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Flux of air and moisture in Bay of Bengal in summer monsoon*

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सार — मॉनेक्स 1979 की अवधि के दौरान जब सोवियत रूस के जहाज बंगाल की खाड़ी में थे, तब उस अवधि के लिए वहां की वायु एवं नमी के अभिवाह की गणना की गई है। ज्ञात हुआ है भूमध्य रेखा के आसपास वायु एवं नमी का उत्तर की ओर बहाव 85° पू० के पश्चिम क्षेत्र तक ही सीमित है। पर 85° पू० के पूर्व की ओर विपरीत बहाव देखा गया। जब जलपोत वहां मौजूद थे, उस अवधि के दौरान जुलाई के लिए बंगाल की खाड़ी के केन्द्र में वायु एवं नमी के अभिवाह के मानों की गणना की गई। मानसून के प्रबल और दुर्बल चरणों में अभिवाह के मानों की तुलना से यह स्पष्ट हो जाता है कि जब उत्तरी अभिवाह में कोई खास परिवर्तन नहीं होता, तब पूर्व की ओर के अभिवाह में महत्वपूर्ण परिवर्तन होते रहते हैं। यह अभिवाह पूर्वी तट और खाड़ी के केन्द्र में दुर्बल चरण की अपेक्षा प्रबल चरण की स्थिति होने पर दुगने से अधिक हो जाता है।

ABSTRACT. The flux of air and moisture in the Bay of Bengal during Monex 1979 period, when the Soviet ships were moving in that area, have been computed. It is found that the northward transport of air and moisture across the equator is confined only to the area west of 85 deg. E. Eastwards of 85 deg. E, the reversal of transport is found to occur. The computations of the air and moisture flux values have also been carried out for the central Bay of Bengal in July for the period when the ships were stationed there. Comparison between the flux values for the comparatively strong and weak phases of monsoon reveals that while the northward flux does not show any appreciable variation, the eastward flux changes significantly, becoming more than double during the strong phase as compared with that of the weak phase, both along the east coast and in the central Bay.

1. Introduction

It is generally believed that a large amount of air and moisture transport occurs across the equator into northern hemisphere from the southern hemisphere during the Indian Summer Monsoon period, *i.e.*, from June to Sept. and is responsible for the widespread rainfall over the Indian sub-continent. Various workers have tried to compute this cross equatorial flow into the Arabian Sea, west of 75 deg. E. Rao (1964), Pisharoty (1965), Findlater (1969), Saha (1970) and Ghosh *et al.* (1978) have all shown that large volume of air does cross the equator particularly over extreme western regions of northern Indian Ocean. Pisharoty (1965) and Ghosh *et al.* (1978) found that the total northward flux across equator was much less than the eastward flux across meridian 75 deg. E, and therefore, argued that the Arabian Sea rather than the southern hemisphere was playing a major role in the influx of moisture into the country. Flohn (1964), Bjerknes (1969) and Ghosh *et al.* (1978) have also suggested the existence of a zonal cell in the Arabian Sea during active monsoon with the ascending limb over east Arabian Sea and west coast of India and the descending branch over the west Arabian Sea. Das (1962) had earlier suggested the presence of zonal cell during the monsoon with ascending motion over northeast India and descending motion with consequent marked subsidence over northwest India.

Except for the study of Ghosh *et al.* (1978), which was based upon the data taken on the Russian ships during Indo-Soviet Monsoon Experiment (ISMEX), 1973, all the above referred studies are based on very meagre upper air observations, *viz.*, those taken at Gan, Nairobi, Seychelles and Dares-Salam, etc. Moreover, out of these, the data of Seychelles and Dares-Salam cannot be strictly considered as representative

*This work is an extension of the study done and presented at the International Conference of the Scientific Results of the Monsoon Experiment held at Bali, Indonesia, in October 1981.

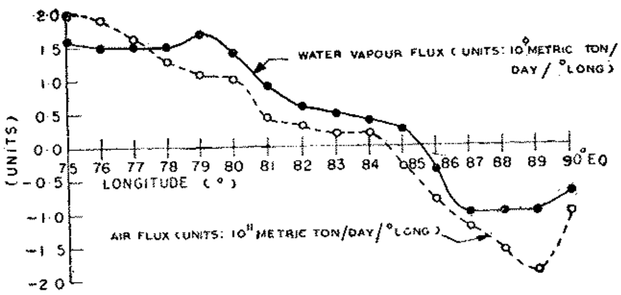
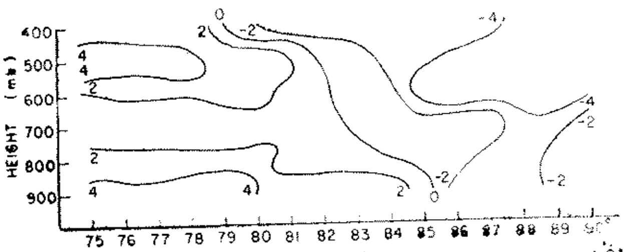


Fig. 1. Vertically integrated net meridional transport of air and water vapour across equator



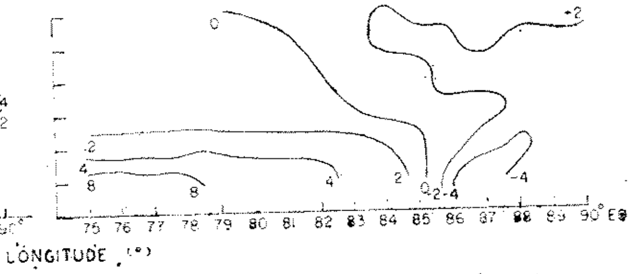


Fig. 2. Vertical distribution of meridional air flux across equator (Unit : 10^{10} metric tonnes per day per deg. Long.)

Fig. 3. Vertical distribution of meridional water vapour flux across the equator (Unit : 10^{8} metric tonnes per day per deg. Long.)

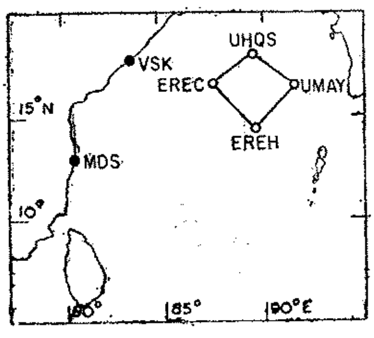


Fig. 4. Ship's positions during June-July 1979

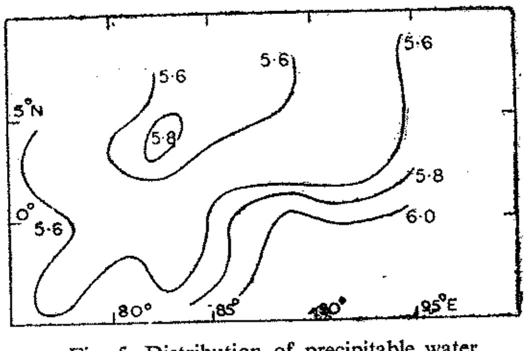


Fig. 5. Distribution of precipitable water (cm) near equator

TABLE 1

Net northward flux values across the equator

Author	Long. range (°E)	Vertical extent from surface to (mb)	Moisture flux in metric tonnes/day (× 10^{10})	Air flux in metric tonnes/day (× 10^{12})
Pisharoty	42-75	450	2.7	..
Findlater	35-75	600	..	7.8
Saha	42-75	450	4.4	5.0
Ghosh *et al.*	50-75	400	3.2* 2.9**	.. ..

*Weak monsoon., **Active monsoon.

of the conditions prevailing at the equator particularly during the Indian Summer Monsoon, as they are situated about 5 deg. to 7 deg. south of the equator, more so since it has been shown by Ghosh and Pant (1976) that the southern hemispheric equatorial trough gives rise to large scale modification of the air flow in the near equatorial lower troposphere.

The values of net northward flux across the equator obtained by various workers have been summarised in Table 1.

All these studies have remained confined to west of 75 deg. E and so far nothing much has been known about the eastward extent of this cross equatorial flow. This, of course, is mainly due to the lack of any observational platforms in that area. During MONEX-79, however, such an opportunity presented itself when five Russian ships took observations in the near equatorial region east of 75 deg. E during last week of June and later four of them moved into the central Bay of Bengal to form a stationary polygon. A large volume of upper air data were, therefore, made available for the first time from these areas during June and July 1979. These data have been utilised in the present study to compute the moisture and air fluxes on the equator, east of 75 deg. E and in the central Bay of Bengal.

2. Data utilised

During International Monsoon Experiment (MONEX-79) five Russian research ships, namely, *UMAY, EREC, UHQS, EREH* and *EREB* made extensive cruises forming polygons in the Bay of Bengal. They moved from 75 deg. E to 91 deg. E in the near equatorial region (2 deg. S to 5 deg. N) from 24 to 28 June 1979, as shown in Fig. 4. During 9 to 24 July, four of these ships moved from 7 deg. N to 18 deg. N between fixed longitudes 85.5 deg. E & 91.5 deg. E forming a polygon. They remained stationary in the central Bay of Bengal from 12 to 24 July on the positions given in Fig. 4. The upper air data of 00 and 12 GMT consisting mainly of wind (direction and speed), temperature and humidity from surface to 400 mb as observed by the ships alongwith similar data of the two coastal stations, *viz.*, Madras (13.0 deg. N, 80.2 deg. E) and Visakhapatnam (17.7 deg. N, 83.3 deg. E) are utilised in the present study.

In the equatorial region from 75 deg. E to 90 deg. E, air and moisture fluxes across the equator have been calculated for the period 24 to 28 June 1979. This was the period when the monsoon was strong along the west coast and in most parts of the country except States of Uttar Pradesh, Bihar and northeast India. The fluxes could not be calculated during the weak monsoon period as by that time the ships had already left the equatorial region. However, in the central Bay of Bengal region, the ships remained there both during active (12 to 16 July) and comparatively weak (17 to 24 July) spells of monsoon, and so the flux values have been calculated on both these occasions.

3. Computations

The fluxes of air and water vapour have been computed using the following well known standard formulae :

(*i*) Air flux $= \frac{1}{g}\int_p\int_s V_n(p, s)\, dp\, ds$

(*ii*) Moisture flux $= \frac{1}{g}\int_p\int_s V_n(p,s)\, q\,(p,s)\, dp\, ds$

(*iii*) Precipitable water $= \frac{1}{g}\int_p q\, dp$

where, g=accelaration due to gravity

q=specific humidity

p=vertical presssure coordinate

s=latitudinal/longitudinal distance

V_n=Wind component normal to the face

The integrations have been carried out in the vertical from 1000 to 400 mb in steps of 100 mb. In the hori-

TALBE 2

Flux values at east coast (82° E) and in the central Bay (89°E)

Flux component	Phase of mon-soon	Flux values at	
		Mean coastal location	Mean ships location in central Bay
Meridional	Active	0.7 (0.6)	1.7 (1.7)
	Weak	0.4 (0.5)	1.1 (1.5)
Zonal	Active	3.2 (3.6)	3.0 (4.0)
	Weak	1.0 (1.6)	1.0 (1.7)

Units : 10^9 metric tonnes/day/degree Lat. or Long. (for moisture flux) and

10^{11} metric tonnes/day/degree Lat. or Long. (for air flux)

zontal values along the equator have been picked up for every degree longitude between 75 deg. E & 90 deg. E from the analysis of the equatorial data of northward fluxes. All calculations have been done on the Computer System EC-1040 installed in the National Data Centre, Pune.

4. Discussion of results

(a) *Air and moisture flux across equator* (24 *to* 28 *June* 1979)

(*i*) *Northward transport of air and moisture across the equator from* 75 *deg. E to* 90 *deg. E*

Vertically integrated fluxes of air and moisture across the equator from 75 deg. E to 90 deg. E as calculated by us, are shown in Fig. 1.

As can be seen from Fig. 1, we find that at 75 deg. E, the air flux is northward, having a value of 2.0×10^{11} metric tonnes/day/degree longitude. As indicated in Table 1, while Saha (1970) finds a value of 1.5×10^{11} metric tonnes/day/degree Long., Ghosh *et al.* (1978) have found a value of 2.0×10^{11} metric tonnes/day/degree Long. for the Arabian Sea in the areas west of 75 deg. E. Thus the value found at 75 deg. E in the present study is in good agreement with the above values. It is interesting to note that air flux decreases gradually eastwards, becomes zero around 85 deg. E and negative thereafter, *i.e.*, the net air flux is then into the southern hemisphere.

Moisture flux has a value of 1.5×10^9 metric tonnes/day/degree Long., at 75 deg. E, remains constant upto 79 deg. E and then gradually decreases eastwards becoming zero around 85 deg. E. This value also is in agreement with that computed by Ghosh *et al.* (1978) across the equator in the Arabian Sea, where they found the average value to be 1.2×10^9 metric tonnes/day/degree longitude.

(*ii*) *Vertical distribution of meridional air and moisture transport across the equator*

The vertical distribution of the meridional transports of air and moisture across the equator from 75 deg. E to 90 deg. E are shown in Figs. 2 and 3 respectively. As can be seen from these figures, both air and moisture transports are positive (northward) in the entire layer from 1000 to 400 mb upto about 79 deg. E. The positive meridional transports gradually decrease east of 79 deg. E and become negative in the entire layer eastward of 85 deg. E. While northward air transport has two maxima, one at about 900 mb and the other at about 500 mb, the moisture transport is maximum near the surface levels only. Corresponding to a secondary air flux maxima near 500 mb, the moisture flux maxima is not so well marked.

The lowest hundred millibar layer contributes about 50 per cent towards the northward moisture flux. In comparison to the larger values of negative air flux in the upper middle troposphere, maximum values of negative moisture transport are confined to the lower troposphere only. This is obviously the result of concentration of high humidity in the lower layer. It is the lower troposphere which contributes mainly towards the net moisture transport across the equator. From the above, it appears, therefore, that the moisture transport across equator in the Bay of Bengal is from south to north in the area west of 85 deg. E only and from north to southeastwards.

(b) *Air & moisture flux during* 12 *to* 24 *July*

Air and moisture flux values, meridional and zonal, have been calculated for Madras and Vishakapatnam also and compared with those obtained from four Russian ships positioned in a box like fashion in the central Bay of Bengal (mean Long. 89 deg. E and mean Lat. 16 deg. N), with a view to finding out significant changes, if any, occurring in the flux values between the longitudes 82 deg. E (taken as mean Long. of MDS and VSK) and 89 deg. E (the position of ships). For comparison purposes, 16 deg. N has been taken as mean latitude of VSK and MDS also. Ship locations are shown in Fig. 4.

The computed air and moisture flux values are given in Table 2. Figures outside the brackets indicate air flux while those inside indicate moisture flux values.

(*i*) *Meridional air and moisture flux*

As is evident from Table 2 above, during the active monsoon spell (12 to 16 July), there is approx. 200% increase in the meridional air and moisture flux from the coast line (82 deg. E) to the central Bay of Bengal (89 deg. E), *i.e.*, while moisture flux varies from the mean value of 0.6 units at coast to 1.7 units in the central Bay of Bengal, air flux changes from 0.7 units to 1.7 units. During the weak monsoon period (17 to 24 July), the corresponding changes for moisture are from 0.5 to 1.5 units and for air are from 0.4 to 1.1 units respectively, again registering an increase of almost the same order. However, it is interesting to note that the northward flux of moisture as well as air does not show any appreciable change from active to weak monsoon period either at the east coast of India or in the central Bay of Bengal. The increase from the coast to Bay can be attributed to the fact that winds almost at all levels take a northward turn in the central Bay of Bengal thus rapidly increasing the northward component of air and moisture flux there whereas they are almost westerly at the east coast.

(*ii*) *Zonal air and moisture flux*

Here the case is just the reverse of what has been stated above. Unlike the meridional moisture flux, zonal moisture flux shows definite variation between weak and active spells by registering an increase of 125% in the latter case. In the case of air flux also, the situation is similar, *i.e.*, the change is about 200% between weak and active monsoon both at the coast as well as the central Bay. However, there is no significant relative change in the air and moisture flux values when compared between the east coast and the central Bay of Bengal either during the weak or during the active monsoon conditions.

This is just opposite to the situation obtaining in the Arabian Sea where there is a large scale change in the zonal moisture transport as found by Pisharoty (1965) and Ghosh *et al.* (1978), etc. The latter had found that in an active monsoon condition, the zonal moisture flux changes from a mean value of 1.3 units along 50 deg. E to about 7.0 units at 70 deg. E giving rise to increase of about 4½ times, which established that the Arabian Sea played a significant role in contributing the enormous moisture carried by the monsoon winds into the country.

5. Precipitable water vapour

The total precipitable water vapour has been calculated for the period between 24 & 28 June 1979 when five Russian ships were cruising in the near equatorial region in the Bay of Bengal. Its distribution may be seen in Fig. 5. There does not appear to be any significant spatial variation as it changes from 5.6 cm to 6.0 cm over the region from 75 deg. E to 95 deg. E.

6. Conclusion

This study which was aimed at calculating the air and moisture flux values across the equator and in the central Bay of Bengal during Indian Summer Monsoon, utilising the data of Monex-79, reveals the following features :

(*i*) The zone of northward transport of air and moisture across the equator from southern hemisphere during the Summer Monsoon period extends eastwards upto 85 deg. E, east of which reversal of air and moisture flux appears to take place.

(*ii*) There is no significant spatial variation of precipitable water vapour in the equatorial regions in Bay of Bengal.

(*iii*) From active to weak monsoon conditions, there is no relative significant variation in the northward air and moisture flux either on the east coast or in the central Bay of Bengal. However, the flux values in the central Bay are about three times those along the east coast.

(*iv*) The eastward air and moisture flux shows significant variation from weak to active monsoon conditions, both along the east coast and the central Bay. Values during the active monsoon period are more than double of those in the weak condition. But there does not appear to be any significant change in the zonal flux as the air travels from east coast (82 deg. E) to central Bay (89 deg. E) along 16 deg. N.

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