551. 513
551. 587 (54)

THE GENERAL CIRCULATION OF THE ATMOSPHERE OVER INDIA AND ITS NEIGHBOURHOOD.

BY

K. R. Ramanathan and K. P. Ramakrishnan.

(Received 21st December 1937).

Summary.—The paper gives charts of mean air movement in each month over the Indian region at different heights up to 8 km derived from observations of pilot balloons at the observatories of the India Meteorological Department. As complementary to the charts of pilot balloon winds, which refer mainly to days of clear weather, charts of movement of low, medium and high clouds are also given for five months. Upper air temperatures deduced from the change of wind with height are also shown on the charts. The charts for the lower levels contain as insets wind-roses for selected stations.

The chief features of the upper wind and temperature distribution in each month are described and their relation to the major climatological features such as monsoons and storms are pointed out. Some of the points discussed are :—

(i) the boundaries between easterly and westerly winds in different months of the year,
(ii) the influence of the Himalayas and adjacent mountain ranges on the circulation,
(iii) the increase of temperature in the upper levels over regions of heavy rainfall, and
(iv) the greater northward movement of air in cloudy weather than in clear weather.

Tables of resultant and predominant winds as well as frequencies of directions of cloud movement are appended.

Introduction.

A discussion of the upper air movement in the Indian monsoons and its relation to the general circulation of the atmosphere was made in 1921 by Harwood[1]. Since then, much new knowledge of the upper atmosphere in India both as regards winds and thermal conditions has accumulated, and particular aspects of the question of atmospheric circulation have been considered in a few departmental publications.[2 to 5] An important contribution has also come from Wagner.[6] In the present paper, a more complete survey of the whole problem is attempted with special reference to the gradual development of conditions from month to month. For the purpose of this discussion, charts of monthly mean stream-lines have been prepared from pilot balloon data for the levels 1, 2, 3, 4, 6 and 8 km. These have been supplemented by charts of frequencies of wind at different levels, of frequencies of direction of movement of low, medium and high clouds and of upper air isotherms which have been computed from the variation of pilot balloon winds with height.

Monthly mean stream-line charts.

The monthly mean resultant winds at a number of levels over each pilot balloon station under the India Meteorological Department are published annually. The resultant winds in each month used in preparing the wind charts given here are the means of all the morning observations till the end of 1931 or 1934. Data up to the end of 1931 only

B 2

Mem. Ind. Met. Dept. 26(10), 189–245, 1939.

have been used for the older stations ; for those started in 1926 or after, data up to the end of 1934 have been used. The resultant monthly directions (D) and velocities (v) and the average speeds irrespective of direction (V) together with the number of observations (n) at each level are tabulated in *Appendix A*.* The relative values of V and v convey an idea of the variability of wind, small values of v/V implying great variability and values approaching 1 implying great steadiness. The directions of the resultant monthly winds at the different pilot balloon stations have been plotted as arrows, the number of feathers on each arrow representing the strength of the wind on the Beaufort scale. Stream-lines have been drawn on the charts, but no attempt has been made to space them quantitatively.

In the charts for 1, 2 and 3 km, wind-roses at some selected stations have also been given as insets.

Frequencies of cloud directions.

Pilot balloon data, by themselves, can give only a partial view of atmospheric circulation as the data would necessarily be lacking at a number of levels on days of clouding. The deficiency will be greater, the higher the level considered. At many stations, in some months of the year, the pilot balloon data will therefore be unrepresentative of mean conditions ; this can to some extent be corrected by considering the directions of cloud movements. Even then, on days with a large amount of low cloud, observations of middle or high clouds will generally be unavailable.

Monthly percentage frequencies of movement of low, medium and high clouds at all the pilot balloon stations of the India Meteorological Department and at Bombay, Jaipur, Kodaikanal, Madras and Trivandrum have been published for the years 1926-35 in the 'Annual Summaries' or in the 'Upper Air Data, Part 13.' From the above data, the average percentage frequencies of cloud movement for each month and for a large majority of the stations were worked out and plotted on charts. Tables of average frequencies of direction of cloud movement are given in *Appendix B*. These average frequencies are obtained by averaging the percentages in the different years ; no account has been taken of the difference in the number of observations from year to year. In this respect, the process of averaging differs from that adopted for pilot balloon winds where each observation (and not each year's average) was equally weighted. Charts of cloud movement have been added as insets in the stream-line charts of January, April, July, October and November—the charts of low cloud in 2 km, of middle cloud in 4 km and of high clouds in 8 km charts.†

Isotherms in the upper atmosphere.

The variation of wind with height has been previously made use of to a limited extent for the calculation of horizontal temperature gradients[7], [8]. This calculation is based on the assumption that, at each level, the geostrophic wind equation holds and that the variation of wind with height is due to a variation of pressure gradient which itself must be brought about by a horizontal temperature gradient in the intervening layer.

* Data for 0·5 km above sea are also given in *Appendix A* ; but charts have not been prepared for 0·5 km.

† The cloud charts for all the months except November are based on data for one or two years fewer than those given in *Appendix B* ; this fact, however, does not affect the main features shown by the charts.

The frequencies of cloud directions are based on observations at 8, 12 and 16 hrs. till the end of 1931 and at 8 and 16 hrs. only in later years.

The procedure adopted for drawing the isotherms was as follows :—

For each station, from the normal values of north and east components of wind at two neighbouring levels, for example at 1 and 2 km, the east and north components of the horizontal temperature gradient (in °C per 100 km) for the layer 1-2 km was calculated by using the equations—

$$\frac{d}{dz}\left(\frac{u}{T}\right) = \frac{g}{2\,\omega \sin \varphi} \quad \frac{1}{T^2} \frac{dT}{dy}$$

$$\frac{d}{dz}\left(\frac{v}{T}\right) = \frac{g}{2\,\omega \sin \varphi} \quad \frac{1}{T^2} \frac{dT}{dx}$$

where u and v are the components of wind velocity along the x and y axes (east and north) respectively and the other symbols have their usual meanings.[9, 10]

It will be seen that T occurs in the equations, but approximate values of it are sufficient for this purpose, as small differences in the values employed will not affect the computed values of dT/dx and dT/dy to the order of accuracy otherwise attainable. The normal values of temperature obtained from sounding balloon ascents at Agra were used for stations in north India and those obtained at Poona or Hyderabad for stations in the south. The gradient calculated from the change of wind from one level to the next was taken to apply for a level midway between the two. Thus the gradient calculated from 1 and 2 km winds was taken as relating to 1·5 km, that calculated from 4 and 6 km winds to 5 km and so on.

The gradients in two perpendicular directions thus obtained were combined into a single vector and these vectors for all the stations charted. The chart for January for the layer 1-2 km (*i.e.*, for the level 1·5 km) is shown in *Fig. 1* as an example. Isotherms were then drawn on this chart remembering that (i) the isotherms should everywhere cut the gradient vectors at right angles and (ii) the spacing of successive isotherms should accord with the magnitudes of the gradient vectors. The actual values of temperature for these lines were then based on the mean temperatures at Agra[11] and Poona (or Hyderabad)[12] and to some extent on those at Peshawar or Quetta.[13] In general, the differences between Agra and Poona agreed well with the gradients between the stations. From the charts of 1·5 km, 2·5 km, etc., the vertical lapse-rates of temperature for each station were tabulated and, combining these with the temperatures at these levels, the temperatures at the standard levels, namely 1, 2, 3, 4 and 6 km, were calculated. These were plotted on charts and smoothed isotherms drawn. On individual days, with a changing system of isobars, it would not be permissible to assume steady-state conditions to calculate pressure and temperature gradients. Even when we are considering the mean conditions over a place and the data are based on a large number of observations under different weather conditions, the method cannot be expected to give accurate absolute values of temperature in different parts of the country nor give definite information about inversions, but nevertheless, they will give a broad indication of the general temperature distribution in the atmosphere both in the horizontal and vertical directions.

The isotherms have been shown in the stream-line charts themselves in broken lines. The temperature values are in degrees absolute, with the hundreds figures omitted. The combined charts of stream-lines and isotherms have been found to be illuminating regarding the properties of air coming over a place at different levels.

Main features of upper wind and temperature distribution in the different months.

JANUARY.

Considering the area as a whole, winter conditions are most marked in this month. Tropical storms are very rare in the neighbouring seas and, when they do occur, they are of moderate or slight intensity, affect only the extreme south of the area, generally south of lat. 13°N. and move in a westerly to northwesterly direction. Disturbances of the temperate latitude type, and often occluded, traverse north India with more or less regularity from west to east. The effect of these disturbances is greatest in Kashmir and the hills of the north and east Punjab.

Upper Winds.

1 km.—The circulation at 1 km is very similar to that at the surface.[14] The main features are :—

(i) The slow drain of cold air from Persia and Baluchistan towards the neighbouring seas and from and along the Himalayas towards the head of the Bay of Bengal. Note the flow of air down the Brahmaputra valley towards north Bengal and the extremely weak wind at Rangpur. Along the Mekran Coast, weak easterly winds (SE, E and NE) are frequent at 0·5 and 1 km above sea level.

(ii) The curving of the north Indian air round the anticyclonic region which extends from Gujarat to Orissa. The anticyclone is more intense over land than over the neighbouring seas.

(iii) The presence of an easterly current in the south of the Bay and of the Peninsula. In the middle of the Peninsula, the easterly stream is mainly anticyclonic continental air, while, as we go farther south, the air although of continental origin has passed for longer and longer distances over the sea. The air which enters the Bay of Bengal from the north or east and moves towards the south of the Peninsula will pick up moisture on its way and being less subject to nocturnal radiation cooling near the ground, will progressively gain in latent instability. Even in the south of the Bay, the air which crosses over to the Bay from the eastern side of Tenasserim is on most occasions continental air which has travelled round the anticyclone in Siam and Cochin China.

The mean velocities at 1 km in most parts of the area are of the order of 2 m/s. Velocities of over 4 m/s occur in the lower end of the Gangetic Valley, in the south of the Peninsula east of the Ghats and in the south of the Bay.

2 km.—At 2 km the effects of local radiational cooling are less marked, but the control exercised by the high mountain system in the north of the country remains strong. Note for example the weakness of wind at Quetta, Lahore, Peshawar, and Tezpur and the large wind-velocities (exceeding 8 m/s) in the Gangetic valley, in the United Provinces, Bihar and Bengal. The anticyclone is still stronger over land than over the neighbouring sea but the flow of air from the north of the Central Indian anticyclone to its south is less pronounced than at 1 km.

3 km.—At 3 km, the influence of the lower ranges of mountains such as the Sulaimans and the Kirthars is becoming unimportant but that of the Himalayas continues strong.

The westerly winds have everywhere increased in strength, without any appreciable change in the position of maximum velocities (12 m/s at this level). The anticyclonic belt has moved southward and the easterly winds in the south of the Bay have weakened.

4, 6 and 8 km.—With increasing height, the westerly circulation becomes stronger and more and more zonal and the anticyclonic belt is gradually pushed southward. Even at 4 km, the control exercised by the Hindukush and the Himalayas is large, as will be seen by the weakness of winds at Lahore, Peshawar and Simla compared with those at Quetta and Agra. The normal wind velocity at 4 km at Quetta is 7 m/s, while at Peshawar it is only 4 m/s. At 8 km, which is well above the average height of the Himalayas, while there is little difference of wind velocity between Quetta, Lahore, Simla and Peshawar, the zone of maximum wind strength remains at 25-27°N. This does not appear to be a mere effect of the Himalayas in obstructing the air movement but is a feature of the upper air circulation in winter caused by the distribution of temperature.

Cloud Winds.

Comparing cloud winds with pilot balloon winds at corresponding levels, the most important feature is the greater frequency of occurrence of southerly components of wind during cloudy weather. This is particularly evident at the low-cloud level in the Punjab and at all levels in the Deccan, north-east India and Burma. In a general way, it may be said that in cloudy weather, the anticyclone is on the mean displaced eastwards and the easterly air in the south of the Bay tends to move north and northeastwards and join the westerly stream of upper India.

Some local peculiarities of wind structure.

(a) Winds in the Punjab.—The plains of the Punjab, being enclosed on their west, north and east by high mountains and open towards the south, form a sheltered area for wind at levels below the surrounding mountains. A little farther south, the westerly winds are less restricted in their movement, and there is consequently a tendency for a cyclonic vortex to be formed in the Punjab especially when there is an acceleration of wind as in front of an advancing depression. Southerly winds are more frequent in the east Punjab than in the west and precipitation is also heavier on the hills on the eastern side. It is instructive to compare the frequencies of winds from different directions at Agra, Lahore and Simla, (*Table 1*).

TABLE 1.

Percentage frequencies of winds from different directions, in January.

	N	NE	E	SE	S	SW	W	NW
			Agra.					
1 km	12	3	8	9	8	3	12	43
2 ,, ...	4	1	3	2	10	13	31	36
3 ,, ...	4	1	..	..	2	17	48	27
4 ,, ...	..	..	..	..	..	16	60	19
6 ,, ...	1	..	..	..	..	11	75	14

Percentage frequencies of winds from different directions, in January—contd.

	N	NE	E	SE	S	SW	W	NW
			Lahore.					
1 km	13	7	5	8	4	3	14	40
2 „	10	6	6	10	12	13	14	23
3 „	9	1	1	4	17	18	28	19
4 „	..	..	..	..	7	19	35	22
6 „	..	..	..	..	1	15	58	22
			Simla.					
3 km	5	3	6	34	17	6	6	16
4 „	1	..	2	13	11	8	10	17
6 „	1	..	..	..	3	18	56	18

The greater frequency of winds from southerly directions at Simla and Lahore may be noted.

(*b*) **Katabatic winds in the Brahmaputra valley.**—Mention has already been made of the katabatic winds in the Brahmaputra valley. The direction of this valley, which runs approximately against the direction of the prevailing upper winds, favours the maintenance of these winds. A stable stream of fluid flowing towards the closed end of a channel will partly flow over the end wall, but the accumulation of fluid on the upstream side of the wall will also set up a return eddy current. When the sides and tops of the surrounding hill are differentially cooled (by the effect of radiation) the flow of cooled air down the hill slopes will facilitate the return flow. The easterly current is generally more than 2 km thick at Tezpur, which lies near the middle of the valley, and about 1 km thick at Rangpur near the mouth of the valley. Naturally, both the thickness and strength of the current will be variable, depending on the strength of the upper current and the stability of the air. At the interface between the westerly upper current and the easterly lower current, waves will easily form just as in the 'Totwasser' of Norwegian fjords.[15] Aeroplanes would therefore experience bumpiness near the places and levels where the easterly and westerly streams meet. The following table (*Table 2*) gives the frequencies of winds from different directions at 0·5, 1, 2 and 3 km in January 1930, at Tezpur, Rangpur and Patna.

TABLE 2.

Frequencies of wind from different directions at Tezpur, Rangpur and Patna in January, 1930.

—	n	N	NE	E	SE	S	SW	W	NW	<1·4m/s
				0·5 km.						
Tezpur	28	..	2	20	1	1	1	2	..	1
Rangpur	30	3	4	7	1	2	2	4	1	6
Patna	31	..	..	1	2	1	1	13	7	6
				1 km.						
Tezpur	28	..	1	17	1	2	2	1	..	4
Rangpur	30	2	2	8	4	1	3	4	1	5
Patna	31	1	..	1	1	..	2	19	5	2
				2 km.						
Tezpur	27	..	1	14	1	1	2	1	..	7
Rangpur	29	2	2	5	..	1	..	11	8	..
Patna	31	..	..	..	..	..	1	13	17	..
				3 km.						
Tezpur	24	1	2	6	1	1	2	9	..	2
Rangpur	26	..	1	..	..	..	..	19	6	..
Patna	30	..	..	..	..	..	..	18	12	..

These valley winds are most marked in the winter months November to February. Similar but shallower return currents also form in the Silchar valley.

Temperature Distribution.

At all levels up to 6 km, the temperature generally decreases towards the north. At 1 km, there is an area of maximum temperature lying over the Deccan and an area of weak horizontal gradient in north-west India. As the height increases, both these features become less and less prominent and ultimately disappear leaving a simple system of temperature distribution, the temperatures decreasing towards the north with gradually increasing horizontal gradients.

Thick incursions of moist air in the south of the Bay from across Tenasserim, which occur very occasionally, lead to the formation of a warm front between this air and the north-easterly streams blowing towards the Madras coast from the head of the Bay.[16]

FEBRUARY.

Conditions in February are generally similar to those in January and we shall not give a detailed description of them.

C

MARCH.

March is also a month of settled weather over the Indian seas. Western disturbances continue to pass eastwards across north India. The surface pressure gradient is weak over most of the area.

Upper Winds.

The main difference of upper air conditions in March from those of January is the setting up of an inflow of wind from sea to land in the coastal districts in the first one kilometre. This is better shown in the afternoon wind charts which are however not reproduced here. The highest temperatures at the surface and at 1 and 2 km occur in the middle of the Deccan in latitudes of 15-17°N. The stream-line chart at 1 km shows air in Gujarat and Bombay Deccan flowing southward, while along the east coast of the Peninsula it moves northward. Occasionally, this causes even the winds in South Bengal and Assam to flow northeastwards towards the hills. This is more marked in the succeeding months April and May.

In Burma also, ground heating is responsible for the development of a shallow low. The winds at Akyab at 1 km remain northerly to northwesterly, while those at Rangoon and Mandalay show that the mean air movement in the Irrawady valley has become southerly.

On the Mekran and Sind coasts there is a slight increase of wind strength at 1 km, compared to the previous two months.

In spite of the marked difference in the stream lines at 1 km between January and March, the difference is small at 2 km and above. The only noteworthy changes are the decrease of wind strength in the region of westerly winds and an increase of strength of the northeasterly to easterly winds in the south of the Peninsula at 3 and 4 km.

Temperature Distribution.

As regards temperature distribution, there is a closed region of high temperature in the Peninsula at 1 and 2 km. At higher levels, the temperature regularly decreases towards the north. Temperature gradients are weaker than in January. At 6 km over the same latitude, the isotherms indicate slightly higher temperatures when the air has been over sea than over land.

APRIL.

In April, storms originate occasionally in the Bay of Bengal between latitudes 10° and 15°N, especially in the latter half of the month, and generally move northwards and northeastwards towards the Arakan coast. The closed area of high temperature in the middle of the country is more intense and deeper than in March and is displaced slightly northward. There are corresponding alterations of air movement in the first two kilometres, the southerly component of wind at 1 km being stronger all along the east coast, in Bengal and in Burma and the northeasterly winds at 2 km in the south of the Peninsula being weaker. As these features become more pronounced in May, we shall pass on to consider the conditions in that month.

MAY.

Storms in Indian seas are common in this month. In the Bay of Bengal, they originate between latitudes 10° and 15°N. They generally have a northwesterly course in the beginning of their career, which later changes to northerly and still later to northeasterly.

The majority of them strike land on the Arakan coast, but many strike the Madras and Orissa coasts also. Once they reach the Indian coast, they show little tendency to penetrate inland but move parallel to the coast northeastwards as weak depressions. In the Arabian Sea, they generally move northwestward towards the Arabian coast. The monsoon usually breaks on the Malabar coast in the last week of May and in Tenasserim in lower Burma a few days earlier. The advances of the monsoon along the west coasts of India and Burma are often accompanied by storms.

Upper Winds.

1 km.—In May, the area of highest temperature at the surface, and at 1 and 2 km lies in an elongated form, running from Central India to Baluchistan and Persia. With the northward shift of the area of maximum temperature the system of coastal winds at 1 km in the Peninsula gets transformed into one of northwesterly to southwesterly winds traversing the whole breadth of the Peninsula, and the winds in the Persian Gulf, the Mekran and Sind coasts and the whole of the Peninsula become steadier and stronger. This is the first stage in the transformation of local land and sea-breezes into the southwest monsoon system of circulation.

In Bengal and Assam also, the afternoon southerly to southwesterly breezes which begin even in March, gain in steadiness and strength in April and May, the mean velocities of morning winds at 1 km in May being about 6 m/s.

2, 3 and 4 km.—2, 3 and 4 km may advantageously be considered together. At all these levels, the main points of difference from April are (i) the more frequent incursion of southerly and southwesterly winds in the south of the Bay of Bengal, (ii) the increased flow of air into the Peninsula and the west Bay of Bengal from north India and (iii) the marked weakening of the westerly to northwesterly winds at these levels in Bengal and Assam. *Table 3* gives the mean percentage frequencies of winds at 2 km in April and May at Waltair, Madras and Port Blair, which show clearly that while in April the frequencies of winds from different directions at Port Blair and Madras are similar, in May there is a greater frequency of southerly winds at Port Blair and of northerly winds at Madras.

TABLE 3.

Percentage frequencies of winds from different directions at 2 km.

—	N	NE	E	SE	S	SW	W	NW
			April.					
Waltair	14	4	4	4	11	..	11	23
Madras	6	28	37	19	2	2	5	1
Port Blair . . .	7	22	36	14	3	8	5	5
			May.					
Waltair	6	6	..	12	..	12	29	36
Madras	18	23	13	8	2	2	8	21
Port Blair . . .	10	5	12	15	6	13	17	12

C 2

At all these levels and also at 6 km, the sweep of the northwesterly continental winds normally extends over an area bounded on the South by a line running from the north of Ceylon to Pegu in Burma. Storms in this month usually form a little to the south of this line.

6 and 8 km.—The westerly winds at these levels throughout north India have diminished in strength, the decrease being most marked over Bengal and Assam. For example, the mean wind velocity at 6 km over this region is 12 m/s in April and 8 to 4 m/s in May, the velocity decreasing towards the east.

Temperature Distribution.

Upper air temperatures in this month (May) show some very interesting features. As mentioned already, at the ground, 1 and 2 km, the area of maximum temperature lies over Central India, Sind and Baluchistan. The temperature falls most rapidly towards Bengal and Assam and also towards the south-east Bay of Bengal. At 3 km, while the area of highest and lowest temperatures remain over Baluchistan and Assam respectively, the gradients have become much weaker. At 4 km, the distribution of temperature is somewhat similar to that at 3 km, but the area of lowest temperature has moved westwards from Assam towards the United Provinces and the rate of fall of temperature from the south Bay towards the north has increased. At 6 km, the *highest* temperatures are over Assam and upper Burma and the lowest over the Punjab and Kashmir—almost a complete reversal of the distribution in the first 2 kilometres.

The high temperature of the atmosphere at 6 km (and presumably also at higher levels) over south Bengal, Assam and upper Burma is no doubt to be attributed to the heat energy released in the upper atmosphere by the frequent thunderstorms which occur in April and May in north-east India and upper Burma. As the prevailing winds at these levels are westerly to northwesterly, it may be expected that the area of highest temperature would be displaced slightly down-stream.

In the light of the upper air information clearly brought out by the charts, a few remarks may be made regarding two conspicuous weather phenomena of this month, namely, the occurrence of Nor'wester thunderstorms in Bengal and the origin of pre-monsoon storms in the Bay of Bengal.

In trying to explain the Nor'westers of Bengal, Blanford wrote : " In March and April too, they (northwesterly winds) frequently blow, as dry winds, right across north India to Bengal, but are rarely felt in the Gangetic delta itself since they pursue their eastward course at the higher level attained on the Chota Nagpur plateau, while the sea-winds from the coast creep in beneath and eddying with the westerly winds, give rise to the local storms called Nor'westers, which are so characteristic of the spring months in lower Bengal ".[17] Mere eddying cannot give rise to the enormous energies released in these thunderstorms and we have to seek further causes for the occurrence of these phenomena. The stream-line charts and wind-roses in May show that air in the first kilometre, though of continental origin, has passed over distances up to about 1,500 km over the Bay of Bengal (and perhaps also a similar distance over the Arabian Sea before entering the north of the Peninsula) ; but the air at 2 to 4 km most frequently comes straight from north-west India. The effect of the passage of the surface layer of air over the sea is to convert part of its heat energy into energy of moisture-content. This addition of moisture in the lowest layer is very important from the point of view of possible thunderstorm formation. An inversion would however form between this surface layer and the drier northwesterly air above. During day owing to solar heating further energy is added to the surface air in the form of temperature increase ; there is an increase of lapse-rate in the surface layers and the inversion is reduced in intensity or even gets wiped out enabling a penetration of moisture above the original level of the inversion.

Above 4 km, we note that northwesterly winds are less common, the direction of maximum frequency of upper wind at Calcutta being westerly at 6 km and southwesterly at 10 km. We also note from the charts of isotherms that at 6 km, the air over Bengal is markedly warmer than that over north-west India. There is little doubt that this is true at 8 and 10 km also. The increased temperature in the higher layers would only have the effect of increasing the comparative stability of the atmosphere over Bengal. How then does it come about that in this month thunderstorms in Bengal are more common and violent than those elsewhere ? The concentration of energy exists essentially in the accumulation of water vapour in the lower atmosphere, the persistence of the southerly stream in the first kilometre keeping up the supply of moisture. But before the energy can be made available, the stability of the upper atmosphere must first be reduced by replacing the air at the upper levels by cooler air (the wind-roses suggest that this generally happens at 6 km and above) and by breaking down the inversion between the southerly moist surface air and the superincumbent drier air. To some extent, the breaking down of the inversion takes place every afternoon by the effect of insolation and the thickening of the southerly stream owing to sea-breeze. The fact that the thunderstorms do not happen every day shows that the replacement of the warmer air above 6 km by colder air occurs only in spells. When a deeper surface stream enters Bengal, as for example owing to the effect of a depression and this happens to coincide with a fall of temperature above 6 km, the release of energy will naturally be greater.*

Pre-Monsoon Storms.

For the formation of storms in the Bay of Bengal in this month, the importance of the flow of north-west Indian dry air at 2 to 6 km into the Bay of Bengal has been pointed out in a paper on pre-monsoon storms by one of the authors and Banerjee.[18] The isotherms at different levels show that rapid flow of air at 6 km. from northwest India into the Bay will lead to extensive cooling at the top and hence to instability. The storms are often associated with an inflow of moist air from some southerly direction of more than 3 km thickness. But whether this inflow is a *necessary* preliminary for the formation of storms has not yet been ascertained.

JUNE.

Before the middle of June, the southwest monsoon normally advances to Bombay on the west coast and penetrates into Burma, Assam and Bengal. By the end of the month it generally affects the whole country except the region west of Rajputana and the Punjab.

* A lucid discussion of "latent instability" and the energy realisable from it is contained in Dr. C. W. B. Normand's presidential address on "The Sources of energy of storms" before the Mathematics and Physics Section of the Indian Science Congress, January 1938 (Proc. Ind. Sci. Congr., 1938). Mr. G. Chatterjee and Dr. N. K. Sur have also recently discussed (Mem. Ind. Met. Dep. Vol. 26, Part 9) the upper air conditions over Bengal in the Nor'wester months with particular reference to latent instability.

Storms in the Bay of Bengal in this month usually originate or strengthen in the extreme north of the Bay where the northwesterly winds from land reach the southwesterly winds at 2 and 3 km.

Temperature Distribution.

As in May, the region of highest temperature at 1 km lies over north-west India and the temperatures fall towards south and east. The gradients are larger than in May. The lowest temperatures lie over the south-east Bay of Bengal and probably also over the south Arabian Sea. With increasing height, the gradient decreases, and at 4 km there is practically no difference of temperature between different parts of the country. At 6 km, the gradients are reversed, the highest temperatures being over Assam and the lowest over the N. W. Frontier Province. In the north Arabian Sea also there is a temperature fall towards Baluchistan and Persia. The winds at 2 and 3 km coming into the north-west corner of the Bay of Bengal from Rajputana and the United Provinces will therefore be bringing air warmer than the southwesterly air, while at 6 km and above the air coming from the south and east will be warmer than the air from the northwest.

JULY.

Upper air conditions in this month have been fairly exhaustively discussed in a previous paper by the authors.[4] We would, however, like to direct attention to a few points.

(i) The heat low over north-west India is shallow, the cyclonic circulation at 1 km being replaced by an anticyclonic circulation at 2 km and above. The low pressure trough parallel to the Gangetic valley is deeper and is progressively displaced towards the south as the height increases from 1 to 4 km ; it practically disappears at 6 km.

(ii) At 3 km and above, the boundary between the old monsoon air and the northerly air from Persia and Afghanistan lies in a northeasterly direction a little to the south of Karachi. The winds at Karachi at 3 km and above are abnormally strong and this feature is perhaps due to the convergence of air from two different sources.

(iii) Cloud winds show only small differences from pilot balloon winds at corresponding levels. Comparing low cloud directions with winds at 1 km, it is seen that the former show a greater frequency of easterly than westerly winds in the United Provinces and the Punjab. The middle cloud movement corresponds to the mean of the pilot balloon movements at 4 and 6 km. High clouds move similarly to pilot balloon winds at 8 km, but the easterly winds in north India push farther westward, the cirrus winds in the Persian Gulf showing a greater frequency of easterlies.

Temperature Distribution.

At 1 km, the main feature of the distribution is the regular fall of temperure eastward from Baluchistan to Assam and Burma and southward along the west ast of the Peninsula towards Malabar. At 2 km, the isotherms have changed their rection running now from WSW to ENE. At 3 km the excess of temperature in rth-west India over that in the north-east has vanished and latitude for latitude, temperatures in the eastern part of the Bay of Bengal are higher than those over the east Arabian Sea. At higher levels, the relative warmth over north-east India increases, with the result that at 6 km the highest temperatures are found over Bengal and the United Provinces. By the time that the monsoon air arriving in the lower levels in the south Arabian Sea and south-west Bay of Bengal as the south-west monsoon has moved up to this region, it has shed a considerable fraction of its moisture and converted its energy of moisture-content in the lower levels to energy of temperature in the higher.

AUGUST.

The monsoon has its farthest northward extension in August. Both in July and August, depressions either originate in the Bay of Bengal off the Orissa-Bengal coast or develop there out of low pressure areas which cross over from the China Sea across Burma[19]. They generally move in a west-northwesterly direction to the eastern side of the Aravallis and, after a day or two of persistence there, move either towards the Punjab or cross over to Sind. The very small area within which different depressions originate or strengthen and the narrowness of the belt along which they travel are noteworthy.

The wind and temperature distributions of August do not show any essential differences from those in July.

SEPTEMBER.

The southward movement of the monsoon begins about the end of August; by the end of September the monsoon is confined to the east and southeast of a line running approximately from Bombay to Shillong. The retreat is effected by the pushing back of the moist currents by drier air from the north-west. Depressions or storms are fairly common in the Bay of Bengal; the region where they originate or strengthen is more widely spread out than in July or August.

Upper Winds.

1 km.—With the southward retreat of the sun, and the increased nocturnal radiation from the Asiatic plateaux the region of highest temperature in the first kilometre is displaced eastwards from Baluchistan and Sind and now lies partly over Rajputana. The Punjab, Sind and Rajputana are over-run by weak northwesterly winds. The shallow cyclonic circulation which lay over Sind in the previous three months, exists now at 1 km in a feeble form over the east United Provinces and Bihar. In the rest of the country, the mean winds are nearly the same as in July but are weaker everywhere and inclined to be more northwesterly in the Peninsula.

2 km.—The circulation at 2 km shows cyclonic movement over the northwest of the Bay. Northwesterly or northerly air cover the whole land area west of the United Provinces and Central India. Occasionally, the northwesterly air reaches out to the Bay.

3 and 4 km.—At 3 and 4 km, the northwesterly land air penetrates farther south into the Peninsula. The southwest monsoon current has weakened considerably and there are only feeble southerly currents in the eastern half of the Bay, Burma and north-east India. In keeping with the diffuseness of the semi-permanent cyclonic circulation at all these levels, caused no doubt by its position away from the mountains to the north and north-east, diffuse depressions often develop over the Bay of Bengal, move slowly westwards across the Peninsula and emerge into the Arabian Sea giving rise to widespread rainfall associated with thunder. The rainfall is generally confined to the east of the region of winds of north-westerly origin and the separation between the region of rain and no rain is often very sharp.

6 and 8 km.—The southerly stream over the east Bay of Bengal and Burma has vanished at 6 km and been replaced by a general easterly current similar to what we had in July and August but now confined to latitudes south of 23°N. Over the Punjab, the westerly circulation of temperate latitudes has already invaded and a saddle-shaped system of stream-lines is formed over north India with northwesterly air moving southwards over Iraq, Persia and Baluchistan to join the easterlies over the Arabian Sea and with the easterly tropical stream in lower Burma and the Bay turning northward and changing to westerly over north-east India and upper Burma. The stream-lines at 8 km are similar, but there is a marked strengthening of the westerly winds over the Punjab. The tropical easterlies also show increase in strength, though less conspicuously than the westerlies in the north.

Temperature Distribution.

The upper air temperature distribution in September is qualitatively similar to that in July or August but shows some changes as regards the positions of the highest and lowest temperatures and the magnitudes of the gradients. At 1 km, the warmest air lies over northwest India, but displaced eastwards ; and the coldest is over lower Burma and the south-east Bay of Bengal. At 2 km. the direction of the gradients changes to more nearly north and south. A separate centre of high temperature makes its appearance over north-east India at 3 km. There is no horizontal gradient to speak of at 4 km, but strong gradients have developed in northwest India at 6 km with temperatures falling towards the northwest Frontier.

OCTOBER.

In this month, air currents of land origin cover northwest and central India and a good part of the Deccan and the monsoon has definitely withdrawn from most parts of north India and from the central parts of the country. October and November are the months when severe storms are most frequent both in the Bay of Bengal and in the Arabian Sea. In October, the storms generally originate south of latitude 16°N. They are often continuations of storms in the China Seas which enter the Bay of Bengal across Tenasserim.

The most striking feature of the stream-lines of this month is the greater strength of the north and south components compared to those of the east and west at 1, 2 and 3 km.

1 km.—At 1 km, air flows from north to south in regions lying approximately to the west of longitude 85° and from south to north to its east. A feeble cyclonic circulation exists in the Bay of Bengal off the Carnatic coast, the weakness of the resultant winds in this region being chiefly due to the variability of wind.

2 and 3 km.—At higher levels, the westerly winds in north India push through to Bengal and Assam and a system of saddle-shaped stream-lines develops with its neutral point over the Bay of Bengal. The development of depressions in the Bay is usually accompanied by an influx of southerly to southeasterly winds in the Andaman Sea. The following table (*Table 4*) giving the percentage frequencies of wind over Madras and Port Blair at 1, 2 and 3 km is instructive as showing the variability of wind direction at the two places.

TABLE 4.

Percentage frequencies of winds from different directions at Port Blair and Madras.

—	n.	N.	NE.	E.	SE.	S.	SW.	W.	NW.
				Port Blair.					
1 km . .	109	3	6	18	10	8	21	19	8
2 km . .	96	4	5	18	12	13	15	18	4
3 km . .	84	6	13	21	12	6	16	13	5
				Madras.					
1 km . .	103	14	31	10	2	5	8	11	18
2 km . .	101	29	20	12	3	0	7	11	14
3 km . .	90	14	12	14	4	2	4	20	22

4, 6 and 8 km.—At still higher levels, the westerly winds in north India rapidly gain in strength and also encroach towards lower latitudes. In the south of the Bay, the winds become systematically easterly. As a result, the zonal movement becomes more important than the meridional.

Temperature Distribution.

The horizontal gradients of temperature are generally very weak in this month, especially in the first three kilometres. At 1 km, there is a weak gradient of falling temperature from Central India and the west United Provinces towards the Bay of Bengal. Even this gradient vanishes at 2 km. At 3 km, a temperature rise towards the south is noticed in the extreme north of the country; this extends southwards at 4 km towards the Bay of Bengal. The same kind of distribution exists also at 6 km, but the gradients are stronger in north India.

NOVEMBER.

November is the month in which the north-east monsoon is most active in the south Bay of Bengal and the east Madras Coast. It is also a month of severe storms in the Bay of Bengal, their places of origin or strength being generally south of latitude 13°N.

Upper Winds.

1 and 2 km.—Compared with October, there is an increase of mean wind velocity in all parts of the country except on the Mekran and the Persian Gulf coasts. Valley winds are conspicuous in Assam between the Khasi hills and the Himalayas both at 1 and 2 km. The land air from north-west India curves round the high pressure area in the central parts of the country and traverses the middle of the Peninsula as a northeasterly current. The wind directions in the south Bay and on the Madras coast have become definitely easterly and north-easterly and the wind speeds are also higher. When the north-east monsoon is active, these easterlies are generally a continuation of the NE trades of the Pacific as is shown by the upper air wind roses at Manila and Guam[20] and the rainfall distribution in Siam and Cochin-China. At intervals between spells of activity, the Chinese anticyclone tends to spread towards the south in Cochin-China and Siam. When storms in the Bay approach the Madras coast south-westerly winds are sometimes stimulated in the extreme south of the Peninsula and in Ceylon.

3 to 8 km.—With increasing height, the north-westerly and westerly winds of north India gradually strengthen and extend southwards and the deformation field of velocity becomes more and more pulled out along the latitudes. A comparison of the circulations in north-east India and Burma in October and November shows that the supply of easterly trade air from the south of the Bay is more easily deflected northwards in the former month than in the latter.

When storms from the Gulf of Siam enter the Bay of Bengal in November and recurve towards the north and north-east, we observe that their movement corresponds more nearly to the mean upper air movement in October than in November.

Temperature Distribution.

In this month, north India has definitely become cooler than the south at all the levels considered. At 1 km, rising gradients in the Bay are from north-west to south-east, but at higher levels, they are everywhere from north to south. At 3 km and above, the gradients south of 20°N are very weak. There is just a suggestion of maximum temperature in the middle of the Bay at 4 km.

DECEMBER.

From November to December the main change that occurs is the southward movement of the region of westerly winds which is very evident in the charts at 3 to 8 km. There is simultaneously a southward retreat of the easterly moist sea winds in the south of the Bay in the lower levels although it is not clear from the wind charts alone that part of the easterlies at 1, 2 and 3 km in December is derived from the anticyclonic air of Cochin-China and Siam.

Discussion of the main features of the circulation.

It would be useful to summarise the important features of the circulation which are brought out by this survey. The area studied extends roughly from latitude 8°N to 35°N and longitude 50°E to 100°E and includes part of the tropics, the sub-tropics and part of the temperate regions.

(i) The most striking feature of the circulation is the regular seasonal northward and southward movement of the upper wind system. The movement cannot correctly be described as meridional; in the summer half of the year, the singularities of the system move from south-east to north-west and back, while in the other half, the movement is mainly meridional. The following table gives the latitudes at which the west-east component of wind vanishes at different heights above sea-level over the longitude of Agra, *viz.*, 78°E.

TABLE 5.

The maximum northerly latitude to which easterly winds extend (Long. 78°E).

Height (km.)	Latitude (degrees north).											
	Jan.	Feb.	Mar.	Apr.	May.	Jun.	Jul.	Aug.	Sep.	Oct.	Nov.	Dec.
0 . .	25	25	25	×	×	×	×	×	×	24	24	24
1 . .	21	21	20 (?)	×	×	×	×	×	×	25	25	24
2 . .	18	17	18	18	×	×	×	×	26	23	23	20
3 . .	16	16	17	18	18	22	30	30	26	23	21	18
4 . .	15	15	16	18	18	22	29	30	26	20	19	16
6 . .	12	12	13	14	17	21	29	29	25	19	17	15
8 . .	11	11	11	11	15	21	28	29	24	18	16	12

The smallness of the meridional shift, from month to month, of the transition zones in the upper air during the dry period from December to April (and even in May) is remarkable and shows that the radiational cooling of the ground in winter and the insolational heating in the hot season do not make any profound modification in the circulation. The big changes come in only with the advent and northward penetration of moist air and attendant rainfall in June and July.

Ground heating by itself rarely affects upper air conditions to a height greater than 4 km, ground cooling affects them to a much smaller height. When ground heating is combined with supply of moist air in the lower layers important modifications take place.

(ii) A very striking feature of the circulation in this region throughout the year is the great influence exercised by the mountain system on the north up to a level of 6 km. This is seen alike in the mean movement of air parallel to the Himalayas during the winter and hot season, and in the existence during this period of a region of maximum wind strength up to 6 km in the east United Provinces and Bihar and also in the localisation of the monsoon low to within the confines of India.

(iii) Regions of heavy rainfall become regions of high temperature and also of divergence of air in levels above 6 km. Stream line and temperature charts in May to September provide examples of this.

(iv) During winter and hot season, the pilot balloon winds show that, on the mean, the winds of the westerly circulation of the higher latitudes turn towards the south and southwest and join the easterly circulation. In cloudy weather in this period the opposite is the case, air coming from the east turning towards the north and northeast. Cloud winds generally show a longer meridional stretch than pilot balloon winds.

West of longitude 70°E, the mean air movement over the land areas as shown by pilot balloon winds is in all the months northerly, carrying air from higher to lower latitudes. Even cloud winds do not show any large movement from the south except during the post-

D 2

monsoon period and, considering the small frequency of clouds in this region, it appears that on the aggregate the net transport of air is from north to south in this region up to a height of 8 km.

In a similar way, there is little doubt that east of longitude 90°E, the net effect of the circulation is to transport air from south to north during the period January to October.

Pilot balloon winds at higher levels over Poona show that, even in the dry season, there is on the aggregate a poleward flow of air above 8 km.*

We shall now make a brief comparison of upper air conditions in this region with conditions in corresponding latitudes in some other parts of the northern hemisphere.

The semi-permanent sub-tropical anticyclones of the northern hemisphere are located at ground-level during winter at latitudes varying from 25°N to 35°N over the oceans and extend over neighbouring land areas (we are excluding from our consideration the great continental anticyclones which lie north of latitude 40°N over Asia and North America). According to the charts of cirrus movement prepared by van Bemmelen, these anticyclones exist in the cirrus level (and during cirrus weather) in winter over latitudes varying from 15° to 20°N. Over India and neighbouring regions the position of the winter anticyclone is about 25°N at the ground, 16—18°N at 2 to 3 km and 11—12° N at 8 km. They are thus located at lower latitudes over India and its neighbourhood.

In *Figs. 3* to *8* are shown the distribution of westerly and easterly components of winds at different levels and at latitudes varying from 10° to 30°N over the meridian 78°E. The charts are drawn for six months of the year. The values of the W-E wind components in metres per second are given by the figures in the appropriate places, positive values signifying easterly winds and negative values westerlies. In the winter and hot seasons, the westerly winds penetrate farther southward at higher levels, and the greater the velocities of the westerlies at say 25°N, the farther is the southward limit of penetration. This is similar to what has been found elsewhere, for example, over the Atlantic [21], but the strengths of the westerly winds over north India are markedly greater than those found in similar latitudes over the Atlantic Ocean.

As the lower wind system up to 4 km in the months November-April has many points of similarity with the trades, it is desirable to examine whether there are any winds corresponding to the anti-trades of the Atlantic. As mentioned already, over the region of longitudes 45°—80°E the upper westerlies come more often from the north than from the south, while east of longitude 90°E, southwesterlies are more common. It also appears that it is only in cloudy weather that the easterlies and westerlies over the Indian Peninsula have very different origins. In clear weather, the air coming from the east is also often westerly air which has turned round, first southward and then westward. Unless we choose to call all the upper westerly winds anti-trades, we do not have a regular anti-trade wind system moving from lower to higher latitudes up to 8 km, except in times of cloudy weather. The general process of circulation between the westerlies and easterlies can be described as follows. At the lower levels, the westerly air moves southwards more directly than at higher levels. As it moves south, it rises owing to gain of heat and then turns round the anticyclone towards the north and joins the westerlies. It again moves slowly towards

* It is desirable that the question be more quantitatively examined taking into consideration the relative frequencies of pilot balloon and cloudy days.

the south, gains heat, and again turns round the anticyclone at a higher level and a lower latitude. This goes on until it either reaches a region of longitudes where the anti-trades are well-developed or gets caught in the northward moving air associated with a disturbance. The probable life-history of the air is shown in *Fig. 2.*

Bjerknes and collaborators[22] have calculated the distribution of pressure in the free atmosphere in a meridional section on the basis of the surface pressure distribution and the distribution of temperature in the atmosphere up to 25 km ; and by application of the gradient wind formula have also calculated the wind field. The good general agreement of the observed wind-system with the calculated wind-system shows that, for a correct understanding of the general permanent circulation of the atmosphere, the ascertainment of the exact distributions of temperature in different regions of the earth and the assignment of the correct physical causes for them are of fundamental importance. In this connection, attention may once again be drawn to the important result brought out from the sounding balloon results in India, namely, that the highest temperatures in the tropical troposphere at levels between 6 and 13 km are found over regions of extensive rainfall. The highest pressures at the levels are also found over the same or near regions. The physical reason for this is that lapse-rates over regions of heavy rainfall tend to come down to those appropriate to saturation adiabatic. We have therefore to seek for regions of highest pressure in the upper atmosphere *at these levels* in other parts of the tropics in similar regions of heavy widespread rainfall, such as parts of Africa, East and West Indies, Brazil, etc. With the seasonal movement of rainfall, areas, the high pressure areas at these levels will also move correspondingly. This is borne out by our 8 km charts and also by van Bemmelen's charts of cirrus movement.

Acknowledgment.

The present work is based on a large amount of observational material, collected over a period of 20 years and from an area extending from the Persian Gulf to lower Burma and from the North-West Frontier Province to Travancore. As such, it rests on the work of a large number of individuals and the authors are deeply conscious of their indebtedness to others. The late Mr. Field, the pioneer of upper air investigation in India, and Mr. G. Chatterjee, his successor as head of the Agra Observatory and organiser of upper air work in India, together with the staff of the various Upper Air Observatories, have built up this great bulk of observational material. In the preparation of the paper itself, most of the members of the Upper Air Section, Poona, have assisted in various ways ; the constant and whole-hearted assistance rendered by the late Mr. L. V. Joshi has been particularly valuable. The authors are grateful to Dr. C. W. B. Normand, Director-General of Observatories, for the encouraging interest taken by him in the work ; and to Dr. N. K. Sur for generously placing at their disposal some of the tables in *Appendix B* which were prepared in the Upper Air Section during the period of his charge.

References.

1. W. A. Harwood.—'Upper air movement in the Indian monsoon etc.', Mem. Ind. Met. Dep., **24**, Pt. 8, (1921).
2. H. C. Banerjee and K. R. Ramanathan.—'The upper air circulation over India, etc.', Ind. Met. Dep. Sci. Notes, **3**, No. 21, (1930).
3. N. K. Sur.—'Winds in higher levels over Agra', Ind. Met. Dep. Sci. Notes, **2**, No. 15, (1930).
4. K. R. Ramanathan and K. P. Ramakrishnan.—'The Indian south-west monsoon etc.', Mem. Ind. Met. Dep., **26**, Pt. 2, (1933).
5. Ind. Met. Department.—Meteorology for Airmen, Pt. I, (1936), pp. 10-17.
6. A. Wagner.—'Zur Aerologie des Indischen Monsuns', Gerl. Beitr. Geophys., **30**, (1931), p. 196.
7. Sir Napier Shaw.—'Upper air calculus, etc.', J. Scot. Met. Soc., **16**, (1913), p. 167.
8. A. Narayanan.—'Horizontal gradients of pressure and temperature, etc.', Ind. Met. Dep. Sci. Notes, **3**, No. 28, (1931).
9. Sir Napier Shaw.—Manual of Meteorology, Vol. 4, (1931).
10. D. Brunt.—'Physical and Dynamical Meteorology', (1934), p. 199.
11. K. R. Ramanathan.—'Discussion of results of sounding balloon ascents at Agra etc.', Mem. Ind. Met. Dep., **25**, Pt. 5, (1930).
12. K. R. Ramanathan and K. P. Ramakrishnan.—'Discussion of sounding balloon ascents at Poona, etc.', Mem. Ind. Met. Dep., **26**, Pt. 4, (1934).
13. A. Narayanan.—'A discussion of......upper air temperatures and humidities......at Peshawar and Quetta', Ind. Met. Dep. Sci. Notes, **4**, No. 42, (1931).
14. Sir John Eliot.—'Climatological Atlas of India', Ind. Met. Dep., (1906).
15. V. Bjerknes and others.—'Physikalische Hydrodynamik', (1933), p. 389.
16. K. R. Ramanathan and A. A. Narayana Aiyar.—'The structure of the Madras storm etc.', Ind. Met. Dep. Sci. Notes, **3**, No. 18, (1930).
17. H. F. Blanford.—'Rainfall of India', Mem. Ind. Met. Dep., **3**, (1886), p. 118.
18. K. R. Ramanathan and H. C. Banerjee.—'A study of two premonsoon storms in the Bay of Bengal, etc.', Ind. Met. Dep. Sci. Notes, **4**, No. 34, (1931).
19. V. Doraiswamy Iyer.—'Typhoons and Indian weather', Mem. Ind. Met. Dep., **26**, Pt. 6, (1936).
20. U. S. A. Hydrographic Office.—'Pilot Charts of the Pacific Ocean.'
21. *E. g.*, H. U. Sverdrup.—'Der nordatlantische Passat', Veroff. Geophys. Inst. Leipzig, II Ser., **2**, (1917).
22. V. Bjerknes and others.—*Loc. cit.*, p. 649.