Indian Journal of
METEOROLOGY & GEOPHYSICS

April 1966
Vol. 17 No. 2

551.515.8

The problem of Fronts in the Indian Atmosphere

C. RAMASWAMY

Meteorological Office, New Delhi

(*Received 1 December 1965*)

ABSTRACT. The present paper contains the results of a detailed synoptic investigation of a western disturbance in the typical winter month of January. This disturbance moved across West Pakistan and northern India and was *prima facie* associated with fronts. The investigation has, however, shown that there were no well-organised sloping surfaces in association with the western disturbance. The slopes were found to be very variable and did not extend above 3·9 km. The potential pseudo-wet bulb temperature curves did not also show any significant air mass contrasts in the vertical, during the movement of the discontinuity surfaces across the stations. The times of commencement and cessation of precipitation had no relationship to the time at which the discontinuity at sea level moved across the synoptic stations. On the basis of these observational facts, the conclusion is drawn that, even in mid-winter, when there is a maximum probability of formation of fronts in the Indian atmosphere, discontinuity surfaces which may form due to juxtaposition of different air masses, probably get disorganised on most occasions leaving merely a broad "indeterminate" type of partition which moves with the western disturbance and causes temperature and other associated changes. The available evidence also suggests that such partitions are of little consequence in the development of hydrometeors and, therefore, would be of little value in forecasting the hydrometeors.

1. Introduction — Historical background

The concept of frontal surfaces was first introduced in Indian Meteorology in the early thirties of this century by Ramanathan and his collaborators (1930, 1931, 1933), Roy and Roy (1930), Mull and Desai (1931) and Sur (1933). During the next two decades, the frontal concept became more and more popular in India in day-to-day weather analysis and in published scientific literature (Malurkar 1945, 1947, 1948, Malurkar and Pisharoty 1948, Desai 1951, Desai and Koteswaram 1951). However, even during the late 40's, doubts were expressed about the existence of fronts over the Indian sub-continent (Pramanik and Rao 1947, 1948). After the early fifties, it was increasingly realised by Indian forecasters that the delineation of fronts and their movements on the daily synoptic charts were not helpful in forecasting. While this was the position in India, there was, from near about this time, increasing evidence in the literature on tropical meteorology elsewhere in the world, especially in U.S.A., which gave less and less support to fronts (Palmer 1951, Riehl 1954) and emphasised more and more on the principle of conservation of vorticity and the dynamical consequences of the same in the development of tropical weather (Riehl 1954). These gave additional strength to the Indian meteorologists to turn their attention to more profitable methods of analysis of Indian weather. The published literature on Indian Meteorology during this period also supported this view (Ramaswamy 1956, Koteswaram and George 1958). Thus came the decline in the popularity of fronts in Indian synoptic practice. The frontal concept has, however, not disappeared in references to Indian weather analysis (Subramanian and Banerjee 1964, Saha 1964). Forecasters even now occasionally delineate fronts in the winter-period in association with "Western disturbances" and also, though rarely, even in other seasons of the year.

2. Statement of the problem

It is against this background of current concepts and practices that the author has asked himself the question "Are there over India even in mid-winter *well-organised sloping* surfaces with *density* contrasts and if there are, what is the usual inclination of these surfaces and to what height above the ground level do the frontal surfaces extend? And how far do these frontal surfaces contribute to the development of hydrometeors? The author has, however, been unable to find answers to these questions in published literature on Indian Meteorology.

The present investigation is an attempt to fill this gap in our knowledge. For this purpose, the author has made a detailed synoptic study of a western disturbance in January 1957 which caused extensive rainfall in northern India and Pakistan and which, *prima facie*, was associated with frontal surfaces. The history of this disturbance is given in the following sections —

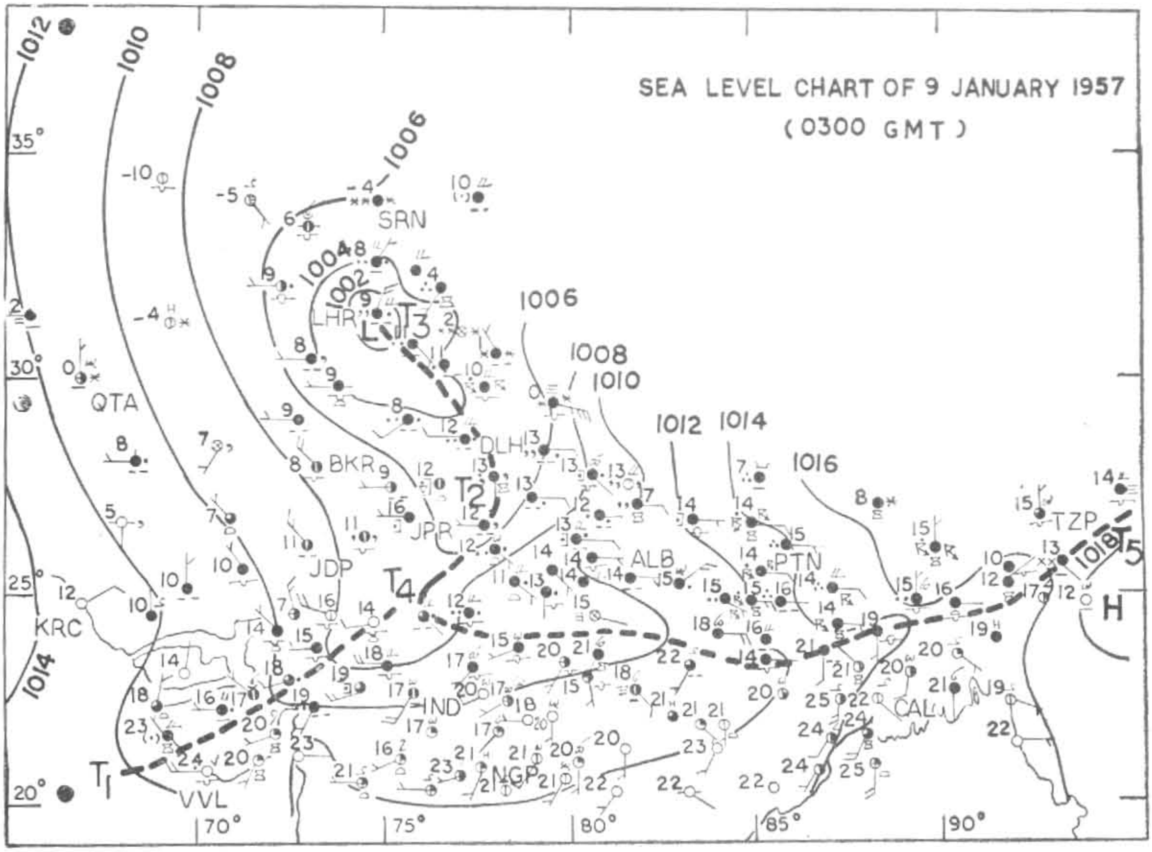

Fig. 1. Sea level chart of 9 January 1957 (03 GMT)

T_1—T_2—T_3 and T_4—T_5 are wind discontinuities as well as thermal discontinuities. There is an extensive area of present weather to the east of T_2—T_3 even as far east as Long. 90°E

3. Sea level systems

On the morning (03 GMT) of 7 January 1957, there was a closed low (two closed isobars drawn at 2-mb intervals) over Sind and the adjoining parts of south Punjab (Pakistan). By the next morning (*i.e.*, by the morning of 8th), the low had moved eastwards and lay as a diffuse low pressure area over Rajasthan with an associated inverted V-shaped trough extending northwards into north Punjab (Pakistan and India). It was becoming increasingly active as was evident from the extensive rainfall caused by it and at 03 GMT on 9th, a deep depression appeared over Punjab (Pakistan and India) with centre between Amritsar and Lahore (Fig. 1). The deficiency of pressure at the centre of the depression was nearly 20 millibars. Associated with this system, there were two sharp wind-discontinuities at the surface-level extending over considerable distances, which may be seen in Figs. 1 and 2. These wind-discontinuities also appeared to be thermal discontinuities: the surface Dry Bulb temperatures to the west of T_1-T_2-T_3 (see Figs. 1 and 2) were 2° to 3°C lower than those to the north of T_4-T_5 discontinuity and 6° to 8°C lower than those to the south of T_4-T_5. The temperatures to the south of T_4-T_5 were 5° to 7°C higher than those to the north of the same discontinuity. Rainfall was also occurring at the synoptic hour of the chart over a very extensive region. The minimum air temperatures had fallen in the rear of the wind-discontinuity T_1-T_2 T_3.

On the 12 GMT chart of the same day (9th) the depression lay over extreme north of Punjab (Pakistan and India) and seemed to have slightly weakened. The wind-discontinuities (at the sea level) had moved eastwards and southwards and occupied the positions T_6-T_7-T_8 and T_7-T_9 as shown in Fig. 2. A low had also appeared over east Uttar Pradesh.

By the morning of 10th (03 GMT) the depression over north Punjab (Pakistan and India) had disappeared, the low over east Uttar Pradesh had slightly shifted eastwards and another diffuse low pressure area had appeared over east Madhya Pradesh and Orissa. The wind-discontinuities at the surface level lay as seen in Fig. 2 (T_{10}-T_{11}-T_{12} and T_{11}-T_{13}). The wind discontinuities also appeared to be thermal discontinuities. The temperatures to the west of T_{10}-T_{11}-T_{12} were

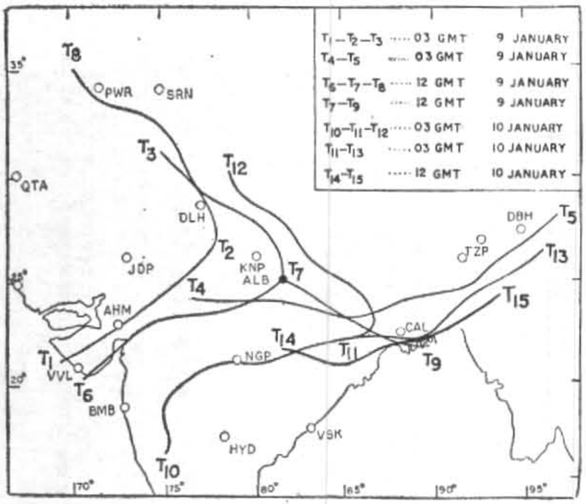

Fig. 2. Surface wind discontinuities 9 and 10 January 1957 (03 and 12 GMT)

T_1—T_2—T_3 lies just to the *east* of New Delhi (DLH) and T_{10}—T_{11}—T_{13} discontinuity lies just to the *south* of Nagpur (NGP)

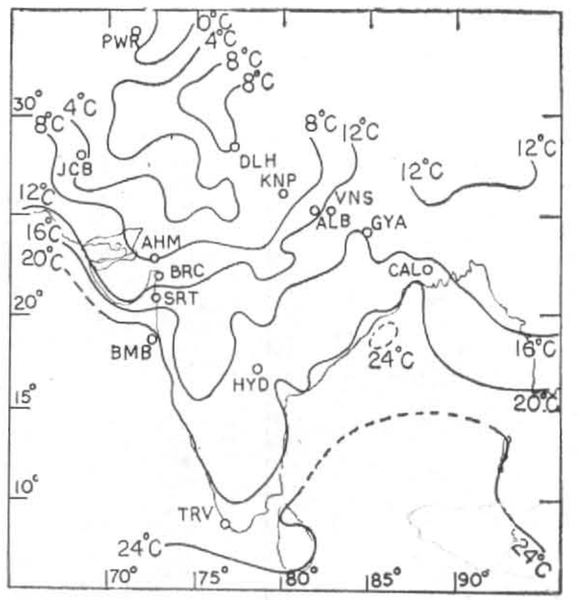

Fig. 3. Minimum temperatures during 24 hours ending 03 GMT (10 January 1957)

There is a general concentration of the isotherms over the region extending from Bombay and Broach to Kanpur and Gaya. The average width of the zone of thermal transition in the central parts of the country is about 400 km

about 6°C lower than those to the south of T_{10}-T_{11}-T_{13} and 3° to 4°C lower than those to the north of T_{11}-T_{13}. The temperatures to the south of T_{11}-T_{13} were about 5°C higher than those to the north of the same discontinuity. The T_{10}-T_{11} (Fig. 2) discontinuity passed very close to Nagpur and T_{11}-T_{12} portion of the discontinuity was much less sharp than T_2-T_3 discontinuity on 9th. The minimum air temperatures and surface dew points had appreciably dropped (not reproduced in this paper) in the rear of the wind discontinuity T_{10}-T_{11}-T_{12}. The actual minimum air temperatures and their departures from normal were interesting* and are reproduced in Figs. 3 and 4 respectively. It will be seen from these figures that in the region extending roughly from Bombay and Broach to Kanpur and Gaya (see Fig. 3) there is a zone of transition in the minimum air temperatures. The average width of this transition zone** over the central parts of the country is about 400 km. The zero anomaly line runs very nearly through Surat and Allahabad. The contrast in the minimum air temperatures as seen in Figs. 3 and 4 was more pronounced than on the 9th morning (not reproduced).

By 12 GMT of 10 January, the low over east Uttar Pradesh and west Bihar had disappeared and the diffuse low pressure area over east Madhya Pradesh and Orissa had extended into deltaic Bengal and the head of the Bay of Bengal. The wind discontinuities had also disappeared except for the one marked T_{14}-T_{15} in Fig. 2.

The subsequent history of this western disturbance is not of any special interest from the point of view of the present paper and hence it is not given here. The author would, therefore, conclude this description of the sea-level systems by stating that this western disturbance which had such a remarkable life-history on 9th and 10th January moved away eastwards and weather cleared up over northeast India by 13 January.

It will be seen from what has been stated in the above paragraphs that the discontinuities on the morning of 9th and 10th satisfied one of the two important conditions for the existence of a front at the *surface*, namely, that there were zones of transition of air masses of different densities at the surface. We are, however, yet to see whether the second important condition for the existence of a front was satisfied, namely, whether these air masses were separated by *well-organised sloping* surfaces. We have also yet to find out upto what height in the atmosphere did these sloping surfaces extend and how far these surfaces contributed to the development of hydrometeors.

4. Lower tropospheric systems

These were analysed by the delineation of streamlines without any attempt to space them on the basis of wind speeds. The wind

*Minimum air temperature is considered as the most representative property for demarcating air masses in India (Roy 1946)

**See also Fig. 10 which shows the transition zone as a stippled area and its position in relation to the sea level and lower-tropospheric wind discontinuities

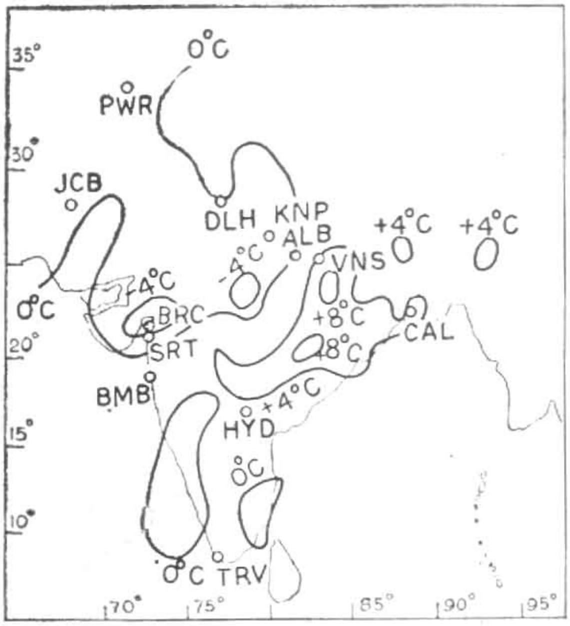

Fig. 4. Departures from normal of minimum temperatures during 24 hours ending 03 GMT (10 January 1957)

The anomaly isopleth of minus 4°C may be seen to the northwest and plus 8°C to the southeast of the central parts of the country. The zone of thermal transition as seen in the anomalies, is nearly as broad as in the isotherms in Fig. 3

discontinuities were drawn at different levels keeping in mind the need for space continuity. This was specially necessary on account of the inadequacy of observations at the higher levels.

The upper winds, stream lines and wind discontinuities at 0·9 and 2·1 km (3000 and 7000 ft respectively) at 02 GMT on 9 January and at 0·9 km at 02 GMT on 10 January are reproduced in Figs. 5, 6 and 7 respectively.

Fig. 8 shows a composite diagram depicting the wind discontinuities at sea level, 0·9, 2·1 and 3·0 km at 02/03 GMT on 9 January 1957. Fig. 9 shows a similar composite diagram for the same levels at 02/03 GMT on 10 January 1957. On the latter diagram, is also shown, as a stippled area, the zone of transition (extending roughly from Bombay and Broach to Kanpur and Gaya) of minimum air temperatures reported on the morning of 10th. This zone of thermal transition has been shown in Figs. 3 and 4 and have also been earlier discussed in detail.

A careful examination of these two composite diagrams reveals the following —

9 Jenary 1957 (Fig. 8)

It is very difficult to see the associations between the sea level wind-discontinuity T_1—T_2—T_3 and the wind discontinuities at the higher levels. It will also be noted that the slopes* of the wind-discontinuity surfaces between sea level and 0·9 km and between 0·9 and 2·1 km are very variable.† For instance, the slope of the surface between sea level and 0·9 km is vertical near Patiala (Lat. 30° 20′N, Long. 76° 28′ E), about 1/170 between Agra (27° 09′N, 77° 58′ E) and Jaipur (26° 49′N, 75° 48′E) and again vertical near Kotah (25° 11′N, 75° 51′E). Beyond Kotah, the discontinuity extends eastsoutheastwards ahead of its position at sea level.

Compared to the T_1—T_2—T_3 discontinuity, the T_4—T_5 discontinuity is associated with somewhat better organised patterns especially at the higher levels. For example, the slope between 0·9 and 2·1 km is fairly uniform and is about 1/190. However, the inclination of the surface of the discontinuity between sea level and 0·9 km is very variable being vertical at Berhampore (Lat. 24° 08′N, Long. 88° 16′E) and about 1/370 near Umaria (23° 32′N, Long. 80° 16′E). The sea level discontinuity also intersects the 2·1 km discontinuity near about Silchar (24° 55′N, 92° 59′E). It will further be noted that the portions of the discontinuities at 0·9 and 2·1 km which lie to the east of the line joining Berhampore and Silchar, are on the *southern side* of the sea level discontinuity. In other words, the slopes are in a direction opposite to what they are to the west of the line joining Berhampore and Gaya.

10 January 1957 (Fig. 9)

It is not possible to draw any conclusions so far as the slope of the T_{11}—T_{12} discontinuity is

* The slopes of the discontinuity surfaces have been computed in the following manner. Take any point A on the discontinuity line on the composite diagram at the lower level say L_1. Draw a perpendicular to the discontinuity line at A and let the perpendicular line intersect the discontinuity line at the higher level, say L_2, at the point B. Measure AB in centimeters and convert it into kilometers, using the scale of the chart at the latitude concerned. Let the distance AB thus computed be n kilometers. If the difference between the altitudes of L_1 and L_2 is, say m km, the slope of the discontinuity surface between the levels L_1 and L_2 can be taken as equal to m/n. This is a good enough approximation for our purposes.

In the special case when the discontinuity at the level L_1 intersects the discontinuity at the level L_2 at a point say C, the slope of the discontinuity surfaces between L_1 and L_2 at the point C is $m/0=\infty$. In other words the slope is vertical.

† The discontinuities T'_2 T'_3 (Fig. 5), T''_2 T''_3 (Fig. 6) although feeble, have been shown in their respective positions as specific discontinuities to maintain space-continuity with reference to the positions of the discontinuity at sea level and at 0·3, 0·6 and 1·5 km levels (not reproduced in the paper). The reader will undoubtedly see that if these discontinuities in the upper air had been drawn, for example, to lie wholly to the east of the position of the discontinuity at sea level, they would be in 'wrong positions' with reference to the sea level discontinuity: the cold air would be *in advance* at the higher levels instead of being *in the rear*, of the sea level position thus completely ruling out the possibility of the discontinuity having any cold front characteristics.

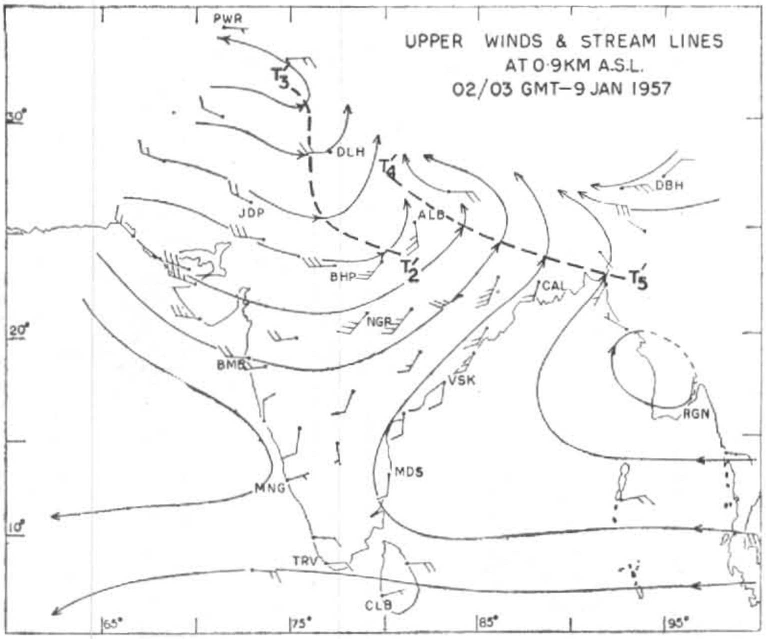

Fig. 5. Upper winds and stream lines at 0·9 km on 9 January 1957 (02 GMT)
The continuous lines ending with an arrow are the stream lines
The broken lines are wind discontinuities

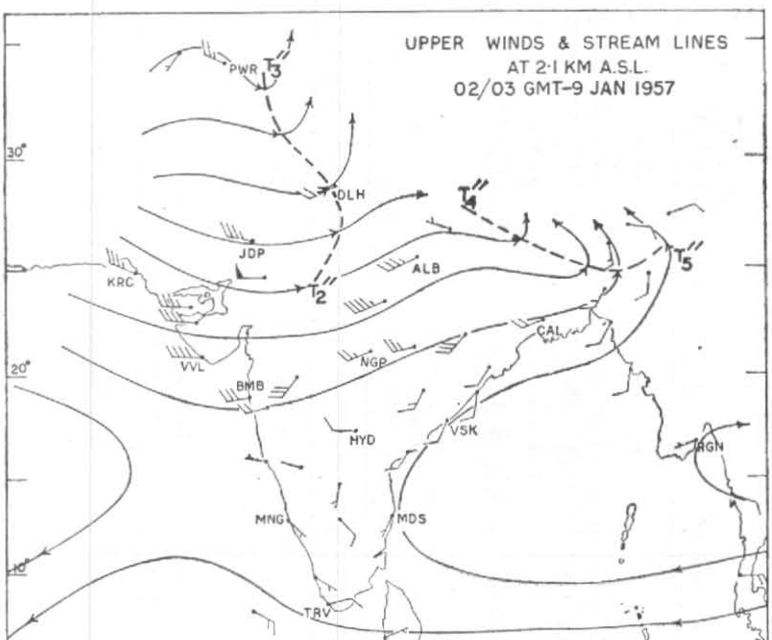

Fig. 6. Upper winds and stream lines at 2·1 km on 9 January 1957 (02 GMT)
Convention in plotting and analysis same as in Fig. 5

concerned. With regard to the $T_{10}-T_{11}-T_{13}$ discontinuity, we can infer that $T'_{11}-T'_{13}$ is the corresponding portion of the discontinuity at 0·9 km, the slope of the discontinuity surface being vertical near Buldana (20° 32′N, 76° 14′E) and about 1/250 near Khulna (22° 49′N, 89° 34′E). Above 0·9 km the picture is not clear; it is difficult to state that the $T''_{12}-T''_{13}$ is the discontinuity at 2·1-km level corresponding to the $T'_{11}-T'_{13}$ discontinuity at 0·9 km as the former extends over a much greater distance. Even if we assume that it is the same system as for instance between 90°E and 77°E, the slope is extremely variable being absolutely vertical at Mymensingh (24° 46′N, 90° 24′E) and about 1/620 between Betul (21° 52′N, 77° 56′E) and

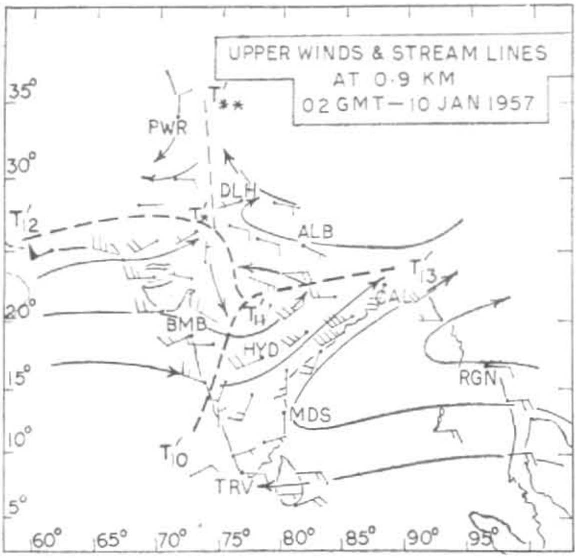

Fig. 7. Upper winds and stream lines at 0·9 km on 10 January 1957 (02 GMT)
Convention in plotting and analysis same as in Fig. 5

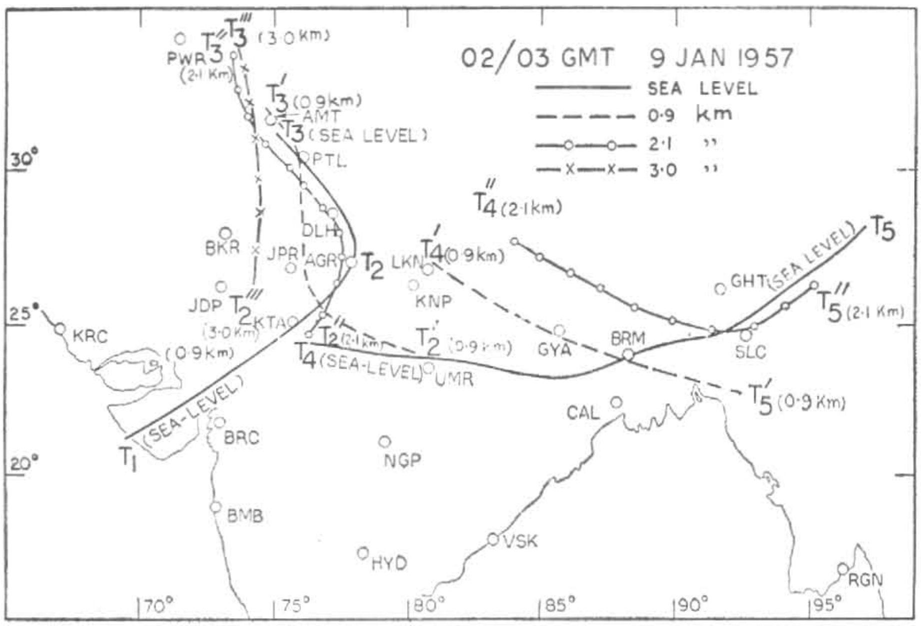

Fig. 8. Wind discontinuities, sea level and lower troposphere — 02/03 GMT (9 January 1957)
The sea level discontinuity T_4-T_5 intersects the T'_4—T'_5 (0·9 km) and T''_4—T''_5 (2·1 km) discontinuities near Berhampore and Silchar respectively and these discontinuities lie to the *south* of the sea level discontinuity east of the line joining Berhampore to Silchar. The discontinuity T'_2—T'_3 at 0·9 km intersects the sea level discontinuity T_1—T_2—T_3 near Patiala and again near Kotah

Sikar (27° 37′N, 75° 08′E). The 2.1-km wind discontinuity also intersects the sea level discontinuity near Mymensingh and extends further on the *southern* side of the sea level discontinuity.

The zone of thermal transition at sea level as seen in the minimum air-temperatures (stippled area) is also rather too far away from the T_{10}—T_{11}—T_{13} sea level wind discontinuity. Further, the thermal zone of transition as seen in the stippled area does not extend over the full length of the wind discontinuity: it does not extend east of Gaya (24° 45′N, 84° 57′E).

It will thus be seen that the discontinuity surfaces are not well-organised even below 2·1 km (7000 ft). Above 3·0 km, it has been found difficult even to identify a discontinuity surface. It is fully realised that this conclusion is based on an analysis which is uncertain in the upper air due to paucity of observations. Notwithstanding this, it cannot be denied that the

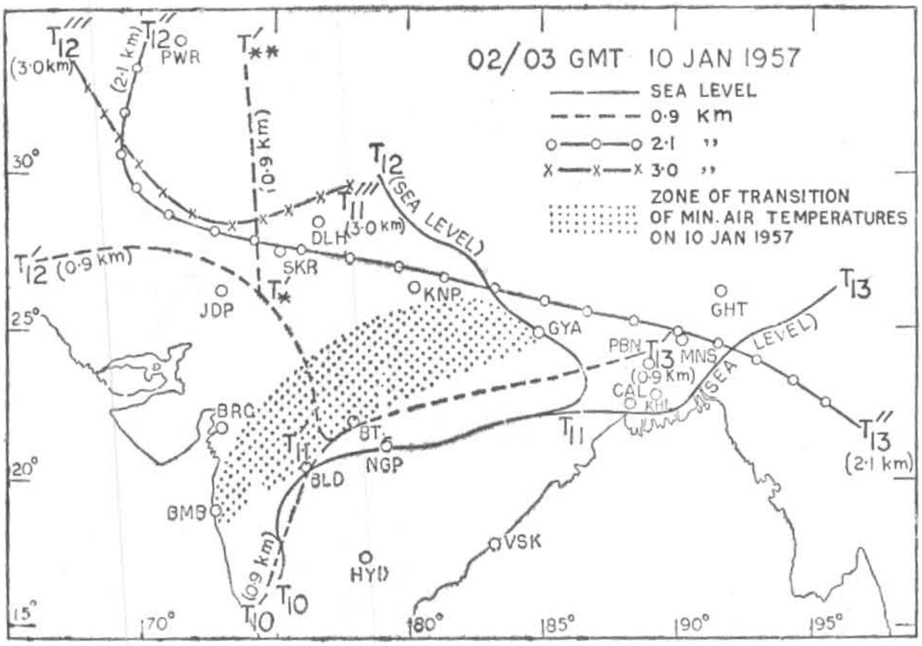

Fig. 9. Wind discontinuities, sea level and lower troposphere — 02/03 GMT (10 January 1957)

Stippled area is the zone of minimum temperature transition discussed in Figs. 3 and 4. Otherwise, convention in plotting same as in Fig. 8. The stippled area is rather far away from the sea level discontinuity and does not also extend east of Gaya, although the sea level and 0·9 km discontinuities extend further to the east

uncertainties in the determination of the slopes by the technique adopted by the author in no way vitiates the broad conclusions arrived at by him. It would be relevant to state in this connection that the discontinuity at sea level had been accurately delineated on account of the availability of a large number of observations. Any redrawing of the discontinuities at the higher levels 'within the limits' fixed by the actual winds would show that upper level discontinuities are very variable in position with respect to the sea level discontinuities.

5. Temperature differences and wind shears required for slopes in north Indian atmosphere

Table 1 would give an idea of the order of magnitude of temperature differences and wind shears required for organised sloping surfaces at latitude 25°N (latitude of Bamrauli approximately). These have been worked out from the well-known Margule's Equation:

$$\tan \theta = \frac{f}{g} \, \frac{T_m (u_1 - u_2)}{T_2 - T_1}$$

where $\tan \theta$ is the slope of the frontal surface,

f = Coriolis parameter,

T_m = Mean Absolute temperature of the air on either side of the frontal surface,

u_1 and u_2 are wind velocities (geostrophic) *along* the front on either side, and

T_1 and T_2 are Absolute temperatures on either side of the front corresponding to u_1 and u_2 respectively.

A slope of 1/50 is usually regarded as steep (Petterssen 1956) and organised slopes of 1/25 and 1/15 should be rare. Nevertheless, they have been included in Table 1 to enable the readers to get a clear picture of the conditions required to be satisfied in the Indian atmosphere if fronts with such steep slopes should exist as organised entities as envisaged by Desai and Koteswaram (1951).

It is pertinent to point out that in the present spell *vide* Fig. 1 there was a mean temperature difference of 6°C on sea level on either side of the thermal and wind discontinuity T_4—T_5 and a mean temperature of 290° A on the two sides of T_4—T_5. In this case the wind shears required for a slope of 1/15 would be as high as 426 knots. Even with a temperature difference of 3°C the wind shear required for a slope of 1/15, would be 213 knots.

A temperature difference of 2°C, if observed in a slope in northern India should, *prima facie,* not be considered as quite reliable in view of instrumental errors in the Indian radiosonde data. However even assuming that they are quite reliable, one would expect that with a temperature difference of 2°C, the partition, even if it is sharp to begin with, would become diffuse in a short period due to turbulent mixing.

The attention of the reader is also invited to the thermal contrasts in the upper air discussed in section 9 and seen in Fig. 13. The large wind shears necessary for maintaining a slope of say

TABLE 1

(T_2-T_1)	7°C			3°C			2°C		
Mean temp. (T_m)	285	290	295	285	290	295	285	290	295 °A
				Slope 1/100					
u_1-u_2 (knots)	76	75	73	33	32	31	22	21	21
				Slope 1/50					
Do.	152	149	146	65	64	63	43	43	42
				Slope 1/25					
Do.	303	298	293	130	128	126	87	85	84
				Slope 1/15					
Do.	505	497	482	217	213	209	144	142	140

1/15 with the actually observed temperature differences in the upper air can easily be computed from the above table.

6. Mid-tropospheric systems (500 mb)

Fig. 10 shows the successive positions of a wave trough in the westerlies at the 500-mb level which moved across India and the neighbouring regions and which was associated with the western disturbance described in the earlier sections. The data to the north of the Himalayas were taken from the 500-mb charts for 15 GMT published by the Meteorological Service of the People's Republic of China. As these charts contained dense coverage of data to the north of India and Pakistan, the contours drawn over that region are reliable.

This wave-trough underwent variations in its intensity as well as amplitude as it moved from west to east. It is of interest to mention that besides the wave-trough shown in Fig. 10, there was another independent trough very roughly along 65°E between 35°N and 52°N on 7th. It merged into the trough T_7-T_7 shown in Fig. 10, as the latter moved eastwards. Consequently, the very deep trough T_8-T_8 seen in Fig. 10 developed.

The trough T9 (3Z)—T9(3Z) is the position of the trough at 0300 GMT* on 9th corresponding to the 03 GMT sea level and lower tropospheric charts reproduced in Figs. 1, 3 and 4. The trough T_9 (3Z)—T_9 (3Z) was highly diffluent and we should expect pronounced positive vorticity advection, *i.e.*, pronounced divergence, ahead of its trough line (Ramaswamy 1956). It is interesting to note that the remarkable cyclogenesis observed at sea level on the 03 GMT charts for 9 January synchronised with the movement of this wave-trough at 500-mb level (and higher levels) across northwest Pakistan and Punjab (India), between 8th evening and 9th evening suggesting that the positive vorticity advection which was superposed on the well-marked trough with thermal contrasts at sea level led to the cyclogenesis at sea level. The author would like specially to emphasize that such positive vorticity advection would lead to cyclogenesis in the region where wind and thermal discontinuities coexist near the ground (Petterssen 1956)** and to pronounced updraught of air in regions of no† thermal contrasts and thereby produce large scale convection in the form of thunderstorms and/or duststorms as described by the author elsewhere (Ramaswamy 1956). It is therefore, quite probable that upper-level divergence and broad low-level convergence might have led to the thunderstorms and showers observed in the spell under study.

7. Vertical time-section and autographic charts of New Delhi

Fig. 11 shows the vertical time-section over New Delhi between 03 GMT of 8 January and 03 GMT of 11 January 1957. An examination of this time-section and the surface autographic charts of Delhi (not reproduced here) leads to the following conclusions —

(*a*) Most of the rainfall at New Delhi occurred between 0820 GMT of 8th and 0330 GMT of 9th. The rainfall occurred almost completely when the surface winds were southeasterlies or easterlies. The time-section also broadly suggests that most of the rainfall occurred in the rear of the ridge and ahead of the wave trough in the westerlies at 4·5 km and aloft, *i.e.*, in the region of upper divergence (Ramaswamy 1956).

* The 0300 GMT charts were prepared from the data published in "the U.S. Northern Hemispheric data tabulations"

** Petterssen refers in his paper to a pre-existing frontal zone at sea level but we would not be wrong if we assume that his hypothesis is applicable in northern India in regions where we have a pre-existing trough with thermal contrasts near the ground

† For instance, in northern India, in the hot weather period, density contrasts in air masses are destroyed by intense heating from the ground and there are little or no thermal contrasts

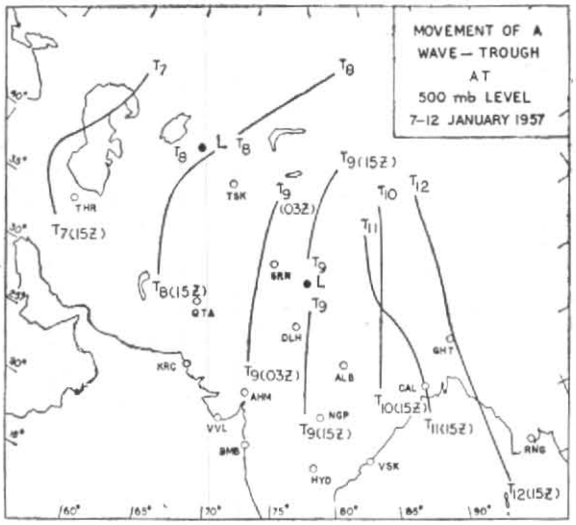

Fig. 10. Movement of wave-trough at 500-mb level (7-12 January 1957)

The suffixes to T denote the dates and the synoptic hours of the charts. For instance, $T_9(3Z)$—$T_9(3Z)$ refer to the position of the trough on 9 January 1957 at 03 GMT. The letter L shows the position of the centres of closed lows wherever such lows exist. The $T_9(3Z)$—$T_9(3Z)$ lies to the west of the centre of the sea level low in Fig. 1. Between 15Z of 8th and 03Z of 9th, the trough line must have been further west of the region where the sea level low developed

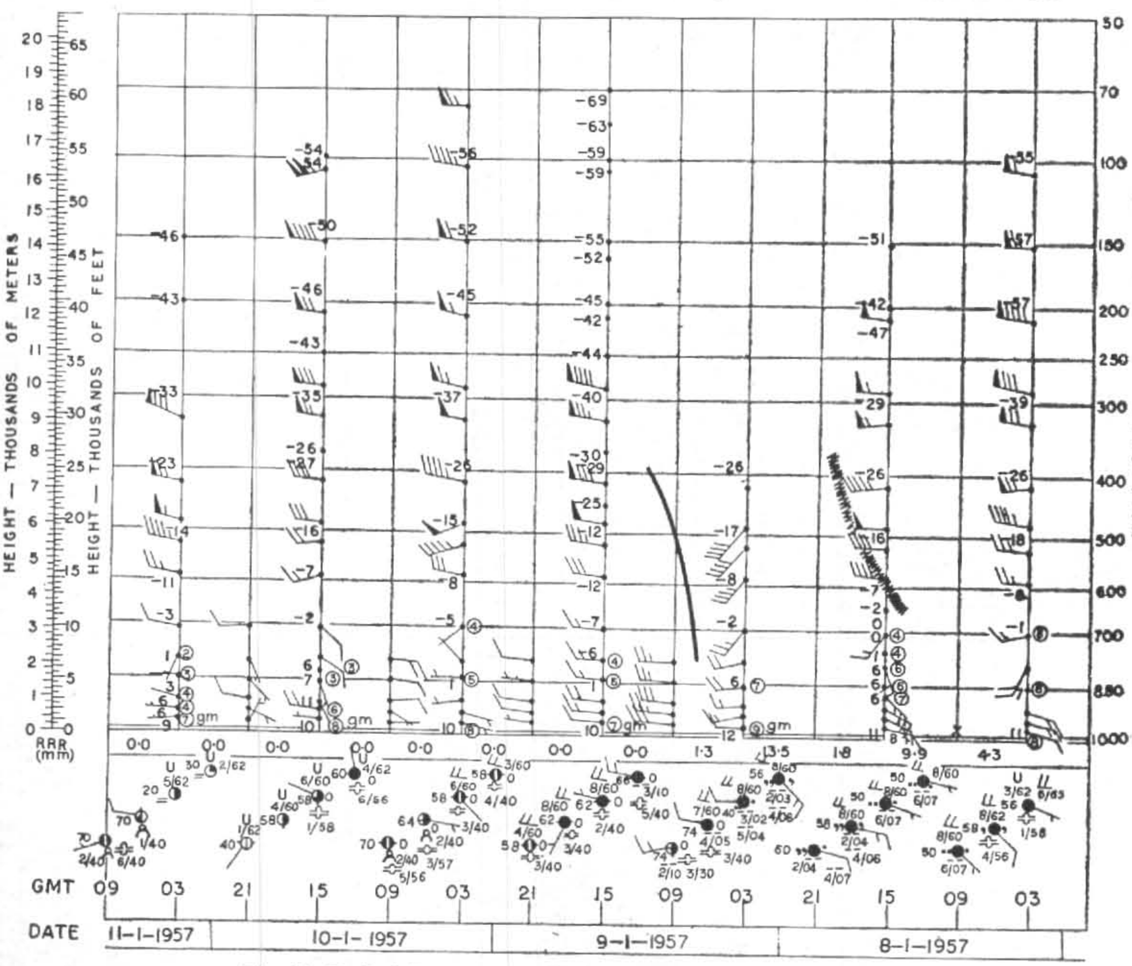

Fig. 11. Vertical time-section over New Delhi (8—11 January 1957)

The rainfall figures represent the amount recorded during six-hour periods. They have been plotted at the mid-point of the six-hour periods. Continuous thick line is a trough line while the zig-zag line is a ridge-line. Aeros have been plotted at three-hourly intervals. Bold figures just to the left of the wind-arrows denote the temperatures in degrees Centigrade. Smaller figures enclosed in circles to the right of the wind-arrows are mixing ratios in grams per kilogram of dry air

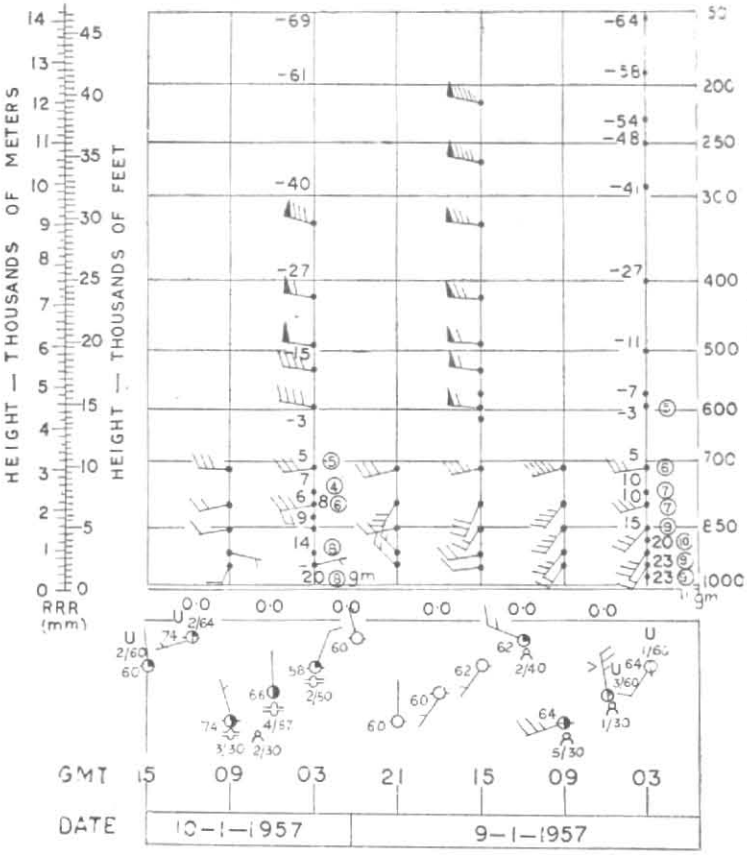

Fig. 12. Vertical time-section over Nagpur (9-10 January 1957)
Same convention in plotting as in Fig. 11

(*b*) It is difficult from the time-section to draw any inference about the slope of the surface of separation between the westerlies and the easterlies.

(*c*) The temperature in the lower troposphere dropped, not immediately at the time of replacement of the easterlies by the westerlies but during the subsequent 12 hours. Compare the temperatures, level for level at 15 GMT on 8th with those of 03 GMT and 15 GMT on 9th.

(*d*) The changes in the mixing ratio when the easterlies were replaced by westerlies were not significant. However, the mixing ratio decreased appreciably when the westerlies persisted for some time.

(*e*) The P. T. anemograms showed that the southeasterly surface winds changed to southwesterlies near about 0245 GMT on 9th. *The other autographic charts did not reveal any unusual features in association with this change in the surface winds.*

8. Vertical time-section and autographic charts of Nagpur

Fig. 12 shows the vertical time-section over Nagpur on 9 and 10 January 1957. It will be seen that the southwesterlies below 1·0 km were replaced by northwesterlies sometime between 09 and 21 GMT on 9th, possibly near about 15 GMT of that day. This replacement was associated with large temperature change in the lower troposphere. However, on account of the unreliable radiosonde data for 15 GMT of 9th (not plotted on the time-section) it is not possible to say whether the temperature change was gradual or abrupt and when exactly temperatures fell. There was, however, no weather development during this period. Only cumuliform clouds developed between 0600 and 1230 GMT which dissipated soon afterwards. *The surface autographic charts did not show any significant changes during the movement of this discontinuity.*

9. Analysis of thermodynamic diagrams

Fig. 13 shows the potential pseudo-wet-bulb temperatures (θ_{sw}) of the air over New Delhi, Bamrauli (Allahabad), Nagpur, Calcutta and Gauhati on 9 and 10 January 1957.

9 January 1957 — The Delhi temperatures are, level for level, about 5°C lower than those over Nagpur and about 3° to 6°C lower than those over Allahabad. The air over Delhi may be classified as Transitional Polar Continental or *PcTc* air (Roy 1946) and the air over Nagpur and Bamrauli

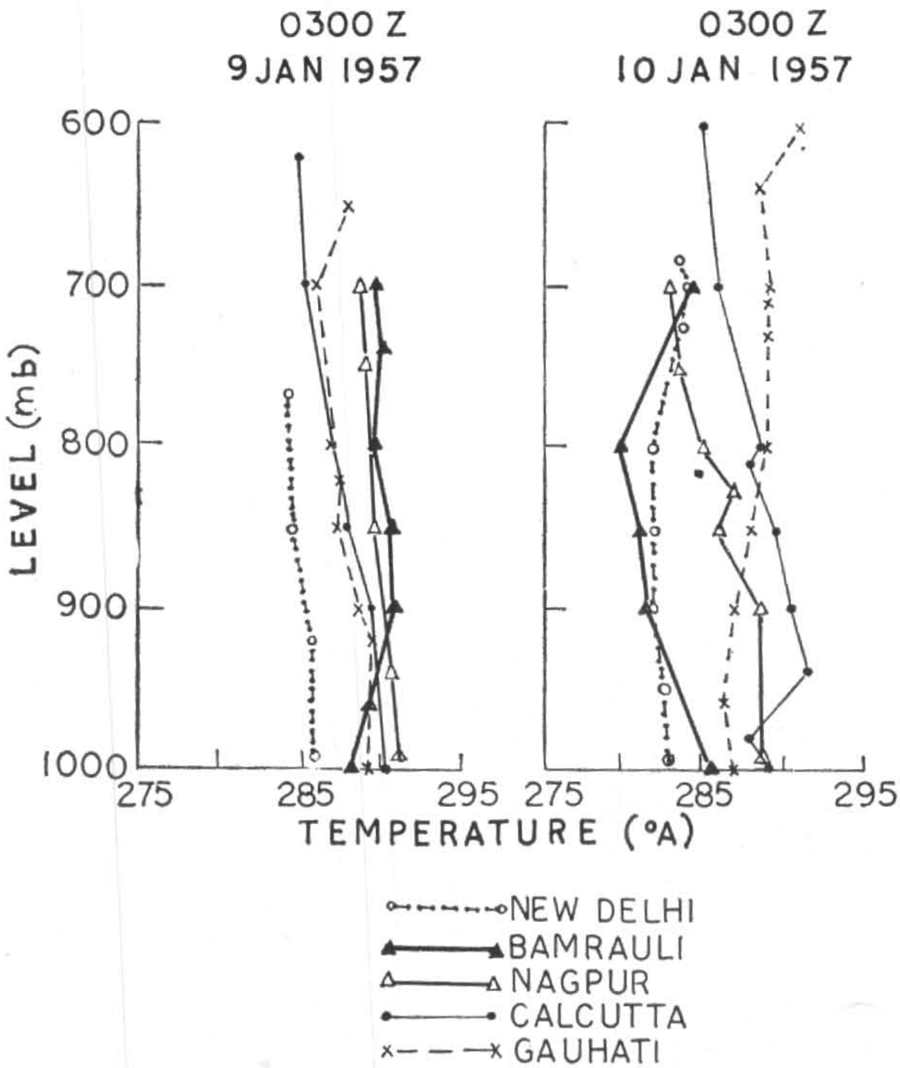

Fig. 13. Potential pseudo-wet-bulb temperatures over stations in northern and central India (9, 10 January 1957)

The curves for 9 January 1957 are all practically vertical. The curves for 10th are also similar although the θ_{sw} values at the stations have changed during the 24-hour period

as Transitional Tropical Continental *TcTm* air in different stages of transition.

Turning our attention momentarily to Fig. 2 we see clearly from the temperature analysis that if the T_1-T_2-T_3 discontinuity were a front, its eastward or southward movement should cause cold front action and the corresponding type of weather development. This should particularly be the case in the central parts of the country where the minimum air temperatures— the most representative property for demarcating air masses over the Indian Region according to Roy (1946)— showed a zone of transition.

10 January 1957 — On this day, we are mainly interested in the temperatures over Bamrauli (Allahabad) in relation to those over Calcutta and Nagpur. The diagram leaves no doubt that the air over Bamrauli which was becoming *PcTc* (Roy 1946) was 3° to 6° colder than that over Nagpur at least upto 800-mb level. It was colder than the air over Calcutta by about 4° C very near* the ground and by 8° to 10°C at the higher levels below the 800-mb level. This means that if the T_{10}–T_{11} –T_{12} discontinuity were a front, its eastward and southward movement should cause cold front action and the corresponding type of weather development. In this case also, as on 9 January, the frontal action and the consequent development of weather should be pronounced over the central parts of the country, *e.g.*, over and near Nagpur

*The Calcutta ascent data at 980-mb level on 10 January 1957 are doubtful. This is reflected in the θ_{sw} value also for that level in Fig. 10

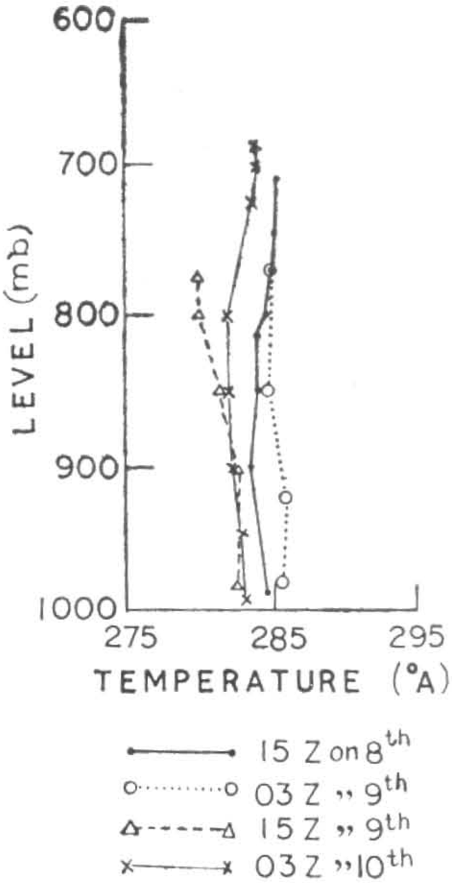

Fig. 14. Potential pseudo-temperature curves for New Delhi between 15 GMT of 8 January 1957 and 03 GMT of 10 January 1957

Same convention in plotting as in Fig. 13. The curves for all the hours of observation are practically vertical and they did not show any abrupt changes with height as the discontinui ty T_1—T_2—T_3 moved across the station during the period 8th evening to 10th morning

as the air mass contrasts (judged by minimum air temperatures) during the replacement of the warmer air by the colder air would be a maximum over this region — even more than on 9 January, *vide* Figs. 3 and 4 and the discussions in Section 3 relating to minimum temperatures. We shall revert to this subject again in Section 10.

Fig. 14 shows the potential pseudo-wet-bulb temperature curves (θ_{sw}) for all the radiosonde ascents taken at New Delhi between 1500 GMT of 8 January and 0300 GMT of 10 January 1957. These curves are to be examined with reference to the positions of the sea-level discontinuities in Fig. 2. It will be observed that although during this period, the discontinuity T_1-T_2-T_3 moved across New Delhi, the θ_{sw} curves show only a general rise or fall in temperatures over the *entire column* of the atmosphere for which data were available in the radiosonde ascents. There are no sharp changes in the characteristics of the curves *in the vertical* to show that a warm moist layer with distinctly different air mass characteristics was superincumbent on a cold dry air mass in the lower levels at any of the positions of the sea-level discontinuity.

The θ_{sw} curves for Allahabad and Calcutta were examined in a similar manner and they also did not show any abrupt changes in the chracteristics of the curves in the vertical. These curves have, however, not been reproduced here.

10. Atmospheric cross-sections

Figs. 15 and 16 show the atmospheric cross-sections along the line running NNW to SSE from New Delhi to Madras *via* Nagpur at 03 GMT of 9 and 10 January 1957 respectively. In order to maximise all available information of these cross-sections, the dry bulb temperatures at the station level pressure of all the surface observatories lying within one degree of the line joining New Delhi to Madras were reduced to 1000-mb level (using a tephigram) and plotted on the cross-sections. The potential temperatures for the surface stations obtained in this manner were reasonably consistent with those obtained from the radiosonde over New Delhi, Nagpur and Madras. A comparison of the two cross-sections prepared in this manner shows the following —

9 January 1957 — (*a*) There is no evidence of a concentration of isentropes near Delhi in the lower levels. In fact, between the ground and the 750-mb level, the isentropes are wider apart over Delhi–Agra–Gwalior sector than over the rest of the Delhi–Nagpur portion of the cross-section. This is also supported by the run of the dry bulb curves between Delhi and Gwalior. These observations are significant in view of the fact that T_1-T_2-T_3 discontinuity at sea level (Figs. 1 and 2) at 03 GMT on 9th passed right over Delhi and close to Agra and Gwalior. It would, therefore, not be wrong to infer from these observations that T_1-T_2-T_3 discontinuity did not have the characteristics of a front which, as is well-known (Petterssen 1956) would be characterised by a concentration of potential isotherms, and by an inversion or a marked decrease in lapse rate.

(*b*) The dry bulb curves and the potential isotherms, suggest a thermal zone of transition over the Gwalior–Chindwara sector between the ground and 850-mb level (see the 20°, 16° and 12°C isotherms and the 292°, 296° and 300°A isentropes). Between 850 and 700-mb levels, there is a slight concentration of the potential isotherms even over the Gwalior–Delhi sector also but it is difficult to draw any conclusions therefrom.

10 January 1957 — (*a*) The isentropes over Delhi–Agra–Gwalior sector between the ground

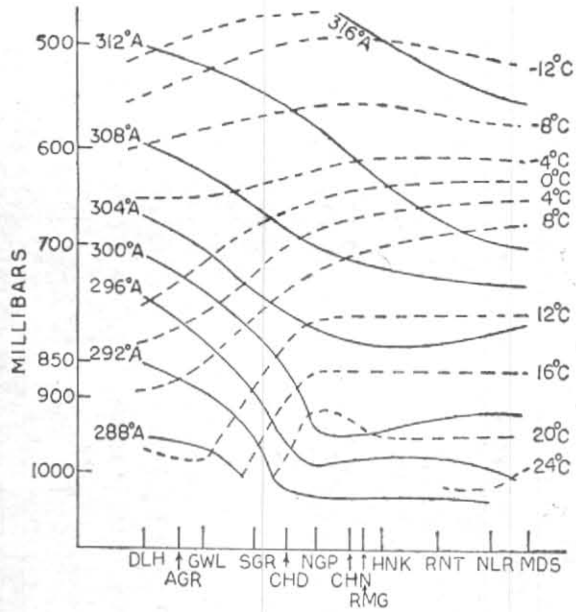

Fig. 15. Atmospheric cross-section along New Delhi—Nagpur—Madras (03 GMT, 9 January 1957)

Dotted lines are dry bulb temperatures while continuous lines are isentropes

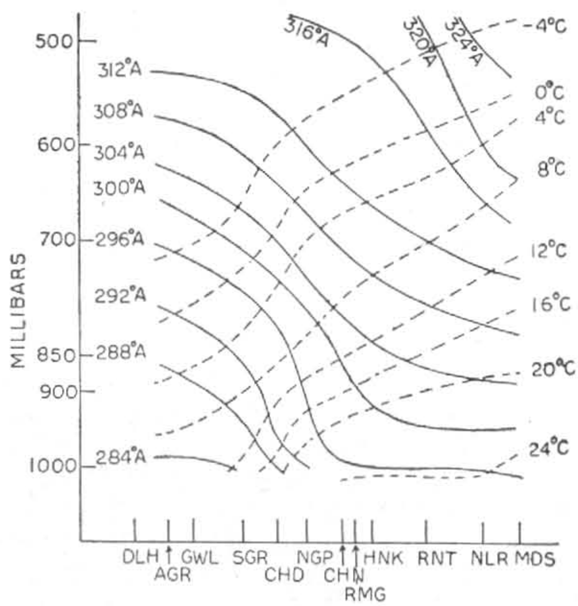

Fig. 16. Atmospheric cross-section along New Delhi—Nagpur—Madras (03 GMT, 10 January 1957)

Same convention in plotting as in Fig. 15

and 850-mb level are even wider apart than on the 9th.

(*b*) The dry bulb curves as well as the isentropes indicate that the thermal zone of transition observed on 9th over Gwalior—Chindwara sector between the ground and 850-mb level has definitely shifted southwards and is now more concentrated between Saugor and Nagpur. Its vertical extent also seems to have slightly decreased: it probably does not extend above 900-mb level.

(*c*) At higher levels betwee 800 and 600 mb, the isentropes are more crowded than on the 9th between Nagpur and Delhi. An examination of the dry bulb, wet bulb and dew point temperature curves for Nagpur for 03 GMT (of 10th) leaves no doubt that there was a marked subsidence inversion over Nagpur on this day, the base of subsidence inversion being at 800-mb level. The available curves for Delhi for 10th are also suggestive of subsidence lapse rates. Hence we need not associate the concentration of isentropes at the higher levels over Nagpur—Delhi sector with the possibility of a frontal surface over that sector.

To sum up, we can state on a broad basis that the atmospheric cross-sections indicate that the T_1–T_2–T_3 discontinuity did not have the thermal characteristics of a front. However, the portion of the T_4–T_5 discontinuity over the central parts of the country on the 9th and the T_{10}–T_{11} discontinuity over the same region on the 10th had thermal characteristics of a front but these frontal surfaces even if they had existed as well-organised surfaces did not extend from the ground above the 850-mb level. The concentration of the isentropes was also much less than what is found in middle-latitude fronts.

11. Hydrometeors in relation to the positions of the discontinuities near the ground

Fig. 17 shows the positions of the wind discontinuities at the surface at 0300 GMT on 9 January 1957 and the *subsequent* 24 hours rainfall. For facility of ready reference, the positions of the wind discontinuities at the surface at 0300 GMT on the following day, namely, on 10 January 1957 are also shown in the same diagram (as broken lines).

Fig. 18 shows a similar diagram for 03 GMT of 10th and the subsequent 24 hours rainfall. The positions of the wind discontinuities at 12 GMT on the same evening have also been shown on the diagram (as broken lines).

9 January 1957 (*Fig. 17*)—It may be recalled that from a study of the potential pseudo-wet bulb temperatures, we had earlier come to the conclusion that if the T_1–T_2–T_3 wind discontinuity had been a front at all, it should have caused cold front action during its eastward and southward movement and that such a cold front action should have been most pronounced in the central parts of the country where the air mass contrasts would have been most pronounced.

Turning our attention now to Fig. 17, we note that the rainfall plotted in the area lying between

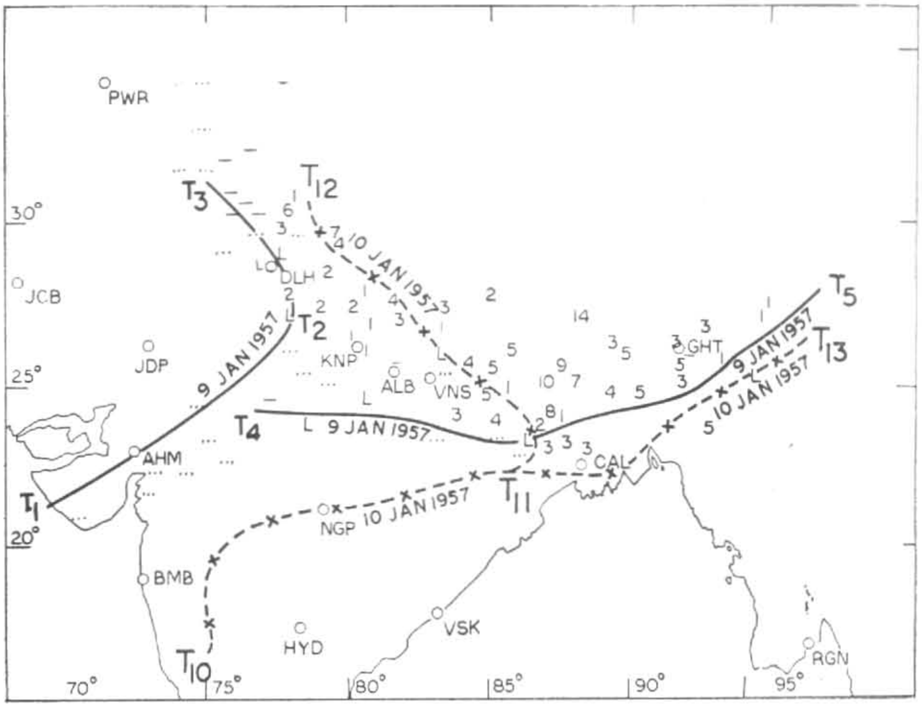

Fig. 17. Surface wind discontinuities (03 GMT, 9 January 1957) and subsequent 24 hours rainfall

The figures represent rainfall in centimeters during the 24 hours commencing from 03 GMT of 9 January. Three dots indicate rainfall less than 2·5 mm. L denotes rainfall between 5·0 and 7·5 mm. Integers represent rainfall in whole centimeters. There is complete absence of rainfall between T_{10}—T_{11} and T_4—T_5 west of Long. 85°E and most of the rainfall east of Long. 85°E has occurred to the *north* of T_4—T_5 which had actually moved southwards during the same period

Fig. 18. Surface wind discontinuities (03 GMT, 10 January 1957) and subsequent 24 hours rainfall

Same convention in plotting as in Fig. 17. Most of the rainfall has occurred to the north of the T_{11}—T_{13} discontinuity which had remained quasi-stationary

T_1—T_2—T_3 and T_{10}—T_{11}—T_{12} could *prima facie* be attributed to the movement of a cold front from the position T_1—T_2—T_3 to the position T_{10}—T_{11}—T_{12}. Three fundamental questions, however, arise immediately in our minds, namely,

(*a*) Was there any time-sequence in the occurrence of precipitation during the 24 hours commencing at 00 GMT of 9 January to justify the view that the precipitation could have been caused by the progressive eastward movement of a front from the position T_1—T_2—T_3 to T_{10}—T_{11}—T_{12}?

(*b*) If T_1—T_2—T_3 were a cold front, why did it not cause any rainfall in the central parts of the country during the course of its movement to the position T_{10}—T_{11}—T_{12}?

(*c*) Why did we not observe any characteristics of a cold front in the autographic charts of Nagpur when the "front" passed right over Nagpur and lay as T_{10}—T_{11}—T_{12}?

We shall answer question (*a*) by giving a table (Table 2) which shows the times of occurrence of precipitation and/or thunderstorms at the synoptic stations in the plains between the longitudes of New Delhi and Gorakhpur and to the north of latitude 25°N on 9 January 1957. The times of commencement as well as of cessation of the precipitation and/or thunderstorms are given in this table.

In many cases, precipitation/thunderstorms actually commenced before 0001 GMT of 9th (*i.e.*, on 8th) and was *continuing* even at 0001 GMT of 9th and hence the rate of commencement of weather has been shown as 8 January 1957 in all these cases.

It may also be stated that the times of only the very first commencement and of only the very last cessation, of precipitation and/or thunderstorm have been given in the table. To cite an example, the actual times of commencement and the cessation of various types of precipitation and/or thunderstorm (in GMT) at Lucknow were as follows —

, 1800 8th / 2100 8th	• 2100 8th / 2300 8th	, 2300 8th / 0040 9th
K 0040 9th / 0200 9th	•• 0200 9th / 0410 9th	K 1025 9th / 1300 9th

The times of commencement and cessation of precipitation/thunderstorms at Luckrow have been given in the table as 1800 of 8th and 1300 of 9th respectively. The other times given above are of no importance for the purpose we have in view and hence have not been given in the table.

The stations have been arranged in the table in the order of increasing longitudes so that the time-sequence, if any, may become obvious even at a glance.

It will be seen from Table 2 that there is no relationship between the times of commencement or cessation of precipitation/thunderstorm in relation to the position of discontinuities T_1—T_2—T_3, T_6—T_7—T_8 and T_{10}—T_{11}—T_{12}.

On the basis of the above table and the analysis presented in the earlier sections, we now give the answer to all the three questions (*a*), (*b*) and (*c*) by stating that T_1—T_2—T_3 did not have well-organised sloping surfaces, that it was not primarily responsible for the rainfall in the area lying between T_1—T_2—T_3 and T_{10}—T_{11}—T_{12} in Fig. 17 and that as the cold air in the rear of T_1—T_2—T_3 spread eastwards and southwards, it merely gradually replaced the warm moist air and consequently did not cause rainfall in the central parts of the country or abrupt changes in the autographic records of Nagpur. It is hardly necessary for us to add that this hypothesis is quite consistent with our other findings in the earlier sections wherein we had referred to other possible causes (*e.g.*, pronounced upper level divergence and broad low level convergence) for the observed rainfall.

The next question which we ask ourselves is : "Was the rainfall referred to in the above paragraph by any chance caused by the discontinuity T_4—T_5 acting as a front, say, as a warm front?"

Our answer to this is in the negative for two reasons. First, with the eastward and southward movement of the T_1—T_2—T_3 system, the T_4—T_5 system *west of Long. 85°E* (*i.e.*, upto L in the diagram) must have been annihilated *vide* Fig. 2. Secondly, even if we assume that it was not annihilated and that the entire length of T_4—T_5 existed as a definite entity during the subsequent 24 hours and that it moved to the position T_{10}—T_{11}—T_{12} by 03 GMT of 10th, we see that T_4—T_5 had moved *southwards* and as such it could not have caused the extensive rainfall *north* of it during its southward movement.

Thus we come to the conclusion that neither T_1—T_2—T_3 nor T_4—T_5 would have been the basic cause for the extensive rainfall west of Long. 85°E.

We shall now attempt to explain the rainfall in Fig. 17 plotted to the east of Long. 85°E. It is obvious that this rainfall could not have been caused by cold front action of T_1—T_2—T_3 as this discontinuity moved only upto the position of T_{10}—T_{11}—T_{12} by 03 GMT of 10th and much of the rainfall extended *far ahead of even this extreme*

TABLE 2

Station	Lat. (N)	Long. (E)	Elevation/ Altitude (metres a.s.l.)	Precipitation/ Thunderstorm	Commencement Time (GMT)/Date (Jan 1957)	Cessation Time (GMT)/Date (Jan 1957)
New Delhi (Safdarjung)	28° 35′	77° 12′	216	Drizzle/Rain	0515/8th	0410/9th
Roorkee	29 51	77 53	274	Thunderstorm/ Rain/Drizzle	0344/8th	1120/9th
Agra	27 09	77 58	169	Drizzle/Rain	0300/8th	0725/9th
Dehra Dun	30 19	78 02	682	Rain/Drizzle	0620/8th	1930/9th
Aligarh	27 53	78 04	187	Drizzle/ Thunderstorm	0000/9th	0850/9th
Najibabad	29 37	78 23	270	Rain/Drizzle	0530/8th	1530/9th
Jhansi	25 27	78 35	251	Rain/Shower	2230/8th	0905/9th
Bareilly	28 22	79 24	173	Drizzle	2200/8th	0945/9th
Hardoi	27 23	80 10	142	Rain	0630/8th	1300/9th
Kanpur	26 26	80 22	126	Rain/ Thunderstorm	0910/8th	1135/9th
Banda	25 28	80 22	121	Drizzle	2315/8th	0010/9th
Kheri Lakhimpur	27 54	80 48	147	Rain	1215/8th	1330/9th
Fatehpur	25 56	80 50	114	Rain	1010/9th	1225/9th
Lucknow (Amausi)	26 45	80 53	128	Drizzle/Rain/ Thunderstorm	1800/8th	1300/9th
Allahabad (Bamrauli)	25 27	81 44	98	Thunderstorm/ Rain/Shower	1842/8th	1610/9th
Gonda	27 08	81 58	110	Rain/Drizzle	1850/8th	1325/9th
Varanasi (Babatpur)	25 27	82 52	85	Thunderstorm/ Rain	2100/8th	1828/9th
Gorakhpur	26 45	83 22	77	Thunderstorm	0200/9th	1130/9th

position of the discontinuity. It also seems reasonable to argue that most of the rainfall cannot be attributed to a warm-front action of the portion of $T_4—T_5$ lying to the east of 85°E as we see that this discontinuity actually moved *southwards* to the position $T_{11}—T_{13}$ by the morning of 10th. The rainfall only at a few stations in West Bengal to the south of $T_4—T_5$ can be attributed to the southward movement of this discontinuity. In this connection we recall our discussions on the slopes of the discontinuity surfaces (Figs. 8 and 9) and note that it was not possible to identify well-organised sloping surfaces east of Long. 85°E on 9th between sea level and 0·9 km and that no sloping surface could be identified above 2·1 km a.s.l. It may also be pointed out that the potential pseudo-wet-bulb temperatures over Calcutta and Gauhati at 03 GMT on 9 January 1957 *vide* Fig. 13 were practically the same (making allowance for instrumental errors). Under these circumstances, it appears improbable that the wind discontinuity $T_4—T_5$ to the east of 85°E was associated with a thermal discontinuity except in a very shallow layer near the ground and, therefore, it would be correct to conclude that the rainfall to the east of 85°E was not associated with a frontal surface.

In passing, it may be mentioned that the surface winds over Calcutta (Alipore) changed from South to Northeast/East at 1000 GMT on 9th and that this was associated with a drop of 5°C in surface dry bulb temperature over Calcutta. The change in the wind direction was due to the southward movement of the $T_4—T_5$ discontinuity. There was, however, no rain over Calcutta although stations to the north of Calcutta had recorded rain. In view of this and of what has been stated in the earlier paragraph about the identity of the air masses to the north and south of the discontinuity, we infer that the drop in temperature was confined to a very shallow layer near the ground. The fall in surface temperature was probably partly due to the southward movement of the sea level discontinuity $T_4—T_5$ (see Fig. 1 which shows a difference in temperature of about 5°C on either side of the discontinuity to the north of Calcutta). The drop in temperature could also partly be attributed to the effect of rain-chilled air brought in by the northeasterlies from neighbouring thunderstorms.

10 January 1957 (*Fig. 18*) — We note from the diagram that most of the rainfall* over northeast India and East Pakistan has occurred to the *north* of the $T_{11}—T_{13}$ discontinuity. This discontinuity was quasi-stationary *to the south* of the latitude of Calcutta up to 00 GMT of 11 January (see also Fig. 2 which shows the position of this discontinuity at 12 GMT of 10 January). It was only after 00 GMT of 11 January that the trough at the head of the Bay associated with this discontinuity developed into a closed low. The synoptic charts also show that the major portion of the rainfall plotted in Fig. 18 occurred before 00 GMT of 11th. Hence, we may proceed on the assumption that most of the rainfall in Fig. 18 occurred when the $T_{11}—T_{13}$ discontinuity was either in the position seen in Fig. 18 or slightly further to the *south*.

As the quasi-stationary discontinuity was close to Calcutta, we may, for the purpose of the present discussion, assume that the air to the south of the discontinuity was roughly represented by the potential pseudo-wet-bulb curve for Calcutta on 10 January and that the air to the north of the discontinuity was represented by the corresponding curve for Gauhati in Fig. 13.

An examination of Fig. 13 shows that the air mass over Calcutta† between the ground and 850-mb level was warmer than that over Gauhati. Between 850-mb and 600-mb levels, however, conditions were just the opposite: the air over Gauhati was significantly warmer than that over Calcutta. We have also seen in Section 4 (see Fig. 9) that there were no well-organised sloping surfaces of discontinuity even upto 2·1 km. We would, therefore, be quite justified in inferring that the rainfall in northeast India and East Pakistan shown in Fig. 18 was not associated with any well-organised frontal surface and that even if such a frontal surface was associated with it, it would have been confined to a very shallow layer near the ground.

12. Arakawa's model of the structure of a cyclone in tropical latitudes

In a recent paper, Arakawa (1965) has shown that a number of line echoes are seen in the radar in the warm sectors of cyclones in the sea to the south of Kyushu in Japan. Arakawa considers these line echoes as prefrontal squall-lines ahead of the cold front of the cyclone. On this basis, he has proposed a revised model of the structure of cyclones in tropical latitudes. Although no radar pictures were available for the spell studied in the present paper, the writer has examined as to how far the development of rainfall and/or thunderstorms in the present spell could be explained on the basis of Arakawa's cyclone-model. It is pertinent

* The rainfall along and near the western Himalayas in Fig. 18 was associated with a *fresh* wave-disturbance in the westerlies. It is, therefore, outside the purview of our present discussion

† See foot-note about the R.S. ascent data for 980-mb level for Calcutta on 10 January 1957 in Section 8

to observe in this connection that the area* south of T_4—T_5 and east of T_1—T_4 in Fig. 1 constitutes the 'warm-sector' of the system and that if Arakawa's model were applicable to the Indian western disturbance, there should have been development of weather in the above-mentioned area. This was, however, not the case. The development, on the other hand, was in the area north of T_4—T_5 where the sea level temperatures were 6° to 7°C *lower* than in the 'warm sector' (south of T_4—T_5) and only 2° to 3°C higher than over the area to the west of T_3—T_4. We had also seen from the detailed study made in Section 10 that T_3—T_4 was not a cold front with an organised sloping surface and that there was no time-sequence in the development of rainfall and/or thunderstorms reported from the dense and extensive network of stations in this area. In view of all these considerations, we come to the conclusion that Arakawa's model for the sub-tropical cyclone in the Japan area is not applicable to the western disturbance studied in the present paper and that our conclusions about the existence or otherwise of fronts in the Indo-Pakistan subcontinent do not need any revision in the light of the findings of Arakawa.

13. Tropospheric and lower and mid-stratospheric general circulation over Asia in early January 1957

The first three weeks of January 1957 were characterised by a quick succession of active western disturbances over India resulting in considerable excess of rainfall over the whole of northern India during that period. This was followed by a lull in the activity of the western disturbances in the last week of the month.

The monthly mean 700-mb chart for the northern hemisphere for January 1957 prepared by U.S. Weather Bureau (not reproduced here) shows a deep closed low in the Arctic Region near Novaya Zemlya and Kara Sea and a large-amplitude trough extending from this low to the Caspian Sea and further south to nearly 20°N. The mean negative anomaly was as much as 430 feet in the closed low and 100 feet in the Caspian Sea region. These observations clearly show that we had, in the mean, a pronounced low index circulation over West and North Asia and that conditions were very favourable for the development of active western disturbance over West Pakistan and northern India and for fresh surges of polar continental air to invade these regions.

Early in January 1957, there were also important developments in the lower and mid-stratosphere over Siberia (Godson and Wilson 1963). According to these authors who had based their conclusion on an analysis of 100-mb charts, "there was" during late December 1956 and early January 1957 "a rapid change in the orientation of the cold vortex over the North Pole which moved eastward across North America to the Atlantic and shifted down over Siberia where minimum seasonal values were recorded". "Cooling was especially intense in east central Siberia".

Extensive investigations by Panofsky, Krawitz and Julian (1958), Craig and Hering (1959) and Frogner (1962) have shown that "strong impulses in the stratosphere may instantaneously influence and disturb all atmospheric layers below" and "*transitory* impulses can contribute to the producing of long lasting effects on the tropospheric circulation" when the "impulses harmonise with the pre-existing conditions in the troposphere".

In view of the above, we would be justified in stating that during early January 1957, conditions were very much more favourable than it normally is, for surges of fresh polar continental air to invade West Pakistan and northwest India and for the development of real fronts over that region, extending from the ground to very high levels in the troposphere. And yet, we did not find during the spell studied in this paper, well-organised slopes in the atmosphere even up to 2·1 km, not to speak of higher levels.

14. Conclusions

The author does not claim that the present investigation, though detailed, would set at rest the controversy about the existence or otherwise of fronts in the Indian atmosphere. More of such detailed investigations will have to be undertaken with much denser coverage of radiosonde and radiowind data and with six-hourly observations of such data recorded by more accurate instruments before a final answer can be given to the questions posed by the author in Section 2 of the paper.

However, the author does claim in this paper that fronts having well-organised sloping surfaces with density contrasts and extending to 500-mb level or aloft should be rather unusual in the Indian atmosphere even in the cold weather period. When sloping discontinuity surfaces form due to surges of polar continental air from northern

---

* While stating that this area constitutes the 'warm sector' of the system, the author is aware that there is no unique method of identifying such sectors and that, in spite of the recent advances in synoptic meteorology, there is an element of subjectivity in all synoptic analysis, even now. Nevertheless, with the detailed evidence presented in this paper including those in the large number of charts analysed by the author but not reproduced in the paper, the author is of opinion that there would be no justification to infer that the 'warm-sector' in Fig. 1 lay to the north of the line T_4—T_5

latitudes in association with western disturbances in winter, they probably get disorganised on most occasions, leaving merely a broad "Indeterminate" type of partition which moves with the western disturbance and causes temperature and other associated changes. The partitions are, in any case, of little consequence in the development of hydrometeors and are, therefore, of little value in forecasting the hydrometeors. The latter seem to be primarily caused by pronounced upper level divergence and broad low level convergence in the manner discussed in Section 5.

15. Acknowledgement

The author is very greatly indebted to Shri M. Venkataramani of the Headquarters Office of the India Meteorological Department at New Delhi for the unstinting help he gave in the preparation of synoptic charts, the thermodynamic diagrams, vertical time-sections, atmospheric cross-sections and many other miscellaneous diagrams.

The author would also express his sincere thanks to Shri Jatinder Kumar Davar for typing the manuscript of this paper.

Grateful thanks are also due to Dr. Jerome Namias, Chief of the Extended Forecast Division, U.S. Weather Bureau for supplying the author with the monthly mean 700-mb charts of the northern hemisphere for January 1957.

REFERENCES

Arakawa, H.	1965	Revised model of cyclone structure in Tropical latitudes (Symp. Met. Results, I.I.O.E. — to be published).
Craig, R. A. and Hering, W. S.	1959	*J. Met.*, **16**, p. 91.
Desai, B. N.	1950	*Indian J. Met. Geophys.*, **1**, pp. 74-76.
	1951	*Mem. India met. Dep.*, **26**, Pt. 5, pp. 217-218.
	1951	*Indian J. Met. Geophys.*, **2**, pp. 113-120.
Desai, B. N. and Koteswaram, P.	1951	*Ibid.*, **2**, p. 250.
Frogner, E.	1962	*Geophysica Norvegica*, Oslo, **23**, 5.
Godson, W. L. and Wilson, C. V.	1963	*Canad. met. Mem.*, **11**.
Koteswaram, P. and George, C. A.	1958	*Indian J. Met. Geophys.*, **9**, pp. 9-22.
Malurkar, S. L.	1945	*Forecasting weather in and near India.*
	1947	*Curr. Sci.*, **16**, pp. 14, 77, 139, 148, 174, 245 and 277.
	1948	*Ibid.*, **17**, pp. 112, 210 and 348.
Malurkar, S. L. and Pisharoty, P. R.	1948	*Ibid.*, **17**, p. 205.
Mull, S. and Desai, B. N.	1931	*India met. Dep. Sci. Notes*, **4**, pp. 87-100.
Palmer, C. E.	1951	*Compendium of Meteorology, Amer. Met. Soc.*, pp. 859-880.
Panofsky, H. A., Krawitz, L. and Julian, P. R.	1958	A study and evaluation of relations between tropospheric and stratospheric flow, Dep. Met., Penns. State Univ.
Petterssen, S.	1956	*Weather Analysis and Forecasting*, **1**, McGraw-Hill Book Co., Inc., pp. 190, 198.
Pramanik, S. K. and Rao, Y. P.	1947	*Sci. and Cult.*, **13**, pp. 36-38.
	1948	*Ibid.*, **14**, pp. 34-35.

Ramanathan, K. R. and Narayana Iyer, A. A.	1930	*India met. Dep. Sci. Notes*, **3**, 18, pp. 3-12.
Ramanathan, K. R. and Banerjee, H. C.	1931	*Ibid.*, **4**, 34, pp. 35-47.
Ramanathan, K. R. and Ramakrishnan, K. P.	1933	*Mem. India met. Dep.*, **26**, Pt. 2, pp. 13-25.
Ramaswamy, C.	1956	*Tellus*, **8**, 1, p. 54.
Riehl, H.	1954	*Tropical Meteorology*, McGraw-Hill Book Co., Inc., pp. 237, 256 and 257.
Roy, S. C. and Roy, A. K.	1930	*Beitr. Phys. frei. Atmos.*, **16**, pp. 224-234.
Roy, A. K.	1946	*India met. Dep. Tech. Note*, 16
Saha, B. P.	1964	*Indian J. Met. Geophys.*, 15, p. 479.
Subramanian, D. V. and Banerjee, A. K.	1964	Eleventh Weath. Radar Conf. Nat. Bur. Standards, U.S.A.
Sur, N. K.	1933	*Mem. India met. Dep.*, **26**, Pt. 3, pp. 37-50.