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Influence of the Arabian Sea on the Indian summer monsoon

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ABSTRACT

Based on aerological observations over the Arabian Sea and adjoining north Indian Ocean, taken on board USSR research vessels during MONEX-1973, patterns of vergence of air and water vapour fluxes are studied. The influence of the Arabian Sea on the fluctuations in intensity of the summer monsoon over the west coast of India is shown. It is inferred that evaporation exceeds precipitation over the east Arabian Sea near the west coast of India even during active monsoon.

A zonal cell with the ascending limb over the east Arabian Sea and the descending branch over the west Arabian Sea is proposed.

1. Introduction

It is believed that the Indian summer monsoon owes its origin to the southern hemispheric trade winds which get deflected at the equator and approach the west coast of India from a southwesterly direction (Rao and Desai, 1973). Various workers (Rao, 1964; Findlater, 1969; Saha, 1970) have estimated that a large mass of air crosses the equator particularly over the extreme western region of the north Indian Ocean and adjoining Somalia (between 38° and 45° E) during the monsoon. Estimates of cross-equatorial transport of water vapour have also been made for the same season (Pisharoty, 1965; Sikka and Mathur, 1965; Saha, 1970; Saha and Bavadekar, 1973). While it is certain that there is movement of large masses of air and water vapour across the equator from the southern hemisphere during the monsoon, from the surface to about 600 mb, it is less certain that the Indian monsoon can be directly attributed to these phenomena. Estimation of water vapour transport across the equator west of longitude 75° E and across longitude 75° E over India between the surface and the 450 mb level, the former being less than half of the latter, led Pisharoty (1965) to conclude that the Arabian Sea monsoon current was essentially of northern hemisphere origin. He suggested that the net flux divergence of moisture which occurs along longitude 75° E is mainly contributed by the evaporation taking place over the east Arabian Sea. Saha (1970) made a similar computation for both air and moisture and concluded that a sizeable portion (60–70%) that enters into the summer monsoon circulation over India is derived from the southern hemisphere. From a study of water vapour budget over the Arabian Sea for monsoon months, Saha and Bavadekar (1973) have shown that the net cross-equatorial flux of water vapour is, on an average, about 30% larger than the evaporation over the Arabian Sea. The above studies, however, are based on sparse upper air observations near the equator, viz., Gan (00°41′ S 73°09′ E) and Nairobi (01° 18′ S 36°45′ E). Saha also utilized the data of Seychelles (04°36′ S 55°36′ E) and Dar-es-Salam (06°53′ S 39° 12′ E) to estimate the fluxes across the equator along these longitudes. Data of these stations, however, may not be representative of the conditions prevailing at the equator. Moreover, the southern hemispheric equatorial trough results in large modification of the air mass in the near-equatorial southern hemispheric lower troposphere (Ghosh and Pant, 1974).

In the present study an attempt is made to compute the fluxes of air and water vapour by utilizing data collected during the INDO–USSR Monsoon Experiment, MONEX-1973. We have also computed the total precipitable water by using the same data. From the computation, fields of horizontal vergence of the vertically integrated air and water vapour fluxes have been constructed and discussed, and the influence of the Arabian Sea on the monsoon circulation over India has been brought out.

2. Data and analysis

The joint INDO–USSR monsoon experiment, which was carried out during the period May to July 1973, provided a large number of closely spaced aerological observations taken on board USSR research vessels over the Arabian Sea and the adjoining north Indian Ocean. Four ships, *Priliv*, *Shokalskiy*, *Voeikov* and *Okean*, made extensive cruises along the equator at latitudes 8.5°, 11.5° and 16° N and made 6-hourly upper air soundings in which wind, temperature and dew point temperature observations were taken. Besides these cruises, the ships also remained stationary for about a week at certain selected locations on the equator, at latitudes 10° N and 18° N, during the different phases of the monsoon. These data, which are available for the first time over the region, have been utilized in the present study. In addition, the aerological data of Gan, Minicoy, Goa and Bombay for the appropriate periods have also been used. It may be mentioned that comparisons of Indian and USSR radiosonde/rawinsonde observations were made on 8 June 1973 and no significant differences noticed.

Computations of fluxes of air and water vapour and of total precipitable water have been made in respect of the two distinct monsoon epochs, active or strong monsoon and weak monsoon conditions prevailing over the west coast of India. The following periods of weak and active monsoon spells for which data are available have been selected:

(a) Weak monsoon—18 to 26 June 1973
(b) Active monsoon—(i) 6 to 15 June 1973
(ii) 1 to 8 July 1973

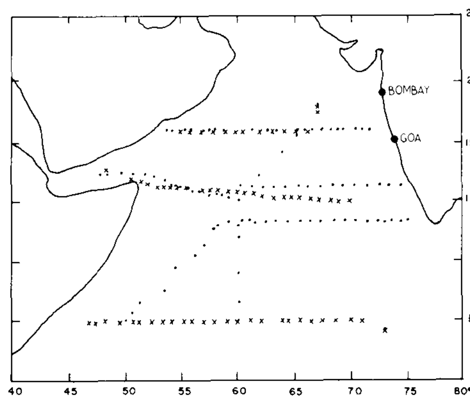

Fig. 1. Locations of aerological soundings on board USSR research vessels during MONEX-1973. Points represent active monsoon, crosses weak monsoon.

The data coverage from the two periods is shown in Fig. 1. Composite charts from all the data available covering the periods of active and weak monsoon spells have been prepared.

3. Computations

Computations of air and water vapour transports and precipitable water have been made by using the following well-known formulae:

$$\text{Air transport} = \frac{1}{g} \int_p \int_s V(p, s)\, dp\, ds$$

$$\text{Water vapour transport} = \frac{1}{g} \int_p \int_s V(p, s)\, q(p, s)\, dp\, ds$$

$$\text{Precipitable water} = \frac{1}{g} \int_p q(p, s)\, dp$$

where the symbols have the usual meanings. Integrations have been carried out in the vertical after computation for each 100 mb layer from the 1000 mb to 400 mb level. In the horizontal, computations have been done for each degree of latitude/longitude.

3.1. *Zonal transport*

The vertical distribution of the zonal transport of air and water vapour for the active and weak monsoon spells was computed across each meri-

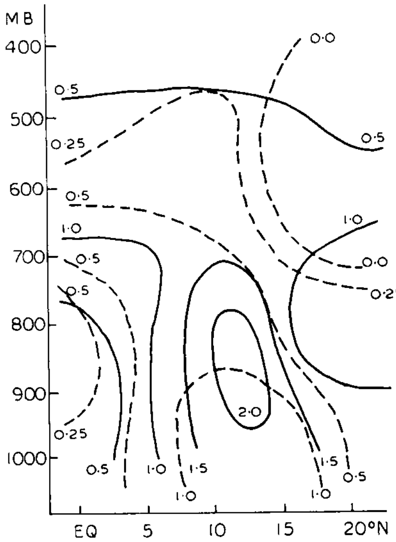

Fig. 2. Vertical distribution of zonal air transport across the 65° E meridian during active (full lines) and weak (dashed lines) monsoon. Units 10^{11} metric tons per day per degree latitude.

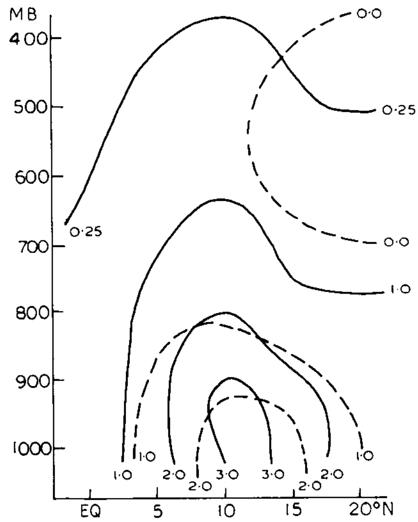

Fig. 3. Vertical distribution of zonal water vapour transport across the 65° E meridian during active (full lines) and weak (dashed lines) monsoon. Units 10^9 metric tons per day per degree latitude.

dian, five degrees apart, between 50° E and 75° E. For want of space, the distribution across only one meridian is presented. Significant features of the zonal transport across other meridians have, however, been discussed in the text.

3.1.1. *Zonal transport of air.* The vertical distribution of the zonal transport of air for the active and weak monsoon spells across the 65° E meridian is shown in Fig. 2.

During weak monsoon the zonal air transport is positive (eastward) in the entire layer 1000 to 400 mb over the region south of about 12° N and becomes negative (westward) in the middle troposphere towards the north. Maximum positive transport, however, occurs in the lowest 100 mb layer over the west central Arabian Sea. There is an increase in the negative zonal transport in the middle troposphere north of about 15° N.

During the active monsoon the zonal transport of air is positive over the entire region considered and shows a significant increase from the weak monsoon. Over the extreme southwestern region of the Arabian Sea the zonal transport, however, does not show any significant increase in the lower troposphere but increases markedly in the middle troposphere. The lower tropospheric maximum occurs in a deeper layer in this spell and shows a significant increase in depth off the west coast of India.

3.1.2. *Zonal transport of water vapour.* The vertical distribution of the zonal transport of water vapour for the active and weak monsoon spells across the 65° E meridian is shown in Fig. 3.

The zonal water vapour transport shows nearly similar features of distribution in the layer 1000 to 400 mb as are seen in the case of zonal air transport. During weak monsoon large positive water vapour transport occurs mainly in the lowest 100 mb layer of the atmosphere with two maxima, one occurring over the west central and adjoining southwest Arabian Sea and the other over the southeast Arabian Sea off the Kerala-Karnataka coast. During active monsoon there is a significant increase in the water vapour transport in the entire layer. Maximum transport is observed to occur over the east Arabian Sea and shows a considerable increase in depth off the west coast of India.

3.2. *Meridional transport*

The vertical distribution of the meridional transport of air and water vapour for the active and weak monsoon spells was computed across each latitude, five degrees apart, between the equator and 20° N. The distribution across only the equator is presented. As in the case of zonal transport, significant features across the other latitudes have been included in the following paragraphs.

3.2.1. *Meridional transport of air.* The vertical distribution of the meridional transport of air for the active and weak monsoon across the equator is shown in Fig. 4.

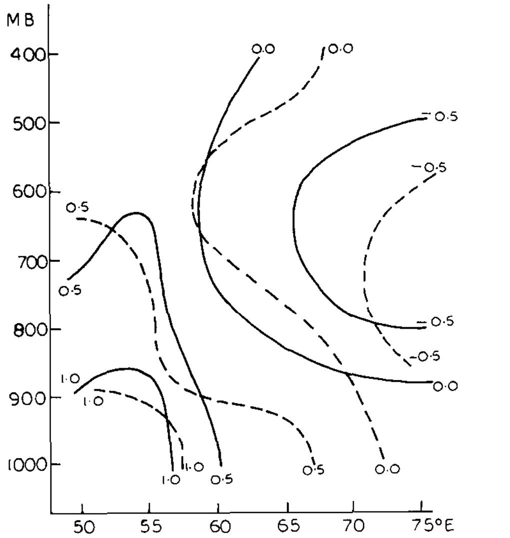

Fig. 4. Vertical distribution of meridional air transport across the equator during active (full lines) and weak (dashed lines) monsoon. Units 10^{11} metric tons per day per degree latitude.

The meridional transport of air is positive (northward) across the equator west of about the 60° E meridian in the entire layer 1000 to 400 mb and becomes negative in the middle troposphere towards the east during both monsoon epochs. Across latitudes 10° and 15° N positive transport is mainly confined to only below the 800 mb level during weak monsoon except over the extreme southeast Arabian Sea (east of 70° E) where it is negative (southward) in the entire layer. During active monsoon the meridional air transport is positive in the entire layer across latitude 10° N over the region east of about longitude 60° E. Across latitude 15° N the transport is, however, positive throughout the layer except off the Goa–Karnataka coast where it is negative in the mid-tropospheric levels.

Maximum positive air transport occurs in the lowest 100 mb layer over the extreme southwestern region during weak monsoon. It occurs in a deeper layer (below about 850 mb) and extends northeastwards over the Arabian Sea during active monsoon.

3.2.2. *Meridional transport of water vapour.* The vertical distribution of the meridional transport of water vapour for the active and weak monsoon across the equator is shown in Fig. 5.

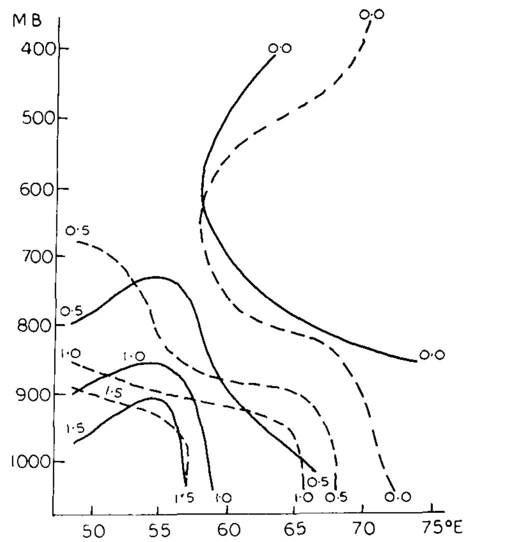

Fig. 5. Vertical distribution of meridional water vapour transport across the equator during active (full lines) and weak (dashed lines) monsoon. Units 10^9 metric tons per day per degree latitude.

The meridional transport of water vapour shows nearly similar features of distribution as in the air transport during both the monsoon spells. During weak monsoon maximum positive transport occurs mainly below the 900 mb level over the region west of about longitude 60° E. During active monsoon the meridional transport in this layer, however, does not show any significant increase over the extreme southwestern region, but increases significantly over the central and adjoining east Arabian Sea.

3.3. *Vertically integrated net transport in the layer 1000 to 400 mb*

Net zonal transports of air and moisture are shown in Figs. 6 and 7 respectively. Both zonal transports of air and moisture are positive over the

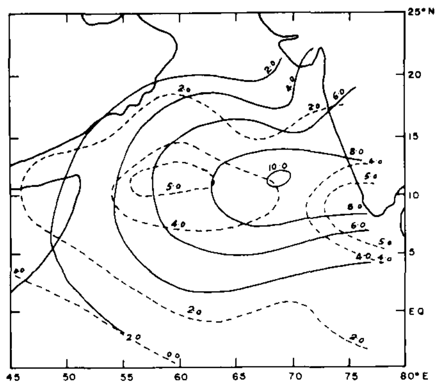

Fig. 6. Vertically integrated net zonal air transport during active (full lines) and weak (dashed lines) monsoon. Units 10^{11} metric tons per day per degree latitude.

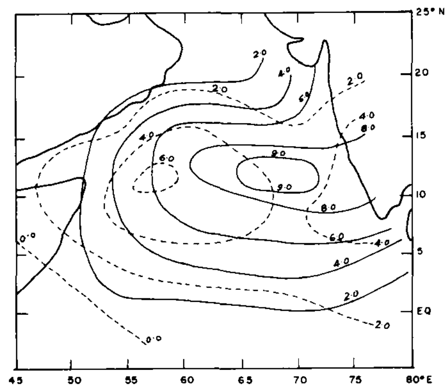

Fig. 8. Vertically integrated net meridional air transport during active (full lines) and weak (dashed lines) monsoon. Units 10^{11} metric tons per day per degree latitude.

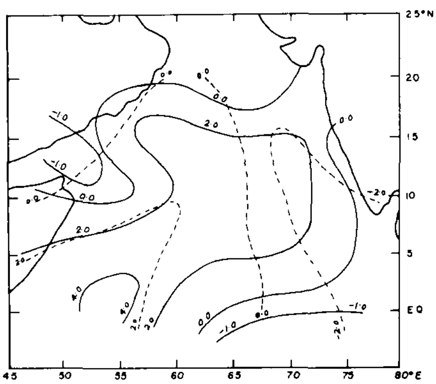

Fig. 7. Vertically integrated net zonal water vapour transport during active (full lines) and weak (dashed lines) monsoon. Units 10^9 metric tons per day per degree latitude.

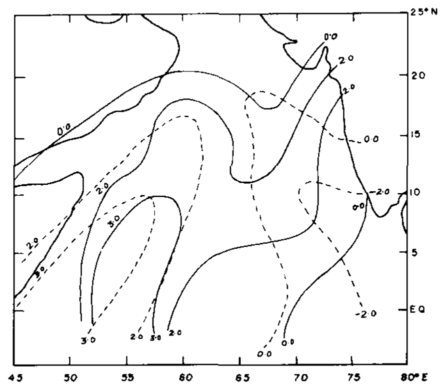

Fig. 9. Vertically integrated net meridional water vapour transport during active (full lines) and weak (dashed lines) monsoon. Units 10^9 metric tons per day per degree latitude.

entire region considered during the active monsoon. Maximum zonal transports occur over the east central Arabian Sea between longitude 65° and 70° E in this period. During weak monsoon the zonal transports are negative over the extreme southwestern region near the equator and positive elsewhere. There appear two regions of large positive transports—one over the west central and adjoining southwest Arabian Sea and the other over the southeast Arabian Sea off the Kerala coast.

Net meridional transports of air and moisture are given in Figs. 8 and 9 respectively. Positive meridional transports of air and moisture occur over a large portion of the Arabian Sea during the active spell. While the air transport is negative over the extreme western, northeastern and southeastern regions, the water vapour transport remains positive over the extreme western region and is negative over the northeastern and extreme southeastern regions of the Arabian Sea. Large positive transport occurs over the southwestern region and extends as a tongue towards the northeast in this spell.

During the weak monsoon positive transports of both air and water vapour occur mainly in the west and northeast Arabian Sea off the Goa–Konkan coast and negative transports elsewhere. Large positive transport, however, occurs over the southwestern region of the Arabian Sea but are directed towards north in this period. Over the southeast Arabian Sea large negative transports occur.

3.4. *Total precipitable water*

Distributions of total precipitable water for the active and weak monsoon spells are shown in Fig. 10.

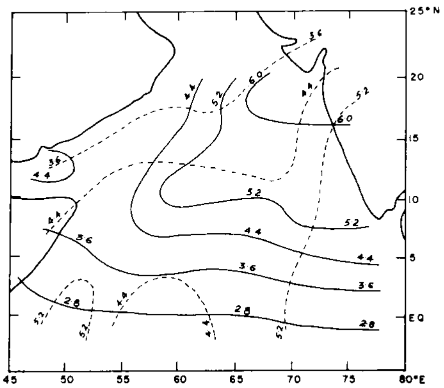

Fig. 10. Total precipitable water, in cm, during active (full lines) and weak (dashed lines) monsoon.

It may be seen that the equatorial region has the lowest precipitable water during active monsoon. A progressive increase in the total precipitable water is observed towards the northeast and very high values occur over the east Arabian Sea particularly north of latitude 10° N. During weak monsoon, the equator appears to be more moist as compared to the active monsoon. Towards the north, the total precipitable water shows a decrease. Large values, however, occur over the southeast Arabian Sea in this period.

4. Interpretation of results

From the above discussion one may immediately infer that the Arabian Sea plays a dominant role in the modification of the monsoon circulation.

4.1. *Influence of the Arabian Sea*

However, to bring out this feature more clearly, the water vapour fluxes across a rectangular box with the following boundaries have been considered:

Southern boundary—the equator
Western boundary—50° E meridian
Northern boundary—latitude 20° N
Eastern boundary—75° E meridian

The top and bottom boundaries of the box are at 400 mb and 1000 mb respectively. Table 1 gives the fluxes for active and weak monsoon conditions.

Table 1. *Water vapour flux* (10^{10} *metric tons per day*)

Boundary	Monsoon condition	
	Weak	Active
Western	2.45	2.53
Southern	3.23	2.93
Eastern	7.12	12.50
Northern	1.19	0.30

It is seen from the table that the water vapour transport during active monsoon across 75° E is more than four times that across the equator and more than double the total inflow into the box from the southern and the western boundaries. Thus water vapour transport across the west coast of India is very large as compared to that across the equator from the southern hemisphere. Secondly, even if the flux across the western boundary is regarded as solely due to the deflected southern hemispheric trades, the total moisture transported by these trades from the southern hemisphere accounts for only less than half the moisture zonally transported across the west coast of India. The additional moisture can only be attributed to the evaporation from the Arabian Sea.

Furthermore, comparison of the fluxes during active and weak monsoon conditions reveals no significant change in the fluxes across the southern and western boundaries, but the flux across the eastern boundary (i.e. 75° E) decreases considerably during weak monsoon and is only about 60% of that during active monsoon. Thus the large variations of water vapour flux across the west coast of India are apparently independent of that across the equator and the extreme west Arabian Sea. This fact inevitably leads to the conclusion that very important changes in the monsoon circulation take place over the Arabian Sea.

4.2. *Monsoon circulation over the Arabian Sea*

How these changes occur and result in wide fluctuations of monsoon rainfall over the west coast of India during active and weak monsoon has been closely investigated by examining the patterns of vergence of air and water vapour fluxes for small areas over the Arabian Sea. As the portion of the west coast of India which receives large amounts of rainfall during monsoon extends from 8° N to 20° N, vergence patterns of air and water vapour fluxes have been examined for the region between 5° N and 20° N. For a detailed examination, values in five rectangles, each 5° apart (in longitude), between 50° E and 75° E, have been studied (Figs. 11 and 12).

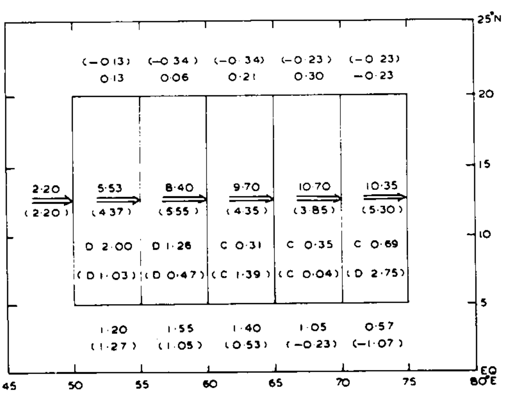

Fig. 11. Airflux into rectangles during active and weak (in parentheses) monsoon. (D—divergence, C—convergence). Meridional inflow is positive and outflow negative. Zonal flow is shown by arrows. Units 10^{12} metric tons per day.

4.2.1. *Air flux.*

During weak monsoon, there is divergence of air flux between 50° E and 60° E, convergence between 60° E and 65° E, convergence (though of small magnitude) between 65° E and 70° E, and divergence between 70° E and 75° E (Fig. 11). Moreover, divergence progressively decreases in magnitude eastward between 50° E and 60° E and becomes negative east of 60° E. Convergence is of maximum magnitude between 60° E and 65° E, decreases considerably between 65° E and 70° E and sharply changes to divergence of very large magnitude between 70° E and 75° E.

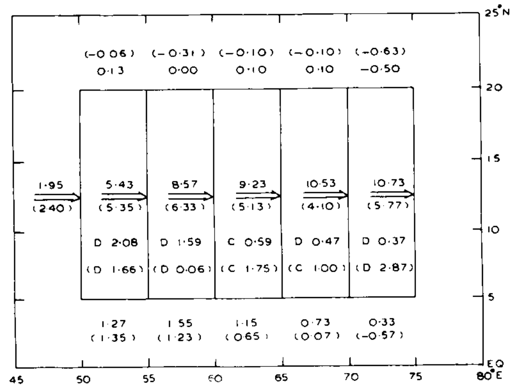

Fig. 12. Water vapour flux in rectangles during active and weak (in parentheses) monsoon (D—divergence, C—convergence). Meridional inflow is positive and outflow negative. Zonal flow is shown by arrows. Units 10^{10} metric tons per day.

During active monsoon, the pattern to the west of 60° E is similar to that during weak monsoon (Fig. 11). To the east of 60° E, however, there is convergence progressively increasing in magnitude eastward.

Thus the most significant change between the weak and strong monsoon appears to occur between 70° E and 75° E. While there is very large divergence during weak monsoon, there is large convergence during active monsoon.

From the above distribution of vergence it is also clear that the 60° E meridian divides the monsoon circulation into two distinct regimes. The west Arabian Sea to the west of 60° E is characterized by air flux divergence both during active and weak monsoon (Regime 1), whereas east of 60° E is generally characterized by convergence except between 70° E and 75° E during weak monsoon when there is divergence (Regime 2). The continuous air flux convergence to the east of 60° E during active monsoon and the large divergence to the east of 70° E during weak monsoon explains the observed intensity of monsoon in terms of rainfall over the west coast of India. The marked convergence between 60° E and 65° E during weak monsoon leads to the development of clouds, which has been verified from satellite pictures (not presented).

The distribution of divergence also suggests the existence of zonal cell, as postulated by Flohn (1964), Ramage (1966) and Bjerknes (1969), with the ascending limb over the east Arabian Sea and west coast of India and the descending branch over the west Arabian Sea during active monsoon. During weak monsoon, however, the ascending limb of the cell appears to get displaced slightly westward, west of 70° E. Das (1962) also found another zonal cell during the monsoon with the ascending limb over northeast India and a zone of marked subsidence over northwest India.

4.2.2. *Water vapour flux.* From the computations of water vapour flux, it is seen (Fig. 12) that divergence occurs to the west of 60° E both during weak and active monsoon although magnitudes of divergence are higher during active than during weak monsoon. To the east of 60° E, however, there are significant differences during weak and active monsoons. During weak monsoon, marked convergence occurs between 60° E and 70° E but divergence between 70° E and 75° E. During active monsoon, however, convergence occurs only between 60° E and 65° E but divergence between 65° E and 75° E. Divergence east of 70° E both during weak and active monsoon indicates that the evaporation is more than precipitation since Evaporation minus Precipitation $\approx$ Divergence of horizontal water vapour flux as shown by Palmen (1967). It is interesting to note that even during active monsoon, when heavy rains occur evaporation exceeds precipitation. From the computations based on the data for the years 1963 and 1964, collected during the International Indian Ocean Expedition, the rate of evaporation in the month of July over the Arabian Sea east of 70° E amounted to about 250 langley per day (Ramage et al., 1972). This is equivalent to a monthly rainfall of 13 cm per unit area which may perhaps appear to be very light for an active monsoon period. But for the vast area under consideration in the present study (the rectangle between latitude 5° N and 20° N and longitude 70° E and 75° E), the amount is not inconsiderable in view of the fact that heavy rainfall occurring on the west coast of India is confined to a narrow strip on the windward side of the Western Ghats and rainfall decreases sharply with increasing distance from the crest of the Western Ghats (Raghavan, 1964). It is to be noted, however, that the evaporation rate of 250 ly per day is the average monthly rate and as such is the mean of the rates during active and weak monsoon spells. No exclusive estimates of the rate of evaporation for an active monsoon period are available.

Again, from above it appears that the 60° E meridian divides the monsoon regime into two parts. The marked difference in moisture conditions prevalent to the east and west of 60° E has also been shown by Rao and Desai (1971).

4.2.3. *Low level temperature inversion.* The importance of the 60° E meridian dividing the monsoon into two regimes is corroborated further by the observational fact that the low level temperature inversion, which occurs in the west Arabian Sea and is very strong there, considerably weakens and lifts up east of 60° E and is not observed east of 70° E especially during active monsoon (Fig. 13).

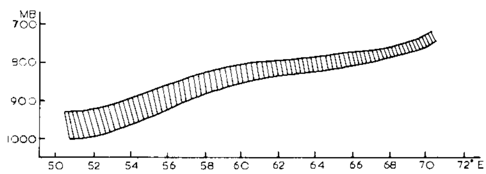

Fig. 13. Profile of low level temperature inversion during active monsoon along 11° N.

5. Conclusions

From the above, it is concluded that:

(a) the Arabian Sea plays a dominant role in the monsoon activity over the west coast of India
(b) a zonal cell with the ascending limb over the east Arabian Sea exists during the Indian summer monsoon
(c) the 60° E merdian divides the monsoon into two regimes
(d) evaporation near the west coast (east of 70° E) is more than precipitation.

6. Acknowledgements

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ВЛИЯНИЕ АРАВИЙСКОГО МОРЯ НА ИНДИЙСКИЙ ЛЕТНИЙ МУССОН

На основе данных аэрологических наблюдений в Аравийском море и прилегающей северной части Индийского океана, полученных советскими исследовательскими судами в период МОНЭКС—1973 изучаются распределения потоков воздуха и водяного пара. Показано влияние Аравийского моря на флуктуации интенсивности летнего муссона над западным побережьем Индии. Показано, что испарение превышает осадки над восточной частью Аравийского моря вблизи западного побережья Индии даже в течение активной фазы муссона. Предложена сезонная ячейка с восходящей ветвью циркуляции над восточной частью Аравийского моря и нисходящей ветвью над западной частью.