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Transport of Water Vapour over the Arabian Sea and adjoining Indian region

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ABSTRACT. A critical examination has been made of the various points discussed in the paper of Sikka and Mathur (1965) on '*Transport of Water Vapour over Arabian Sea and adjoining Indian region during an active Monsoon situation*' and it is shown that their interpretations of the IIOE data are not acceptable in many cases.

1. Introduction

Sikka and Mathur (1965) have studied transport of water vapour over the Arabian Sea and the adjoining Indian region during an active monsoon period 7 to 10 July 1963 for which 19 dropsondes data were available besides the Indian pibal and rawin stations' data. They have prepared for the purpose charts for the area bounded by 4° and 28°N and 61° and 81°E from the surface to 500 mb. Their study has confirmed, according to them, that the bulk of moisture is transported by the lower tropospheric wind flow. It is proposed to examine the IIOE data presented in their paper and their interpretations to see how far their conclusions on various points are justified.

2. Discussion

2.1. *Synoptic conditions* — At the outset it might be stated that the activity of the monsoon began to decrease from the 7th and there were break conditions on 10 July 1963 (Desai 1967 and *see* Ref.). The synoptic conditions on the 7th and 8th and 9th and 10th for which data have been composited, were not the same on each day of the two periods, *i.e.*, 7th and 8th or 9th and 10th. A depression from the Bay lay as a low pressure area near 23°N, 82°E on the 7th, over northeast Rajasthan and neighbourhood on the 8th, over the west Uttar Pradesh on the 9th and a little further east on the 10th; it was continuously weakening during its movement. They have stated that over the north Arabian Sea and adjoining Gujarat, an active cyclonic circulation lay in the middle troposphere between 700 and 500 mb with maximum intensity at 600 mb and that this circulation was active between the 7th and 8th and weakened after the 9th. Desai (1967b and *see* Ref.) has examined in detail day-to-day synoptic conditions for the period studied by Miller and Keshavamurthy (1965). His conclusions are —

(*i*) There was no mid-tropospheric cyclone of the type contemplated by them with maximum intensity at 600 mb. The temperature differences on the basis of which they have postulated existence of a subtropical cyclone type circulation near Bombay, become intelligible if one considers the differences in the lapse rates of the air masses involved.

(*ii*) The cyclonic circulations come into existence near Bombay during active or strong monsoon conditions above about 850 mb and upto about 500 mb as a result of the climatological features over the area and the influence of the Western Ghats.

(*iii*) There was no cyclonic circulation over Bombay area on the 7th, 8th, 9th and 10th. There was only east-west oriented axis of trough at different levels with perpendicular action conditions along them at some levels and locations; at the western end there were triple point conditions at some levels and locations which have been erroneously taken by them as cyclonic vortices.

(*iv*) Rainfall amounts over the area can be understood if one considers the influence of the Western Ghats mentioned in (*ii*) and of the trough lines and perpendicular action and triple point conditions mentioned in (*iii*). The rainfall over the area affected by the low from the Bay can also be understood if one considers partitions or trough lines between different air masses in its field of activity.

From the above it can be stated that the entire period 7th to 10th or the two periods 7th and 8th and 9th and 10th cannot be considered to have more or less similar synoptic situations as presumed by Sikka and Mathur (1965).

2.2. *Results for 7-8 July 1963*

Vertical distribution of Water Vapour—It is stated in remarks on Fig. 1 (a) of their paper that (*i*) there is a pronounced ridge of high values along 24°N which coincides in position with the lower tropospheric monsoon trough over the area; and (*ii*) the values of q (specific humidity) fall off rather rapidly with height on the western longitudes, *i.e.*, 61° and 65°E, the rate of decrease, decreasing from the high values at 61°E to lower values between 69-73°E and remained constant east of 73°E.

Regarding their above conclusions, the following remarks might be offered.

It has been shown by Desai (1966, 1967 and *see* Ref.) that the inversion over the Arabian Sea is due to air masses—characteristic stratification of deflected trades with unstable lapse in the lower levels and drier unstable continental air above. The inversion weakens and its base is raised as the air masses move eastwards due to the influence of the Ghats on the configuration of the isobars and the streamflow and forced ascent of moist air due to their acting as barrier; on the west coast and over the Peninsula there is no inversion and the depth of the moist current becomes about 6·0 km in contrast to the depth of 1·0 to 1·5 km west of about 65°E. The variation in moisture content with height from 61°E to 69°-73°E—rate of decrease decreasing from west to east and the rate remaining constant from about 72° to 81°E, can thus be understood.

The distribution of moisture north of 20°N and it becoming maximum along 24°N was due to the actual synoptic conditions during the period which were quite different from the normal monsoon trough conditions (Desai 1967c and *see* Ref.).

On the basis of Fig. 1(b) of their paper, they have remarked that largest values of total water vapour content occurred over Gujarat, west Madhya Pradesh, south Rajasthan and adjoining area and that the gradients over north Rajasthan and West Pakistan were quite high. Regarding this it may be stated that largest values over the area referred to by them were due to the movement of the low referred to earlier over and near the area and the associated trough axis and air mass partitions and the triple point and perpendicular action conditions over Gujarat and neighbourhood during the period. The large gradient northwestwards was due to the fact that there was continental air over the area.

The statement that the distribution of moisture referred to above is a seasonal feature over India due to location of the monsoon trough is not correct as the conditions during the period studied by Sikka and Mathur were not those associated with the normal monsoon trough. The lowest values of total moisture in the central Arabian Sea near 10°N, 65°E might even be considered as a normal feature of the season.

The distribution of q for 9th and 10th as stated by them was also similar to that of 7th and 8th except that the values for the 9th and 10th showed slight general decrease corresponding to the weakening phase of the monsoon activity and that these patterns may be taken generally representative of the conditions during the southwest monsoon period. In this connection, it might be stated that it is observed that even during weak monsoon conditions as judged from rainfall on the west coast, there is enough moisture to get appreciable precipitation, but there is absence of mechanism to cause the same in contrast to active or strong monsoon conditions (Desai, *see* Ref.). Thus we see the study of moisture distribution alone without the study of accompanying synoptic conditions, cannot help forecasting of rainfall.

Distribution of latitudinally averaged zonal and meridional wind components—Sikka and Mathur (1965) have given distribution of u and v in Figs. 2a and 2b of their paper. The westerlies extended upto 500 mb south of about 20°N; there was a zone of weak easterlies along 22°N and 28°N between 700 and 500 mb. These features were associated with the movement of low from the Bay during the period 7-8 July.

The same remarks also apply to Fig. 2b, the synoptic conditions on the two days determining the northward and southward components at different levels and over different areas.

Water vapour transports—In Figs. 4a and 4b they have given data for vertically integrated meridional and zonal water vapour flux respectively. Comparison of their results in Fig. 4a with the findings of Starr and Peixoto (1959) would not appear meaningful as the latter authors must have based their computations on average conditions without knowledge of existence of air mass inversion over the Arabian Sea; further, study of particular day conditions would naturally show much different values over different areas as the synoptic conditions were quite different on the 7th-8th from the normal conditions. Discussion of Figs. 3(a, b, c, d) and 4 (a, b) would have been meaningful if they are of each day with reference to the prevailing synoptic conditions.

The distribution of integrated water vapour transport values for surface to 500 mb would become clear if the positions of low from the Bay and the positions of air mass partitions at different levels on the two days in questions are taken into consideration (cf. Fig. 5). These conditions cannot be taken as typical of the average monsoon trough.

Following Pisharoty (1965) they have given an estimate of the budget of the integrated water vapour fluxes across the boundaries of the box between 8°—20°N and 61°—75°E, the eastern boundary representing conditions on the west coast between Trivandrum and Bombay. The fluxes at the southern and northern boundaries were about the same on both the days, but they had significantly fallen at the western and eastern boundaries from the 8th to 9th. They have concluded that the weakening of the wind system over the Arabian Sea on the 9th had contributed more to the fall in the fluxes since the specific humidity distribution remained very nearly the same on both 8th and 9th. The total rainfall on the coast between Trivandrum and Dahanu (both stations inclusive) in 24 hours ending at 03 GMT of the 8th, 9th and 10th was 65, 32 and 7 cm respectively. Thus although the specific humidity distribution was about the same on both the 8th and 9th and the flux across the eastern boundary was about 17 per cent less on the latter than on the former date, the total precipitation differences on the two dates were very large. Desai (1966b) has examined Pisharoty's viewpoint. The weaker winds on the 9th might be responsible for less rainfall than on the 8th, the normal component to the Ghats which causes forced ascent being also probably small. The specific humidity distribution being about the same on the two days, it can be stated as mentioned earlier (Desai-*see* Ref.) that it is the mechanism which can produce rainfall which is most important. Thus the moisture values obtained from radiosonde data, the lapse rate on the coast being near saturation adiabatic will not help the forecaster in predicting rainfall on the coast; what the forecaster should know is the nature of air mass stratification over the Arabian Sea to the west of about 68°E (Desai, *see* Ref.) and the synoptic conditions, the amount of precipitation being larger with characteristic stratification than when there is uniform moist air mass upto about 500 mb, other conditions remaining about the same.

Spatial eddy flux — Sikka and Mathur (1965) have shown that the meridional eddy flux is negligibly small compared to the total vapour flux over the entire latitudinal belt 4°—28°N, the entire moisture is being transported by a single cell over the Indian monsoon area. The following remarks might be made regarding their conclusions —

(*i*) It is seen that at 28°N total zonal and eddy fluxes are nearly the same. At this latitude there will be correlation between east or west direction of wind and specific humidity, the westerly air being dry and the easterly air relatively very moist. At 24°N as a result of the location of the trough axis the westward transport of eddy flux has decreased and at 20°N there is no westward transport of eddy flux at all.

(*ii*) It has to be recognised that during the southwest monsoon season there is no correlation between wind direction and specific humidity. It is known that westerly winds can either be moist or dry depending upon their trajectory.

(*iii*) 7th and 8th July data do not represent average conditions as mentioned earlier.

2.3. *Thermal structure of the lower levels over the Arabian Sea*

While examining the 1963 and 1964 RFF data over the Arabian Sea, Sikka and Mathur (1965) stated that (1) there is no inversion from the equator to 8°N east of 50°E, (2) inversions exist north of that latitude, their bases being gradually lifted up from near surface layer along the east African coast to near 800 mb between 65°—70°E and (3) inversions disappear east of 70°E. In this connection, a reference is invited to papers by Desai (*see* Ref.) where positions of partitions between different air masses at different levels over the Arabian Sea have been given for occasions when the air mass above the deflected trades is relatively dry and has unstable lapse. The rise in the height of the base of the inversion which is due to air masses, increases *rapidly* within about 500 km of the Somalia-Arabian coast and gradually further east, upto about 70°E. The rapid increase in the height of the base of the inversion near the Somalia-Arabia coast is supported by jet winds over the area observed by Bunker (1965) and the velocities falling off further east. The causes of the disappearance of the inversion within about 500 km of the west coast of the Peninsula as contemplated by Desai have already been given in Section 1. Sikka and Mathur's statement that the convergence in the air flowing towards the active monsoon trough zone extending upto

500 mb lying over northeast Arabian Sea plays a predominant part in the same, cannot be accepted. It has been shown by Desai (1967 a,b and *see* Ref.) that there is no cyclonic vortex over northeast Arabian Sea of the type contemplated by Ramage (1965, 1966), and Miller and Keshavamurthy (1965). Sikka and Mathur have stated that the effect of the trough over the northeast Arabian Sea is more prominent since during persistent weak monsoon conditions along the Konkan coast the stable mid-tropospheric layers appear over Bombay though not over Minicoy and Trivandrum which are nearer the equator. Their interpretation of the appearance of the stable mid-tropospheric layers during weak monsoon over Bombay cannot be accepted due to the following reasons. It will be seen from the paper of Sawyer (1947) that stable lapse can occur over Bombay-Poona area (nose effect), during even active monsoon if the continental air from West Pakistan side flows southeastwards under suitable synoptic situations; extension of this air does not take place upto 8°N and hence the absence of stable mid-tropospheric layers there. If the synoptic conditions are not such that the inversion over the Arabian Sea west of 68°E is not broken up within 500 km of the coast due to the Ghats' influence, then also there will be stable mid-tropospheric layers over Bombay or over the whole west coast, the activity of the monsoon in terms of rainfall on the coast being weak on such occasions.

Sikka and Mathur have classified data over and around the Arabian Sea into four types— (*i*) equatorial, (*ii*) east Arabia coast and Persian Gulf, (*iii*) central Arabian Sea and (*iv*) west coast of India. The following remarks might be made regarding their classification.

(*i*) *Equatorial type* (*Fig. 6 a*) — According to them the layer from the surface to about 900 mb has dry adiabatic lapse rate (DALR) and inversion layer is non-existent. The moisture content is more or less similar from 70° to 93°E, but the data off the African coast showed very dry conditions a few hundred metres from the surface, the higher moisture content at Gan being due to the greater activity of the southern hemisphere equatorial trough in comparison with its weak activity off the African coast.

On the other hand Desai (1966a, 1966b, 1966c and *see* Ref.) has stated that only air crossing equator west of about 60°E enters the Arabian Sea and moves towards the west coast of India, while that entering to its east enters the Bay either across the Arabian Sea south of 8°N or directly. It is not correct to say that there is no isothermal layer or inversion in the data over and near the equator south of 8°N to the west of Long. 60°E. The data at 00°02′S, 44°36′ E for 29 June 1963 are also given in Fig. 3 of Pisharoty's paper (1965) in which data for another location for the same day at 00°00′ (Equator), 49°20′ E are also included. Both these cases show isothermal region between 850 and 800 mb and so also other IIOE data over the area. From Fig. 2 of Ramage's papers (1965, 1966) it is also seen that the height of the base of inversion varies between 1 and 3 km over the area between equator and 8°N to the west of about Long. 60°E. If there are no inversion or isothermal regions or less drier conditions above in any case, they are due to a difference in the actual synoptic conditions which are different from the normal ones. It is agreed that absence of inversion and higher moisture content above 900 mb east of 60°E over the equatorial region than to its west is due to the fact that the inversion is broken up by mixing in the equatorial trough, moisture penetrating into higher levels at the same time; the moisture content above about 950 mb in Fig. 6a of Sikka and Mathur in the other three ascents is quite high due to this effect.

It will be clear from the foregoing discussion that the nature of air masses in the equatorial region to the west and east of about 60°E is quite different and that they cannot be considered as belonging to the same category.

(*ii*) *East Arabia coast and Persian Gulf type* (*Fig. 6b*) — The data for 10 July at 21°N, 67°E (in Fig. 6b) have also been discussed by Desai (*see* Ref.) along with data at 22°N, 62°E and 22°N, 65°E for the same day. While there was DALR in the first 3-4 hundred metres from the surface level at 21°N, 67°E, there were no DALR layers in the other two cases at 22°N, 62°E and 22°N, 65°E. In the first case where there was DALR in the first 40 mb or so, there were deflected trades and in the next 40 mb where there were isothermal conditions, there was mixed monsoon air with very light humidity. Near 22°N, 65°E, there was mixed monsoon air with 100 per cent humidity and about 2°C lapse per km from surface to 920 mb, while in the third case there was continental air right from the surface, the inversion being produced due to travel of the drier hotter air over the sea and its cooling in the lower layers. The causes of DALR at Bahrein in the layers above surface are not quite clear for there could not be deflected trades over that area. It is possible that the continental air over the station was of different origins below and above the inversion; this presumption would be supported by the fact that while the dew point decreased by about 20°C from the surface upto about 875 mb, it decreased only by about 10°C between 850 and 500 mb. The dew point variation with height at Aden (Fig. 6c) is quite different where it has decreased at about the same rate throughout—about 45°C from the surface to about 600 mb, the nature of the continental air being the same at all levels.

It is thus clear that the classification of Sikka and Mathur of the two cases in Fig. 6b as being of the same type, is not correct. The dew point variation in the layer of DALR at 21°N, 67°E is only about 3°C, while it is much larger at Bahrein.

In the cases in Fig. 6(c) the inversion begins right from the sea surface. Desai (*see* Ref.) has discussed data for two cases in the Gulf of Aden and off Somalia on 30 August 1964 in which case also there was inversion right from the sea surface. Temperature off Somalia at the surface is much lower than at Aden because of lower water surface temperature off Somalia than at the latter location.

It is to be expected that the moisture content in the continental air where the inversion begins right from the sea surface and there is no convective transport of moisture upwards, will be much less than at Gan where there is an air mass without an inversion and there is convective transport of moisture upwards due to the equatorial trough.

(*iii*) *Central Arabian Sea type* (*Fig. 6d*) — In the curve for 12°N, 62°57′E, the air mass above the inversion has near SALR and higher humidity, while that at 17°48′N, 69°50′E has near DALR and lower humidity; the air above the inversion is not dry and unstable in the first case. The data for these two locations have been discussed by the author and they do not represent the same air masses conditions (Desai, *see* Ref.).

The characteristic air mass stratification in the central Arabian sea which gives active or strong monsoon in terms of rainfall over the coast has deflected trades with DALR and concentration of moisture in the lower levels and drier air with unstable lapse above with an inversion or isothermal region between the two as shown by data at 13·7°N, 56·9°E and at 18·6°N, 63·5°E on 2 July 1963 given in Colon's paper (1964). The air masses at 12°N, 62°57′E even if they reached the coast would not be able to give rainfall there more than during active monsoon conditions.

(*iv*) *West coast of India type* — The air mass over the west coast has near SALR in all the levels and there is no inversion generally upto about 500 mb. The causes for the depth of the moist current changing from 1·0 to 1·5 km over the central Arabian Sea to about 6·0 km over the west coast of the Peninsula have been discussed by Desai (1966, 1967 and *see* Ref.).

From the discussion of various points in Sikka and Mathur's paper (1965), it will appear that their interpretations cannot be accepted in all the cases.

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