Indian Journal of
METEOROLOGY & GEOPHYSICS

January 1972
Vol. 23 No. 1

551·553·21 (267·37)

On the activity of the Arabian Sea monsoon

K. M. RAMAMURTHI

Meteorological Office, Poona

(*Received 13 August 1969*)

ABSTRACT. In connection with the activity of the Arabian Sea monsoon, Ramage's postulate regarding the relationship between the intensity of the heat low over West Pakistan and the monsoon rains was examined and it was found that the heat low does not contribute to the strengthening of the low level monsoon flow. The effects of monsoon perturbations are found to extend from sea level and are therefore considered directly responsible for strengthening the low level monsoon flow. A method of identifying the effects of perturbations of active as well as weak Arabian Sea monsoon is postulated. This brought out that active Arabian Sea monsoon is associated with two cyclonic vertices which in the mean are located over the Gulf of Cambay (Gujarat low) and the northern parts of east coast 'eastern low' respectively and extend from sea level upwards affecting the wind flow practically throughout the entire troposphere. The reason for the cyclonic circulation associated with the Gujarat low not being obvious in lower tropospheric levels is discussed. The importance of contribution to northerly meridional flow along the west coast at upper tropospheric levels by the perturbations of strong monsoon is highlighted. The strength of upper level east wind maximum over south Peninsular India is found to be less during strong than in weak monsoon. This goes against the hypothesis regarding the role of release of latent heat in causing the summer time easterly jet. The effects of perturbations of weak Arabian Sea monsoon are found to be just the reverse of those of strong monsoon. Certain aspects of the transformation of airmass over the east Arabian Sea are also discussed.

1. Introduction

During the International Indian Ocean Expedition (IIOE) the Arabian Sea was one of the areas which was extensively probed by several research vessels and also by the research aircraft of the U.S. Weather Bureau, the Woods Hole Oceanographic Institution, U.S.A. In a study of the summer atmospheric circulation over the Arabian Sea using the above data Ramage (1966, 1967) pointed out that the precipitation agency south of Kutch and north of Goa is almost always a quasi-stationary mid-tropospheric depression in the vicinity of Bombay. A detailed case study by Miller and Keshavamurty (1967) of one of these 'mid-tropospheric cyclones' shows the depression to be more intense at around 600 mb and to have a cold-core character below that level and a warm-core character above. Ramage postulated interaction between this 'subtropical cyclone' and the heat low over West Pakistan and stated that the surface pressure at Jacobabad near the centre of the heat low is inversely related to the intensity of the monsoon rains over the subdivisions of India lying between 18°N and 27°N. In day to day analyses and study of weather charts during the southwest monsoon seasons of 1966 and 1967 typical instances were noticed when the inverse relationship mentioned by Ramage was not found to exist. The present study was, therefore, undertaken with a view to examine more closely the role of the heat low over West Pakistan and neighbourhood in relation to the activity of the Arabian Sea monsoon and also to ascertain what are the dominant synoptic features which determine the activity of the Arabian Sea monsoon.

2. The role of the heat low

2.1. Ramage (1966, 1967) stated that the 'subtropical cyclone', by increasing subsidence above the heat low, intensifies it and its associated low level monsoon circulation and that subsidence in the heat low waxes and wanes in unison with the monsoon rains. When the rains are heavy, the heat low is vigorous, etc. If there is close relationship between the intensity of the heat low and the Arabian Sea monsoon as postulated by Ramage this should become evident on a comparison of the pressure anomalies over Jacobabad and the rainfall along the west coast of India, particularly in diametrically opposite situations

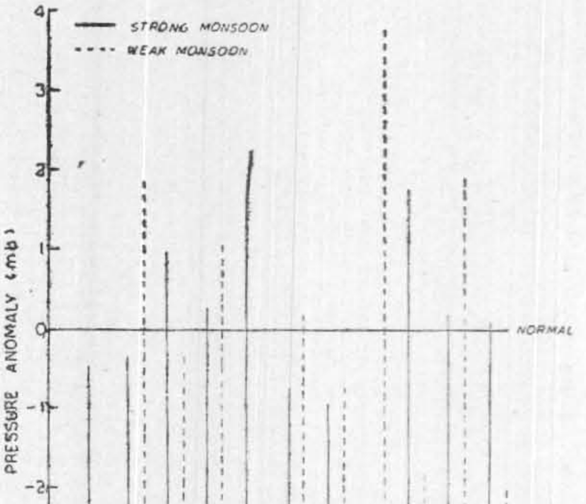

Fig. 1

Mean pressure anomalies for Jacobabad

such as typical spells of weak and of strong Arabian Sea monsoon. In this connection, it may be stated that in sea areas, the activity of the monsoon is judged by the strength of the winds while over land areas, it is judged by the rainfall produced by it. In the present study, the activity of the Arabian Sea monsoon is assessed by the rainfall produced along the west coast of Peninsular India. 9 spells were chosen for weak monsoon and 11 for strong monsoon during the typical monsoon months of July and August in the 10-year period 1957--1966. The spells chosen were such that the mean rainfall per day along the west coast of Peninsula was 39 mm during strong monsoon which was slightly more than twice the normal (normal was 19 mm) and 6 mm during weak monsoon which was only 30 per cent (departure was –70 per cent) of the normal rainfall. The selected periods of weak Arabian Sea monsoon also generally corresponded to 'break monsoon conditions' over India.

2.2. *Discussion of results*

2.2.1. In Fig. 1 is shown two sets of vertical lines representing respectively the mean pressure (03 GMT) anomaly over Jacobabad during each of the spells of weak and of strong Arabian Sea monsoon (On some occasions when 03 GMT pressure values for Jacobabad were not available these were interpolated from isobaric charts). It is seen that except on three occasions (1958, 1964 and 1965), the pressure anomalies are not inversely related to the strength of the monsoon. In some cases of strong monsoon spells, *i.e.*, in years 1959, 1960, 1961, 1965 and 1966, particularly in 1961, the pressure departure was very much above normal and the heat low was therefore relatively weak. In some other cases (years 1959, 1963, 1965 and 1966), the pressure anomaly was negative and although the heat low was more intense the monsoon was weak. It is significant to note that during a spell of weak monsoon in August 1966 the heat low was quite intense and on an individual day (24 August 1966) the negative pressure anomaly near the centre of the heat low was over 6 mb. On this day there was steep pressure gradient upto 23°N and strong dust raising winds prevailed over Rajasthan, Sind and north Gujarat. A similar synoptic situation existed on 8 July 1967. APT pictures from NIMBUS II Satellite (Orbit No. 5578) at 1216 hours IST of 8 July 1967 showed clearly the cloud of dust over Rajasthan caused by the dust raising winds associated with the intense heat low. On this occasion too, the monsoon was weak along the west coast. It is, therefore, evident from the foregoing that there is no consistent relationship between the intensity of the heat low and the monsoon rains. On occasions when an inverse relationship is noticed, it would imply more of an accident of association rather than a direct heat low responsibility for the same as pointed out by Desai (1967). Moreover, Ramage's explanation that subsidence over the heat low from upper levels increases its intensity due to rise of temperature is not theoretically quite satisfactory. If there is convergence at lower levels and subsidence at upper levels there should be net increase of mass in the column which cannot result in pressure falls.

2.2.2. Means of the pressures (0830 IST) reduced to sea level were worked out in respect of selected stations adjoining the heat low and also for selected stations along the west coast of India for each spell of weak and of the strong Arabian Sea monsoon. In Fig. 2 are shown two curves representing respectively the mean for all the spells of weak and of strong monsoon. It is seen that over Jacobabad the difference between the two values is less than one mb indicating that the intensity of the heat low has practically no influence on the monsoon rains. On the other hand, the differences between the two curves is about 4 mb for stations between Ahmedabad ond Vengurla with a maximum over Surat. The large pressure defect over stations in Gujarat and Konkan during strong monsoon *vide* continuous line in Fig. 2 indicates that over that area the effect of perturbations extends from the sea level upwards. It is also seen from Fig. 2 that the pressure gradient between Jacobabad and Surat during strong monsoon is only about half that of weak monsoon. This shows that the intensification of the heat low over West Pakistan has no role in the strengthening of the low level monsoon flow. On the other hand, during strong monsoon the pressure gradient between Bombay and Trivandrum is more than double that of weak monsoon, indicating that the monsoon perturbations themselves by producing large pressure defect over north Konkan and Gujarat deepens the pressure gradient south of Konkan and thus directly influence the low level monsoon flow also. The mean pressure anomaly over Surat (which is nearer the centre of the perturbation over the west coast) corresponding to each of the spells of weak and of strong monsoon is shown by two sets of vertical lines in Fig. 3(a). This brings out that an inverse relationship exists between the pressure anomaly over Surat and the monsoon rains along the west coast of India. It should, however, be noted that large fluctuations of pressure anomalies in Fig. 3(a) indicate that this relationship is not strictly proportional and has to be considered only qualitative.

3. Monsoon perturbations

3.1. With a view to make a general assessment of the extent to which the perturbations influence pressure patterns at sea level over the entire Arabian Sea, pressure values were picked out at 5-degree grid points from analysed sea level charts and mean pressure values were worked out separately for all the spells of weak and of strong monsoon. Isopleths of the mean pressure differences (strong monsoon—weak monsoon) for all the spells are shown in Fig. 3(b). It is seen that in the mean, large pressure defect associated with strong monsoon lies over the Gulf of Cambay and the adjoining land and sea areas. The gradient of pressure difference is maximum over the east Arabian Sea. It is evident from Fig. 3(b) that the effect of the perturbations of the strong monsoon is to cause a deepening of the SSE--NNW pressure gradient over the Arabian Sea and strengthening of the low level SW/W winds south of 20°N. It is, therefore, concluded that the monsoon perturbations themselves are directly responsible for the strengthening of the low level monsoon flow and not the heat low over West Pakistan as postulated by Ramage. In this connection, it is of interest to note that Dallas (1900) in a study of the failure of the monsoon in 1899 established that in July and August of 1899 there was an area of maximum positive anomaly over the central parts of the Arabian Sea. The positive anomaly over the heat low was very much less.

3.2. In order to make a proper appreciation of the manner and the extent to which the pertur-

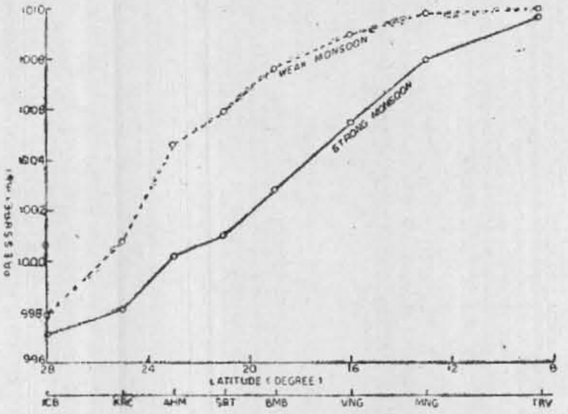

Fig. 2

Mean pressure during spells of weak and of strong Arabian Sea monsoon

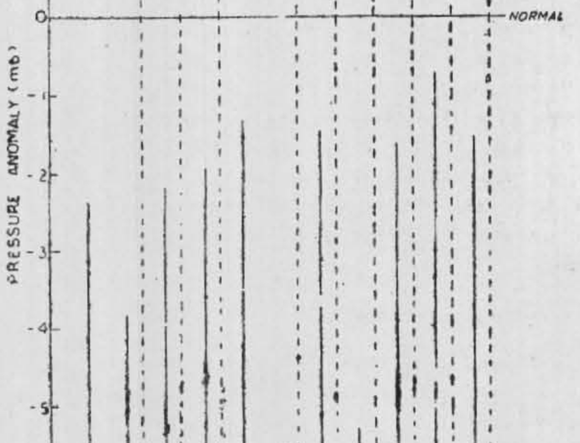

Fig. 3(a)

Mean pressure anomalies for Surat

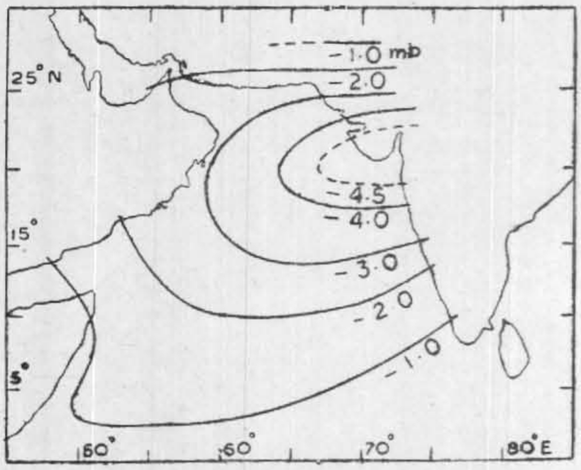

Fig. 3(b)

Isopleths of mean pressure differences (mb) between strong and weak Arabian Sea monsoon

bations of the strong monsoon affect flow patterns at different levels in the troposphere it will be necessary to isolate the contributions due to these perturbations from the typical flow pattern prevailing during the regime of strong Arabian Sea monsoon. This can be achieved only by filtering out from the strong monsoon flow pattern the residual flow which would have prevailed had there been no monsoon perturbations. However, this is not possible as there is no satisfactory method for constructing precisely this residual flow pattern. Nevertheless, one can make a general assessment of the predominant effects of the monsoon perturbations from an examination of the departures from the normal flow pattern. In the present study this has been attempted.

3·2·1. Selection of upper wind data has to be confined to Rawin stations only, as it is only for these stations that data were available upto at least 150-mb level for all or most of the spells of strong monsoon. The procedure followed in the present study is given below.

3.2.2. Monthly normals of upper winds (0001 GMT) for July and August for all Rawin stations in India for all the standard levels corresponding approximately to standard pressure surfaces 900, 850, 700, 600, 500, 400, 300, 250, 200, 150 and 100 mb were worked out using all available data for the period 1955-1966. It is well known that strong monsoon conditions are associated not only with depressions or storms from the Indian Seas but also with perturbations of less intensity. In order to distinguish between these two types, the selected spells of strong monsoon were classified under two groups, *viz.*, Type A which was associated with the movement of a depression or storm from the Bay of Bengal or the Arabian Sea and Type B which was not associated with a depression or storm. It was found that for each spell falling under the same types the salient features of the pattern of departures from normal were very similar and hence all such spells were combined into a composite one. For this purpose mean resultant winds (for 0001 GMT) for all available Indian Rawin stations for all standard levels as mentioned above were computed for all the spells falling under each of the two types A and B described above. As the selected spells fell more or less equally in the months of July and August, combined normals for the period July—August were worked out for all selected stations and levels using all available Rawin data for the period 1955-66 as mentioned earlier. For each level and for each station the normal wind was vectorially subtracted from the mean resultant wind corresponding to each of the above two categories of strong monsoon and these vector differences were plotted in appropriate charts. Similarly using all available Radiosonde data for the period under consideration mean pressure height (contour) values and temperatures were worked out for each station and for each level. Contour anomalies and temperature anomalies were also computed and plotted in the appropriate wind anomaly charts. The patterns arising out of curves drawn tangentially to these vectors keeping in view the contour anomalies also, bring out the predominant effects of perturbations which prevailed during the spells of each of the two types of strong monsoon. Out of the charts thus prepared for all the standard levels from 900 to 100 mb four charts for the levels 900, 700, 500 and 200 mb are shown in Figs. 4 and 5 representing strong monsoon types A and B respectively.

3.3. *Strong Arabian Sea monsoon — Type A*

3.3.1. It is seen that at 900 mb (Fig. 4a) in the mean, the perturbations appear as two cyclonic circulations, one over the Gulf of Cambay and the other over Orissa with the trough line joining them running roughly along 21°N. This brings out that strong Arabian Sea monsoon is associated not only with a vortex which in the mean lies over the Gulf of Cambay but also with another vortex existing simultaneously at the eastern end of the monsoon trough. For convenience, the term 'Gujarat low' is used to designate the former and the 'eastern low' the latter in subsequent discussions. Obviously, the 'eastern low' is merely the mean effect of the monsoon depressions or 'monsoon low pressure areas' which moved from the Bay of Bengal into the country. It is interesting to note that an

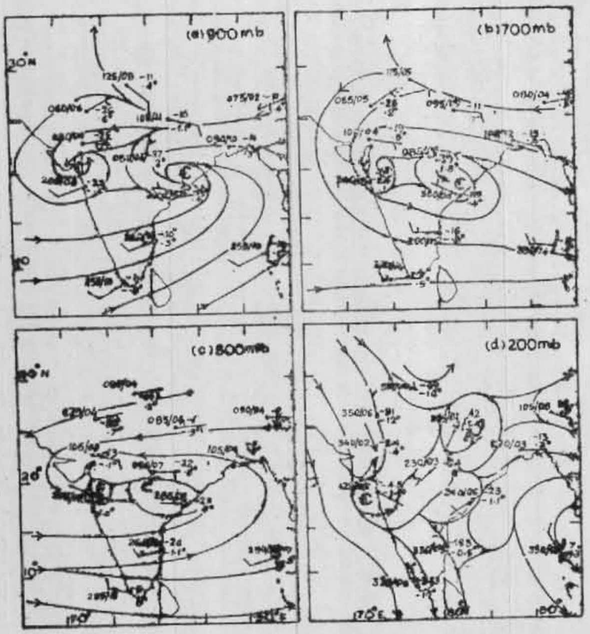

Fig. 4. Type A

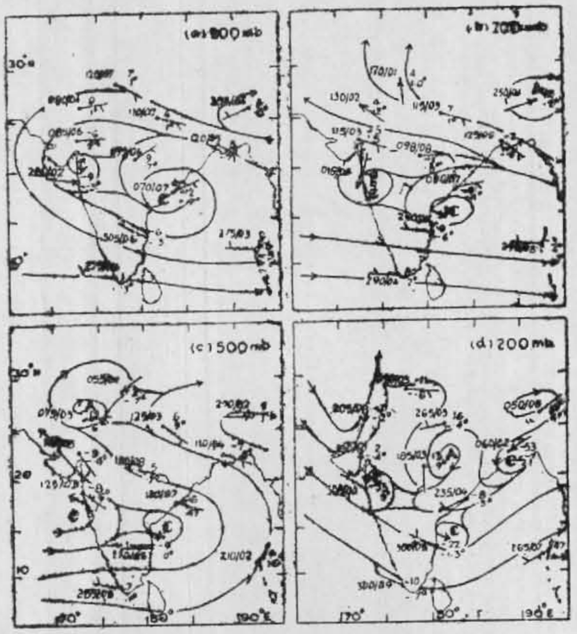

Fig. 5. Type B

Perturbations of strong monsoon

earlier study by the author and Jambunathan (1966) had also revealed close association between the 'Gujarat low' and the 'eastern low' existing simultaneously.

3.3.2. Upto 500 mb the 'Gujarat low' is centred between Ahmedabad and Bombay and shows only slight vertical tilt with height. Above this level the vortex rapidly shifts southwards and is seen upto 200 mb with its centre south of the latitude of Bombay. It is interesting to note that the effect associated with the abrupt southward shift of this vortex at 400-mb level is seen to result in marked fanning out of the stream lines between Ahmedabad and Bombay in the mean stream line chart for that level. Over this region one can visualise qualitatively upper level divergence superposed on low level convergence and hence large vertical motion. The 'eastern low' extends in the vertical upto 400 mb and as a trough aloft upto 150 mb. In lower tropospheric levels winds are relatively stronger near the outer periphery of this vortex. It is important to note that Figs. 4(a)—4(d) bring out clearly that the perturbations of strong Arabian Sea monsoon affect the wind flow practically throughout the entire troposphere (It is beyond the purview of the present study to examine whether they affect the stratospheric circulations also). Essentially, there is no difference between the two vortices excepting that in day to day analysis one finds that 'Gujarat low' as quasi-stationary on most occasions whereas the 'eastern low' is migratory.

As these perturbations extend from sea level upwards to very great heights and have maximum intensity in lower tropospheric levels, associated vertical motion and cloud development may exist from very low levels and this is in conformity with the remarks of Rao and Desai (1965) and Desai (1967) as well as the aircraft observations made during flights in strong monsoon. The influence of simultaneously existing perturbations from the Bay 'eastern low' on the west coast rainfall as brought out in this study and also discussed earlier by Malurkar (1950) and Desai (1967) is an important factor which should be taken into consideration in any model for the Arabian Sea monsoon. From the foregoing it appears that the structure of the Arabian Sea monsoon is not represented by the models proposed by Ramage (1966, 1967) and Miller and Keshavamurty (1967).

3.3.3. The effect of perturbations of strong monsoon on the upper tropsopheric flow above 200 mb (diagram not presented) is seen as contribution of some westerly component over south Peninsular India. Therefore, the east wind maximum over this region is less than normal during strong monsoon while during weak Arabian Sea monsoon, the easterly maximum is often above normal (due to contribution of an easterly component south of 20°N *vide* Fig. 6). In this connection, it may also be pointed out that if the hypothesis that 'the summer time easterly jet in the high troposphere over southern India was caused by a steepening north-south temperature gradient resulting from release of latent heat through heavy rain over central India' (Ramagé 1968, Raman and Ramanathan 1964) were correct then the east wind maximum over south India should be greater during strong monsoon and less during weak monsoon. As observational evidence shows that the actual conditions are just the opposite, the 'latent heat' hypothesis is untenable. The sharply defined maximum in the upper tropospheric easterlies noticed by Raman and Ramanathan (1964) to the south of the region of heavy rains is the second maxima which arises as a result of the strong monsoon perturbations extending to great heights in the upper troposphere (Ramamurthi 1968).

3.3.4. It is also interesting to note *vide* Figs. 4(b) to 4(d) that along the west coast of south Peninsula, south of Bombay whereas the meridional component associated with the perturbations is insignificant between 700 and 500 mb, the southward flow becomes prominent between 250 and 150 mb (not shown in the diagram). In the absence of any data between Bombay and Trivandrum, it is not possible to determine where this southward outflow begins. This upper tropospheric meridional flow is probably a part of the meridional circulation of the 'monsoon cell' (Koteswaram 1960, Rao 1961, 1962) characteristics of strong monsoon conditions (Ramamurthi *et al.* 1967, Raman *et al.* 1967).

3.4. *Strong Arabian Sea monsoon — Type B*

3.4.1. The mean flow patterns associated with perturbations of this type are similar to Type A in their essential features, *viz*., the existence of two vortices at either end of a trough line running more or less E-W, significant N-S meridional flow between 250 and 150 mb along the west coast of Peninsular India and the effect of perturbations in affecting wind flow practically throughout the entire troposphere. However, Type B shows certain significant differences from Type A. These are —

(*i*) The 'Gujarat low' is seen centered between Ahmedabad and Bombay upto 850 mb only. Above this level it shifts rapidly southwards and remains with its centre south of the latitude of Bombay between 700 and 400 mb (not shown in the diagram).

(*ii*) The 'eastern low' lies not over Orissa but in a more southerly latitude off coastal Andhra Pradesh.

3.5. *Weak Arabian Sea monsoon*

3.5.1. In order to get an idea regarding how the patterns of the wind flow at various levels are affected by the perturbations prevailing during the regime of weak Arabian Sea monsoon the same procedure as described in para 3.2.2 was adopted using the mean resultant winds, mean pressure height (contour) values and temperature values of all the spells of weak monsoon and the combined normals for July-August. Fig. 6 shows the wind anomaly charts for pressure levels 900 850, 700 and 200 mb. It is interesting to note that these charts demonstrate that the effects of perturbations of weak monsoon are practically the reverse of those of strong monsoon. The noteworthy features are — (1) The effects of perturbations of weak monsoon also extend practically throughout the entire troposphere; (2) At lower (upto 700 mb) and upper (300-200 mb) tropospheric levels the perturbations appear as two anticyclonic vortices at either end of a ridge line running E-W over north Peninsula. Near mid-tropospheric levels this line has shifted slightly southwards and there is only one anticyclonic vortex; (3) At 300 mb (not shown in the diagram) and aloft there is a strong southerly meridional component over west and southeast Peninsula.

3.5.2. In a discussion on the monsoon trough, Ramaswamy (1967) has drawn attention to the fact that 'the total shift of the axis from its position during well distributed monsoon activity over the country to its position in a break-situation is far too small to account for the enormous difference in the rainfall in these diametrically opposite situations'. It is well known that there is little or no rainfall over the central parts of the country and north of the Peninsula in break situations on account of the upper level high pressure ridge over that area. Ramaswamy (1962, 1967, 1969) considers that these ridges are not separate entities over India only : they are extensions of the ridge from Arabia and Iran or at times extension of the ridge from the northwest Pacific. Dixit and Jones (1965) have also discussed how high pressure ridges from northwest Pacific and southeast Asia extend across the central Bay of Bengal into central parts of India, particularly at 500 mb and cause 'break-situations'. It is obvious from Fig. 6 that the cause for little or no rainfall over the central parts of the country during a break situation is attributable to the effect of the anti-cyclonic perturbation over north Peninsula extending vertically to very great heights, from sea level upwards.

3.6. In order to ascertain whether the salient features of the perturbations of strong Arabian Sea monsoon as revealed from a study of the resultant wind anomaly charts of all the spells are also noticeable in individual situations, a suitable smoothing technique was attempted. The principle involved is described below.

3.6.1. The actual motion at any given time may be thought of as the resultant of a basic flow and of the perturbations superposed on this flow. At a given level the monsoon perturbations are generally found to extend laterally between 3 to 7-degree latitude. Assuming for simplicity that a monsoon perturbation exists as a circular vortex of uniform strength at points equidistant from the centre, its effect on the zonal component of the basic flow at a distance, say 5° north of the centre, will be equal and opposite to its effect at 5° south of the centre. Similarly its effect on the meridional components at 5° east and west of the centre respectively will be equal and opposite. Therefore, for a selected location if we average the zonal components at two points 5 degrees to its north and south (*i.e.*, 10 degrees apart) and the meridional components at two points 5 degrees to its east and west, the effect of perturbations will be practically nullified and the resultant of the two averages can be regarded at least as a rough approximation to the basic flow over the selected location. This wind is vectorially subtracted from the actual wind and the vector difference is taken to represent approximately the contribution due to the perturbations. In this manner, when the centre of a disturbance is located a further refinement may be obtained by a second smoothing in the region surrounding the disturbance.

3.6.2. Using the charts published by IMC Bombay (1964) for 1200 GMT on 7 July 1963 when the Arabian Sea monsoon was moderately strong, winds were picked out at 5-degree grid points in the area between Lat. 5° to 35°N and Long. 55° to 85°E for the levels — surface, 850, 700 and 500 mb. Following the method of smoothening as described in the previous paragraph charts showing the effects of perturbations over northwest Peninsula and the Arabian Sea were constructed. These are reproduced in Fig. 13. Similar smoothing was not attempted for higher levels in view of the complications involved due to the existence of the tropical easterly jet stream. It is seen that Fig. 13 also substantiates the finding that the 'Gujarat low' affects the wind flow from surface upwards.

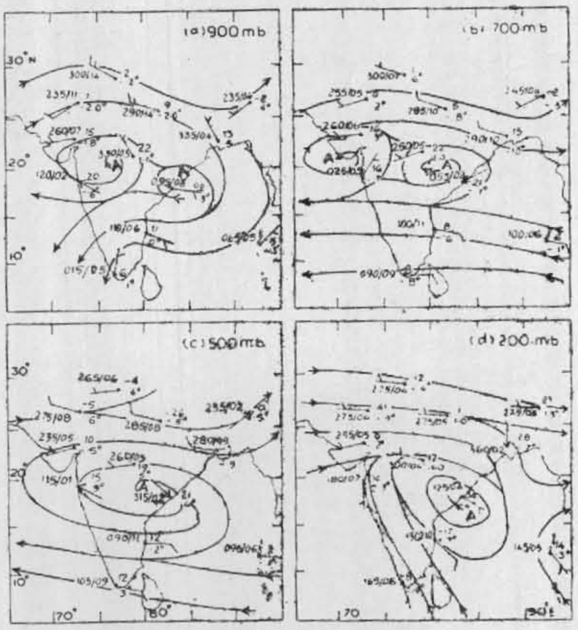

Fig. 6

Perturbations of weak monsoon

3.7. *Salient features of mean stream line patterns pertaining to weak Arabian Sea monsoon*

3.7.1. Figs. 7 (a) to 7 (e) depict stream line charts of mean resultant winds for 0001 GMT for all the available Rawin stations in India for (approx.) standard pressure levels 900, 850, 700, 200 and 100 mb for all the selected periods of weak Arabian Sea monsoon. The wind shear and thickness lines in layers 900-700 mb, 700-500 mb and 500-200 mb are also shown in Figs. 7(f) and 7(h) respectively. It is seen that upto 850 mb the effect of the heat low is well marked over Rajasthan and Saurashtra & Kutch. The winds over Jodhpur and Ahmedabad are about 20 kt strong. The trough line running to the west of these stations disappears at 700 mb and at this level weak NW/W winds prevail over this region. The wind shear between 900 and 700 mb are strong NE/E over Jodhpur and Ahmedabad indicating how the surface heat low over these areas rapidly diminishes and is replaced by a high at 700 mb. There is also another trough which lies over northeast India. Winds over this region are, however, weak (less than 10 kt). Wind shear between 900 and 700 mb indicates that the air over this region is relatively cold. Hence this trough does not weaken at 700 mb but extends upto 500 mb. Thus, there is a marked difference between the trough over northwest India and that over northeast India in their intensity and thermal characteristics. The former is warm and the latter cold. Koteswaram and

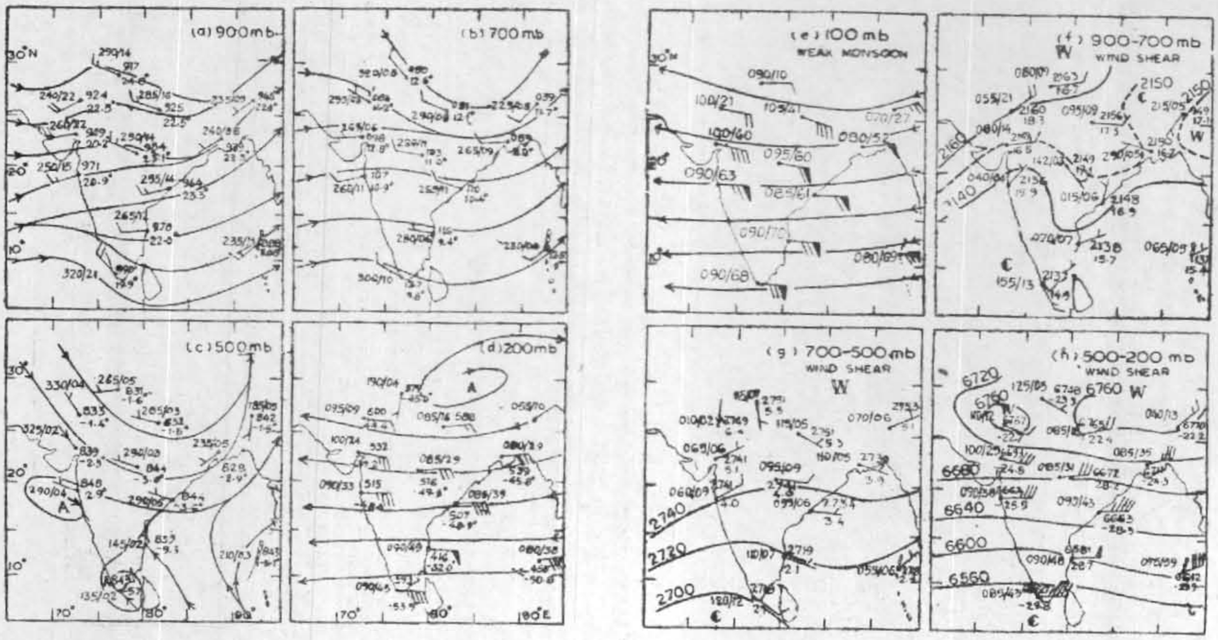

Fig. 7 (a—h)

Weak Arabian Sea monsoon

Bhaskara Rao (1963) pointed out that the 'break' in the monsoon appears to be due to the maximum northward extension of the cold monsoon air rather than its replacement by warm continental air from the west. The cold thermal low over northeast India is the seat of the heaviest rains during 'weak' monsoon periods. At 500 mb upper winds over the entire country are very weak *vide* Fig. 7(c). At 400 and 300 mb (charts not reproduced) winds over Delhi have a westerly component and the subtropical ridge lies to the south of that station. Aloft the subtropical ridge line remains over Tibet as usual.

3.8. *Salient features of mean stream line patterns associated with strong Arabian Sea monsoon-Type A*

3.8.1. Stream line charts of mean resultant winds for 0001 GMT for all the spells of strong monsoon Type A are shown in Figs. 8(a) to 8 (e). Wind shear and thickness lines in layers 900-700 mb, 700-500 mb and 500-200 mb are also shown in Figs. 8(f) to 8(h). It is seen from Fig. 8(a) that even at 900 mb winds over Rajasthan and Gujarat are weak in marked contrast to weak monsoon conditions. At 700 mb a cyclonic circulation appears over Gujarat and extends upto 500 mb tilting southwards at 400 mb. Although we have seen earlier that the 'Gujarat low' extends from sea level upwards with very little vertical slope upto 500 mb *vide* Figs. 4 (a) to 4 (c), we do not find any cyclonic circulation below 700 mb in Fig. 8(a). The reasons is that the westerlies at these levels associates with the heat low are very much stronger [*vide* Fig. 7 (a)] as compared to the winds associated with the perturbation and, therefore, suppress the easterlies on the northern side of the perturbation. As such we have only westerlies and no cyclonic circulation at these levels. The effect of perturbation is seen only as a reduction in the speed of westerlies over Rajasthan and Gujarat. At 700 mb as the heat low over northwest India disappears the normal wind over Ahmedabad has become light and therefore, the perturbation is recognisable as a cyclonic circulation at this level. Conditions are similar at 500 mb also. On the other hand, on the eastern side a cyclonic circulation is discernible over Orissa even at the lowest level. This is because the normal winds over this area are weak westerlies and are outbalanced by the relatively strong easterlies associated with the strong cyclonic perturbation. The net result is that the perturbation is recognisable as a cyclonic circulation even at lower tropospheric levels. Due to progressive contribution of easterly components with height over Peninsular India arising from the north to south temperature gradient

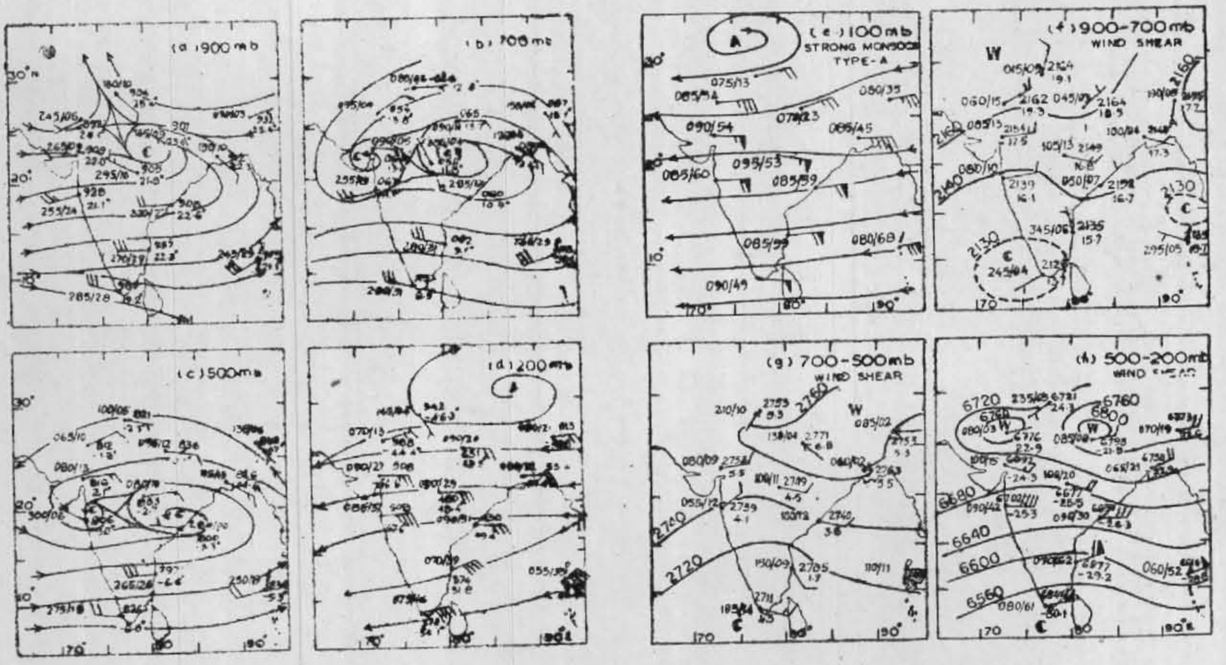

Fig. 8 (a—h)

Strong monsoon: Type A

characteristic of this season, this cyclonic circulation progressively weakens aloft and **shows** a gradual southward slope with height upto 400 mb; both the cyclonic circulations disappear above 400 mb. The effect of peturbations is seen only as an increase of easterly wind speed north of the perturbation trough line and a decrease of easterlies south of that line as mentioned earlier (Ramamurthi 1968).

3.8.2. In contrast to weak monsoon conditions, winds over Delhi have an easterly component between 400 and 200 mb indicating that during strong monsoon Type A the subtropical ridge line at these levels is at a higher latitude (Ramaswamy 1958, Ramamurthi 1967). At 200 mb winds along the west coast have a significant northerly component.

3.8.3. Wind shear between 900 and 700 mb shows NE/E over Ahmedabad and Jodhpur *vide* Fig. 8 (f) and their strength is relatively less as compared to weak monsoon conditions. Air over the east central and southeast Arabian Sea and over the central Bay at these levels seems to be cold. It is seen from the wind shear charts that the warmest area is to the north and coldest is to the south corresponding to the generally north to south decrease of temperature at all levels.

3·8·4. The wind shear charts for the layer 500-200 mb (*vide* Figs. 7 h and 8 h) bring out significant differences between weak and strong monsoon conditions, *viz.*, that during weak monsoon the shear is relatively strong over Calcutta and Visakhapatnam and relatively weak over south Peninsula in contrast to the conditions during strong monsoon. However, paradoxically as stated in para 3.3.3. the upper tropospheric east wind maximum over south India is relatively weaker during strong monsoon but stronger in weak monsoon. This is due to opposite types of perturbations prevailing during strong and weak monsoon regimes extending their effects from surface to great heights in the upper troposphere.

3.9. *Mean stream line patterns characteristic of strong monsoon—Type B*

3.9.1. Mean stream line charts for this type are depicted in Figs. 9 (a) to 9 (d). These show features which are essentially similar to that of Type A excepting that the strength of cyclonic vortices is less as it should be. It is interesting to note that in Figs. 9 (a) and 9 (b) the low at the eastern end lies over Orissa whereas Fig. 5 shows that the perturbation ('eastern low' in Type B) as such lies over and off coastal Andhra Pradesh. This is because in lower tropospheric levels the normal winds over Visakhapatnam are westerlies of moderate strength and the easterlies associated with the northern half of the perturbations of Type B are not sufficiently strong to outbalance them and cause a reversal in direction. Therefore, the effect of perturbations is seen only as a

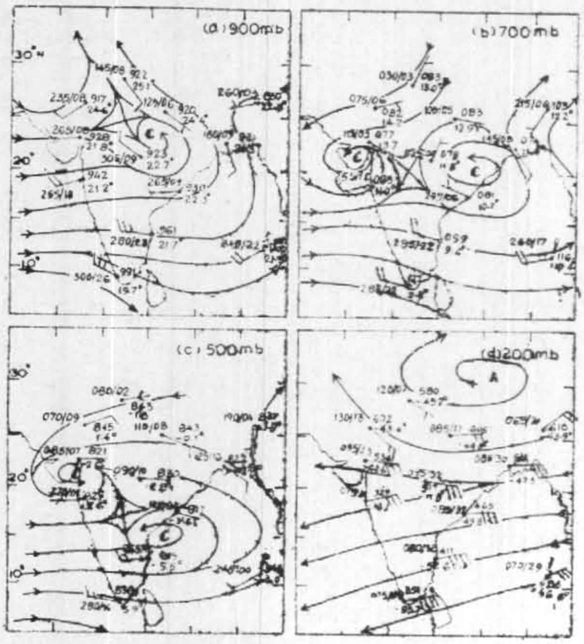

Fig. 9

Strong monsoon : Type B

reduction in the westerly speed over coastal Andhra Pradesh. In the case of perturbations of Type A, as they are centred in a northerly position and coastal Andhra Pradesh is south of their centre, their contribution is to increase considerably the strength of westerlies over coastal Andhra Pradesh. Thus Visakhapatnam shows a marked contrast between the regimes of strong monsoon Type A and of Type B in the strength of lower tropospheric westerlies. Therefore, low level winds over Visakhapatnam may be of utility as an indicator in predicting whether a disturbance is likely to intensify into a depression or not. In this connection it is interesting to note that in the storm tracks over the Bay of Bengal (India met. Dep. 1964) the region having a large frequency of origin in the month of July and August lies north of the latitude of Visakhapatnam. It is also significant to note that in Type B the cyclonic circulation at the eastern end shows a vertical tilt southwards between 600 and 500 mb whereas such a tilt occurs in Type A at a higher level.

4. Modification of monsoon airmass

With a view to ascertain the modifications, if any, which the monsoon airmass in the neighbourhood of the 'Gujarat low' undergoes during the regime of strong Arabian Sea monsoon, mean T-Φ grams for Bombay (Santacruz) for 0530 IST corresponding to all the spells of weak and of strong monsoon were computed. These are shown in Figs. 10 and 11. The dry bulb curves in both the cases are practically identical. Between 800 and 700 mb, however, the lapse rate decreases from 5° to 4·5°C/km in weak monsoon. During strong monsoon the air over Bombay is very moist upto 600 mb and even higher whereas during weak monsoon the moisture content falls off rapidly above 800 mb. The increase in the moisture content of the air during strong monsoon could not have been due to evaporation from falling rain as in that case the dry bulb temperature would have been lower on account of cooling due to evaporation. This is also borne out by the fact that the potential pseudo wet bulb temperatures at available standard pressure levels are different in the two cases as shown by Table 1.

To have a proper understanding as to how this modification is effected it would be necessary to examine the vertical distribution of temperature and moisture conditions over the Arabian Sea at various locations during strong as well as weak monsoon regimes. Unfortunately data in respect of typical weak monsoon periods are not available. However, available dropsonde data relating to a spell of moderate monsoon (7 to 9 July 1963) were examined.

4.1. In Fig. 12 are shown ten dropsondes over selected points in the eastern Arabian Sea. It is seen that along 67°E, there is a shallow layer of moist air above which is a layer of inversion or very low lapse rate with its base near about 900 mb. The moisture content drops off almost abruptly above the base of the inversion layer. The height of base of inversion layer is also seen to increase eastwards and the inversion layer disappears east of a line joining the points Lat. 9°N, Long. 74°E and Lat. 20°N, Long. 70°E (Ramage 1966, 1967; Sikka and Mathur 1967; Desai 1967), *i.e.*, about 2 degrees off the west coast. Table 2 shows the distribution of potential pseudo wet bulb temperatures at standard pressure levels over four selected points lying between 17° and 20°N on either side of this line. As we proceed east of 66°E values of θ Sw above 900 mb increase gradually and at 20°N, 70°E they are generally higher by 2-3°C over the values at 18°N, 66°E. Therefore, the increase in moisture content on the eastern side can be attributed to vertical transport of both moisture and heat from the surface of the Arabian Sea (Pisharoty 1967).

4.2. Dropsonde data over points 12°N, 73°E; 16°N, 72°E and 18°N, 71°E *vide* Fig. 12 show that although these points are practically about the same distance (2 degrees) away from the coast and from the Ghats, at 12°N, 73°E the air is almost saturated only upto 790 mb and above this level moisture decreases rapidly while at 18°N, 71°E nearly saturated air extends to 750 mb and above

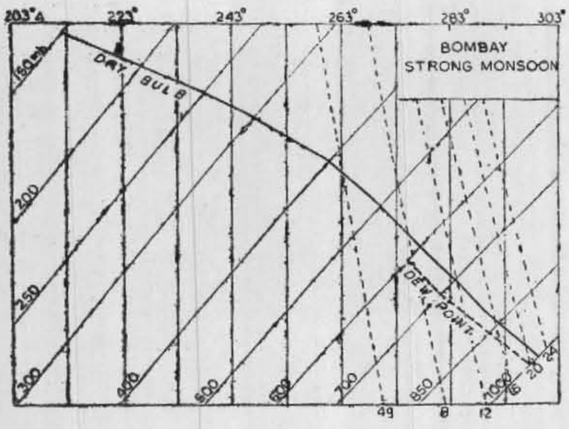

Fig. 10

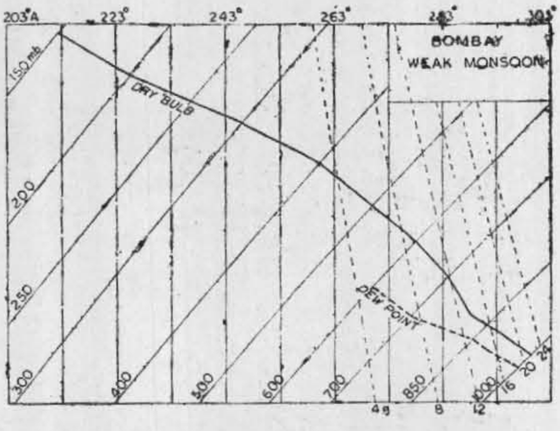

Fig. 11

TABLE 1

Mean potential pseudo wet bulb temperature(°A)over Bombay during spells of strong and of weak Arabian Sea monsoon

Pressure level (mb)	Strong monsoon	Weak monsoon
1000	298·0	297·5
950	297·3	297·0
900	297·0	295·5
850	296·5	294·5
800	296·0	294·2
750	295·5	294·0
700	295·5	293·3
650	295·5	293·4
600	295·0	293·5

TABLE 2

Potential pseudo wet bulb temperatures (°A) over selected points in the Arabian Sea

Pressure level (mb)	Positions of drop-soundings			
	18°N,66°E	17°N,70°E	18°N,71°E	20°N,70°E
1000	296·5	298·0	297·0	298·2
950	297·0	297·0	297·2	298·0
900	297·0	297·2	297·5	297·0
850	291·0	297·0	296·0	296·6
800	293·0	295·5	295·6	296·0
750	293·5	291·5	294·5	295·5
700	294·5	293·5	294·7	295·7
650	295·0	292·3	293·5	297·4
600	293·0			296·5
550	292·5			294·8

this level also the moisture content is quite high although it decreases. The point 20°N, 70°E altough more than two and a half degrees away from the coast and far from the mountain range, is very near the centre of the 'Gujarat low' (Fig. 13) and the air over it is almost completely saturated upto 570 mb. This shows the overwhelming influence of the dynamic processes associated with the 'Gujarat low' in effecting transport of moisture upwards. At a location which is far to the south of the 'Gujarat low' as represented by point 12°N, 73°E the effect, if any, due to the Ghats remains the same as at any other point 2 degrees off the coast. However, the transport of moisture at this point is found to be confined to about 800 mb only. Therefore, in this area the breaking up of inversion is not accompanied by significant convective activity. From this region, as one proceeds northwards and thereby nearer the 'Gujarat low', the moisture content at mid-tropospheric levels also increases. This brings out the important point that so far as convective activity and vertical transport of moisture in the air over the eastern Arabian Sea is concerned it is the 'Gujarat low' rather than the orographic effects of the Western Ghats (Desai 1967) which plays a dominant role. In this connection it is significant to note that from theoretical considerations (Sarker 1967) found that the contribution of orography to coastal rainfall is hardly 20 per cent and that

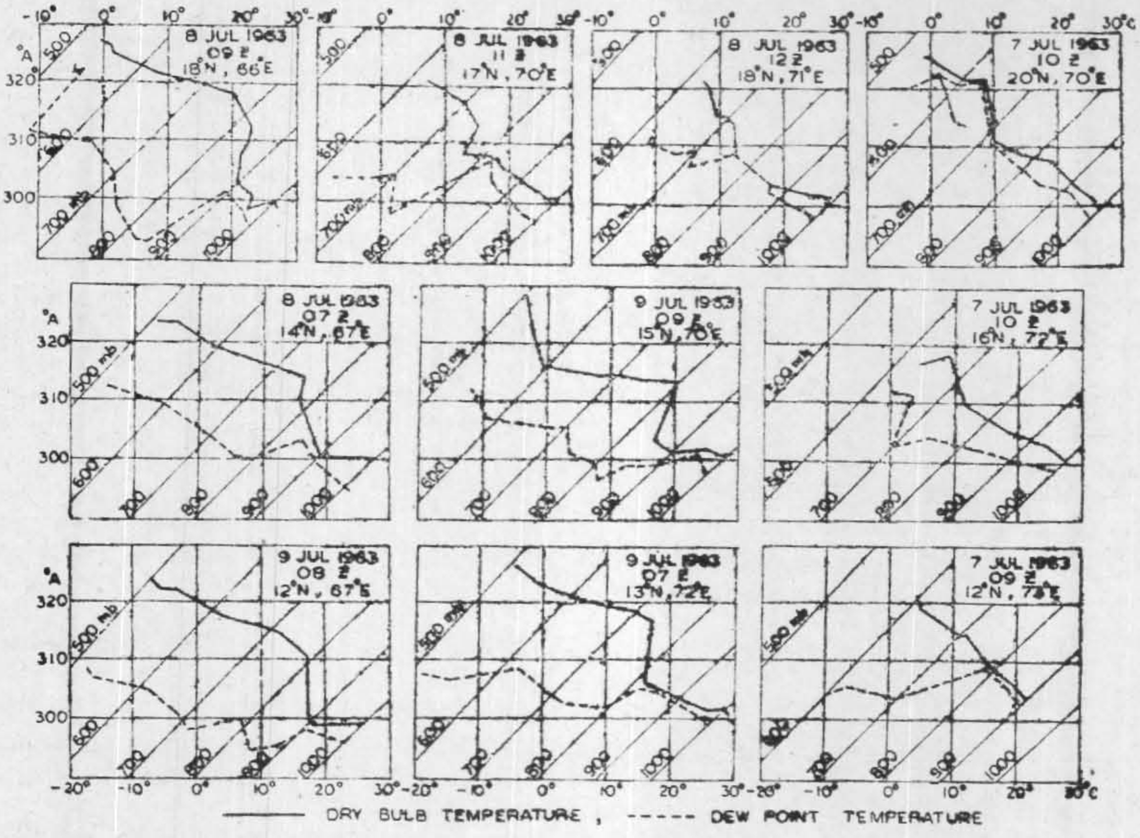

Fig. 12

Selected drop-soundings

only beyond about 30 km from the coast the effect of orography becomes dominant. That the rainfall on the west coast in the southwest monsoon period is not merely due to orography but also due to other important dynamical factors was emphasized as early as in 1958 by Koteswaram (1958) and from more recent high level data by Ramaswamy (1969).

4.2.1. Under the influence of the perturbations of the strong monsoon large areas of cloud and weather occur in the neighbourhood of 'Gujarat low' (Miller and Keshavamurty 1967). As regards areas farther to the south it may be stated that as mentioned earlier *vide* para 3 the effect of perturbations is to cause an increase of SSE-NNW pressure gradient over the Arabian Sea south of 20°N with a maximum roughly along 70°E. Due to such an increase of pressure gradient the effect on the zonal flow as well as the (southerly) meridional flow (Keshavamurty 1968) both contribute to the strengthening of westerlies over the east Arabian Sea south of 20°N with a maximum roughly along 70°E. To the east of this longitude decrease of speed down wind will contribute to speed convergence and consequent vertical motion and cloud development. Further, to the east the horizontal speed also probably decreases eastwards as a result of the barrier provided by the Western Ghats and the winds which blow practically perpendicular to the Ghats are forced to ascend over the Ghats and cause considerable rainfall on the windward side of the Ghats (Desai 1967).

4.2.2. In an earlier study of strong monsoon making use of satellite cloud data, the author and Jambunathan (1967) found that in the Arabian Sea the area of heavy overcast clouding extended westwards upto about 7 degrees off the west coast. This has also been confirmed by observations made by Meteorologists aboard U. S. Research Vessel *Oceanographer*. It appears possible that such a large westward extension of cloud mass is associated with low level convergence arising from decrease of speed down wind as mentioned in para 4.2.1 above.

5. Conclusions

(*i*) It is found that the intensity of the heat low over West Pakistan and neighbourhood does

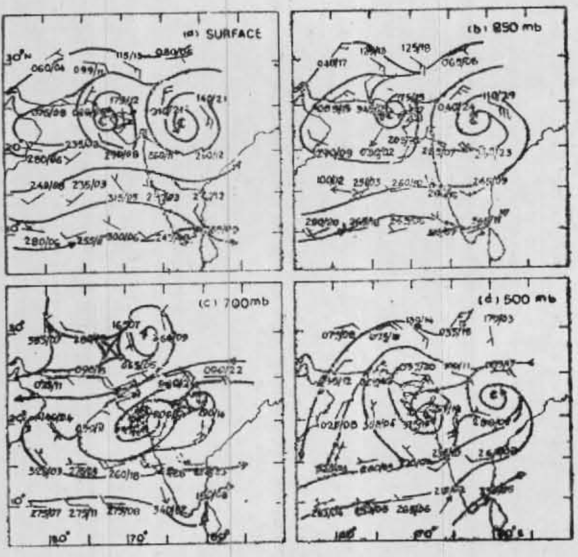

Fig. 13

Perturbations over the Arabian Sea at 1730 IST on 7 July 1963

not contribute to the strengthening of the low level monsoon flow as postulated by Ramage (1966, 1967). There is no consistent relationship between the intensity of the heat low and the monsoon rains along the west coast of India.

(*ii*) The perturbations of strong monsoon affect the wind flow from sea level upwards and are directly responsible for increasing the strength of low level flow.

(*iii*) Qualitatively an inverse relationship exists between the pressure anomaly over Surat and the monsoon rains along the west coast of India.

(*iv*) The strength of the monsoon circulation over India is associated with two cyclonic vortices which in the mean are located over the Gulf of Cambay ('Gujarat low') and northern parts of east coast ('eastern low') respectively and extend vertically upto 500 mb.

(*v*) In view of (*ii*) and (*iv*) above, the structure of the Arabian Sea monsoon seems to be quite different from the model proposed by Ramage (1966, 1967). Essentially, the Gujarat low also has its maximum intensity in lower tropospheric levels but this does not appear in the wind circulation due to the counteracting effect of the relatively strong flow associated with the heat low over West Pakistan in lower levels. The pressure departure charts at the surface clearly indicate the presence of this low off the Gujarat coast in the surface pressure field. As the heat low decreased rapidly with height, the cyclonic circulation associated with the 'Gujarat low' appears near mid-tropospheric levels. Moreover, in any model of the Arabian Sea monsoon the influence of the 'eastern low' should also be considered.

(*vi*) Wind anomaly charts bring out that weak monsoon is associated with two anticyclonic vortices and their ridge line lying generally over the northern parts of the Peninsula and affecting wind flow practically at all the tropospheric levels.

(*vii*) The strength of upper tropospheric east wind maximum over south Peninsular India is less during strong monsoon than in weak monsoon. Therefore the cause of east wind maximum is also not attributable to the release of latent heat through heavy rain over central India during strong monsoon.

(*viii*) The 'eastern low' associated with strong monsoon of Type B is located generally at a lower latitude as compared to Type A. In the stream line pattern associated with Type B the vertical axis of the cyclonic circulation over coastal Andhra Pradesh also shows a larger southward tilt between 600 and 500 mb.

(*ix*) The perturbations of strong monsoon contribute a significant northerly component to the wind flow along the west coast of the Peninsula at upper tropospheric levels whereas the perturbations of weak monsoon contribute a southerly component at these levels. The former is conducive to upper level divergence and consequent increase in rainfall activity over those areas while the latter produces the opposite effect.

(*x*) Overcast clouding in the Arabian Sea extending westwards to about 500-700 miles off the west coast of Peninsula during strong monsoon are chiefly attributable to the direct and indirect dynamical processes associated with the monsoon perturbations rather than to orographic effects of the Western Ghats.

(*xi*) Items (*v*) and (*vi*) above bring out the usefulness of wind anomaly charts in understanding the effects of monsoon perturbations.

Acknowledgement — The author is greatly indebted to Dr. P. Koteswaram, Director General of Observatories, New Delhi for his helpful criticism and extremely valuable suggestions. Sincere thanks are also due to Dr. R. Ananthakrishnan, Director, Institute of Tropical Meteorology, Poona, Shri Y. P. Rao, Deputy Director General of Observatories (Forecasting), Poona, Shri M. Gangopadhayaya, Deputy Director General of Observatories (Climatology & Geophysics), Poona, Shri N. M. Philip, Director, Regional Meteorological Centre, Madras and Dr. A. S. Ramanathan, Meteorologist, INOSHAC, DDGF's Office, Poona for the facilities provided.

REFERENCES

Dallas, W. L.	1900-02	*Mem. India Met. Dep.*, **12**, Pt. I, pp. 1-30.
Desai, B. N.	1967	*J. atmos. Sci.*, **24**, pp. 216-200.
Dixit, C. M. and Jones, D. R.	1965	I.M.C. Report No. 3, International Meteoroloigical Centre, Bombay.
India met. Dep.	1964	*Tracks of Storms and Depressions in the Bay of Bengal and Arabian Sea (1877-1960).*
Keshavamurty, R. N.	1968	*Mon. Weath. Rev.*, **96**, 1, pp. 23-31.
Koteswaram, P.	1958	*Tellus*, **10**, 1, pp. 43-58.
	1960	*Monsoons of the World*, India met. Dep., pp. 109-110.
Koteswaram, P. and Bhaskara Rao, N. S.	1963	*Australian met. Mag.*, 42, Sep. 1963, pp. 35-56.
Malurkar, S.L.	1950	*Mem. India met, Dep.*, **28**, Pt. IV, p. 163.
Miller, F. R. and Keshavamurty, R. N.	1967	Proc. Symp., Met. Results of the IIOE, Bombay, India, met. Dep., pp. 337-349.
Pisharoty, P. R.	1967	*Ibid.*, pp. 43-50.
Ramage, C. S.	1966	*J. atmos. Sci.*, 144-150.
	1967	Proc. Symp. Met. Results of the IIOE, India met. Dep., pp. 197-207.
	1968	*Weather*, **23**, 1, p. 32.
Ramamurthi, K. M. and Jambunathan, R.	1966	An objective method of forecasting the daily rainfall over north Konkan and south Gujarat during July and August (*Unpublished*).
	1967	Use of Satellite Cloud Pictures in the study of the Indian Summer Monsoon (under publication in the Proc. NISI/INCAR Symp. 'Indian Ocean', March 2-4., 1967)
Ramamurthi, K. M., Keshavamurty, R. N. and Jambunathan, R.	1967	Proc. Symp. Met. Results of the IIOE, India Met. Dep., pp. 350-361.
Ramamurthi, K. M.	1968	*Indian J. Met. Geophys.*, **19**, **3**, pp. 347-349.
Raman, C. R. V. and Ramanathan, Y.	1964	*Nature*, **204**, pp. 31-35.
Raman, C. R. V., Keshavamurty, R. N., Jambunathan, R. and Ramanathan, Y.	1967	Proc. Symp. Met. Results of the IIOE, India met. Dep., pp. 401-412.
Ramaswamy, C.	1962	*Tellus*, **14**, **3**, pp. 337-349.
	1967	Proc. Symp. Met. Results of the IIOE, India met. Dep., pp. 317-327.
	1967	Prince Mukarram Jah Lectures, 1967 (Published by the *Indian Geophys. Un.*), p. 13.
	1967	*Ibid.*, pp. 19-20.
	1969	*Curr. Sci.*, **38**, **3**, pp. 33-58.
Rao, Y. P.	1961	*Indian J. Met., Geophys.*, **12**, 3, pp. 413-418.
	1962	*Ibid.*, **13**, 2, p . 157-166.
Rao, Y. P. and Desai, B. N.	1965	*Ibid.*, **16**, pp. 479-481.
Sarker, R. P.	1967	*Mon. Weath. Rev.*, **95**, 10, p. 683.
Sikka, D. R. and Mathur, M. B.	1967	Proc. Symp. Met. Results of the IIOE, India met. Dep., pp. 55-67.