Air and water vapour transport across the equator in Western Indian Ocean during Northern Summer

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ABSTRACT

Magnitudes of net total northward fluxes of air and water vapour into the Arabian Sea across an equatorial section extending from 42° E to 75° E and from sea surface to the 450 mb level are computed for September 1963 and June through September 1964, a period during which a large number of ships' reports in the equatorial West Indian Ocean and Seychelles (04°36′ S, 55°30′ E) aerological data were specially available as part of the International Indian Ocean Expedition meteorology programme in addition to routine meteorological data. The computed values exhibit seasonal variation from 4.11×10^{12} tons/day for air and 3.34×10^{10} tons/day for water vapour during June to 3.99×10^{12} tons/day for air and 3.04×10^{10} tons/day for water vapour during September with a maximum of 5.02×10^{12} tons/day for air and 4.43×10^{10} tons/day for water vapour during July, in 1964. The transports during September 1963 are 2.52×10^{12} tons/day for air and 2.35×10^{10} tons/day for water vapour. The above equatorial fluxes for both air and water vapour are seen to constitute about 60–80 % of the net total eastward fluxes across a meridional section of the same vertical extent as the equatorial section but extending from the equator to about 26° N roughly along the West coast of India. The computed value of the net total northward flux of water vapour during July 1964 is shown to be nearly double that computed earlier by Pisharoty (1965), which is 2.2×10^{10} tons/day. The difference is largely due to a stronger meridional component of wind used in the present investigation for the middle and western sectors of the equatorial section as suggested by Seychelles aerological data and ships' reports along the equator. Occurrence of very strong meridional components of winds in equatorial East Africa and Somalia during the northern summer has been reported by Findlater (1969). Strong evidence in support of large-scale cross-equatorial flow in the west Indian Ocean is found from radio-activity and satellite data.

1. Introduction

In a recent paper (Saha, 1968), the author, using the streamline-isotach analysis of a monsoon situation during July 1963, has shown that in the vertical section along meridian 60° E, there is indication of considerable cross-equatorial flow of air in the lower troposphere from the southern to the northern hemisphere. Pisharoty (1965) who computes net total northward flux of water vapour across an equatorial section extending from 42° E to 75° E and from sea surface to the 450 mb level finds a value of 2.7×10^{10} tons/day during July 1963 and 2.2×10^{10} tons/day during July 1964. He shows, however, that these values are rather small, being almost one-half to one-third those of the net total eastward fluxes across a meridional section of the same vertical extent but extending from equator to about 26° N roughly along the west coast of India. From his investigation Pisharoty concludes that "the Arabian sea branch of the Indian SW monsoon appeared to be primarily a northern hemispheric trade wind system blowing from the equator northeastwards into peninsular India, (thus differing from the NE trades of the Pacific), rather than the deflected southeast trades of the southern hemisphere". More recently, Findlater (1969) has computed the net total northward flux of air across an equatorial section extending from 35° E to 75° E and from surface to the 600 mb level and finds a mean value of 7.8×10^{12} metric tons/day for July. In the present investigation, the magnitude of the cross-equatorial flux of air as well as water vapour has been computed for September 1963 and June through September 1964, using a method similar to Pisharoty's but additional data which were specially available as part of the International Indian Ocean Expedition meteorology programme during these months. Computed value of the flux of water vapour for July 1964 is shown to be much higher than that computed earlier by Pisharoty. Evidence in support of large-scale cross-equatorial flow of air and water vapour in the western Indian Ocean during the northern summer monsoon season is produced from radioactivity and satellite radiation data.

2. Pisharoty's work

Pisharoty (1965) computed net total northward flux of water vapour across the equatorial section referred to earlier using a working formula,

$$\frac{dF}{dl} = \frac{1}{20}[(qu)_{1\,000} + 3(qu)_{850} + 3(qu)_{700} + 2(qu)_{600} + 2(qu)_{500}]$$

where dF/dl is the horizontal flux per unit length normal to the lateral boundary, q is the specific humidity expressed in grams per kilogram of the moist air, u is the wind speed normal to the boundary wall, and the subscripts refer to the millibar level to which the values of q and u apply. The above formula is based on the assumption that the 1 000 mb data applies to the 1 000–950 mb layer, the 850 mb data to the 950–800 mb layer, the 700 mb data to the 800–650 mb layer, the 600 mb data to the 650–550 mb layer and the 500 mb data to the 550–450 mb layer. Although not specifically stated, it appears from Pisharoty's paper referred to above that he used the mean aerological data of Gan Island (00°41′ S, 73°09′ E), Dar-es-Salaam (06°53′ S, 39°16′ E) and Nairobi (01°18′ S, 36°45′ E) for July, 1963 and 1964 and daily dropsonde temperature and humidity observations on a few days in June and July, 1963 at a few isolated locations in the extreme western and eastern parts of the Arabian Sea near the equator, for his computations. In the paper, Pisharoty states that the total fluxes were computed by him "using the above data and taking each station to be representative over an appropriate length of the boundary". The details of the representative lengths, important though they are, are, however, not given; nor are given the values of winds and humidities used in the computation. The adequacy of using the above method and data for computing net water vapour fluxes across the equator in the western Indian Ocean, however, requires close examination. Observations show that there is considerable longitudinal variation in the wind and humidity structure of the lower troposphere along the equator in the west Indian ocean. Meridional components of winds which are generally strong and steady in the west and middle sectors of the equatorial section become progressively weak and unsteady in the eastern sector (Crowe, 1952). Fig. 1 which shows the daily upper winds of Seychelles and Gan Island during July 1964 brings out clearly the difference between the two stations in regard to cross-equatorial flow. Further, the use of meteorological data at standard pressure levels to represent conditions in finite pressure layers, especially that at 1 000 mb to apply to 1 000–950 mb layer, does not appear to be quite justified in view of the observational fact that both wind and humidity undergo rapid variation with height. For this reason, it appears more appropriate to use a mean value for the layer than the reported value at a fixed level.

3. Present work

(a) *Method*

The author has, therefore, carried out fresh computations of the net northward fluxes of water vapour as well as air across the equator in the West Indian Ocean using a method similar to Pisharoty's but additional data and more realistic representative lengths.

The formulae used for the fluxes are:

$$F_a = \frac{1}{g}\int_0^L \int_{p_t}^{p_b} V(p, l)\, dp\, dl, \text{ and}$$

$$F_q = \frac{1}{g}\int_0^L \int_{p_t}^{p_b} V(p, l)\, q(p, l)\, dp\, dl$$

where F_a and F_q are the net total northward fluxes of air and water vapour respectively across the equator,

p is barometric pressure

l is length along the equator

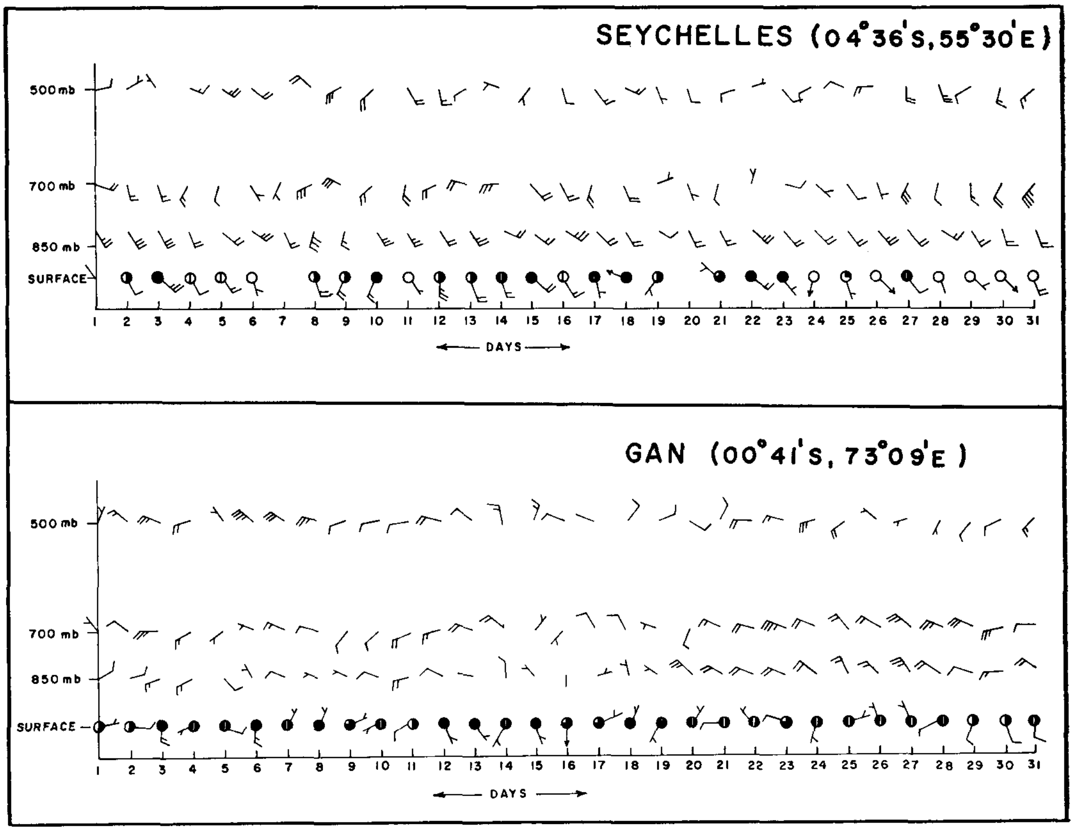

Fig. 1. Daily upper winds at Seychelles and Gan Island up to 500 mb level during July, 1964.

$V(p, l)$ is meridional component of wind, expressed as function of p and l, V – positive to north.

$q(p, l)$ is humidity mixing ratio, expressed as function of p and l.

g is acceleration due to gravity

p_b, p_t are respectively pressures at bottom and top of the vertical section.

and L is the total length of the section along the equator.

The computation is carried out by dividing the total length L into four representative sectors and the total depth $(p_b - p_t)$ into five pressure layers. The representative sector lengths and pressure levels used are:

L_1 = 42–50° E (880 km)

L_2 = 50–60° E (1 100 km)

L_3 = 60–70° E (1 100 km)

L_4 = 70–75° E (550 km)

p_b = 1 000 mb p_1 = 950 mb

p_2 = 800 mb p_3 = 650 mb

p_4 = 550 mb p_t = 450 mb

Mean values of meridional component of wind and humidity mixing-ratio in individual pressure layers in each sector are worked out and the net total flux across each sector computed. Sector fluxes are then algebraically added to obtain the net total northward flux across the equatorial section.

(b) *Data and analysis*

All available surface reports including ships' observations within about 5 degrees of the equator and the aerological soundings of Nairobi (above 800 mb), Dar-es-Salaam, Seychelles and Gan Island are used in the study. Fig. 2 shows the distribution of the mean meridional

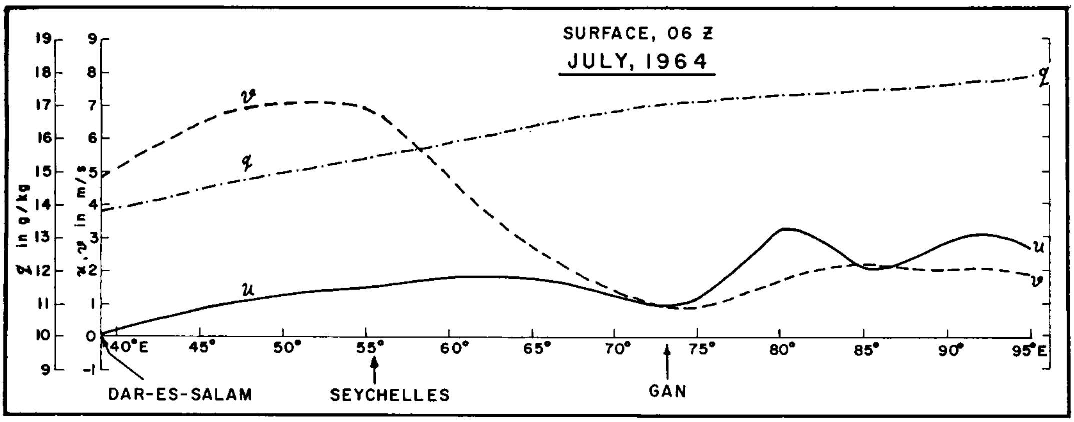

Fig. 2. Distribution of mean meridional (v) and Zonal (u) components of the wind and humidity-mixing-ratio (q) values at surface from 40° E to 95° E along the equator during July, 1964. v, positive to north; u, positive to east.

(v) and zonal (u) components of the wind and humidity-mixing-ratio (q) at surface from 40° E to 95° E along the equator during July, 1964. For lack of space, data for 1 month only are presented. It may be seen that the values of the relevant parameters at surface at five-degree (longitude) intervals together with the aerological data at standard pressure levels of stations mentioned above enable a reasonable analysis to be made of data required for computation of fluxes. In this context, availability of aerological data from Seychelles Island appears very crucial and important. The aerological data of Seychelles, however, were available for September, 1963 and June through September, 1964, hence the computation could be carried out for this limited period only. Fig. 3 shows a typical analysis of the distributions of the mean meridional component of the wind and the mean humidity-mixing ratio during July, 1964. The relevant values were picked up from such analysed maps and used for computation. It may be noted in passing that the vertical pressure layers used in the present

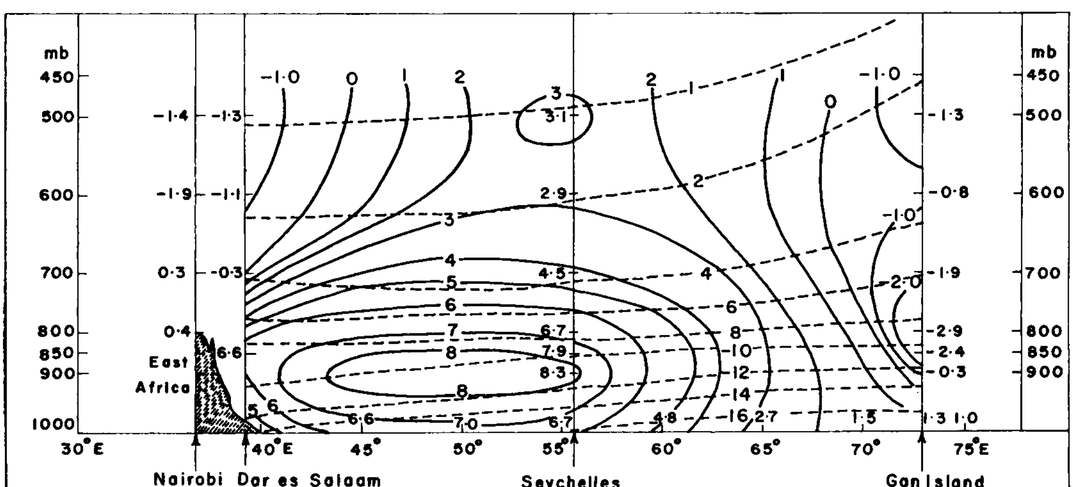

Fig. 3. Distribution of mean meridional component of wind (v) and humidity-mixing-ratio (q) values in the vertical section along the equator during July, 1964. ——, isolines of meridional components of winds in m/sec; ---, isolines of humidity-mixing ratio values in g/kg. v, positive to north.

Table 1. *Values of mean meridional component of wind (v) and humidity-mixing ratio (q) used in the computation of fluxes across the equator*

Layer (mb) v, m/sec; q, gm/kg	Sector 42–50° E v	Sector 42–50° E q	Sector 50–60° E v	Sector 50–60° E q	Sector 60–70° E v	Sector 60–70° E q	Sector 70–75° E v	Sector 70–75° E q
September, 1963								
Surface–950	4.0	13.0	4.5	13.5	1.6	14.0	0.5	15.0
950–800	3.0	10.0	4.0	10.5	1.0	10.6	0.0	10.8
800–650	2.0	6.0	2.5	6.2	0.6	6.3	0.3	6.8
650–550	0.5	3.0	0.8	3.5	0.4	3.7	−0.3	4.0
550–450	−0.5	1.5	0.2	1.8	0.3	2.0	0.5	2.0
June, 1964								
Surface–950	5.2	12.5	4.8	14.0	2.7	14.5	1.5	15.0
950–800	6.0	9.5	5.0	10.0	2.5	10.2	0.5	10.5
800–650	3.0	5.0	4.0	5.0	2.0	5.2	0.2	5.5
650–550	0.5	2.0	1.8	2.0	0.8	2.5	−0.2	3.0
550–450	0.2	1.5	1.0	1.8	0.5	2.0	0.0	2.2
July, 1964								
Surface–950	6.5	13.0	7.0	15.0	3.5	15.5	1.8	16.0
950–800	7.0	9.0	8.0	10.5	4.0	11.0	−1.2	12.0
800–650	3.5	4.5	5.0	5.0	2.8	5.3	−1.0	5.5
650–550	−0.5	1.7	3.2	2.0	0.5	2.5	−0.5	3.0
550–450	−1.3	1.0	2.0	1.0	−0.6	1.5	−1.0	2.0
August, 1964								
Surface–950	6.5	11.0	6.0	13.0	3.6	13.5	2.3	14.0
950–800	7.0	9.0	6.5	10.2	4.0	10.4	1.0	10.5
800–650	4.0	4.5	4.0	4.5	2.0	5.5	−0.2	6.0
650–550	−2.0	1.5	1.0	1.5	0.5	2.0	0.1	2.5
550–450	−1.8	1.5	−0.5	1.6	0.2	1.8	−0.1	2.0
September, 1964								
Surface–950	4.0	12.5	5.0	13.5	2.5	13.8	1.5	14.0
950–800	5.0	8.5	5.5	10.0	2.2	10.2	−0.5	10.5
800–650	3.0	5.0	3.5	5.2	2.0	5.4	0.1	5.5
650–550	1.5	2.5	1.5	2.8	1.0	2.9	0.6	3.0
550–450	1.0	1.5	0.5	1.6	0.8	1.8	0.4	2.0

investigation are the same as used by Pisharoty, but basic computational data for each layer are obtained in the manner stated above. Table 1 gives the values of the mean meridional component of wind (v) and the humidity-mixing ratio (q) for the different sectors and pressure layers, actually used in the computation.

(c) *Results*

Results of the computation are presented in Table 2.

The values in Table 2 may be compared with the corresponding net total eastward fluxes across a meridional section of the same vertical extent but extending from equator to about 26° N along the west coast of India which are given in Table 3.

The percentage ratio of the net total northward flux across the equatorial section to the net total eastward flux across the west coast section, without allowing for differences in the horizontal extents of the sections, is given in Table 4.

If the flux densities per degree latitude/longitude are compared, the percentage ratios given in Table 4 would vary from 50 to 66% in

Table 2. *Magnitudes of net total northward air and water vapour fluxes across the equatorial section in the Western Indian Ocean*

	Sept. 1963	June 1964	July 1964	Aug. 1964	Sept. 1964
Net air flux (10^{12} tons/day)	2.52	4.11	5.02	4.33	3.99
Net water vapour flux (10^{10} tons/day)	2.35	3.34	4.43	3.94	3.04

the case of air and 47 to 58% in the case of water vapour, on the basis of reduction by a factor of 26/33 i.e. 0.788.

As already mentioned, Findlater found a mean value of 7.68×10^{12} metric tons/day during July for the net total northward flux of air across an equatorial section extending from 35° to 75° E and from surface to 600 mb level. His values of cross-equatorial components of winds at low levels over the eastern slopes of Kenyan Highlands were very large and this substantially accounts for his higher value of net total northward flux of air across the equator during July than in the present investigation.

4. Radioactive evidence

A large-scale interhemispheric transport of air in the Indian monsoon region is strongly indicated by recent measurements of increased radioactivity in surface air at Bombay (18° 57′N 72°55′ E) and a few other monitoring stations in India following French nuclear tests in the southern hemisphere (test site, 21° S, 138° W) during the Indian summer monsoon season, 1966–68 (Rangarajan et al., 1969) with a time lag of about 2½ to 3 weeks. Since the back-

Table 3. *Magnitudes of net total eastward fluxes of air and water vapour across a meridional section along the west coast of India (about longitude 75° E)*

	Sept. 1963	June 1964	July 1964	Aug. 1964	Sept. 1964
Net air flux (10^{12} tons/day)	3.987	5.228	6.019	5.660	5.476
Net water vapour flux (10^{10} tons/day)	3.604	5.051	5.906	5.803	5.127

Table 4. *Percentage ratio of net total northward flux across the equatorial section to the net total eastward flux across the west coast section*

	Sept.	June	July	Aug.	Sept.
Air flux	63.0	78.5	83.6	76.5	72.9
Water vapour flux	65.2	66.1	73.4	68.0	59.2

ground radioactivity was low prior to most of these tests which were in the low and medium-yield ranges, the conclusion is irresistible that the fission-product activity from the tests was transported by the prevailing tropospheric circulation from the test site to India. Available meteorological data may point to two possible transport routes, one via the lower tropospheric trade-wind circulation and the other via the upper westerlies (UNSCEAR, 1967). The author has, however, recently shown (Saha, 1970*a*) that the trade-wind layer in the region of the test site is rather shallow (< 1.5 km a.s.l.) and that the trade-winds are not strong and steady enough to effect transport within the observed time. The probable route to India, therefore, appears to be one via the tropospheric zonal westerlies round the globe to the western Indian Ocean, whence the strong meridional components of the lower tropospheric southeast trades south of the equator and southwest winds north of the equator effect rapid transport to India, in a total period of about 2½ to 3 weeks. There appears to be support for this route from the radioactivity data of two southern hemispheric monitoring stations, viz. Pretoria (26° S, 28° E) and Aspendale (38° S, 145° E), both of which responded to the French tests in the same manner as Bombay but with different time lags. A remarkable feature of the transports to India is that while the effects of tests carried out during the monsoon months were recorded at Bombay with appreciable intensity, that reaching the station in June or October about the time of onset or withdrawal of the monsoon was hardly detectable. Possibility of a major exchange of radioactive tracers between the hemispheres by way of the monsoon circulation was first pointed out by Junge (1962).

5. Satellite evidence

By far the most impressive visual evidence of the interhemispheric character of the monsoon circulation is provided by recent satellite television photographs and infra-red radiation pictures of cloud bands extending across the equator into both the hemispheres in the Indian Ocean region.

In a paper to be published shortly in *Tellus* (Saha, Sikka & Krishna Rao, 1970*b*), the authors have reported a photoprint of NIMBUS-II night time HRIR data on 16 June 1966, which shows an interhemispheric cloud band between 50° E and 60° E which is clearly suggestive of cross-equatorial flow. They have discussed the formation of such cloud bands on the basis of velocity shears developing in the southeast trades as they move from the southern to the northern hemisphere and turn into the southwest monsoon.

6. Conclusion

Results of the present investigation show that a sizeable portion of the total amount of air and water vapour that enters into the summer monsoon circulation of India is derived from the southern hemisphere. Evidence in support of large scale cross-equatorial flow of air is found from radio-activity and satellite data.

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ПЕРЕНОС ВОЗДУХА И ВОДЯНОГО ПАРА ЧЕРЕЗ ЭКВАТОР В ЗАПАДНОЙ ЧАСТИ ИНДИЙСКОГО ОКЕАНА В ПЕРИОД ЛЕТА В СЕВЕРНОМ ПОЛУШАРИИ

Вычислены величины полных потоков воздуха и водяного пара к северу в сторону Аравийского моря через экватор в районе от 42° в. д. до 75° в. д. и от поверхности моря до уровня 450 *Мσ* за сентябрь 1963 г. и июнь–сентябрь 1964 г. — период, во время которого в добавление к обычным метеорологическим данным были доступны большие количества сводок с кораблей в экваториальной области в западной части Индийского океана и аэрологические данные в районе Сейшельских островов (4°36′ ю. ш., 55°30′ в. д.). Эти измерения проводились в течение метеорологической программы Международной экспедиции в Индийском океане. Вычисленные значения обнаруживают сезонные изменения от $4{,}11 \cdot 10^{12}$ тонн/день для воздуха и $3{,}34 \cdot 10^{10}$ тонн/день для водного пара в сентябре с максимумом, равным $5{,}02 \cdot 10^{12}$ тонн/день для воздуха и $4{,}43 \cdot 10^{10}$ тонн/день для водяного пара в июле 1964 г. Потоки в сентябре 1963 г. составляют $2{,}52 \cdot 10^{12}$ тонн/день для воздуха и $2{,}35 \cdot 10^{10}$ тонн/день для водяного пара. Приведенные выше экваториальные потоки воздуха и водяного пара составляют около 60–80% полных потоков в восточном направлении через меридиональное сечение той же вертикальной протяженности, что и экваториальное сечение, но простирающееся от экватора до 26° с. ш. приблизительно вдоль западного берега Индии. Вычисленное значение полного потока к северу для водяного пара и июле 1964 г. приблизительно в два раза больше значения, полученного ранее Пишароти (1965), которое составляет $2{,}2 \cdot 10^{10}$ тонн/день. Разница в основном объясняется бóльшими меридиональными компонентами ветра, использованными в данном исследовании для средней и западной частей экваториального сечения, которые получаются согласно аэрологическим данным с Сейшельских островов и судовым сводкам вдоль экватора. Наличие очень сильных меридиональных компонент ветра в экваториальной Восточной Африке и Сомали летом северного полушария было отмечено Финдлейтером (1969). Хорошее подтверждение наличия крупномасштабного потока через экватор в западной части Индийского океана можно найти по данным радиоактивности и спутниковым данным.