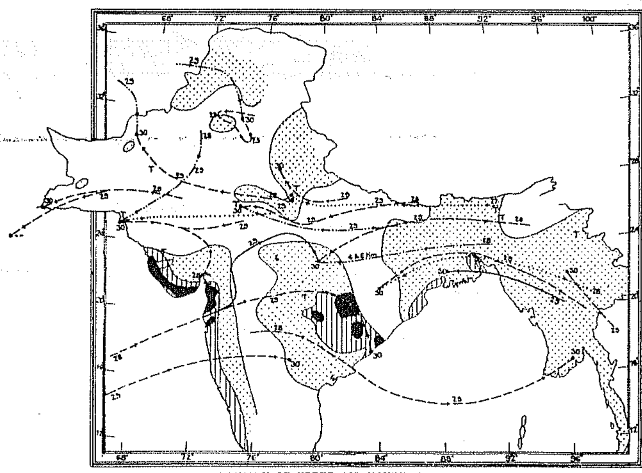


FIG. 26 (b). HISTORY OF UPPER AIR MOVEMENT AT 8 HOURS ON 30-6-1930 AND RAINFALL DURING NEXT 24 HOURS.

G.P.Z.O. POONA, 1933.

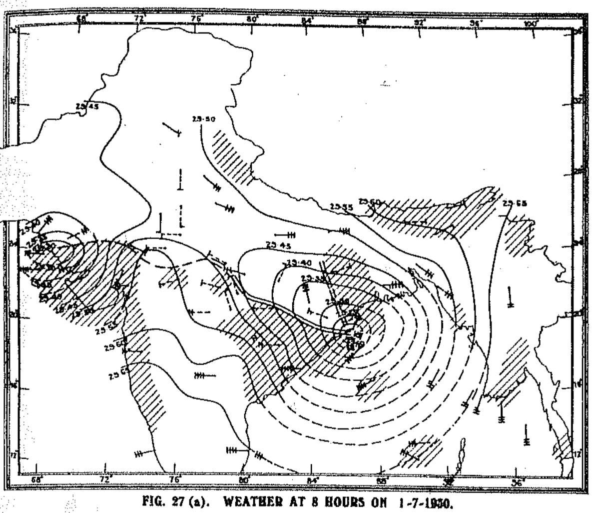


FIG. 27 (a). WEATHER AT 8 HOURS ON 1-7-1930.

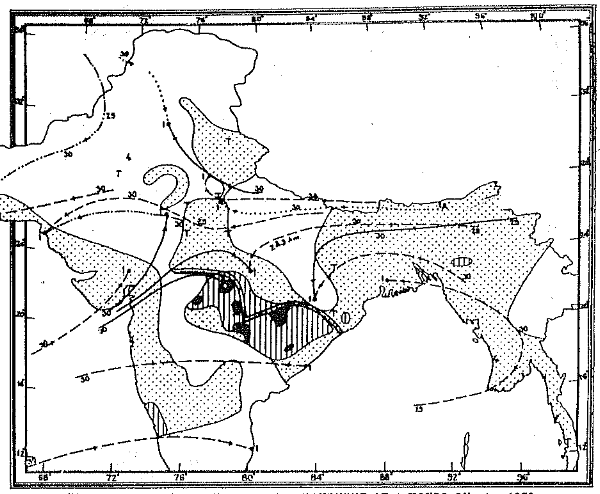


FIG. 27 (b). HISTORY OF UPPER AIR MOVEMENT AT 8 HOURS ON 1-7-1930 AND RAINFALL DURING NEXT 24 HOURS.

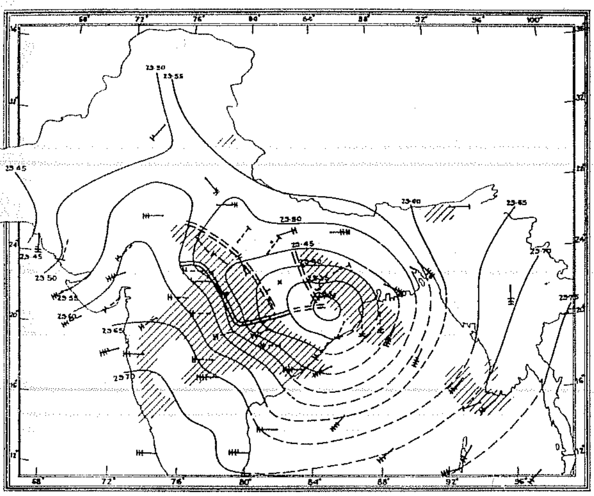


FIG. 28 (a). WEATHER AT 8 HOURS ON 2-7-1930.

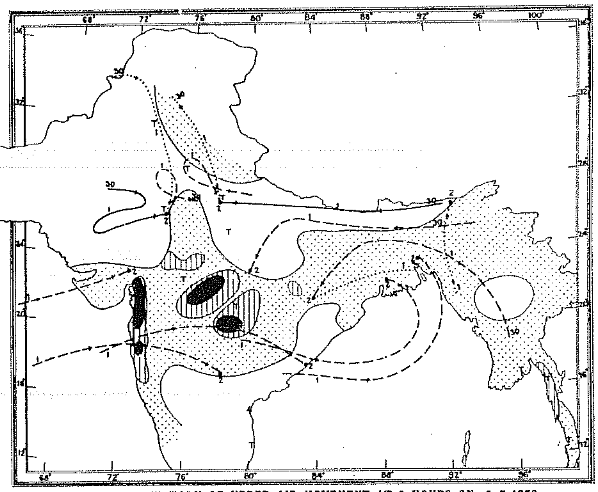


FIG. 28 (b). HISTORY OF UPPER AIR MOVEMENT AT 8 HOURS ON 2-7-1930 AND RAINFALL DURING NEXT 24 HOURS.

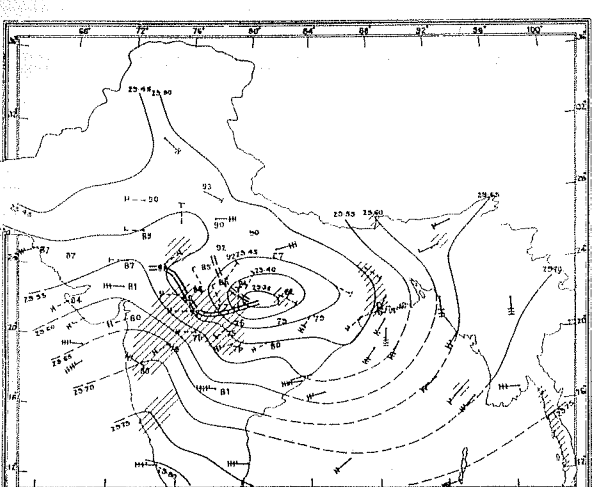


FIG. 29 (a). WEATHER AT 8 HOURS ON 3-7-1930.

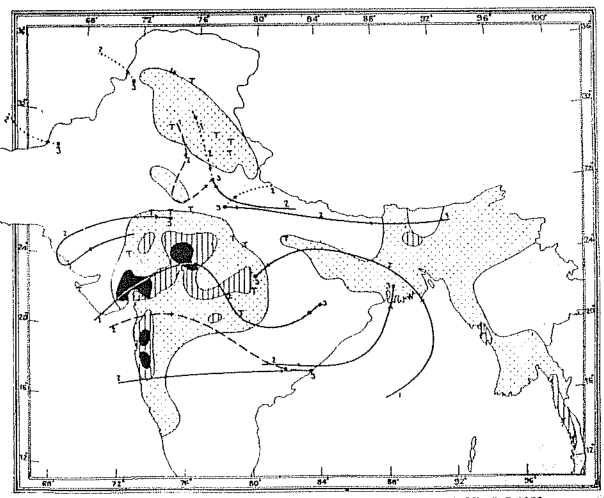


FIG. 29 (b). HISTORY OF UPPER AIR MOVEMENT AT 8 HOURS ON 3-7-1930 AND RAINFALL DURING NEXT 24 HOURS.

G.P.Z.O. Poona, 1933.

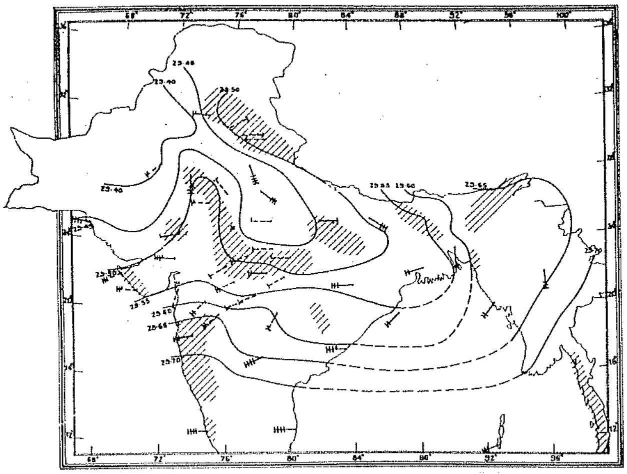


FIG. 30 (a). WEATHER AT 8 HOURS ON 4-7-1930.

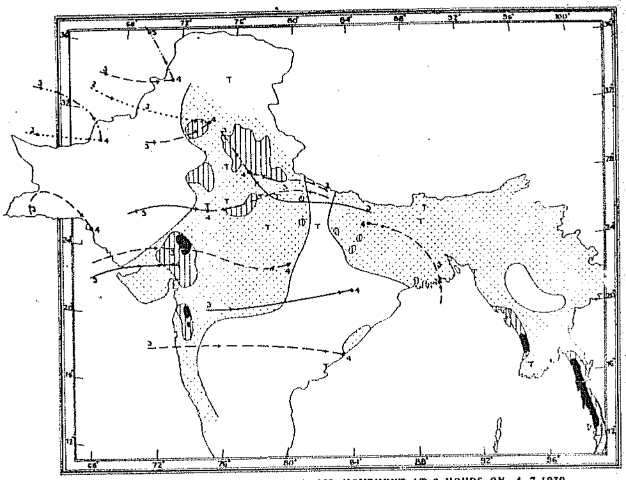


FIG. 30 (b). HISTORY OF UPPER AIR MOVEMENT AT 8 HOURS ON 4-7-1930 AND RAINFALL DURING NEXT 24 HOURS.

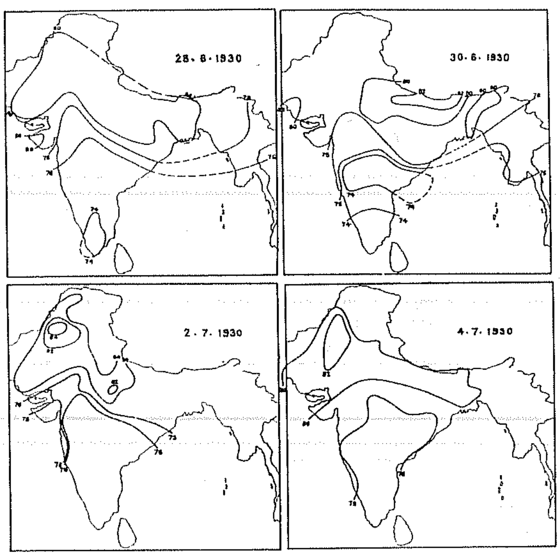


FIG. 31. DISTRIBUTION OF WET BULB TEMPERATURE IN °F ON 28 & 30-6-1930 & 2 & 4-7-1930 (REDUCED TO SEALEVEL ON THE ASSUMPTION THAT IT VARIES WITH HEIGHT AS THE CURVE OF SATURATION ADIABATIC).

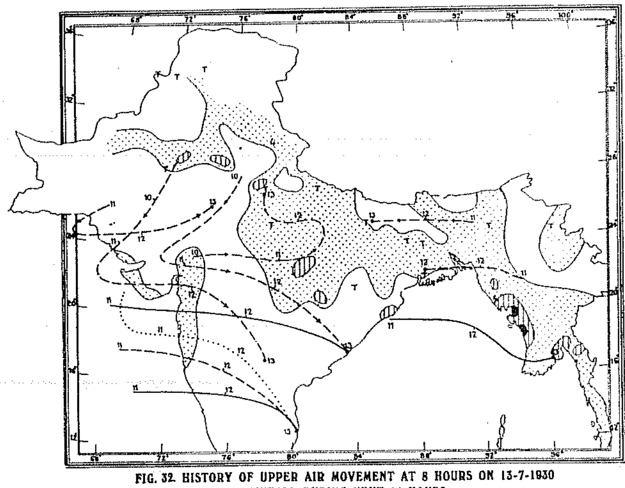


FIG. 32. HISTORY OF UPPER AIR MOVEMENT AT 8 HOURS ON 13-7-1930 AND RAINFALL DURING NEXT 24 HOURS.

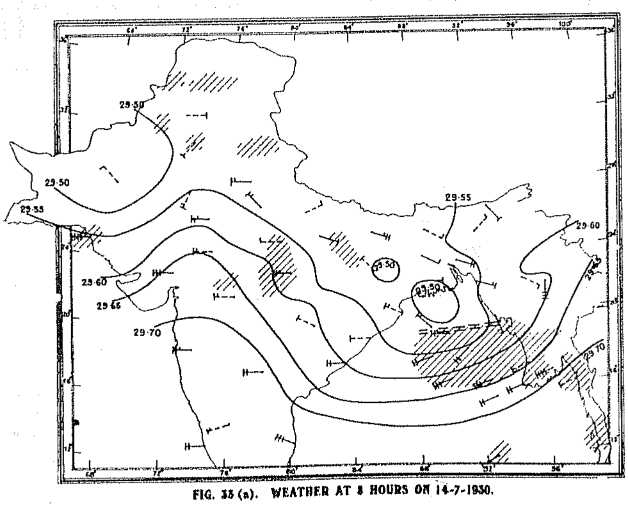


FIG. 33 (a). WEATHER AT 8 HOURS ON 14-7-1930.

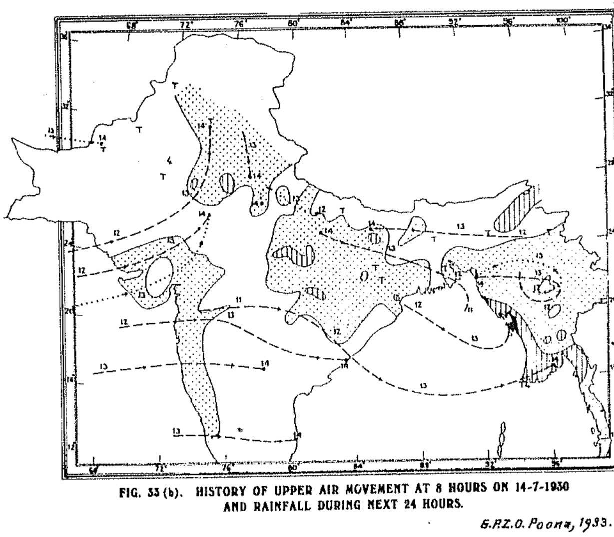


FIG. 33 (b). HISTORY OF UPPER AIR MOVEMENT AT 8 HOURS ON 14-7-1930 AND RAINFALL DURING NEXT 24 HOURS.

G.P.Z.O. Poona, 1933.

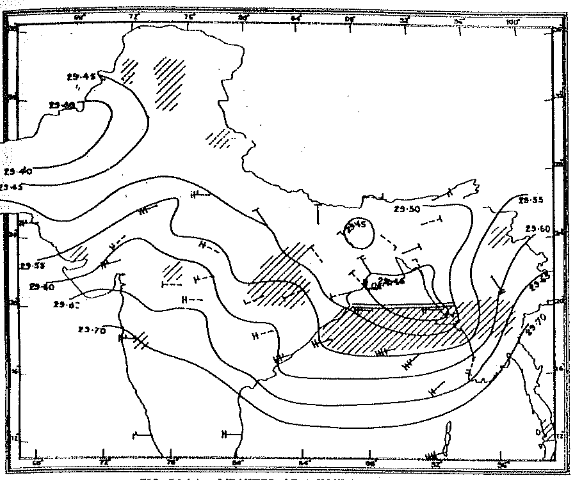


FIG. 34 (a). WEATHER AT 8 HOURS ON 15-7-1930.

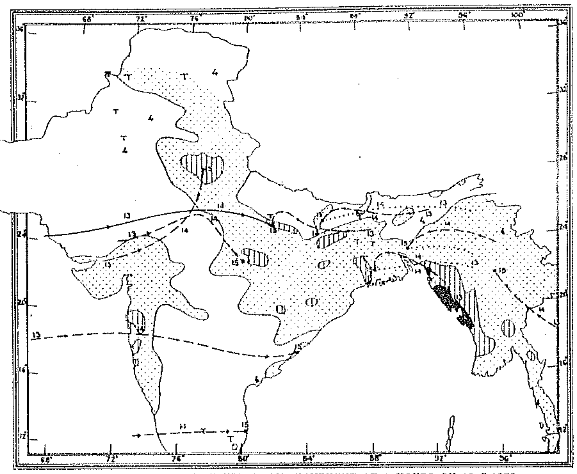


FIG. 34 (b). HISTORY OF UPPER AIR MOVEMENT AT 8 HOURS ON 15-7-1930 AND RAINFALL DURING NEXT 24 HOURS.

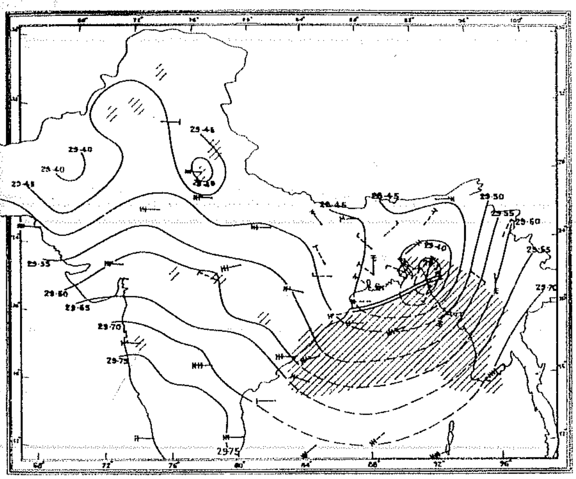


FIG. 35 (a). WEATHER AT 8 HOURS ON 16-7-1930.

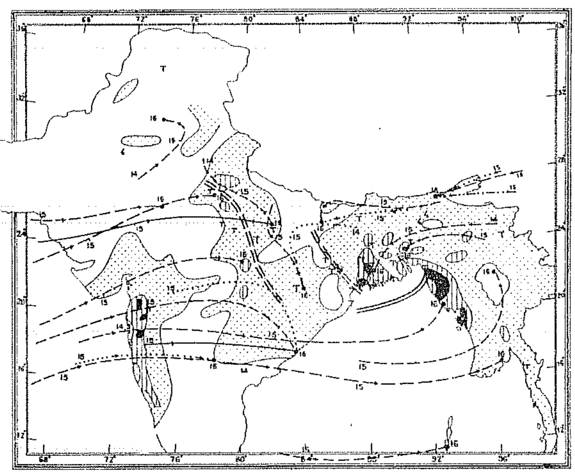


FIG. 35 (b). HISTORY OF UPPER AIR MOVEMENT AT 8 HOURS ON 16-7-1930 AND RAINFALL DURING NEXT 24 HOURS.

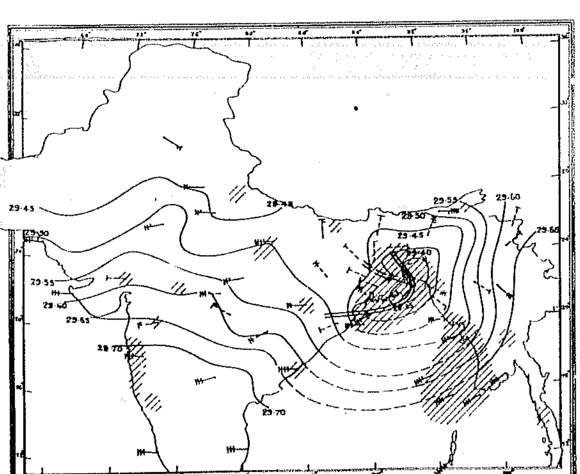


FIG. 36 (a). WEATHER AT 8 HOURS ON 17-7-1930.

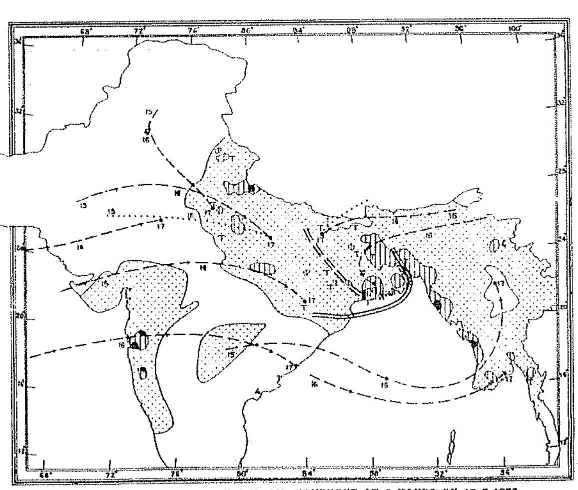


FIG. 36 (b). HISTORY OF UPPER AIR MOVEMENT AT 8 HOURS ON 17-7-1930 AND RAINFALL DURING NEXT 24 HOURS.

G.P.Z.O. Poona, 1933.

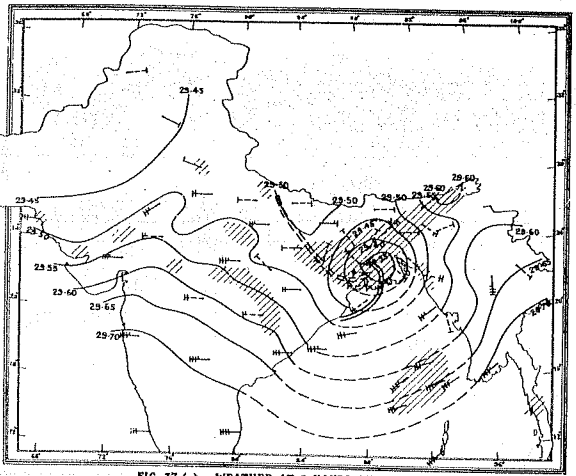


FIG. 37 (a). WEATHER AT 8 HOURS ON 18-7-1930

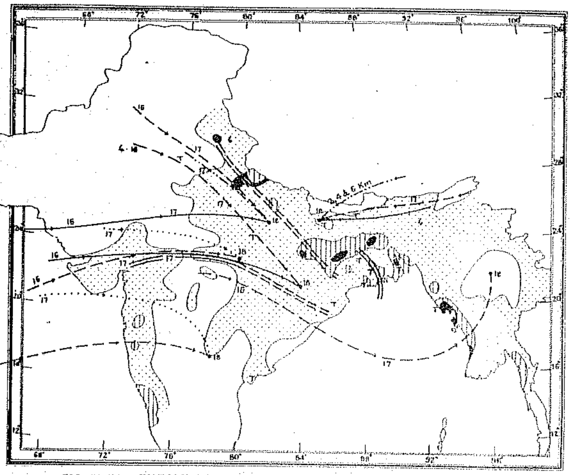


FIG. 37 (b). HISTORY OF UPPER AIR MOVEMENT AT 8 HOURS ON 18-7-1930 AND RAINFALL DURING NEXT 24 HOURS.

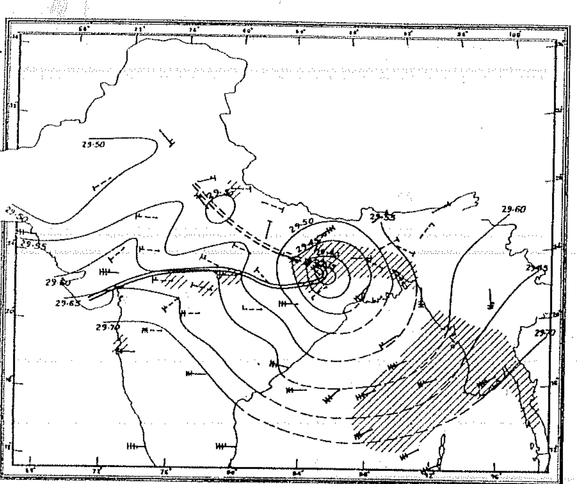


FIG. 38 (a). WEATHER AT 8 HOURS ON 19-7-1930

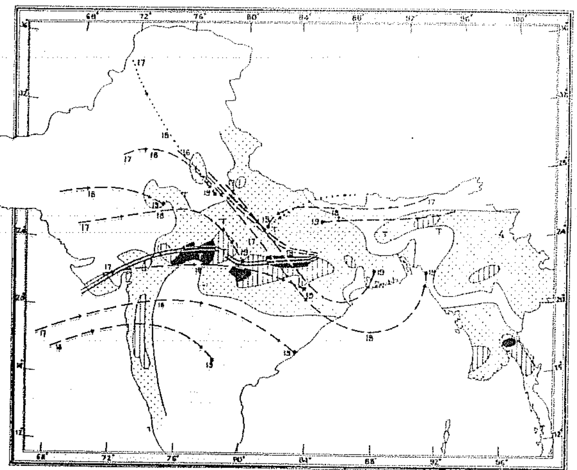


FIG. 38 (b). HISTORY OF UPPER AIR MOVEMENT AT 8 HOURS ON 19-7-1930 AND RAINFALL DURING NEXT 24 HOURS.

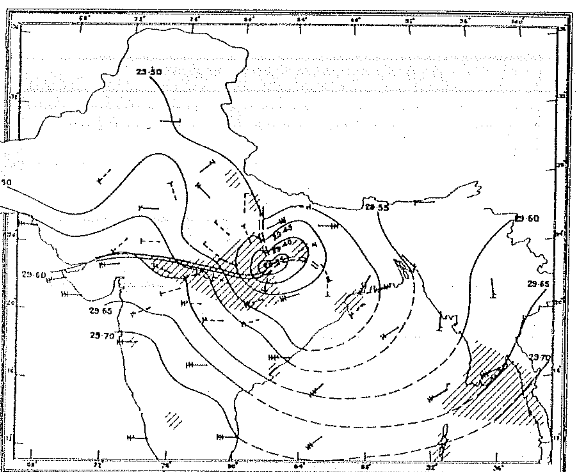


FIG. 39 (a). WEATHER AT 8 HOURS ON 20-7-1930

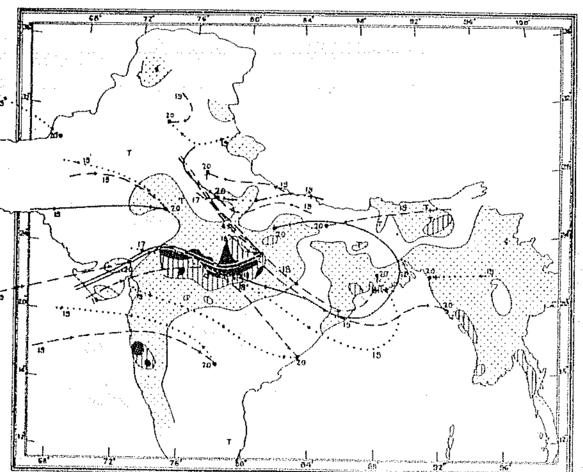


FIG. 39 (b). HISTORY OF UPPER AIR MOVEMENT AT 8 HOURS ON 20-7-1930 AND RAINFALL DURING NEXT 24 HOURS.

G.P.Z.O. Poona, 1933.

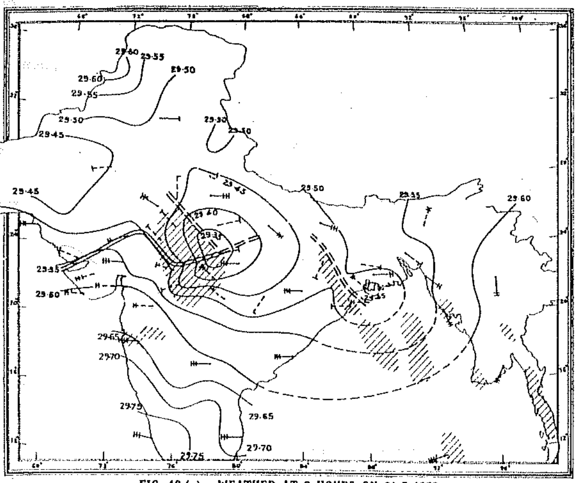


FIG. 40 (a). WEATHER AT 8 HOURS ON 21-7-1930.

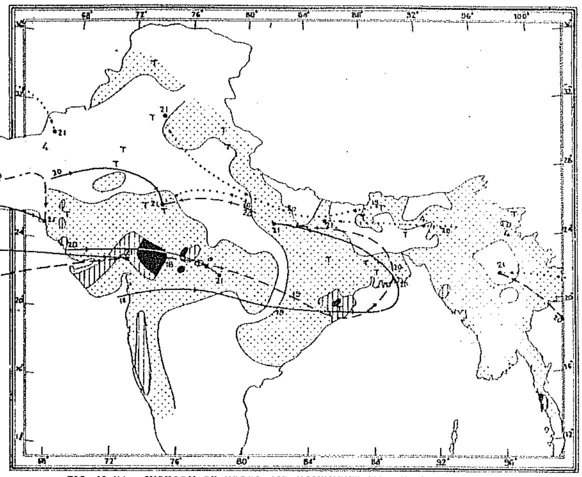


FIG. 40 (b). HISTORY OF UPPER AIR MOVEMENT AT 8 HOURS ON 21-7-1930 AND RAINFALL DURING NEXT 24 HOURS.

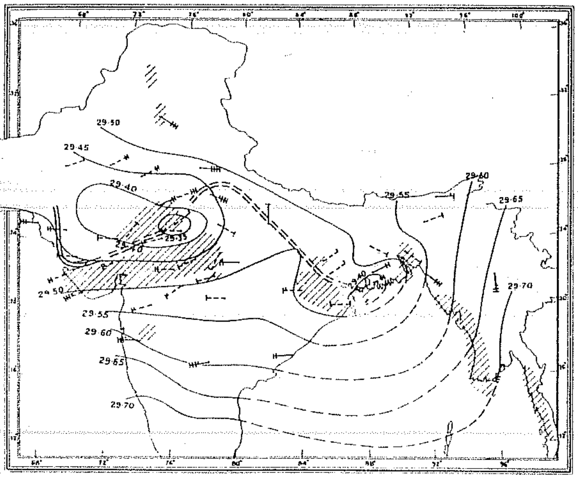


FIG. 41 (a). WEATHER AT 8 HOURS ON 22-7-1930.

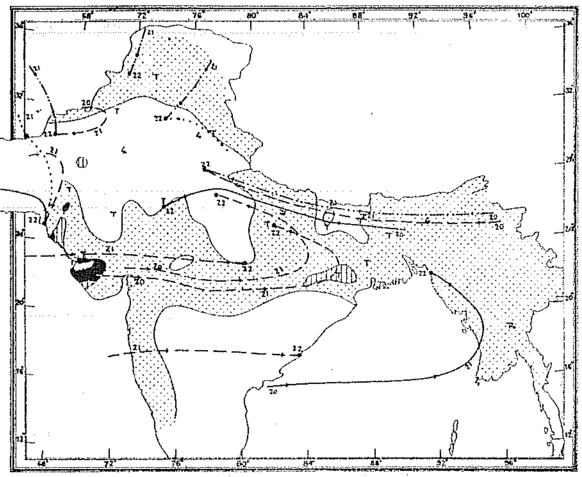


FIG. 41 (b). HISTORY OF UPPER AIR MOVEMENT AT 8 HOURS ON 22-7-1930 AND RAINFALL DURING NEXT 24 HOURS.

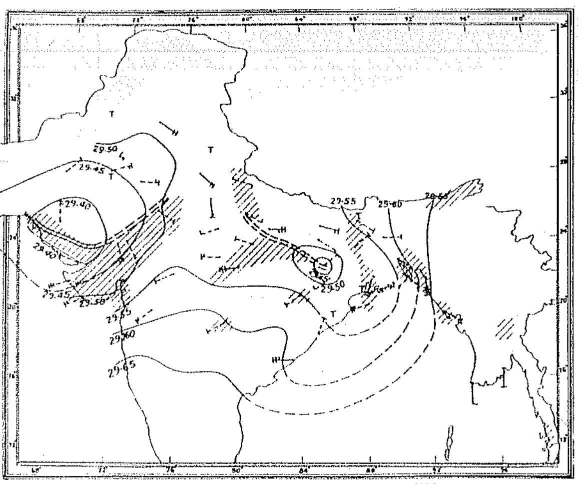


FIG. 42 (a). WEATHER AT 8 HOURS ON 23-7-1930.

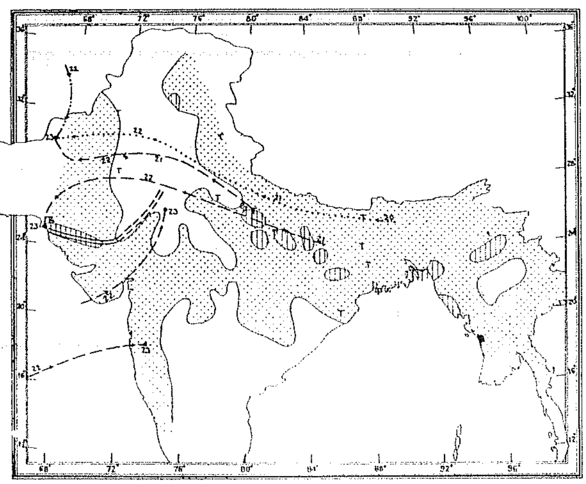


FIG. 42 (b). HISTORY OF UPPER AIR MOVEMENT AT 8 HOURS ON 23-7-1930 AND RAINFALL DURING NEXT 24 HOURS.

G.P.Z.O. Poona, 1933.

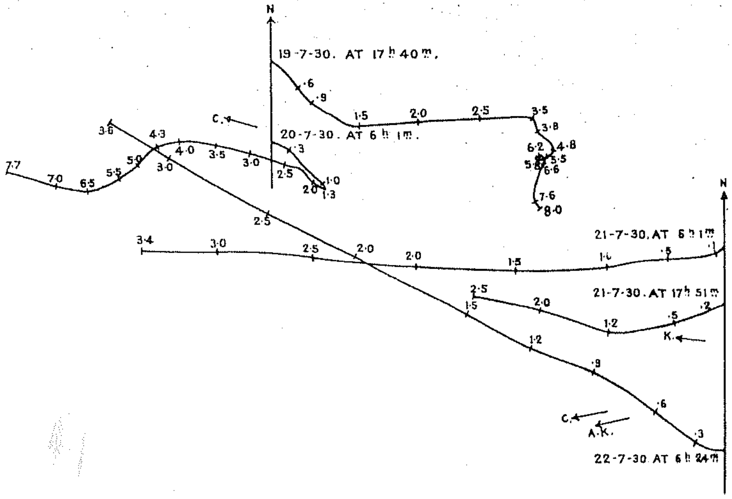


FIG. 43. PILOT BALLOON TRAJECTORIES AT AGRA.

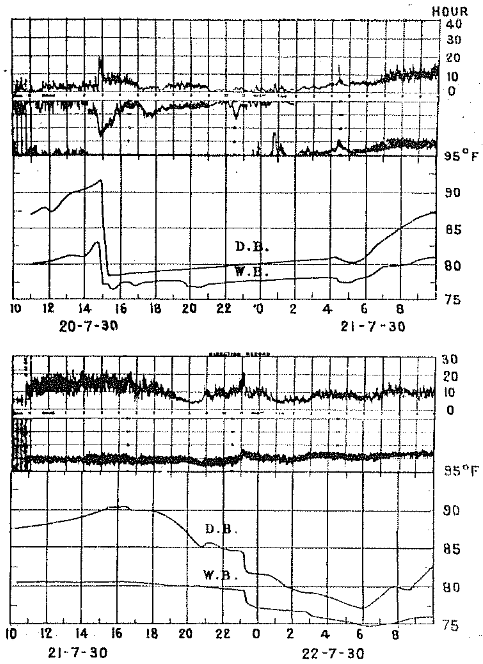


FIG. 44. WIND VELOCITIES & DIRECTIONS & DRY & WET BULB TEMPERATURES AT AGRA ON 20 TO 22-7-1930.

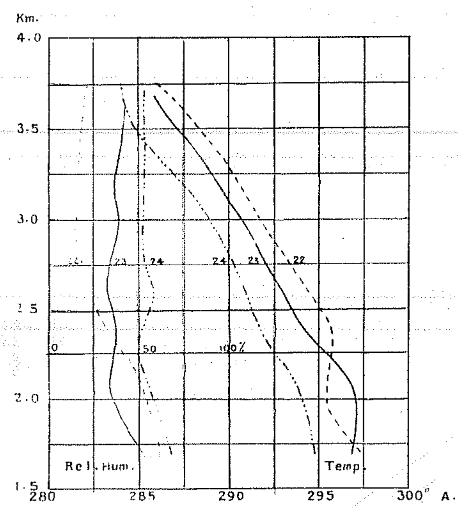
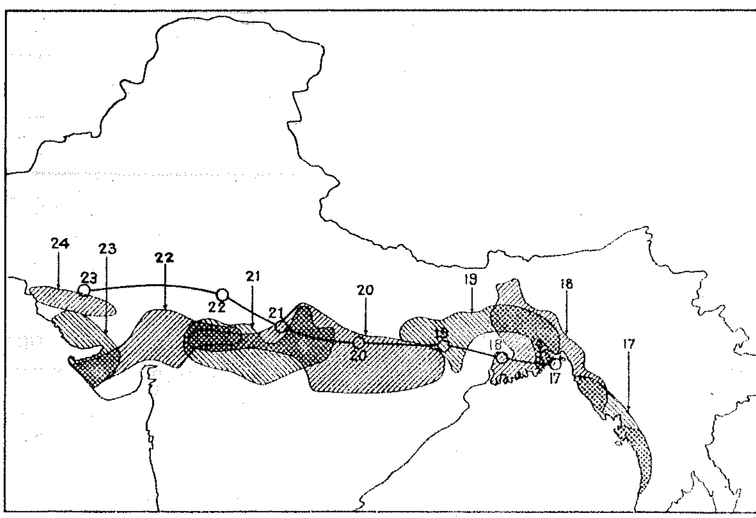


FIG. 45. UPPER AIR TEMPERATURES AND HUMIDITIES AT QUETTA ON 22, 23 & 24-7-1930. (EROPLANE ASCENTS)



Chief areas of heavy rainfall during past 24 hrs. recorded at 8 hrs. on 17, 19, 21 & 23-7-1930.

" " " " " " " " " " " 18, 20, 22 & 24-7-1930.

○ Positions of centre of depression at 8 hrs. on the respective dates.

FIG. 46. TRACK OF CENTRE OF LOW PRESSURE AND AREAS OF HEAVY RAINFALL ON EACH DAY FROM 17 TO 24-7-1930.

G.P.Z.O. Poona, 1933.