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Air Masses and Fronts in the Monsoon Depressions in India

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ABSTRACT. From a synoptic and aerological study of the data of radiosonde ascents at Vizagapatam, Cuttack, Calcutta and Akyab during a depression in the Bay of Bengal in the beginning of July 1945, it is observed that different air masses took part both in the formation stage of the depression and during its subsequent intensification into a storm and movement westnorthwestwards. The depression formed with the passage of a low pressure wave from the east across Burma into the northeast Bay of Bengal and the simultaneous arrival of *Em* air which underwent a cyclonic vorticity under the combined influence of the Arakan-Chittagong-Khasi hills and the seasonal trough of low pressure. It is seen that very heavy rain which occurred locally in southwest Bengal and Orissa before the formation of the depression and in the southwest sector of the depression or storm was associated with the quasi-stationary partition between the westerly *NEm* monsoon air from the Arabian sea which had travelled across the Peninsula and the easterly (bending southwards) warm *NTm* air or "old monsoon air" (mixture of *NEm* and *TmS*-subsided Tropical maritime air) in the lower levels and *Tm* air in the higher levels; the intensity of the rainfall varied with the slope of this partition, the slope being at times as much as 1 in 30.

It is also shown that during the monsoon season the northern boundary of the westerly *NEm* air constitutes a sloping surface running west to east, its height increasing north to south and steepness and vertical extent depending upon the strength of the monsoon current. If moist easterly air current backs and strikes and ascends over this sloping partition under the influence of the prevailing pressure distribution, rainfall will occur even without temperature and moisture contrast between the westerly and easterly currents, the partition acting like a mountain barrier, the amount and extent of rainfall depending upon its steepness.

This study supports the mechanism of the formation of depressions in the north Bay of Bengal during the monsoon season suggested by Desai in an earlier paper.

1. Introduction

During a discussion in the Meteorological Office, Poona in February 1948, Petterssen[1] presented the results of his analysis of a cyclonic storm in the Bay of Bengal in the beginning of July 1945, particularly with a view to determine its thermal structure. According to him, analysis of the pressure contour charts of the storm showed decisive evidence of at least two air masses apart from the dry warm air over northwest India. The differential analysis of the layer from 850 to 450 mb showed a marked cold mass extending from the equator towards the storm. Although the ascent at Cuttack showed indication of a frontal surface, the distance between the radiosonde stations was too large to establish the structure in detail. Petterssen stated that his study indicated that the storm formed as a frontal disturbance on the boundary aloft between the warm air that had a trajectory from the southeast and cold air that has come from the southern hemisphere; it was difficult to say whether the warm and dry air from the northwest played any important part in the initial formation of the storm although it might have become important for the further development.

From a study of a depression in the Bay of Bengal during July 1947, Desai [2,3] has shown that conditions during the monsoon months are generally such, that if favourable circumstances develop, a depression can form in the north Bay of Bengal at the southeastern end of the seasonal trough of low pressure. The essential favourable condition for the formation of a depression is the extension northwards in the Bay of Bengal of the fresh cold monsoon air (*Em*) from the southern hemisphere and its deflection northwestwards under the combined influence of (i) the Arakan-Chittagong-Khasi hills and the eastern Himalayas and (ii) the seasonal trough of low pressure. The deflection northwestwards of the cold *Em* air leads to the formation of a wave at the southeastern end of the axis of the seasonal trough and its subsequent development into a depression or storm. Heavy rain in the southwest sector of the monsoon depression has been considered to be generally due to steep slope of the front at which the warm moist air is rising over the cold monsoon air ; considerable convergence in the southwest sector near the centre will also further help occurrence of heavy rainfall there.

In a study of the same storm which Petterssen[1] analysed, Pramanik and Rao[4] have stated that different air masses did not take part and that there was no evidence of any front with temperature contrasts either during the formation stage of the depression or later when it developed into a storm. The rise in temperature at Cuttack between the evenings of 30 June and 1 July 1945 was explained as due to release of large amount of latent heat of condensation, as heavy rain was occurring at the station since the morning of the 1st.

While discussing the same July 1945 storm, Mull and Rao [5] have concluded that examination of data of radiosonde ascents in the southwest sector did not reveal existence of any front between the Arabian Sea monsoon air which has travelled across the Peninsula towards the north Bay of Bengal and the old monsoon air[6] over Bengal and neighbourhood and of any marked temperature discontinuities. They have offered an alternative explanation for rainfall in the southwest sector of monsoon depressions and have tried to show that area of maximum convergence is in the southwest sector but somewhat away from the centre, and that as convergence leads to rainfall, the occurrence of widespread and heavy rain in that sector is explained.

It is proposed to show in this paper that neither Pramanik and Rao[4] nor Mull and Rao[5] are justified in drawing the above conclusions regarding air masses in the case of monsoon storm in the north Bay of Bengal during the first week of July 1945.

2. Synoptic analysis and time-altitude cross-sections on different days

In Figs. 1-4 are given time-altitude cross-sections during the disturbance in question for Vizagapatam, Cuttack, Calcutta and Akyab respectively on the basis of radiosonde ascents made at the stations. Dry bulb temperatures (°C) at different levels are given to the right and the mixing ratio (gm/kgm of dry air) to the left. Available upper winds and the different air masses which are considered present over the station are also shown in the figures, the latter being determined with the help of the synoptic and pressure contour charts. The symbols used to indicate different air masses are the same as those used by Desai[2,3] and are given below—

Em — Equatorial Maritime air, *i.e.*, cold fresh monsoon air entering coast either from the Arabian Sea or the Bay of Bengal direct; in the latter case the *Em* air has not entered and travelled across the Peninsula but has entered into the Bay directly from the Arabian Sea.

NEm — *Em* air which has caused precipitation over coast and has travelled over land subsequently and undergone a change in its temperature and moisture content, particularly in the lower levels. As such *NEm* air is less cold than *Em* air in the lower levels.

Tc — Tropical continental air, dry and warmest at the surface, present over northwest India in the monsoon season.

Tm — Tropical maritime air from the east—generally in the higher levels in northeast India and upper Burma—warmer than *Tc* air above the reversal level due to a difference in the lapse rates of the two air masses. *Tm* air has as its source the "high" in the north Pacific Ocean.

TmS — *Tm* air which has subsided while moving westwards as a result of orography.

NTm — Mixture of *NEm* air and *TmS* air (old monsoon air) in the lower levels and *Tm* air in the higher levels. It is less warm than *Tc* air in the lower levels but can be warmer than it above the reversal level.

29.6.1945

From the synoptic charts for 0800 IST of 29 June, it is seen that there was a depression over southeast Rajasthan with centre near Kotah and the Arabian Sea current was being diverted into the depression across Saurashtra and south Gujarat coasts. The pressure changes that evening indicated that a low pressure wave was apparently moving westwards through upper Burma. From the radiosonde ascents and upper wind charts it is seen that there was Arabian Sea monsoon air (*NEm*) over Vizagapatam (Fig. 1) upto about 500 mb level, over

Cuttack (Fig. 2) upto about 600 mb level and over Calcutta (Fig. 3) upto about 650 mb level ; above these levels there was easterly *NTm* air over all the stations. The Vizagapatam ascent shows inversion or isothermal conditions at two levels ; the inversion between 970 and 930 mb levels was possibly due to subsidence as a result of hills to the west of the station. The causes of the isothermal layer between 700 and 685 mb levels are not clear; from the synoptic charts, it can, however, be inferred that there was *NEm* air over the station even between 700 and 600 mb levels. While there was no appreciable difference in the temperatures of the *NTm* air over the three stations, there were significant differences in those of the *NEm* air, temperatures being lowest at Calcutta and rising gradually towards Vizagapatam. One of the possible causes for these temperature differences of the *NEm* air as can be seen from the synoptic and pressure contour charts is that the *NEm* air further north of Vizagapatam was a part of the *NEm* air from the fresh cold *Em* air flowing into the depression over southeast Rajasthan across east Saurashtra and south Gujarat coasts as mentioned before, while that over Vizagapatam was a part of the other *NEm* air from relatively less cold air entering coast further south.

From Fig. 4 it will be seen that temperature fell somewhat over Akyab below 800 mb level between 28 and 29 June. In the absence of other observations from Burma it is not possible to discuss in detail the conditions revealed by the radiosonde ascents there. It would, however, appear that on the 28th there was *NEm* air over that station upto about 750 mb level and *NTm* air above. The inversion at about 950 mb level might be due to cloud (the station was having rain at the time of ascent). In the lower layers of *NTm* air there also appears evidence of subsidence. By the 29th evening temperature had fallen upto about 750 mb level, the specific humidity slightly decreasing at the same time, although air was saturated above 950 mb level ; above that level moisture had increased at all heights and air was also saturated but temperature had risen only above 625 mb level. It would appear that fresh *Em* air from the south Bay had arrived over the station below 750 mb level and fresh *NTm* air higher up. There was thus relatively colder air in the Bay off the Arakan coast in about the first 8000 ft when compared with that over south Bengal, Orissa or the Circars coast and the adjoining Bay area. No *Tc* air was coming over the north Bay on the 29th as its flow southeastwards was prevented by the depression which was over southeast Rajasthan (cf. Petterssen[1]).

30.6.1945

By the 30th June the depression over southeast Rajasthan had moved westnorthwestwards and was centred just to the southeast of Jodhpur. It was seen from the synoptic charts of the 30th morning that pressure had fallen over Assam, east and south Bengal and the northeast Bay and weather had become markedly unsettled in the northeast Bay of Bengal, with cyclonic circulation setting up there; this was presumably due to movement westwards of the low pressure wave across north Burma and the northwestward movement of the cold *Em* air from Akyab side under the combined influence of the Chittagong-Arakan-Khasi hills and the seasonal trough of low pressure [2,3].

From the upper winds it appears that the Arabian Sea current was strengthening on the 30th morning in the Peninsula south of about Lat. 18° N in the first 3 kilometres. As a result of the cyclonic circulation, *NTm* air over Bengal began to move towards south and west and a partition between it and the Arabian Sea monsoon air (*NEm*) moving eastwards across the Peninsula, began to get established both at the surface and in the upper levels. The following changes in the upper winds between the 29th evening and the 30th morning are significant—

(*a*) *Asansol and Jamshedpur upper winds had veered from W to NW at least upto* 7000 *ft.*

(*b*) *Cuttack winds had veered from W to NW above* 2000 *ft and at least upto* 7000 *ft.*

(*c*) *Sambalpur winds had veered from W to NW between* 7000 *and* 15,000 *ft.*

(*d*) *Calcutta winds had become NEly at least upto* 2000 *ft.*

With the partition getting established, rain occurred over the northwest angle of

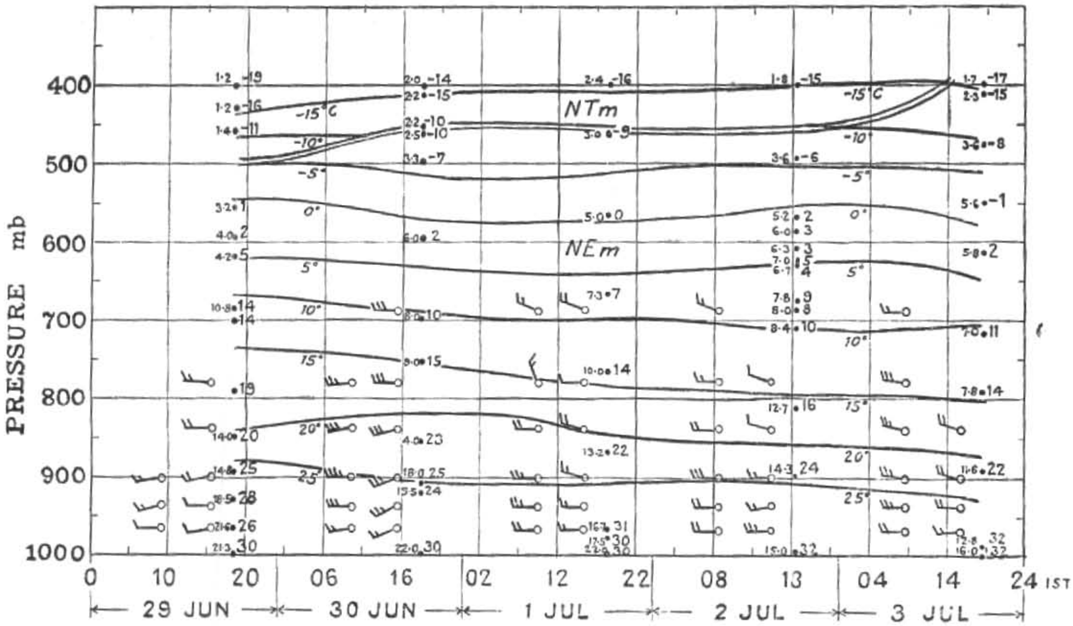

Fig. 1. Time-altitude cross-section for Vizagapatam

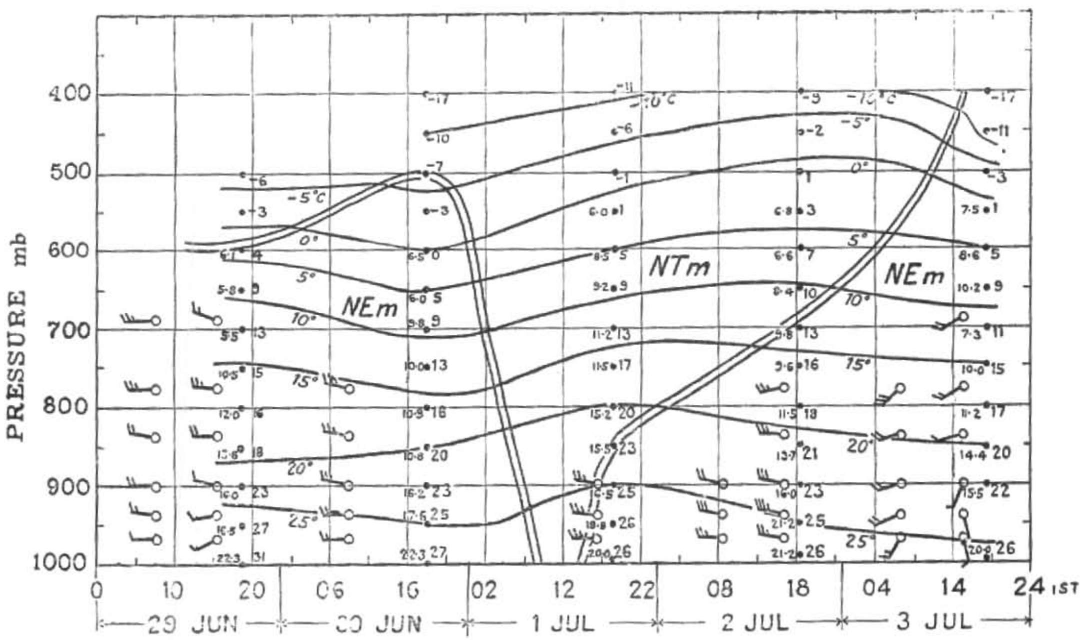

Fig. 2. Time-altitude cross-section for Cuttack

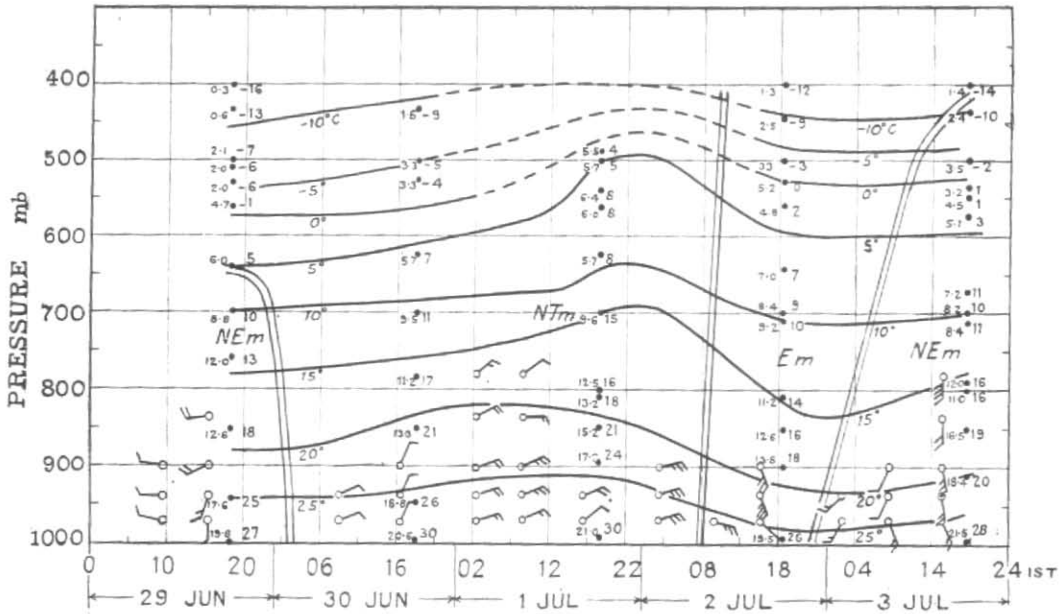

Fig. 3. Time-altitude cross-section for Calcutta

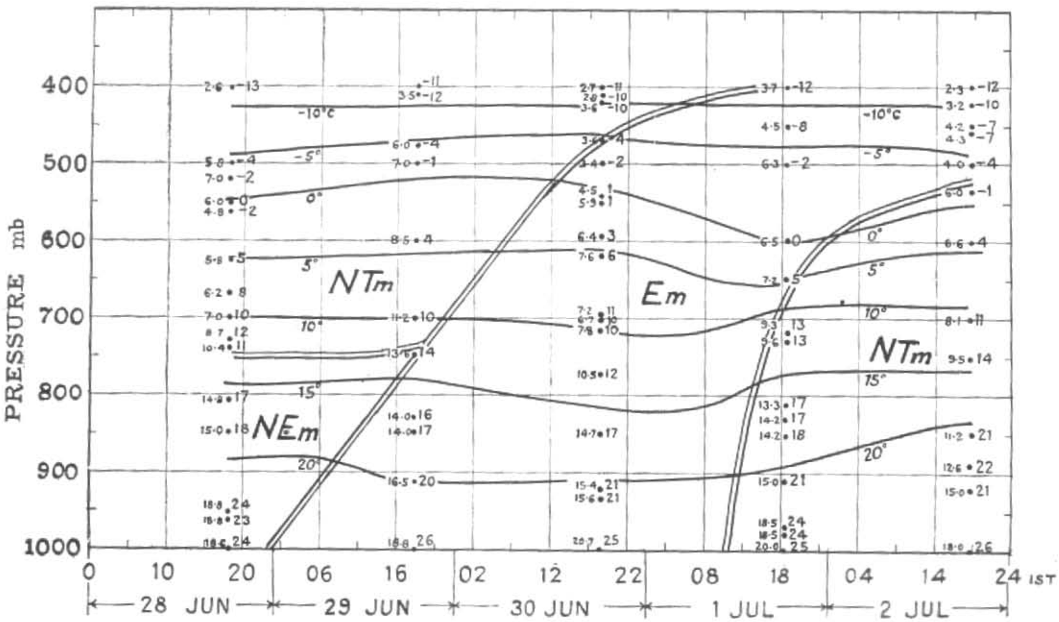

Fig. 4. Time-altitude cross-section for Akyab

Bay, Saugor Island having 7″ and Sandheads 1½″ rain between 1700 IST of the 29th and 0800 IST of the 30th; Balasore had ¾″ and Chandbali ¼″ during the same period. On an examination of the reports of the provincial raingauges in southwest Bengal and the adjoining Balasore district of Orissa, it is seen that locally heavy rain also occurred there between the 29th and the 30th mornings in connection with the establishment of the partition between the *NTm* and *NEm* air masses; thus Dantan (Midnapore district) had 3″ rain and Baliapol, Jallesore and Bhograi in Balasore district 7″, 3″ and 6″ respectively.

In Figs. 5(a), 5(b) and 5(c) are given amounts of rainfall of 3″ or more and the

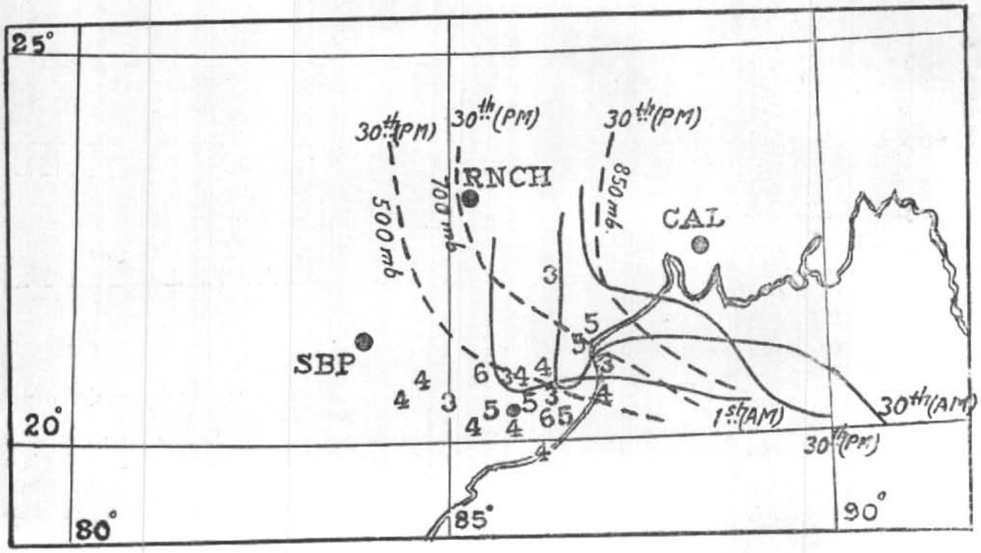

Fig. 5(a)

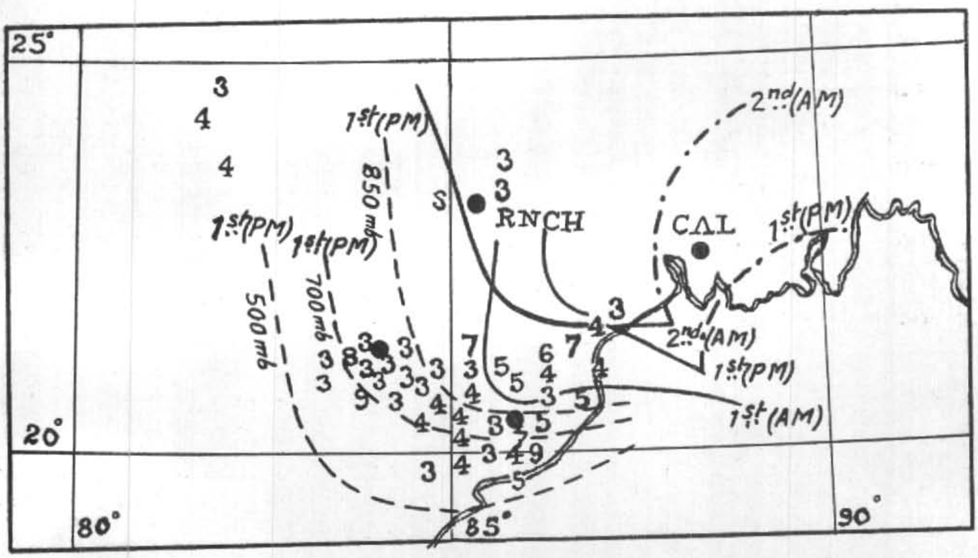

Fig. 5(b)

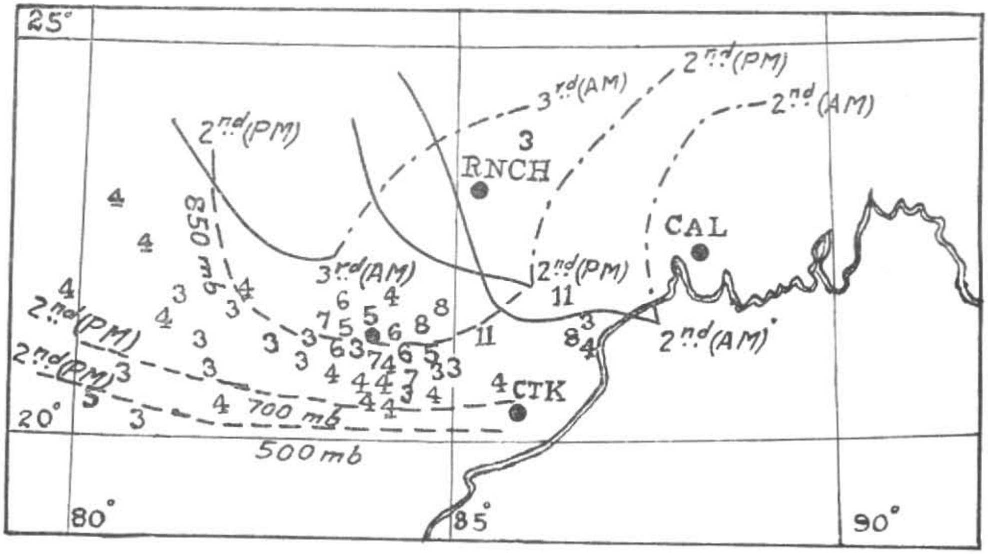

Fig. 5(c)

In Figs. 5(a), (b) and (c), the following notations† have been used—

——— Partition at the surface between *NTm* air and relatively colder *NEm* air, the former rising over the latter.

— —·— Partition at the surface where cold *Em* air or relatively colder *NEm* air is pushing warm *NTm* air. This has been indicated only for periods for which sufficient observations are available to demarcate the same.

- - - - - Partitions in the upper air between *NTm* and *NEm* air masses, different levels being indicated by the values of pressure in mb.

† Partition between cold *Em* air and less cold *NEm* air has not been shown due to absence of observations over sea.

positions of the partitions between different air masses at different levels with a view to see if there is any relation between them. The positions of the partitions at the surface have been determined taking only wind into consideration keeping in view the previous history of the air current. For upper air partitions *, the available pilot balloon winds and the contour lines on the 850, 700 and 500 mb level charts prepared from the radiosonde data, have been used. Each figure contains the positions of the partitions at the surface at 0800 and 1700 IST of the day and 0800 IST of the following day, partitions at 850, 700 and 500 mb levels on the evening of the day and heavy rainfall amounts—3″ or more (in whole inches) recorded at the departmental observatories and the provincial raingauge stations in the southwest Bengal, Bihar, Chota Nagpur, Orissa, Hyderabad, Madras, Madhya Pradesh, Madhya Bharat and east Uttar Pradesh in 24 hours between 0800 IST of the day and of the next day. Thus the positions of the partitions in the evening can be taken roughly as the mean positions for 24 hours between 0800 IST of the day and of the following day, this being also the period for which heavy rainfall amounts are given ; the 0800 IST positions of the surface partitions help to know the distribution of rainfall with reference to them.

On referring to Fig 5 (a) it will appear that between the morning and evening of the 30th, the partition between the westerly

*Although there is a difference of about three hours in the times of the pibal and radiosonde ascents and neither the net-work of the stations is very close nor the radiosonde ascents are more than one, the data of both have been used to get an idea about the approximate positions of the partitions at different levels in Fig.5 and of the cross-sections in Fig.6. No high degree of accuracy is claimed for the positions of the partitions at different levels or in the vertical, but it is considered that they can be used without any serious objection to find out if there is any connection between their positions and the area of heavy rainfall.

NEm air and the easterly *NTm* air at the surface had shifted somewhat northwards between about Lat. 21½° and 22° N and Long 86½° and 89° E. This shifting of the partition was probably due to movement of *NEm* air from southwest.

By the 30th evening, the upper winds at Asansol, Jamshedpur and Sambalpur had veered further. Those at Calcutta had strengthened. At Comilla, winds were moderate to strong easterly at least upto 10,000 ft. From the radiosonde ascents on the 30th evening the following changes are seen—

(a) Vizagapatam (Fig. 1) — The isothermal layer in the lowest level as a result of local features extended only between about 920 and 900 mb levels and was shallower than on the previous day. Temperature had fallen and specific humidity increased generally except for the following—

(i) Temperature had risen between about 850 and 780 mb levels, and above 460 mb level ; the causes of the former are not clear although the latter was probably due to arrival of fresh *NTm* air in those levels.

(ii) Moisture content had decreased near about 700 mb level ; causes of this are not clear.

The changes in temperatures and specific humidity below 460 mb level were apparently due to a strengthening of the Arabian Sea current and consequent arrival of relatively fresher monsoon air than on the previous day. This is also supported by upper winds.

(b) Cuttack (Fig. 2)—There were no regular changes in temperature and moisture content in about the first 200 mb above the surface, but there was a fall in temperature between about 800 and 500 mb levels and increase in specific humidity (above 750 mb level). Irregular changes in temperature and specific humidity in the lower levels were possibly due to thunderstorm which the station had that afternoon. The changes in the upper levels might be due to the same causes as those mentioned above for changes at Vizagapatam. The effect of the partition between the easterly and the westerly air masses was felt at Balasore about 125 miles to the northeast of Cuttack which had 4″ of rain with thunderstorm between 0800 and 1700 IST of the 30th ; Chandbali (about 70 miles east of Cuttack) had 1½″ and Cuttack ¼″ of rain during the same period.

(*c*) Calcutta (Fig. 3)—There was increase in temperature and moisture content at all levels. Upper winds had got easterly component and were under the influence of the cyclonic circulation over the northeast angle of the Bay as mentioned earlier. Thus air over Calcutta had presumably changed from the Arabian Sea monsoon air (*NEm*) to *NTm* air. The positions of the partitions between *NEm* (westerly) and *NTm* (easterly backing towards north) air masses at 850, 700 and 500 mb levels on the 30th evening are shown in Fig 5(*a*) ; these have been determined on the basis of the upper winds and contour lines for those levels as mentioned above.

The cross-section between Calcutta and Vizagapatam through Cuttack at the time of the ascent on the 30th evening is given in Fig 6(*a*). The position of the partition in the vertical has been determined with the help of the radiosonde data and the available winds. It will appear that the slope of the partition between the cold and warm air masses between 950 and 550 mb was steep and of the order of about 1 in 40*, and the partition in the cross-section will pass between Balasore and Calcutta at the surface. This accounts for heavy rain between the morning and evening of that day over and around Balasore.

(*d*) Akyab (Fig. 4)—There was not much change between surface and about 825 mb level, but above that level although

*As mentioned earlier, the positions of the partitions in Fig.6 are only approximate. It is quite possible that the slope of the partition may not be uniform throughout in the vertical; it might be more in some levels and less in others and the same will affect intensity and amount of rainfall over the places where such conditions exist. For the purpose of this paper, however, there cannot be any objection to assume uniform slope as it is intended to show only connection between the steepness of the partition and the amount of rainfall over the places concerned in a general way.

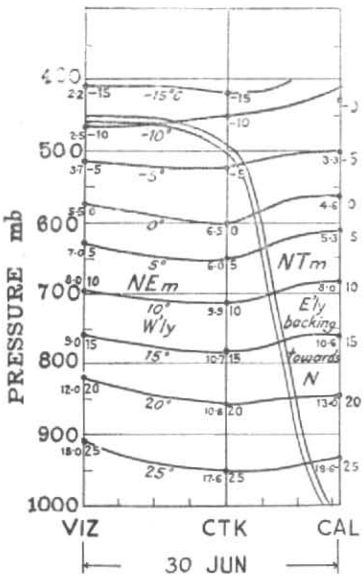

Fig. 6(a)

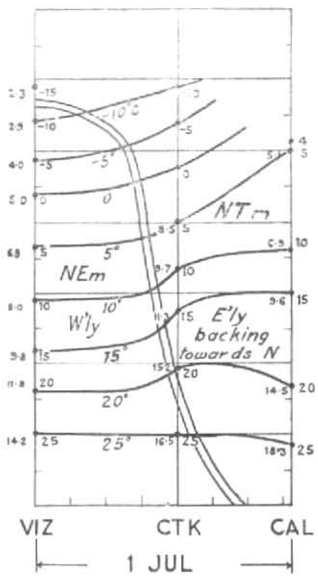

Fig. 6 (b)

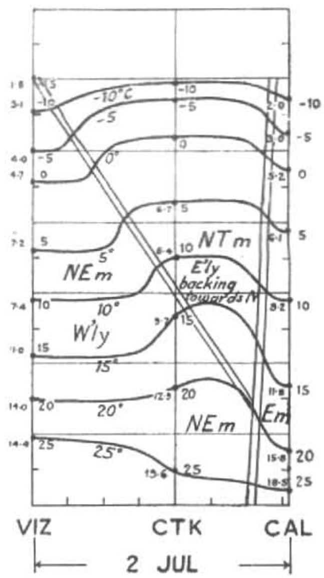

Fig. 6 (c)

temperature had not appreciably changed, specific humidity had significantly decreased, the air being also not saturated. In the absence of information from Burma one cannot say with certainty the causes responsible for decrease of specific humidity above 800 mb level, although it is possible that the same might be due to the *Em* air which was already in the lower levels. A number of isothermal or inversion layers are also found in the record; the causes of the same are not clear in the absence of other data from Burma.

1.7.1945

From the synoptic charts of the morning of 1 July it was seen that a depression had formed in the north Bay with central region near Lat. 20½°N and Long. 89°E about 150 miles to the SSE of Calcutta. The fresh *Em* air had probably moved northwestwards. The position of the partition between *NEm* and *NTm* air masses at the surface on the 1st morning is shown in Fig 5 (a).

Upper winds round the head of the Bay were also under the influence of this depression. Regarding upper winds on the 1st morning the following points are significant—

(*a*) *Sambalpur winds had veered further and were NWly to Nly upto 7000 ft and Nly at 10,000 ft.*

(*b*) *Calcutta winds had strengthened and were NEly at least upto 7000 ft.*

(*c*) *Asansol winds had veered to NE at least upto 3000 ft.*

(*d*) *Comilla winds were strong Ely at least upto 15,000 ft.*

With the movement southwards of the old monsoon air and of the partition between it and the Arabian Sea monsoon air, Cuttack had thunderstorm rain of 1¼″ during the night of 30 June—1 July and Puri 1″ rain during the same period; Balasore had another 1″ and Chandbali 2½″ but rain stopped there by the 1st morning. The depression which was near Jodhpur on the 30th morning had moved further northwestwards towards the border of Sind and the circulation round it was weakening. The Arabian Sea current was continuing strong generally over the Peninsula.

In Fig. 5 (a) are also given rainfall amounts of 3″ or more recorded between 0800 IST of 30 June and 1 July at the observatories and raingauge stations in the areas mentioned earlier. On referring to Fig. 5 (a) it will be seen that the area of heavy rainfall is to the south of the partitions at the surface. The partitions at different levels in the upper air on the 30th evening which are shown in Fig. 5( ) had moved south and westwards by the 1st morning. The heavy rainfall thus appears to be closely associated with the partitions between the *NEm* and *NTm* air masses at the surface and in the upper air.

On comparing the position of the partition between the westerly and the easterly air masses at the surface on the 1st morning and evening —Fig. 5(b), it is seen that it had moved considerably towards north and east. This was probably due to the movement northwestward of the depression and its intensification as well as advance of *NEm* air northeastwards.

The following points may be mentioned in connection with the winds and radiosonde data of the evening of 1 July—

(*a*) *Vizagapatam*—There was an inversion upto about 960 mb level and dry adiabatic lapse rate thereafter upto 870 mb level. Above, there were no appreciable changes in specific humidity, but temperature somewhat fell upto about 650 mb level, probably under the influence of the *NEm* air. This station continued to be under the influence of the Arabian Sea current—*NEm* air—upto about 450 mb level.

(*b*) *Cuttack*—This station was having heavy rain accompanied with thunderstorm since morning and had recorded 4″ rain; Puri had also 4″ and Angul 2″ and Gopalpur ½″ rain during the period from morning to evening. Both temperature and moisture content had increased since the previous day generally in all levels, the increase being relatively more in higher levels. This increase in temperature and mositure content was presumably due to arrival of the easterly *NTm* air, whose flow was stimulated under the influence of the depression as mentioned above. Its effect had already been felt over Calcutta by the morning of the 30th. Heavy rain occurred due to nearness of partition between the easterly and westerly air masses. With the northwestward movement of the depression, the partition, however, began to shift back northward and was to the north of Cuttack upto about 4000 ft above the surface at the time of the ascent (1900 IST); this perhaps explains relatively less rise of temperature in the lower levels than higher up.

(*c*) *Calcutta*—Upto about the 800 mb level moisture had somewhat increased since the previous day, but there were not any appreciable temperature changes. Above that level, temperature had, however, generally increased appreciably; moisture had also increased above the 600 mb level. It would appear that air in the higher levels, particularly between about 800 and 600 mb levels, might have suffered subsidence. The station had rain between 1328 and 1624 IST and again at 2004 IST. The causes of the temperature and moisture changes above 800 mb level are not clear. It is, however, seen from the available upper winds and the constant pressure charts that Calcutta had probably *NTm* air above 800 mb level, although it is not possible to say whether it had any different history when compared with the *NTm* air there on the previous day.

(*d*) *Akyab*—Temperature had generally increased upto about 700 mb level and somewhat fallen above that level. Presumably *Em* air had got replaced by *NTm* air in the lower levels. There was apparently still *Em* air over the station above about 700 mb.

The positions of the partition between *NEm* and *NTm* air masses at 850, 700 and 500 mb levels on the 1st evening are shown in Fig 5(b). On comparing the same with those for the 30th—Fig. 5(a), it will appear that at each level the positions of the partitions to the west of Long. 88° E had shifted south and westwards. These changes affected the rainfall but this point will be discussed later when the rainfall recorded between 0800 IST of the 1st and 2nd is considered.

On the 1st there were apparently three air masses at the surface in the field of the depression, *NEm*, *Em* and *NTm*. *Tc* air was not over the head of the Bay, it being only over northwest India due to causes mentioned earlier. This agrees with the findings of Petterssen[1] generally except that he did not consider any difference between the *NEm* and *Em* air masses.

This has, however, to be done as properties of *Em* regarding temperature and moisture content get modified after its entering inland and during travel over land at least in about the first 3 kilometres.

From Fig. 6(b) in which the cross-section between Vizagapatam and Calcutta through Cuttack is given, it will appear that the slope of the partition between 850 and 500 mb was about 1 in 30. This explains heavy rain over Cuttack and neighbourhood.

2.7.1945

By the 2nd morning the depression had intensified into a cyclone and was centred at 0800 IST about 75 miles to the southsouthwest of Calcutta and 150 miles to the northeast of Cuttack. The position of the partition between *NEm* and *NTm* air masses on the 2nd morning is as shown in Fig. 5(b). Cuttack had 3″ more rain between 1700 IST of the 1st and 0800 IST of the 2nd and Puri 1″ and Gopalpur ¼″ during the same period. With the movement northwards of the partition between the easterly air and the westerly Arabian Sea monsoon air, rainfall decreased at Puri, Cuttack and Angul, but increased further north ; Chandbali recorded 5″ of rain with thunder and Balasore 4″ between 1700 IST of the 1st and 0800 IST of the 2nd.

As the partition between *NTm* air and the fresh monsoon air (*Em*) began to approach Calcutta and the stations over the head of Bay of Bengal, rain began to occur there. The upper winds over Calcutta veered from NE to SE between 0230 and 0930 IST of the 2nd, showing arrival of *Em* air over station. Sandheads had 1″ rain and Saugor Island, Calcutta and Barisal ¼″ each between 1700 IST of the 1st and 0800 IST of the 2nd, the last two stations and Burdwan and Faridpur having also rain at the time of observation at 0300 IST. The position of the partition between *NTm* and *Em* air masses on the 2nd morning is also shown in Fig. 5(b).

The Arabian Sea monsoon had strengthened between the 1st and the 2nd. The depression over Sind had, however, weakened and merged into the seasonal low over northwest India.

It will be seen on a reference to Fig. 5(b) that most of the heavy rainfall between the 1st morning and 2nd morning has occurred to the south of the partition at the surface between *NEm* and *NTm* air masses and that there is a close relation between the positions of the partitions between these two air masses at different levels in the upper air. Further, only the positions of the partitions running roughly east to west from the centre of the disturbance appear to be significant for producing heavy rainfall, the positions running approximately south to north being not associated with heavy rainfall—Figs. 5(a) and (b). It has also to be recognised that besides the partitions, orographic features might also have contributed to heavy rainfall in some of the cases.

It may be mentioned here that there are errors in the charts for the 2nd morning as reproduced by Mull and Rao[4] in Fig. 2 of their paper ; the isobaric pattern with southwest monsoon depression given in Fig. 8 of their paper also does not agree with the isobars given in Fig. 2 and 9(a) and (c) of the paper.

The storm passed inland near Balasore at about noon of the 2nd ; Balasore had another 3″ and Chandbali ¼″ of rain between 0800 and 1700 IST of the day, Cuttack having very little rain. Sambalpur and Raipur had also ½″ of rain each during the same period.

The upper winds and radiosonde data of the 2nd evening show the following—

(*a*) *Vizagapatam*—There was no appreciable change in temperature except that inversion had disappeared near the surface, but inversions were present in two shallow layers between about 700 and 600 mb levels. The causes of these inversions are not clear. The air over the station was, however, a part of the Arabian Sea current as on the previous day.

(*b*) *Cuttack*—Temperature had fallen by upto 2°C below 700 mb level and moisture decreased between 870 and 700 mb levels ; this was probably due to replacement of the easterly *NTm* air by the westerly Arabian Sea monsoon air—*NEm*. Above 700 mb there was presumably still *NTm* air ; the rise in temperature was probably due to arrival of warm air from Calcutta side.

(*c*) *Calcutta*—Temperature had fallen and moisture somewhat decreased at all levels since the previous day. This was due to the arrival of the cold *Em* air over the station. From the upper winds in the morning and aeroplane ascent data of that noon, it appears that this air had begun aff cting the station after early morning of the 2nd.

The temperature and specific humidity over Calcutta on the 2nd evening in the *Em* air were about the same, level for level, as at Akyab on the 30th evening when *Em* air was over that station upto about 460 mb level. On comparing temperature and specific humidity in the *Em* air over Calcutta with those at Vizagapatam, level for level, when that station had *NEm* air, it would appear that *NEm* air was warmer and somewhat more moist than *Em* air in about the first 10,000 ft above the surface.

(*d*) *Akyab*—At Akyab the *NTm* air had presumably increased in depth and extended upto 530 mb level.

It may be mentioned here that the cold air which moved towards Calcutta from Akyab side did not affect appreciably Chittagong as it was just on its (*Em* air) eastern fringe due to its movement northwestwards under the influence mentioned earlier.

The positions of the partitions between *NEm* and *NTm* air masses at the surface and at different levels in the upper air on the 2nd evening are given in Fig 5 (c).

The cross-section between Vizagapatam and Calcutta on the 2nd evening is given in Fig 6(c). It will be seen that its slope between about 850 and 500 mb levels is, only about 1 in 110 when compared with 1 in 30 in Fig. 6(b) on the previous day. This probably explains decrease of rainfall over Cuttack and areas to the east.

The slope of the partition between *Em* and *NTm* is about 1 in 20. At this partition the wind was backing from W to SSE in the lower levels and veering from E to SSE in the higher levels. Rain had fallen with the movement of this partition over Bengal and neighbouring areas.

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The depression continued to move westnorthwestwards and was centred about midway between Chaibasa and Pendra at 0800 IST of the 3rd ; the position of the different partitions at the surface at the time are given in Fig 5(c). *Em* air having got mixed up with *NEm* and having travelled over land had got modified. As seen from the upper winds, *Tc* air from the northwest was beginning to enter the field of depression in the northwest sector between about 3000 and 8000 ft.

Heavy rain which had fallen between the mornings of the 2nd and 3rd is shown in Fig. 5(c). It will appear from the figure that there is relation between the positions of the partitions between *NEm* and *NTm* air masses at different levels and the area of heavy rainfall as was also evident on other days as mentioned earlier.

By the evening of the 3rd the depression had moved further westnorthwestwards. The following points may be mentioned regarding the radiosonde ascents on the 3rd evening at Vizagapatam, Cuttack and Calcutta—

(*a*) *Vizagapatam*— Temperatures had generally slightly fallen at all levels except near about 700 mb level where they had slightly risen. Specific humidity had decreased upto about 550 mb level. It would appear from the upper winds that the station was still having *NEm* air mass.

(*b*) *Cuttack*—Upto about 750 mb level temperature had generally slightly fallen but specific humidity did not show regular changes. Above that level temperature had, however, decreased, the fall being more at higher levels ; specific himidity had increased above 700 mb level. As seen from the synoptic charts the air mass over the station was *NEm* from the Arabian Sea side, the *NTm* air having been replaced.

(*c*) *Calcutta*—Temperature and specific humidity had increased generally upto about 700 mb level ; above that level the temperature and specific humidity changes were not so regular and significant. These changes were due to the *Em* air getting mixed up with the *NEm* air from the Arabian

Sea side. Calcutta temperatures (Fig. 3) upto about 700 mb level were generally lower than those at Vizagapatam (Fig. 1) or Cuttack (Fig. 2), level for level, probably because the latter stations did not get at all the fresh cold *Em* air.

3. Results of the analysis

The following points are brought out from the present analysis—

1. With the arrival of a low pressure wave from the east across upper Burma into northeast Bay of Bengal and advance northwestwards of the cold fresh monsoon air (*Em*) along and off the Arakan coast, weather became unsettled in the northeast Bay of Bengal and a depression formed.

2. With the weather becoming unsettled as in 1, the flow southwards of *NTm* air (easterly backing towards north) was initiated and stimulated and a partition was established between it and the westerly Arabian Sea monsoon air (*NEm*) which had travelled across the Peninsula. The former air mass was warmer than the latter as shown by the radiosonde ascents over Calcutta and Cuttack. This partition had at times a slope of even 1 in 30. Heavy rain occurred near and to the south of the partition, on the *NEm* air side where the partition was steep.

3. There was no continental air (*Tc*) from northwest India over the north Bay of Bengal to take part in the cyclonic circulation, its flow southeastwards being prevented due to another depression which had moved westnorthwestwards from Chota Nagpur side.

4. With the replacement of the *NTm* air over Calcutta by the fresh monsoon air (*Em*), temperature fell over the station ; rain occurred in association with this. Temperature also fell in the lower levels over Cuttack with the replacement of the easterly *NTm* air by the westerly Arabian Sea monsoon air (*NEm*). *Em* air was also colder than *NEm* air in the lower levels.

5. *Em* air flow weakened after the storm passed inland and this air mass was transformed and got mixed up with *NEm* air from the Arabian Sea side which moved across the Peninsula into the north Bay.

6. The depression moved along the partition between the easterly *NTm* and the westerly *NEm* air masses.

7. Locally heavy rain occurred to the south of the partition even before the depression formed and as soon as it was established and the area of heavy rain shifted with the partition. Heavy rain also fell in the southwest sector of the depression both at a distance from and even close to the centre.

4. Discussion of the results

From what has been stated above, it is clear that different air masses (three in the present case) did take part during the formation of the depression and that they were also present later. The conclusion of Pramanik and Rao[4] regarding the absence of more than one air mass in this monsoon depression is, therefore, not justified. While there are conclusive evidences about different air masses taking part in the monsoon depressions, it has to be stated that from the data available one cannot by a casual examination of the same, find on a large number of occasions sharp typical frontal characteristics as are noticed at the air masses partitions associated with depressions of the middle latitudes. A critical examination of the ascents in conjunction with upper winds etc. does, however, reveal definite existence of partitions between different air masses. Some of the causes responsible for not observing typical frontal characteristics in the radiosonde ascents during the periods of monsoon depressions are given below—

1. The ascents are far apart both from the point of view of space and time distribution (cf. Petterssen[1]).

2. The Arabian Sea and Bay monsoon currents have the same source, *i.e.*, the South Indian Ocean, but their characteristics will be different when they reach the west coast of the Peninsula or the east coast of Burma respectively due to different trajectories followed by them over the ocean ; further, precipitation which they cause over the coast as a result of the

mountain barriers in their path and their travel over land after crossing coast, will modify their temperature and specific humidity in the lower levels. Thus the Arabian Sea monsoon air would be different in lower levels when it enters the Bay of Bengal after travel across the Peninsula, both as regards its temperature and moisture content from what it was when it arrived at the west coast of the Peninsula ; it is because of this reason that the *Em* air from the Arabian Sea is called *NEm* air after it has crossed the west coast. The same arguments also apply to the Bay monsoon current. The *NEm* air over Bengal will become stagnant and get mixed up with the subsided easterly *Tm* air as a result of hills to the east. Thus the old monsoon air *NTm*(*NEm*+*TmS*) will be different at the surface from the *NEm* air over the Peninsula. Easterly *Tm* air mass, as mentioned before, has as its source the " high " over the north Pacific Ocean but its properties get modified considerably during its westward movement to Burma and India. The continental air (*Tc*) from northwest India will also get modified regarding its temperature and moisture content as it travels eastwards over wet land. Further, the differences in the lapse rates in the different air masses will alter the nature of the partitions between them at different heights and there will be a chance of mixing and sharp boundaries being obliterated or replaced by extensive transition zones.

3. *NEm* air over different latitude b lts over the Peninsula may not have the same temperature and specific humidity if the *Em* air, when it enters the coast, has different properties in different latitudes. The same considerations also apply to *NTm* air. However, day to day changes at different levels over the same station, particularly in temperatures when considered with reference to upper winds, give a good idea about changes in air masses over the station, if any ; specific humidity changes do not appear to be as helpful as temperature changes in identifying *Em*, *NEm* and *NTm* air masses during the monsoon season although they are equally important for identification of *Tc* air. On the other hand, specific humidity changes are found to be more helpful than temperature changes in classifying *Em*, *Tm* and *TcTm* air masses in the post-monsoon season[7].

All the above factors make identification of partitions between different air masses very difficult, and one has, therefore, to be very critical in arriving at conclusions regarding existence or non-existence of the same. Organisation of close net-work of radiosonde stations even 25 miles apart taking more than one ascent per day in the field of depression will help to find out the exact nature of the partitions between the different air masses and to see in what respect the partitions or fronts are different in tropics from those in the middle latitudes.

Pramanik and Rao[4] have stated that the large amount of the latent heat of condensation released during the heavy rain at Cuttack and not a change in air mass over the station was responsible for observed rise in temperature between 30 June and 1 July. It may be mentioned that, while condensation of water vapour will undoubtedly lead to warming up of the upper air, the air over the station at the time of sounding was not air which was stagnant and had been heated by local rainfall at the station, but air which had acquired its warmth elsewhere by different physical processes including rainfall.

The centre of the depression passed just close to Balasore. This station had also 7" of rain. Mull and Rao[5] have stated that according to their theory, the area of maximum convergence and consequently of heavy rainfall is somewhat away from the centre. It will be seen that their conclusion is not justified, as in this case heavy rain occurred both close to and at some distance from the centre and even before the depression formed while the partition between the easterly and the westerly air masses was getting established. They have also given Figs. 9(a), (b) and (c) (reproductions from Figs. 26(a) and (b) and 27(a) respectively with some deletions from the paper of Ramanathan and Ramakrishnan[6]) in support of their views. On a close examination of the same it will, however, appear that the facts about the rainfall given by Ramanathan and Ramakrishnan[6] can be understood without much difficulty in the light of what has been said earlier in this paper, also keeping the influence of orography in mind.

5. General remarks

Desai[2] has given positions of partitions between different air masses during July on the basis of normal winds. It is known that depth of the westerly monsoon current increases from north to south. As such, the northern boundary of the westerly current will be a sloping surface under normal conditions. In fact, it is probably as a result of this and the rise of the easterly *NTm* air at this sloping surface under the combined influence of the pressure distribution and orographic features that well-distributed rainfall occurs during the monson season to the south of the partition on the *NEm* air side even without the presence of a depression whenever the seasonal trough of low pressure is well-marked. This sloping surface can be assumed to be quasi-stationary and stable during the season.

The steepness of this quasi-stationary sloping surface at the northern boundary of the westerly current will vary with its strength at different heights (the steepness being either uniform or varying throughout in the vertical) as well as with its depth. It may happen to be very steep if the westerly monsoon current is strong or vigorous; under such circumstances, the rainfall due to ascent of *NTm* air at it, will be relatively heavy and also over a narrow belt to the south of the partition at the surface. Similarly the rainfall amounts will also increase with the strength of the easterly *NTm* current; if the easterly *NTm* current backs towards north under the pressure distribution as it happens when there is cyclonic circulation, the component normal to the sloping surface will increase and if the sloping surface is steep, will also give rise to strong vertical currents at it. It is probably such an effect which is responsible for large cumulus and even cumulonimbus clouds and thunder (generally without squalls) with heavy rain in the southwest sector of the monsoon depressions and storms. In view of the nature of the sloping boundary discussed above, the question of its becoming unstable due to its steepness and presence of strong vertical currents at it if the rising *NTm* air has a large component normal to it, will not ordinarily arise. It is also because of the same reasons that the monsoon depressions generally move along the axis of the seasonal trough at the surface, the same coinciding with the northern boundary of the westerly *NEm* air. Computations of rainfall amounts under different slopes of this quasi-stationary surface as a result of the varying strength and depth of the westerly *NEm* air current and different strength of the *NTm* current and value of the component normal to the sloping surface, are being made and will be published in due course.

From the nature of the quasi-stationary sloping surface at the northern boundary of the westerly current during the monsoon season, it will be apparent that the air which rises at it, need not necessarily be even warmer and more moist than the *NEm* air; the essential conditions are the presence of the stable sloping surface and of an air current directed towards and forced to rise at it under the prevailing pressure distribution. If the rising air is warmer and also more moist, the clouds will be thicker and rainfall relatively more. Under the circumstances, even *NEm* air, instead of *NTm* air, which has turned round under the combined influences of the prevailing pressure distribution and orographic features and begun moving westwards over northern India, will be forced to rise at the sloping surface and cause cloud and rainfall. These natural conditions will to some extent make it unnecessary to have large differences in temperatures and specific humidities of the westerly and easterly currents. In this connection a reference to the air mass equatorial maritime air in the lower levels and transitional equatorial maritime air in the upper levels ($Em\ \overline{EmT}$) during the southwest monsoon season according to Roy[5] is also relevant. The quasi-stationary sloping surface acts something like a sloping mountain barrier extending from west to east and which cannot be destroyed by the vertical currents in the air current which is forced to ascend; rain will occur on the windward side of such a barrier, the position of the partition at the surface being something like the foot of the barrier. Rain will be found to the south of the partition at the surface, as the west-east barrier with the sloping surface consists of gaseous instead of solid medium. The sloping surface gives rise to an upglide surface which, however, cannot be considered a front in the usual sense as it does not move in the direction of the ascending air, *i.e.*, in a direction between south and west although the rainfall associated with it has a distribution similar to that at a warm front.

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