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Moisture distribution and water vapour flux over the Arabian Sea during an active and weak spell of southwest monsoon, 1973

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ABSTRACT. The radiosonde data collected during the Indo-Soviet Monsoon Experiment, 1973 have been utilised to study some aspects of the moisture distribution over the Arabian Sea during an active and weak spell of southwest monsoon in that year. The study shows that there is stratification of moisture field over the Arabian Sea during the weak monsoon except the equatorial region, particularly the eastern parts. During the active monsoon, the stratification is broken to the north of about 10°N and east of 60°E, resulting in the building up of a deep moist layer over this area from surface to 400 mb. The equatorial region is conspicuously dry in the middle layers during the active spell. The moisture build up in the middle layers during both the spells is mainly brought about by large-scale vertical motion associated with synoptic scale disturbances rather than by advective processes. During active monsoon, large-scale upward motion is envisaged over north and east central Arabian Sea and subsidence near the equator.

The moisture flux computations show that there is a large net flux divergence over the Arabian Sea during the active monsoon and small net convergence during the weak monsoon.

1. Introduction

The establishment of the southwest monsoon over the Arabian Sea and most parts of India is generally complete by the middle of June. It covers the entire country by the second week of July. It is well known that during an epoch of active monsoon over India, the westerlies over the Peninsula attain a speed of 40-50 kt in the lower troposphere and they extend to 400 mb under the influence of low pressure systems forming or moving in the monsoon trough over the plains of north India. During such a phase, the rainfall is well distributed over most parts of the country. During the other extreme phase of the monsoon activity known as break or weak monsoon, the lower tropospheric wind field over the Peninsula is rather weak, the middle tropospheric field unsteady and the rainfall generally much below normal over most parts of the country.

Although during the International Indian Ocean Expedition (1963-65), certain important features about the structure of the southwest monsoon over the Arabian Sea were brought to light, the information so obtained does not give a detailed picture of the structure of the southwest monsoon over the Arabian Sea during its active and weak phase over India. Some of the features brought out during the IIOE are :

(*i*) The existence of a sharp moisture change near about 65° E with a shallow moist layer over west Arabian Sea and equatorial region capped by an inversion, and a deep moist layer over the east Arabian Sea without any inversion (Colon 1964; Miller and Keshavamurthy 1968; Pisharoty 1965; Sikka and Mathur 1965).

(*ii*) Existence of subsidence over central and west Arabian Sea restricting low cloud development (Ramage 1965 and Saha 1968).

Desai has also examined the results of the IIOE and holds the view that there are two air masses over the Arabian Sea—the low level monsoon airmass of southern hemispheric origin and the drier

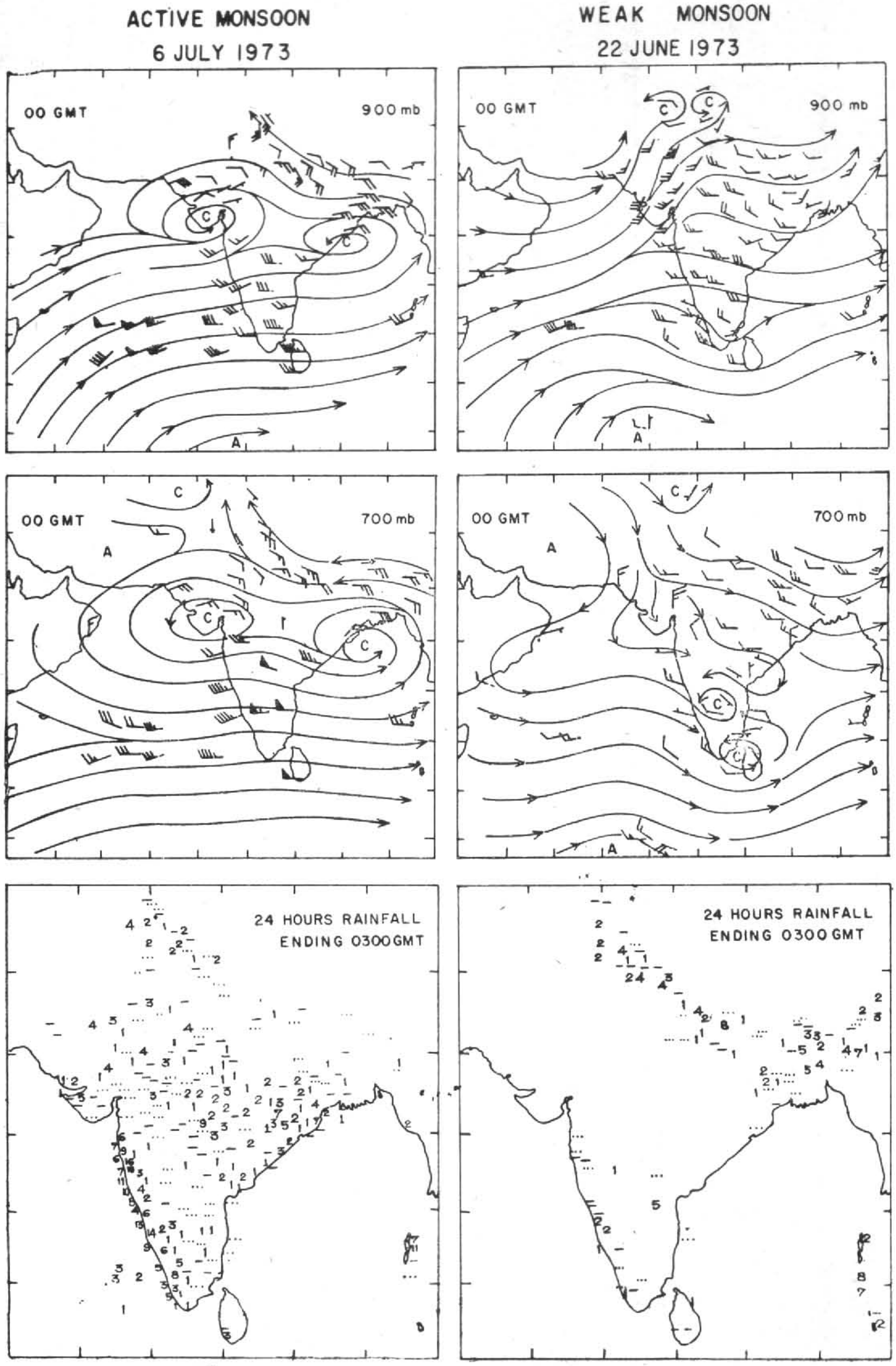

Fig. 1(a). Wind flow and rainfall

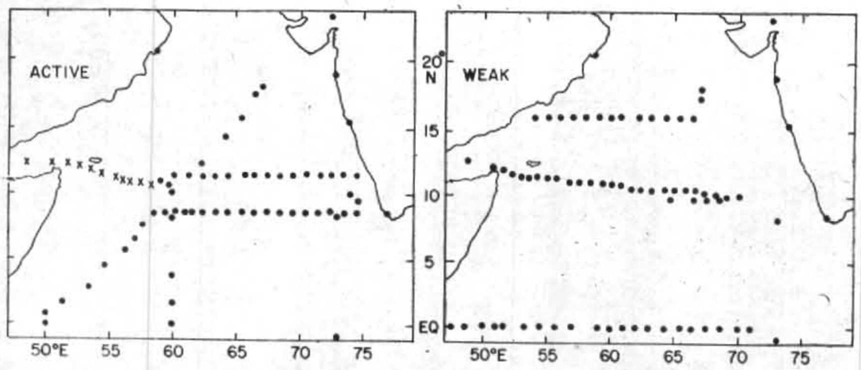

Fig. 1(b). Data coverage

continental airmass overlying the monsoon airmass. The monsoon activity defined in terms of rainfall over the west coast depends upon the nature of interaction between the two airmasses.

During ISMEX, 1973, four Russian research ships — *Priliv, Shokalskiy, Okean* and *Voeykov* — made extensive cruises over the Arabian Sea along the equator, 10° N and 16° N making upper air soundings, sometimes even four times a day. Whereas during the IIOE period, the dropsonde data were mainly below 500 mb and were lacking in space and time continuity during the various phases of the monsoon, the ISMEX data provided a fairly satisfactory coverage in time and space over the Arabian Sea in different phases of the monsoon and gave information about the wind, temperature and moisture, extending well into the stratosphere.

Utilising the ISMEX data, Jambunathan and Ramamurthy (1974, 1975) have studied the structure of the wind and temperature fields over the Arabian Sea during active and weak monsoon spells.

The present study has been undertaken to understand the changes in the moisture field over the Arabian Sea during active and weak monsoon spells and the atmospheric processes that lead to such changes.

Section 2 gives information about the dominant synoptic features which prevailed during the two spells. In Section 3, we discuss the procedure followed for the analysis of the data. Section 4 deals with the description of the moisture field in terms of relative humidity and mixing ratio of water vapour during the two spells. Moisture flux computations are presented in Section 5.

2. Synoptic features during active and weak monsoon

In 1973, the southwest monsoon advanced over Kerala on 4 June and covered most of the Arabian Sea, the Peninsula, central and northeast India by 13 June. This was followed by a lull in the monsoon in the latter half of June when the rainfall over most parts of the country was less than 50 per cent of the normal. The monsoon revived in the beginning of July and covered the entire country by the 6th. It was active during the first fortnight of July. The present study is concerned with the periods 19-25 June (representing a spell of weak monsoon) and 1-8 July (representing a spell of active monsoon).

A weak monsoon spell during July/August (which months climatologically represent the peak of monsoon activity) would have been preferable for contrasting it with an active monsoon spell in July/August. However, this was not possible as the ISMEX over Arabian Sea came to a close by the end of the first week of July . Hence, we have chosen a weak spell during the month of June, although June normally represents the advancing phase of the monsoon.

The synoptic features during these two spells are depicted by the flow pattern and the rainfall distribution on a typical active monsoon day (6 July 1973) and a typical weak monsoon day (22 June 1973) *vide* Fig. 1(a).

3. Data and Analysis

The data coverage for this study is shown in Fig. 1(b). As no observations were available from the extreme west Arabian Sea during the active monsoon spell, the radiosonde data provided by the Russian ship *Shokalskiy* which was in this area (indicated by crosses in Fig. 1b) during the period

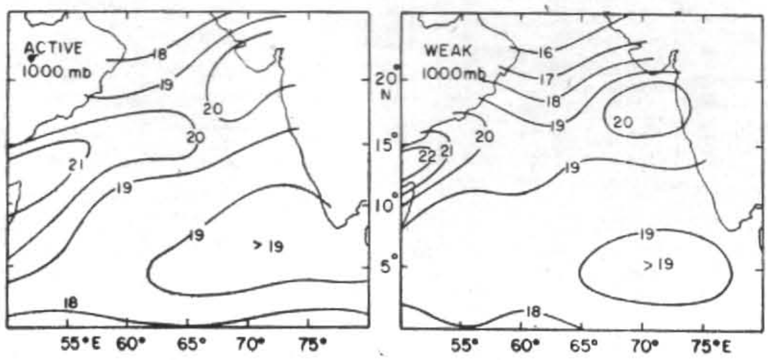

Fig. 2. Mixing ratio of water vapour (gm/kg) during (a) active and (b) weak monsoon

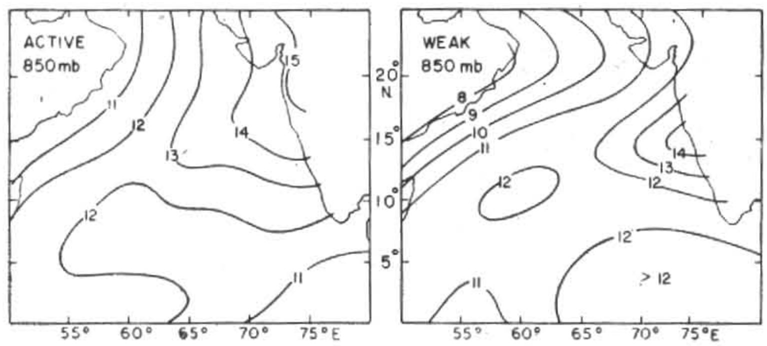

Fig. 3. Mixing ratio of water vapour (gm/kg) during (a) active and (b) weak monsoon

8-11 June have been utilised as a guide for a more confident analysis in that area. The situation in this period over the area could not be considered strictly identical to the conditions during the first week of July. However, the data for the period (8-11 June) may be regarded as representative of the active monsoon conditions as this period (8-11 June) was also one of active monsoon in its advancing phase.

From the radiosonde ascents made by the four ships during these two spells, mixing ratio of water vapour was computed for every 50 mb interval from 1000 to 700 mb and for every 100 mb interval higher-up upto 300 mb. For each of the above levels, composite charts covering the period of the active and weak monsoon spells were prepared for this element combining data for all the hours and for all the days. Over the sea area, data over 3-4 degrees longitude were averaged and the mean value put in the centre of the longitudinal belt for the final analysis, giving due weight to the more consistent values. Over the land area, the mean value for the stations in respect of each spell has been used. The diagrams for 1000, 850, 700 and 500 mb only are reproduced in this paper in respect of mixing ratio of water vapour. Similar composite charts were also prepared in respect of relative humidity and analysed upto 200 mb. From these charts, relative humidity cross-sections along every five-degree meridian from 50° E to 75°E were also constructed and the sections for 55°, 60°, 65° and 70° E only are presented.

4. Mixing ratio and relative humidity distribution

(a) *Mixing Ratio*

1000 to 850 mb (Figs. 2a & 2b and 3a & 3b) — At these levels there is no significant difference in the mixing ratios between the active and weak monsoon spells generally over the Arabian Sea. Whereas there is no significant gradient of mixing ratio across the longitudes at 1000 mb, the mixing ratio at higher levels increases from west to east during both the spells north of 10°N.

800, 750 and 700 mb (Fig. 4 for 700 mb) — At these levels, the east to west gradient in mixing ratio

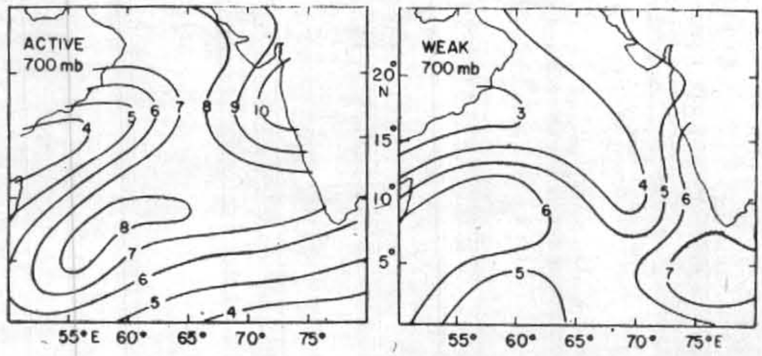

Fig. 4. Mixing ratio of water vapour (gm/kg)

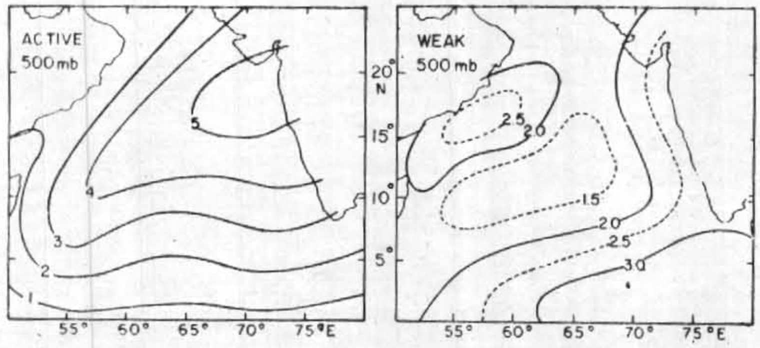

Fig. 5. Mixing ratio of water vapour (gm/kg)

continues to prevail north of 10°N and is more marked during the active monsoon. A significant feature noticed at these levels is the presence of high mixing ratio over east central and north Arabian Sea during the active monsoon and over southeast Arabian Sea during the weak monsoon. Another notable feature during the weak monsoon at these levels is the extension of a dry tongue from northwest to the central Arabian Sea, which is very marked at 700 mb.

600 and 500 mb (*Fig. 5 for 500 mb*) — At these levels, the central Arabian Sea is driest during the weak monsoon, the lowest mixing ratio being of the order of 1·5 to 2 gm/kg over this area. The highest mixing ratio is obtained near the equatorial region, particularly in the eastern parts (Maldive area). During the active monsoon, the highest mixing ratio continues to be concentrated over east central Arabian Sea. The equatorial region is dry during the active monsoon.

400 and 300 mb — At these levels also the highest mixing ratio during the active monsoon is observed over east central Arabian Sea and the lowest occurs near the equatorial region. During the weak monsoon, the highest mixing ratio persists near the equatorial region. The lowest value occurs over north and central Arabian Sea.

To highlight the difference in the moisture content over the different parts of the Arabian Sea between the two spells, the mean mixing ratios for the layers 1000 to 850, 850 to 700, 700 to 400 and for the whole layer 1000 to 400 mb were computed and their difference between the two spells (active *minus* weak) worked out. A significant difference in the mixing ratios between the two spells is observed over north and east central Arabian Sea from 850 mb upwards, the mixing ratio being 3 to 5 gm/kg higher over this area during the active spell. Over the equatorial region east of 65°E, it is in the weak monsoon spell that the mixing ratio is slightly higher in all these layers.

(b) *Relative humidity*

Figs. 6 to 9 show the vertical distribution of relative humidity along 55°, 60°, 65° and 70° E respectively for the active and weak monsoon epochs. The salient features which emerge from a study of these cross-sections are given below.

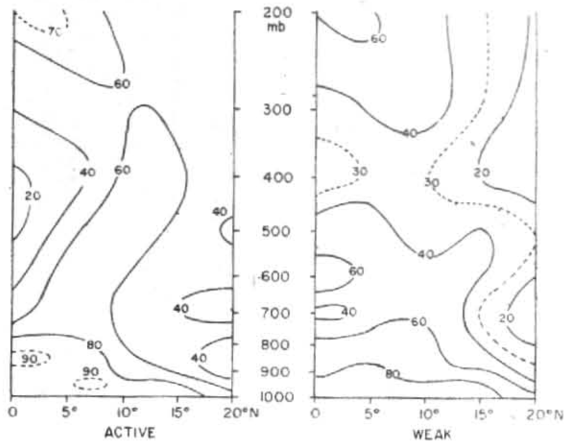

Fig. 6. Relative humidity (%) along 55°E

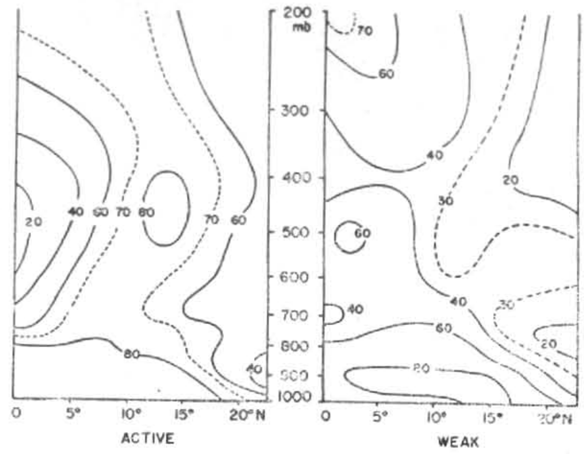

Fig. 7. Relative humidity (%) along 60°E

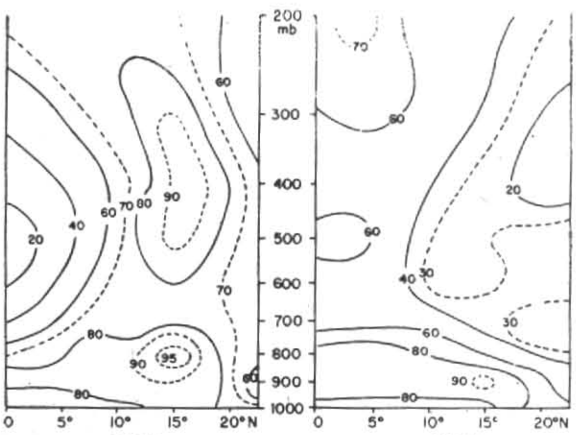

Fig. 8. Relative humidity (%) along 65°E

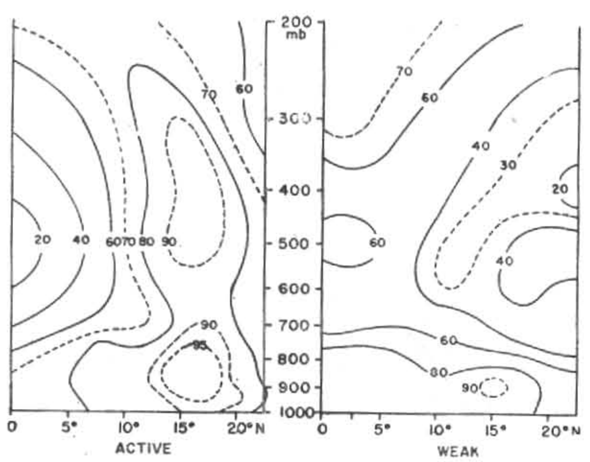

Fig. 9. Relative humidity (%) along 70°E

Meridian 55°E—In the weak monsoon, the relative humidity stratification is such that the vertical gradient of relative humidity is less to the south of 15° N and more to the north of this latitude. This suggests that the monsoon air prevails upto about 15° N in the lower troposphere and dry continental air to the north of 15°N. During the active spell, the relative humidity distribution suggests that the column between surface and 400 mb is more moist in the belt 5° to 12°N. Near the equator, the middle troposphere is drier during the active spell. Similar features are observed along 50° E also.

Meridian 60° E—During the active spell, the features along this meridian are nearly the same as at 55°E. However, it is significant to note that in the middle troposphere the relative humidity has increased to 80 per cent or more and the 60 per cent isopleth has extended further northwards to about 20°N. During the weak spell, the features are similar to those at 55°E, the belt north of 15°N continuing to remain very dry as compared to active monsoon. In the middle troposphere a dry tongue extends southwards to about 10°N.

Meridian 65°E—Along this meridian, the relative humidity has further increased in the whole troposphere during the active spell north of 10°N reaching as high a value as 80 to 90 per cent near 15°N. The middle troposphere over the equator remains dry. In the weak spell, the Arabian Sea to the north of 15°N is dry. The dry tongue persists in the middle troposphere north of 10°N.

Meridian 70°E — During the active monsoon, the entire troposphere north of 10°N continues to be highly moist—the 90 per cent relative humidity isopleth having extended to 17°-19° N. The equatorial belt is dry in this longitude also. During the weak spell the same conditions as at 65° E prevail along this meridian also. The features along 75° E (west coast of India) are similar to those along 70° E except for the fact that during weak monsoon, the relative humidity has increased to 60-70 per cent near the equatorial region and extends upto 400 mb.

Discussion of the results of moisture analysis

From the description of the moisture field presented in the foregoing paragraphs, the following points stand out :

(*i*) The boundary layer (1000 to 850 mb) is equally moist in both the spells over the Arabian Sea, except the extreme northern parts, where it is less moist during weak monsoon. The moisture generally increases from west to east.

(*ii*) In the layer 850 to 400 mb, there is a pronounced increase in moisture over the Arabian Sea north of 10° N and east of 60° E during the active monsoon as compared to weak monsoon spell. This type of moisture distribution during active and weak monsoon spells over east Arabian Sea is similar to what has been observed in respect of the land stations along the west coast of India (Rao *et al.* 1970; Srinivasan *et al.* 1972). The moisture in this layer also increases from west to east, only during the active spell.

(*iii*) In the equatorial region, the layer 700 to 400 mb is dry during the active spell whereas it is relatively moist, particularly over the southeast Arabian Sea, during the weak spell.

Thus, we find that the moisture field is stratified over the Arabian Sea to the north of 10°N during the weak monsoon. During the active monsoon, this stratification disappears to the east of 60°E and north of 10°N and water vapour is transported to very high levels. As the wind fields in the lower and middle troposphere during the active monsoon is predominantly westerly over most parts of the Arabian Sea and as the moisture decreases from east to west, the presence of high moisture in the middle levels to the east of 60°E cannot be attributed to horizontal advection. The only other mechanism which can cause increase of moisture in the middle levels is large scale upward motion over this part of the Arabian Sea during the active monsoon.

The active spell was characterised by the movement of a depression from the northwest Bay of Bengal to north Madhya Pradesh and the activation of the monsoon trough upto the middle troposphere from north Arabian Sea to north Bay of Bengal. These features in turn resulted in strong cyclonic shear between 12° and 20° N (*vide* Fig. 1a). Besides, there was also a trough of low pressure off the west coast of India during the active monsoon period contributing to cyclonic vorticity near the surface. These dynamical features provided the basic mechanism for large scale upward motion over the east Arabian Sea north of 10° N during the active spell. The effect of the upward motion during active monsoon is reflected in the dome-shaped relative humidity profile to the east of 60°E. This feature combined with the dryness of the air over the equatorial region suggests that there is maximum upward motion between 15°N and 20° N and possibly subsidence near the equator. Koteswaram (1958) has postulated a direct meridional cell during the summer monsoon with its ascending branch near the monsoon trough and the descending branch near the equator.

During the weak spell, the monsoon trough in the low levels was absent over India, while in the middle troposphere, it had become weak and diffuse. At the surface, a ridge of high pressure had developed over east Arabian Sea north of 12°N. These features are unfavourable for providing the mechanism for large scale upward motion over this part of the Arabian Sea. Consequently, moisture could not be pumped up to higher levels from the boundary layer and as such the middle troposphere remained significantly dry over this area. From a study of the temperature field over the Arabian Sea during these spells, Jambunathan and Ramamurthy (1975) have deduced the possibility of subsidence also over this region. The south Peninsula and adjoining southeast Arabian Sea were under the influence of cyclonic circulations in the lower and middle troposphere (*vide* Fig. 1a). The cyclonic vorticity associated with this feature caused large scale upward motion over this part of the Arabian Sea leading to more moisture in the middle levels over this area. This is in agreement with Koteswaram's (1950) findings that during weak or break monsoon spells, cyclonic disturbances move from east to west across the south Peninsula. The upward transport of moisture over this area is revealed by the dome-shaped structure of the relative humidity field (relative humidity being 60 to 70 per cent) near 5° N, 75°E.

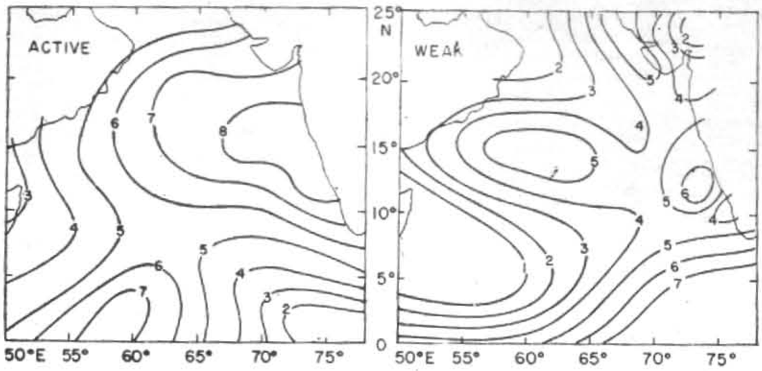

Fig. 10. Mean cloud amount (okta)

The existence of large scale upward motion and subsidence in the different parts of the Arabian Sea during the active and weak monsoon as deduced from the above discussions is supported by the cloudiness and the computed vertical motion field over the Arabian Sea.

Fig. 10 represents the composite cloudiness (low and medium) in oktas during these two spells based on reports from all ships and coastal stations. 6 to 8 oktas of clouds observed over central and east Arabian Sea north of 10° N during the active monsoon and over the southeast Arabian Sea during the weak monsoon were multi-layered, with nimbostratus, altostratus, towering cumulus and cumulonimbus. Although about 5 oktas cloudiness was observed during weak monsoon over central and adjoining east Arabian Sea, these clouds were mainly low level stratiform/cumuliform types as distinct from the dense layer of altostratus and towering *Cu*/*Cb* clouds observed over north and east central Arabian Sea during the active monsoon spell. The existence of shallow convection during weak monsoon over the central Arabian Sea lends support to our earlier suggestion of the prevalence of subsiding motion in the middle troposphere over this area based on moisture analysis. A study of the cloud distribution over the Arabian Sea during active and weak monsoon situations by Thiruvengadathan and Jambunathan (1971) has brought out such contrasting features in the cloud structure during the two types of situations.

Based on the composite wind field charts for the active and the weak monsoon spells presented by Jambunathan and Ramamurthy (1974), the vertical velocity was computed by solving the continuity equation,

$$\frac{\delta u}{\delta x} + \frac{\delta v}{\delta y} + \frac{\delta w}{\delta p} = 0$$

where u is the zonal wind component, v is the meridional wind component and w is the vertical velocity in pressure co-ordinate. For these computations, vertical motion in the lower boundary (surface) was assumed to be zero and the computations were restricted upto 500 mb. This method of computing vertical velocity has its own limitations. However, since our computations have not been carried out beyond 500 mb and the data have been derived from composited charts which would give a smooth horizontal wind field, it is expected that the vertical velocity computed for the lower and the middle troposphere would be fairly representative of the actual vertical motion field during the two spells. Fig. 11 depicts the vertical velocity at 500 mb. The sign of the computed vertical velocity over different areas is found to be in general agreement with what has been inferred from the moisture profile and the synoptic situation.

From a study of the wind, temperature, moisture and cloud distribution over the Arabian Sea during the active and weak phases of the southwest monsoon, based on ISMEX data, the weather over the Arabian Sea during the two spells appears to be controlled by the following processes.

During the weak monsoon, when major synoptic systems are absent over the Indian sub-continent and the Arabian Sea (except perhaps over south Peninsula and the adjoining equatorial region), large scale upward motion does not take place over the Arabian Sea. Consequently, the moisture field is stratified. Air stream from the southern hemisphere prevails over most parts of the Arabian Sea

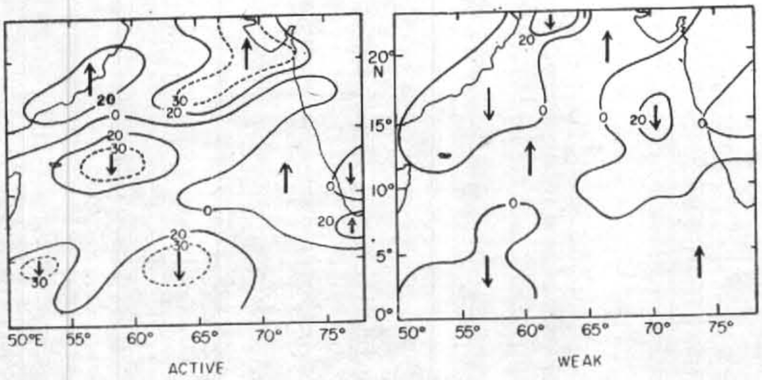

Fig. 11. Vertical velocity (mb × 10^{-4} sec^{-1})

upto about 850 mb. In this airmass, the moisture is relatively higher over the east Arabian Sea due to greater turbulent mixing. Above this level, dry continental air generally prevails over the Arabian Sea north of 10°N upto the middle troposphere. Between equator and 10°N, the prevailing airmass is of southern hemispheric origin (deflected southeast trades) upto 700 mb and higher-up of continental origin. The higher moisture in the middle troposphere over the equatorial region (south of 10°N) and relative dryness over central and north Arabian Sea is suggestive of vertical mixing in the equatorial region as against subsidence in the northern latitudes.

During the active monsoon, the dry continental air over the north and east Arabian Sea above 850 mb gets modified by large scale upward motion associated with synoptic scale disturbances, resulting in a deep nearly-saturated cool airmass up to the middle troposphere over that area. The large scale compensating downward motion takes place over the equatorial region in the middle troposphere making the airmass in the equatorial region dry.

5. Moisture flux

Water vapour flux computations in respect of the monsoon months over the Arabian Sea were first computed by Pisharoty (1965) utilising the land stations' data around the Arabian Sea box bounded by Eq., 26°N, 42° E and 75° E with vertical extent between surface and 450 mb. Sikka and Mathur (1965) computed the fluxes for an active monsoon situation during the period 7 to 10 July 1963 utilising the dropsonde data over the Arabian Sea and the radiosonde data of stations over the Indian region. Their computations were in respect of a box bounded by 4°-28° and 61°-81°E with vertical extent between surface and 500 mb. These two studies showed that there is a net flux divergence over the Arabian Sea during the monsoon, which is mainly contributed by the evaporation taking place over the Arabian Sea. Saha (1970) computed the water vapour flux across the equator between 42° E and 75° E and found that a sizeable portion (60 to 80 per cent) of the water vapour flux flowing across the west coast of India is contributed by the northward flux across the equator. Saha and Bavadekar (1973) computed the water vapour budget over the Arabian Sea for the months September 1963 and June to September 1964 for the same box as considered by Pisharoty (1965). Taking into account the precipitation and the evaporation over the Arabian Sea, they concluded that the net cross equatorial flux of water vapour is on an average about 30 per cent larger than the evaporation over the Arabian Sea. However, for their computations, Saha and Bavadekar had only one station at or near the equator, *viz.*, Gan (00° 41′ S, 73° 09′E) and had utilised the data for Seychelles (04° 36′S, 55° 30′ E) and Dar-es-Salaam (06° 53′ S, 39° 12′ E) to estimate the fluxes across those longitudes at the equator. There was, therefore, scope for improving the computation if the data were available all along the equator itself across the west Indian Ocean. The ISMEX (1973) provided this valuable information to some extent for certain selected epochs when the ships were stationary at certain points over the equator or were cruising right along the equator as shown in Fig. 1(b). The data coverage over the equator for the weak monsoon composite is very good as one of the ships was moving right along the equator and we were able to get information for almost for every degree longitude along the equator for this epoch. During the active monsoon spell, the ships were stationary at 50° and 60° E over the equator.

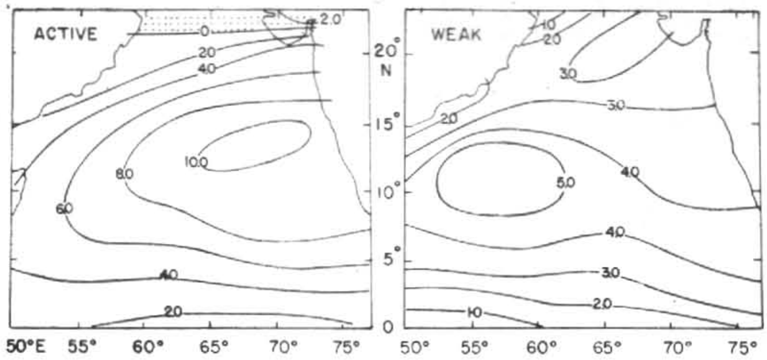

Fig. 12. Integrated zonal water vapour flux (1000 to 500 mb)
Stippled area represents flux from east/north (Unit: kg/cm/sec)

Utilising the wind and mixing ratio values at every $2\frac{1}{2}$-degree grid point from the composite charts for the active and the weak monsoon spells, the net integrated water vapour flux from surface to 500 mb was computed over different five-degree squares as well as a few rectangular boxes (along the northern boundary) of the Arabian Sea so as to study the field of horizontal water vapour flux divergence. Besides, we have also computed the fluxes across the various lateral walls surrounding the Arabian Sea, with a view to estimate the contribution from the various sides. Our computations across the equatorial boundary were restricted to the area to the east of 50° E as the ships did not cruise west of 50° E. We are aware of the fact that the equatorial belt west of 50° E contributes significantly to the cross-equatorial flux in the lower troposphere and this aspect will be dealt with in a subsequent paragraph.

The net water vapour flux for each of the boxes referred to above was assigned to the centre of each box. Assuming the flux to be negligible above 500-mb level, the integrated horizontal flux of water vapour (F) per unit length normal to any boundary can be expressed by

$$F = -\frac{1}{g}\int_{1000}^{500} q\, V_n\, dp$$

where q is the mixing ratio of water vapour (in gm per kg) and V_n the component of wind normal to the boundary. The integral was evaluated by following the trapezoidal rule for the levels 1000 950, 850, 800, 700, 600 and 500 mb for each side of the representative boxes. The net flux from the box was evaluated as the sum of the above integral from all the four sides of the box.

Figs. 12 and 13 give the distribution of integrated zonal and meridional fluxes at different grid points during the active and weak monsoon spells and Fig. 14 the information in respect of vertically integrated net horizontal water vapour flux into different boxes. The following are the noteworthy features brought out by these diagrams.

(a) *Zonal and meridional fluxes*

(*i*) The zonal flux is generally very much higher compared to the meridional flux during both the spells, being particularly so during active monsoon.

(*ii*) The maximum in the zonal flux during active spell is nearly twice that during the weak spell. While the zonal flux maximum during the weak spell lies over west central Arabian Sea (the region of the low level wind maximum), it has shifted to the east central Arabian Sea during the active spell. This shift has resulted due to a combination of two factors, *viz.*, a significant increase in the moisture over the east central Arabian Sea in the layer 850 to 500 mb and the prevalance of strong winds of the order of 30 to 40 kt in the same layer over that area during the active spell.

(*iii*) During the active monsoon, the meridional flux is from south upto 17·5° N and is generally from the north over the extreme north Arabian Sea. During the weak monsoon, the field of meridional flux shows a cellular structure to the south of 15° N, the west Arabian Sea being dominated by southerly flux and east Arabian Sea by northerly flux. North of 15° N, the flux is from the south. The southerly flux maximum in the southwest Arabian Sea is about 30 per cent more during the active spell than during the weak spell.

(*iv*) During the active monsoon, the zonal and meridional fluxes show reversal of sign over north Arabian Sea which is due to the mean location of the monsoon trough in that spell.

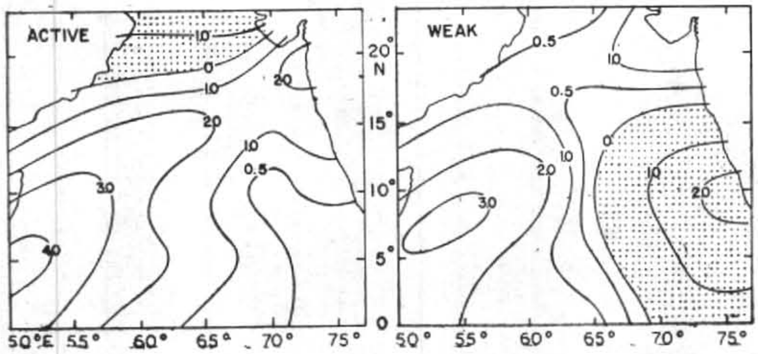

Fig. 13. Integrated meridional watar vapour flux (1000 to 500 mb)
Stippled area represents flux from east/north
(Unit : kg/cm/sec)

(b) *Net flux over different boxes*

It is seen that during the active monsoon spell, flux convergence takes place over the Arabian Sea north of 15° N and off the west coast of India. The rest of the Arabian Sea shows flux divergence with the maximum between 10° and 15° N and 55° and 65° E, the area which is also the seat of low level wind maximum. During the weak spell, flux divergence occurs over southwest Arabian Sea and over east central and adjoining north Arabian Sea. In between these areas of flux divergence, flux convergence takes place over an area extending from Arabian coast to southeast Arabian Sea. High values of flux convergence over west central Arabian Sea during the weak spell can be accounted for mainly by the speed convergence in the wind field.

The net flux over the whole Arabian Sea computed from the flux in the individual boxes works out to be a net *flux divergence* of $3 \cdot 42 \times 10^{10}$ metric tonnes per day during active monsoon and a net *flux convergence* of $0 \cdot 19 \times 10^{10}$ metric tonnes per day during weak monsoon. Table 1 shows the net vertically integrated flux across the southern, western, northern and eastern boundaries of the entire Arabian Sea box shown in Fig. 14 during the active and weak monsoon.

As seen from Table 1, the most significant contrast between the two spells is in the flux across the eastern boundary, where the outflow during active monsoon has increased by 6·5 units compared to that during weak monsoon. The increase in northward flux across the equator during the active spell is only about 0·9 units. The contribution from the western boundary is nearly the same during both the spells. If we consider the net flux into the Indian sub-continent across the eastern and the northern boundaries in relation to the flux across the equator, it is seen that only about 30 per cent (29 per cent during active monsoon and 33 per cent during weak monsoon) of the flux into the Indian sub-continent comes from across the equatorial boundary of the box.

TABLE 1

Water vapour flux in units of 10^{10} metric tonnes/day

Boundary	Active monsoon	Weak monsoon
Southern	3·58 (inflow)	2·73 (inflow)
Western	5·42 (inflow)	5·69 (inflow)
Northern	1·00 (inflow)	1·31 (outflow)
Eastern	13·42 (outflow)	6·92 (outflow)
Net flux	3·42 (outflow)	0·19 (inflow)

Table 1 also shows that during the active monsoon, the water vapour obtained by evaporation in the Arabian Sea is transported towards the Indian sub-continent across the eastern boundary, a part of it having been utilised in precipitation over the Arabian Sea. On the other hand, during the weak monsoon spell, the outflow across the northern and eastern boundaries is nearly balanced by the inflow from the south and west. From this, we infer that all the evaporation in the Arabian Sea is utilised locally in the weather development in the Arabian Sea itself during weak monsoon. Since net flux divergence over Arabian Sea is large during active spell and a small net flux convergence occurs during the weak spell, it shows that the evaporation over the Arabian Sea is expected to be much larger in the active spell compared to the weak spell.

6. Comparison of flux computations with earlier studies

As already stated, due to lack of data, flux computations across the equator were restricted upto

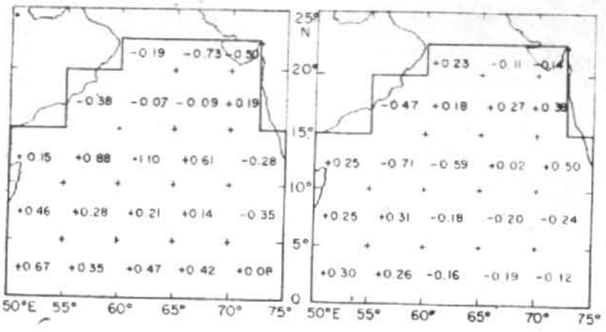

Fig. 14(a). Active Fig. 14(b). Weak

Fig. 14. Net integrated horizontal water vapour flux (1000 to 500 mb) in different boxes over the Arabian Sea. (Unit : 10^4 million metric tonnes per day)

TABLE 2

Flux estimates ($\times$ 10^{10} metric tonnes per day) by different studies

Boundary	Present study Active	Present study Weak	Pisharoty July 1964	Saha and Bavadekar July 1964
Eastern (outflow)	13·4	6·9	5·8	5·9
Southern (inflow)	7·2	5·5	2·2	4·4
Ratio of flux [Southern to Eastern boundary (in percentage)]	55	80	38	75

50° E on the western side in the present study. To compare our results with those of Pisharoty (1965) and Saha and Bavadekar (1973) whose computations extended upto 42° E, we have estimated the flux across the equator in the belt between 50°and 42°E in the following way. The northward flux across the equator between 55° and 50°E was $1{\cdot}5\times10^{10}$ metric tonnes per day during active monsoon and $1{\cdot}1\times10^{10}$ metric tonnes per day during weak monsoon. Assuming that the moisture in the belt 50° to 42° E is nearly the same as but the wind speed in this belt is on an average 3/2 times that in the belt 55°-50° E in the layer 1000 to 500 mb, the northward flux across the equator in the belt 50°-42° E works out to be $3{\cdot}6\times 10^{10}$ metric tonnes per day during the active monsoon and $2{\cdot}8\times10^{10}$ metric tonnes per day during the weak monsoon. Thus the total northward flux across the equator between 42° and 75° E is about $7{\cdot}2\times10^{10}$ metric tonnes per day during the active spell and $5{\cdot}5\times10^{10}$ metric tonnes per day during the weak spell.

Table 2 shows the comparative flux estimates of different workers along the eastern and the southern boundaries.

The above figures show that the flux across the equator during the weak monsoon is less by 1.7 units as compared to the active spell. However, we find that its contribution during the weak spell to the flux across the eastern boundary has increased to 80 per cent from 55 per cent during the active spell. This apparent percentage increase in the cross-equatorial contribution during *weak monsoon* is due to the fact that the flux across the eastern boundary has significantly *decreased* (by about 50 per cent) during this spell as compared to the active monsoon.

7. Conclusions

(*a*) The distribution of moisture over the Arabian Sea during the active and weak monsoon spells as obtained from the above study suggests that—

(*i*) The moisture field is stratified over the Arabian Sea to the north of 10° N during the weak monsoon;

(*ii*) This stratification disappears during the active monsoon to the north of 10° N and east of 60° E and water vapour is transported to very high levels over this area by upward motion associated with synoptic disturbances;

(*iii*) There is evidence of possible subsidence in the middle troposphere over the equatorial region during active monsoon;

(*iv*) During the weak monsoon, there is large scale upward motion over the equatorial region east of 70° E and subsidence over the central and northern parts of Arabian Sea.

(*b*) The computation of net integrated horizontal water vapour flux over the Arabian Sea shows that :

(*i*) There is a net outflow of $3 \cdot 42 \times 10^4$ million metric tonnes per day from the Arabian Sea across the west coast of India during active monsoon. This net outflow is contributed by evaporation from the Arabian Sea, which has necessarily to be in excess of the precipitation by this amount.

(*ii*) During weak monsoon, there is a small net inflow of $0 \cdot 19 \times 10^4$ million metric tonnes per day into the Arabian Sea. This would mean that the evaporation and condensation processes over the Arabian Sea are nearly balanced during weak monsoon. As the area of precipitation over the Arabian Sea is very small during weak monsoon, the evaporation is also bound to be very much less in this spell than in active monsoon.

(*c*) Vapour flux convergence :

(*i*) Flux convergence takes place over north Arabian Sea north of 15° N and east Arabian Sea off the west coast of India during active monsoon. The rest of Arabian Sea shows flux divergence with the maximum over west central Arabian Sea. During weak monsoon, flux convergence extends from Arabia coast to southeast Arabian Sea while flux divergence takes place over the north, east central and southwest Arabian Sea.

(*ii*) Over the region of water vapour flux convergence, it is expected that the mean vertical motion field would transport the moisture upward from the moisture-rich boundary layer. However the lack of vertical growth of the clouds (shallow convection) over the central Arabian Sea over the region of net water vapour flux convergence during weak monsoon conditions indicates that the subsiding motion prevails in the mid-troposphere leading to suppressed convection over that region. On the other hand, during active monsoon conditions, the predominance of active convection off the west coast of India and over the northeast Arabian Sea suggests that besides the mean vertical upward motion, the convective transport processes would be very important in tapping the moisture from the boundary layer during this spell. Thus to work out the complete moisture budget, it is perhaps necessary to estimate the role played by the convective transports over the region of deep convergence.

We would like to submit that quite a few results of this study confirm those arrived at by several workers based on the IIOE data. However, we have been able to come to the conclusions given above with greater confidence as a result of more data coverage over the Arabian Sea during the ISMEX 1973.

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