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Water vapour transport over the Indian Ocean during summer 1975

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ABSTRACT

Water vapour transport over the Indian Ocean during the 1975 Indian summer monsoon is investigated. The main data set used in this study is constituted of twice-daily surface assimilated meteorological fields determined on a 2·5 degree long grid from an objective assimilation of surface data over the Indian ocean. Upper air data are also used. Daily evolution of surface water vapour fluxes across different sections are presented. In the Arabian Sea, the onset of the monsoon is characterized by a large increase of the surface water vapour fluxes. The main feature of the fluxes is the existence of an oscillation with a fundamental period of 10 ± 2 days. The analysis of correlation coefficients between fluxes across sections in the Arabian Sea suggests that periodic variations of water vapour fluxes result from downstream forcing.

Mean monthly water vapour budgets have been estimated over the Arabian Sea and the Bay of Bengal. The results show that about 70% of the water vapour that crosses the western coast of India comes from the Southern Hemisphere whereas 30% is picked up by evaporation over the Arabian ocean. In the Bay of Bengal, water vapour picked up by evaporation over the ocean seems to be largely used for local weather development.

1. Introduction

The origin of moisture which produces intense rainfall during the monsoon season over the Indian sub-continent is a question of great importance. The evidence in support of large cross-equatorial flux of air over the western Indian Ocean during the northern summer suggests the importance of cross-equatorial water vapour transport. Thus, Findlater (1969) found a correlation between the amount of rainfall over the western coast of India and the intensity of low-level equatorial winds over Kenya, although this question deserves careful consideration (Raghavan et al., 1975). Spectral analysis of the intensity of the Somali jet demonstrates the existence of a quasi-biweekly oscillation in rainfall over India associated to break and active monsoon phases (Krishnamurti and Bhalme, 1976). It has also been found that cross-equatorial winds are stronger during a good monsoon than a bad one (Krishnamurti et al., 1976). Cadet and Reverdin (1981) showed that at the surface level the cross-equatorial water vapour flux is important over the western Indian Ocean and takes into account more than 50% of the total cross-equatorial flux in the Indian Ocean. Ramage (1966) suggested that the Bay of Bengal constituted in addition to the Arabian Sea a non-negligible source of moisture for rains over the west coast of India due to incursion of deeply moist air from the Bay of Bengal.

Several scientists have tried to evaluate the balance of moisture over the Arabian Sea using line integral techniques over the region north of the equator. Due to the lack of equatorial observations (only Dar-es-Salaam, Seychelles and Gan Islands implemented in the vicinity of the equator were taken to obtain the upper air information), these studies were not very conclusive and were inconsistent. Using the data collected during IIOE, Pisharoty (1965) concluded that the influx across

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the equator to the water vapour budget was small compared to the outflux across the west coast of India and that the Indian south-west monsoon picked up most of its moisture from the surface of the Arabian Sea. However in this study, only Nairobi and Gan were used and the large cross-equatorial flux within the Somali jet was missed. From a further analysis of IIOE data, Saha (1970) found, using the central station of Seychelles Islands, that 60–80% of the net total fluxes across the west coast of India was constituted by cross-equatorial fluxes. Saha and Bavadekar (1973) showed that the cross-equatorial flux of water vapour into the Arabian Sea was about 30% larger than the evaporation from the surface of the sea.

In the present study, twice daily assimilated fields of meteorological parameters obtained during the 1975 summer monsoon over the Indian Ocean at the surface level (Cadet and Reverdin, 1981) are used to determine water vapour transport over the Indian Ocean. Upper air data are also used to obtain some information about the vertical structure of the moisture field in order to infer water vapour budgets. Compared to the previous studies, the present one is more complete, because it adds the surface flux every 2.5 degrees over the Indian Ocean which permits the catching of the large spatial variation of the fluxes and because it used also a large number of tropospheric data.

In Section 2, the data are presented. Daily variation of surface fluxes across different sections in the Indian Ocean are presented and discussed in Section 3. In Section 4, water vapour budgets over the Arabian Sea and the Bay of Bengal are presented.

2. The data

This study is based mainly on surface assimilated fields determined over the Indian monsoon area (35° E–100° E–25° S–25° N) on a 2.5 degree long grid during the period from May to September 1975. The determination of these fields is presented in Cadet and Reverdin (1981) where the mean fields are discussed. The method of successive corrections of an initial guess field on the basis of observed data was used as an objective analysis. These fields determined twice a day represent the most detailed data set ever obtained over the monsoon area, from which many studies can be performed. In this paper, water vapour transport over the monsoon region is studied using the wind and mixing ratio fields. The quality of these fields is good due to the large number of data (more than 85,000) collected for the period from May to September 1975 and to their even distribution in space over all the Indian ocean except for the southeast region which is not covered by this study. However, since these data concern only the surface level, upper air data were also compiled to deduce some information about the vertical structure of the parameters. The World Data Centre (Asheville, NC, U.S.A.) and F.S.U. (Florida State University, Tallahassee, Dept. of Meteorology) provided us with these data which were taken at stations implemented on the coast of India, Africa and Arabia, and on a few islands in the Indian Ocean. These data concern the surface level and the 850, 700 and 500 mb levels, except the Indian stations which concern the surface level and upper air levels every 50 mb.

3. Surface flux of water vapour across different sections

Surface fluxes of water vapour across different sections in the Indian Ocean can give some ideas about the water vapour transport and its fluctuations across the ocean. In this section only surface fluxes determined from the wind and mixing ratio fields are studied, i.e. $\rho q_s V_s l$ where ρ is the air density, q_s the surface mixing ratio, V_s the wind component at the surface level perpendicular to the section and l the horizontal length of the section. The flux unit is kg m^{-1} s^{-1}, i.e. the surface flux of water vapour over a 1 m height. Fig. 1 gives the geography of the area and the different sections across which fluxes have been determined. The fluxes across the sections were determined as the sum of individual fluxes calculated across the unit sections (2.5 degrees long) which approximate the section (see the example of Section AA on Fig. 1). High frequency features have been reduced using a running rectangular weighting function which filtered out fluctuations, the period of which is less than 2 days. The length of each section is identical and so the intensity of fluxes can be directly compared. In the following sections, we are going to refer to the onset of the monsoon. It corresponds to

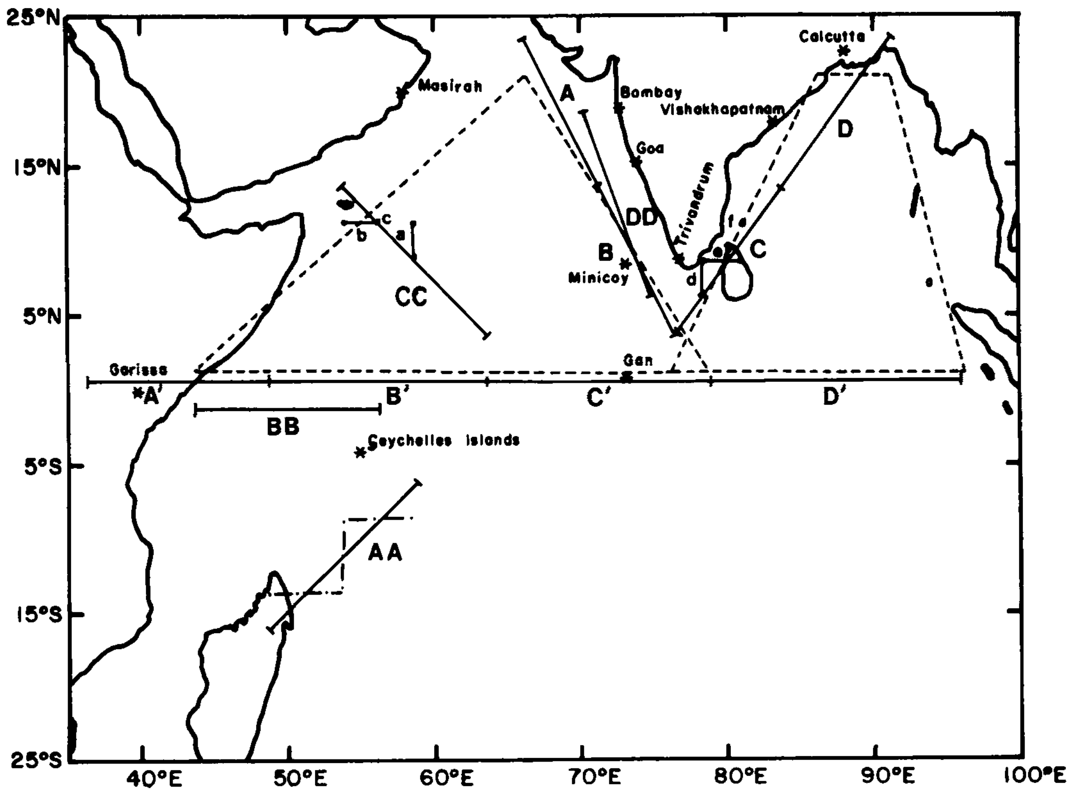

Fig. 1. Map of the influence area of the Indian summer monsoon depicting the different sections across which surface fluxes were computed and polygons for which water vapour budgets were estimated. An example of the approximation used to determine the fluxes across the sections is given for AA. The meteorological stations for which upper air soundings were used are also indicated.

the beginning of the rainy season over the western coast of India. In 1975 the onset took place on 28 May (Indian Daily Weather Report).

3.1. *Surface fluxes of water vapour across equatorial sections*

Fig. 2 shows four different fluxes determined across the equatorial sections. A′ concerns Africa, B′ the western Arabian Sea, C′ the eastern Arabian Sea and D′ the Bay of Bengal.

The most important flux takes place across B′ which takes into account a large part of the cross-equatorial flux in western Arabian Sea. During May and a large part of June, there is an increase of the water vapour flux which can be associated with the establishment of the intense cross-equatorial flow and the subsequent intense rainfall along the western coast of India. Periodic variations are noticed during that period. Across A′, a similar pattern exists but well attenuated due to the influence of Africa. The slow increase of the water vapour flux shows that the onset of the monsoon at the equator was not sudden during 1975. After the onset, large oscillations with typical periods of 10–15 days can be noticed as well as oscillations with smaller periods. Similar oscillations can be seen across the A′ section but with much smaller amplitudes.

The fluxes across C′ and D′ are quite different from the fluxes across A′ and B′. At the end of May and at the beginning of June no increase can be noted. Thus in May a large cross-equatorial water vapour flux exists in the eastern part of the Indian Ocean and brings moisture into the Bay of Bengal. Across C′ negative fluxes can be noted after mid-July and are due to the existence of equatorial westerlies between 75° E and 80° E. Thus the monthly mean value of the meridional vertically

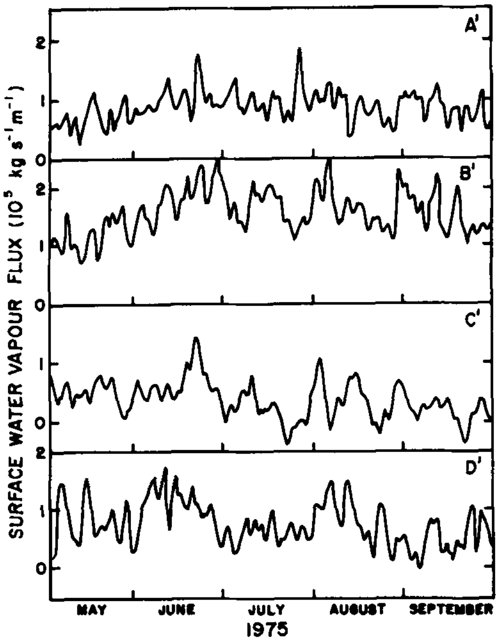

Fig. 2. Surface fluxes of water vapour ($\times 10^5$ kg s^{-1} m^{-1}) across different sections along the equator: A′, B′, C′, and D′.

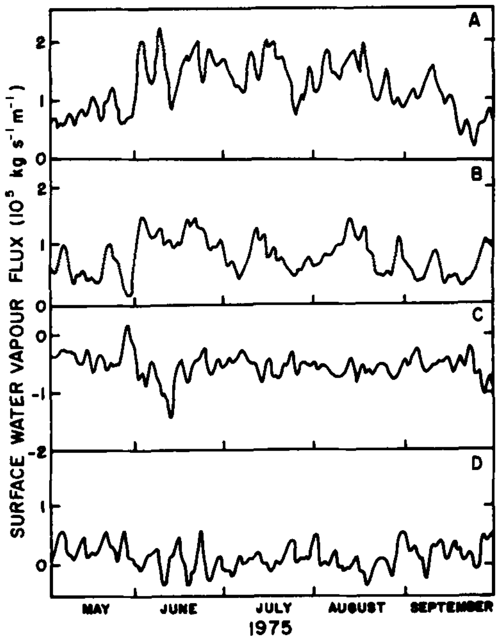

Fig. 3. Surface fluxes of water vapour ($\times 10^5$ kg s^{-1} m^{-1}) across different sections along the Indian coast: A, B, C and D.

integrated water vapour flux at Gan (0.4° N, 73.1° E) is negative for July indicating a southward flux. The surface water vapour fluxes across C′ and D′ are characterized by large amplitude oscillations with periods around 20 days.

3.2. *Surface fluxes of water vapour across the coast of India*

Four sections were defined (Fig. 1) along the coast of India. A corresponds to the northern part of the western coast and B to its southern part; C and D are respectively along the southern and northern part of eastern coast of India in the Bay of Bengal. A is characterized by a large increase of the surface flux at the date of the onset (over the western coast of India), followed by large amplitude fluctuations (30% of the mean value) and a small but regular decrease during September (Fig. 3). The surface flux is also increasing across B during the onset and it can be noted that the intensity of the flux is about the same during May and September. The onset is much more marked along the western coast of India than at the Equator. The onset can also be noted on C. The first rainfall along the western coast of India is linked to an increase of the intensity of the westerlies over the Arabian Sea, which cross the peninsula and give rise to important water vapour fluxes across the Orissa Coast. The amplitudes of the fluctuations are much smaller than those found on A and B. For D, the transition from the pre-monsoon month of May to the monsoon season can hardly be noticed but oscillations with typical periods of 8–10 days occur. After 1 June, a large number of the major peaks can be associated with monsoon lows in north Bay of Bengal. Thus, relatively large positive surface fluxes are followed by negative fluxes during the passage of the perturbations.

3.3. *Surface fluxes of water vapour across different sections perpendicular to the low-level jet*

Across AA which is located to the east of the northern tip of Madagascar, the surface flux is as strong as across BB which is along the equator (Fig. 4). However, the onset of the monsoon cannot be noted on AA whereas it does on BB. Fluctuations have larger fluctuations on BB than on AA. Across CC, the onset is clearly visible

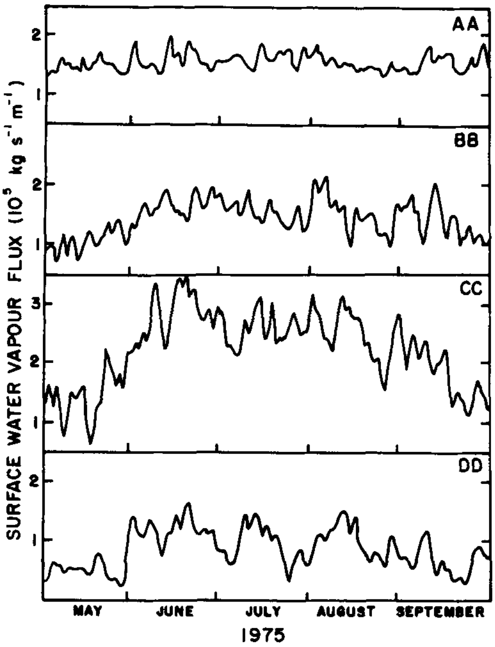

Fig. 4. Surface fluxes of water vapour ($\times 10^5$ kg s^{-1} m^{-1}) across different sections perpendicular to the East-African jet stream: AA, BB, CC and DD.

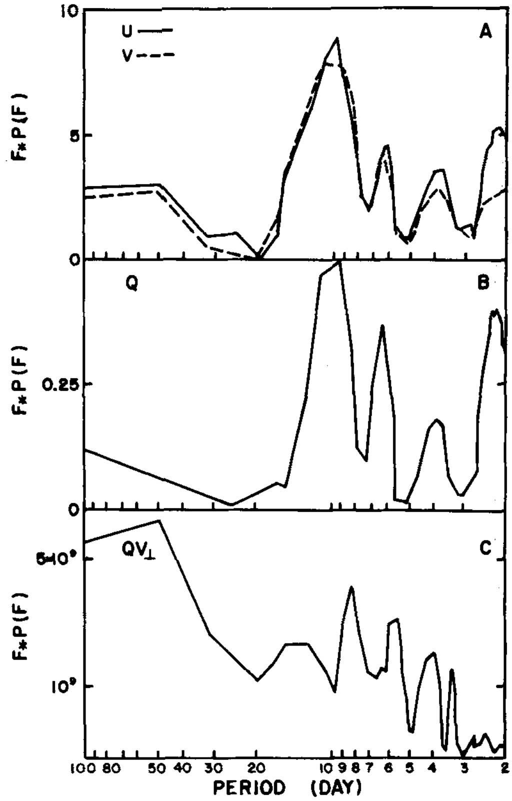

Fig. 5. Power spectra ($F \times P(F)$) of the wind components (A), water vapour mixing ratio (B) and surface water vapour flux $QV_{\perp}$(C) for section CC. The spectra of U and V is computed with the mean value of the wind component across a unit section: respectively indicated by the letters a and b on Fig. 1. The mixing ratio series corresponds to the point indicated by the letter c on Fig. 1.

indicating an increase of the air flow and of the water vapour content over the Arabian Sea while the air is moving towards India. During June, July and half of August, the flux reaches about twice its value during May. After mid-August and to the end of September, a slow decrease does exist. Large amplitude oscillations are also noted with typical periods around 10 days. For DD, the onset of the monsoon is followed by large amplitude fluctuations which reach about 20 to 30% of the mean flux.

3.4. *Spectral analysis*

To study the fundamental periods of oscillation of the fluxes, lag-correlation power spectral analysis was performed on the data series of fluxes, wind components and water vapour mixing ratio.

Fig. 5 gives the power spectra for the different parameters for section CC, i.e. in the Arabian Sea. The wind component (U and V) (Fig. 5a) and the water vapour mixing ratio (Fig. 5b) oscillate with a typical period of 10 days. The power intensity of the latter parameter is about 20 times less than the power intensity for the wind components. Due to this fact, the surface flux which is proportional to the product of wind component by the mixing ratio, also oscillates with a period close to that frequency range 8 days. The other peaks are due to the harmonics of the fundamental period. For the other sections in the western Indian Ocean (BB, DD, A and B), similar results are found, i.e. the period of oscillation of the fluxes, wind components and water vapour mixing ratio is around 10 days. However, the peaks are less marked for the fluxes than for the related parameters.

The fluctuations of rainfall along the west coast of India oscillate with two typical periods (power spectra not shown). There is a long one around 20 days which has no correspondence in the power spectra of the surface flux, and a shorter one around 8 days which may be related to the oscillations of the surface flux. This period is certainly the fundamental cycle of oscillations of the monsoon elements for 1975 as shown by Krishnamurti and Bhalme (1976) for other years (1957, 1962, and 1967).

Fig. 6 gives the power spectra of the different parameters for section C (south Bay of Bengal). The wind components (U and V), the water vapour mixing ratio, and the surface flux oscillate with a typical period of 10 days ± 2 days. This is also the period of fluctuation of rainfall over northeast India (West Bengal, Orissa, Biher and Assam) (not shown). These periodic fluctuations do not seem to be related to the existence of monsoon lows which do not occur with the same frequency.

3.5. *Correlation coefficients*

Correlation coefficients were computed between the different fluxes across AA, BB, CC, and DD.

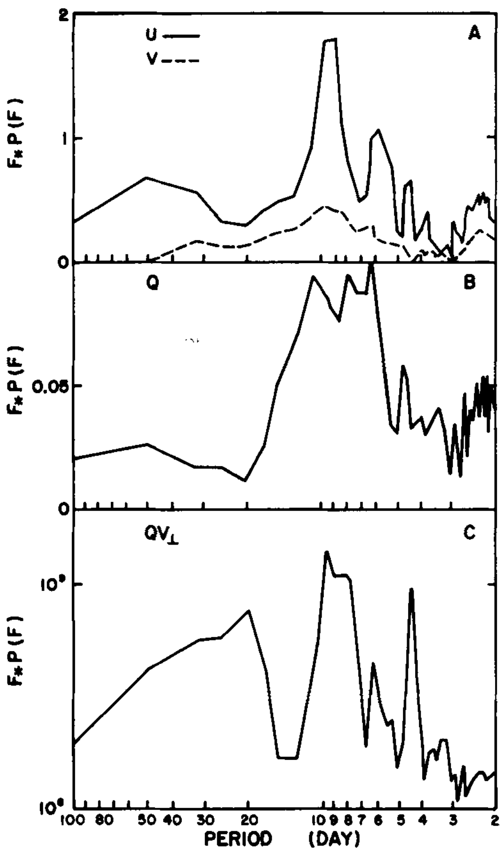

Fig. 6. Same as Fig. 5 except for C. U and V time series across unit sections indicated by letters d and e on Fig. 1. Mixing ratio series at the point indicated by the letter f on Fig. 1.

Table 1 gives the different values. The correlation is high between the fluxes across sections in the Arabian Sea, i.e. BB, CC, and DD, whereas the correlation is very weak between flux across AA and fluxes across the other sections. The correlation coefficient between rainfall along the western coast of India and the flux across DD is 0.383.

The different fluxes have been lag-correlated to determine which flux is leading. Fig. 7 gives the different curves. The values on the abscissa axis give the lag (positive or negative) in days between the first flux and the second one. The correlation between flux across AA and fluxes across the other sections is maximum for positive values of the lag. It means that AA is leading the other fluxes. However, the correlation being weak, it seems hazardous to deduce some results. For the fluxes

Table 1. *Correlation coefficients between the different sections AA, BB, CC and DD perpendicular to the intense low-level air flow over the Indian Ocean. The correlation between the flux across the section north of Madagascar and the fluxes across other sections is very weak whereas it is good between BB, CC and DD when the low-level East-African jet is fully developed*

	AA	BB	CC	DD
AA	1.00	0.22	0.27	0.32
BB	0.22	1.00	0.68	0.51
CC	0.27	0.68	1.00	0.73
DD	0.32	0.51	0.73	1.00

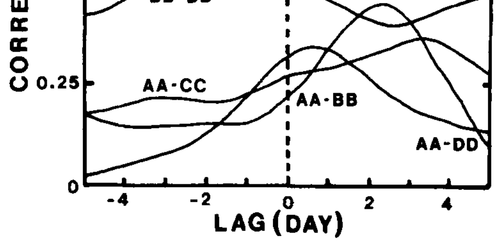

Fig. 7. Correlation coefficients between the different fluxes versus the lag.

across the sections in the Arabian Sea, the correlation coefficient is maximum for negative values of the lag. The lag is equal to −1 day for CC–DD and BB–CC and equal to −1.5 day for BB–DD. The second flux is leading the first one: variations of surface fluxes (mainly due to variations of wind intensity) across a section in the Arabian Sea and across the equator along East African coast occur after the flux variations across the western coast of India. These results suggest that the variations of wind intensity and surface fluxes in the Arabian Sea result from downstream forcing. The fluctuations of the fluxes and associated parameters having a period around 10 days may suggest that this oscillation of the flux across the western coast of India is leading the similar oscillation of the other upstream fluxes. Thus, the study of the oscillation of large-scale monsoon elements (Krishnamurti and Bhalme, 1976) suggested that variations of wind intensity along the East African coast are a result of downstream forcing.

4. Water vapour budgets

To determine the importance of input flux in the northern Indian Ocean, water vapour budgets have been estimated over two different polygons located over the Arabian Sea and the Bay of Bengal. The polygons are given by Fig. 1.

The monthly mean net flux of water vapour $\bar{F}$ across a boundary wall is given by:

$$\bar{F} = \frac{1}{g}\int_{P_s}^{P_t}\int_0^L \overline{qV}dp\,dl \tag{1}$$

where g is acceleration due to gravity, p the barometric pressure, P_s the barometric pressure at the bottom, P_t the barometric pressure at the top, l the length along the boundary, q the mixing ratio expressed as a function of p and l, V the component of the wind normal to the boundary wall and L the total horizontal length of the boundary wall. The bar indicates a monthly mean.

In order to estimate mean monthly water vapour budgets over the Indian Ocean, some assumptions have been made. These budgets are estimated within a box horizontally bounded by the polygons and limited vertically by the 500 mb level. It is assumed that there is no vertical flux at the top of the box and that the horizontal flux above 500 mb can be neglected. It is also assumed that there is no accumulation or loss of water over a month.

The net flux divergence of the water vapour fluxes across the different walls represents the difference between the evaporation and the precipitation within the given volume:

$$\bar{E} - \bar{P} = \text{Net flux divergence of water vapour.} \tag{2}$$

where $\bar{E}$ represents the monthly mean evaporation and $\bar{P}$ the monthly mean precipitation.

As only surface data and some upper air soundings are available, we made an assumption by introducing the concept of equivalent humidity height. Thus, the surface flux has to be multiplied by a height, the equivalent humidity height, in order to obtain the total flux across a vertical wall. Thus, if the equivalent humidity height, he, is constant along the length of the wall, the assumption is given by the following equation:

$$\bar{F} = \sum_{l=1}^{n} \rho\,(\overline{q_l V_l})_{\text{surface}}\, l_1\, he = \bar{E} - \bar{P} \tag{3}$$

where l_1 is the distance between two grid points, n the number of grid points, V_l the wind component perpendicular to each unit section and ρ the density.

However, the equivalent humidity height is not necessarily constant with location. Thus eq. (3) becomes:

$$\sum_{l-1}^{n-1} \tfrac{1}{2}\rho l_1\,[\overline{q_l V_l}\,\overline{he_l} + \overline{q_{l+1} V_{l+1}}\,\overline{he_{l+1}}] = \bar{E} - \bar{P} \tag{4}$$

where he_l is the equivalent moisture height at the grid point i, j.

4.1. *Determination of the equivalent humidity heights*

The equivalent moisture height was estimated using the upper air sounding data. At each station located near a section of a polygon, the total flux and the surface flux were computed. The ratio of these two fluxes gives the equivalent moisture height:

$$he = \frac{\frac{1}{g}\sum_{P_S}^{P_{500}} qV\Delta p}{\rho q_S V_S}$$

where g is the acceleration of gravity, p pressure, and Δp the pressure interval. Subscript S indicates a surface value. The top of the box is at 500 mb.

Table 2. *Comparison between total water vapour fluxes estimated using the surface fluxes and the equivalent moisture height (column 1) and computed with the upper air data from nearest stations (column 2) (Unit: 10^{10} metric ton day^{-1}). Positive sign corresponds to northward or eastward directions. A: Garissa (East African coast); B: Gan (equatorial eastern Indian Ocean); C: Trivandrum, Goa, Bombay (western coast of India); D: Calcutta (Bengal coast); E: Vishakhaptnam (Orissa coast)*

Month	1A	2A	1B	2B	1C	2C	1D	2D	1E	2E
May	1.56	No value	0.27	0.29	1.60	1.28	0.50	0.30	−0.22	−0.36
June	2.63	2.21	0.33	0.54	3.80	3.05	0.69	0.62	−0.64	−0.54
July	2.40	2.25	0.09	−0.31	3.00	3.05	0.95	1.27	−0.42	−0.55
August	2.40	1.70	0.12	0.03	3.30	3.20	0.67	1.51	−0.56	−0.85
Sept.	1.17	1.39	0.01	−0.34	2.20	2.50	0.78	1.08	−0.23	−0.01

The ratio, *he*, was computed for every day and its monthly mean value was determined at each station. These computations were made for 1975 for the following stations: Garissa (0.5° S, 40° E), Masirah (20.5° N, 59° E), Gan (0.4° N, 73.1° E), Trivandrum (8.5° N, 77° E), Bombay (19° N, 73° E), Goa (15.5° N, 73.5° E), Minicoy (8.5° N, 73° E), Calcutta (22.5° N, 88.5° E), Vishakhapatnam (18° N, 83° E) and Seychelles Islands (4.5° S, 55.5° E), (Fig. 1). These mean values were used for the computations of the fluxes across the different sections. In order to check the validity of the assumption, the total flux near a station was computed by multiplying the surface flux by the local equivalent humidity height and compared to the total flux determined at the station. Some results are given in Table 2 (throughout the paper metric tons are used). The mean fluxes were computed across 2, 3, or 4 unit sections. The agreement is fairly good. If the vertically integrated flux is taken as a reference, the accuracy of the determination of the total flux using the surface flux and the concept of equivalent moisture height is within 30%. Thus, there is some confidence in water budgets which can be obtained using this method. From the values of the equivalent moisture heights at the stations, an interpolation or extrapolation is made to determine the value of this parameter at different points along the boundaries. Evaporation over the ocean was computed from the bulk aerodynamic formulas (Cadet and Reverdin, 1981). Precipitation is estimated as a residual in eq. (2).

4.2. *Water vapour budgets over the Arabian Sea*

The southern boundary of the polygon is located at 1.25 degrees north. The western boundary line lies along the East African coast. The eastern boundary is along the western coast of India at a distance of about 200–300 km. This boundary has not been taken too close to the coast in order to obtain a true estimate of the flux. Choosing a boundary closer to the coast would have resulted in a smaller flux due to the influence of the decrease of the surface wind intensity at the coastal stations used in the assimilation scheme. The Arabian Sea is quite appropriate to the type of analysis performed in this paper. Thus one assumption is that the vertical flux at the top of the box (500 mb) is equal to zero. This is true if convective activity is weak over the considered polygon. Over most of the Arabian Sea there is an inversion layer which inhibits the development of convective clouds: thus, the vertical flux of water vapour at 500 mb is very weak.

Fig. 8 gives the fluxes at the grid points, the total fluxes across the different walls, the evaporation and the precipitation for July. The larger input occurs on the western part of the southern boundary. The larger output flux takes place on the northern part of the eastern wall. The total output flux across that boundary is greater than the input flux across the southern boundary. The flux across the western boundary is also positive. The positive value of the net flux divergence which represents the difference between the evaporation and the precipitation within the volume implies that a part of the moisture is picked up by evaporation from the Arabian Sea. Thus, the percentage ratio of net total northward flux across the equatorial section to the net total eastward flux across the west coast section is about 70%. Similar percentages were found by Saha (1970). The ratio of flux budget to the output flux is about 50%. This result suggests

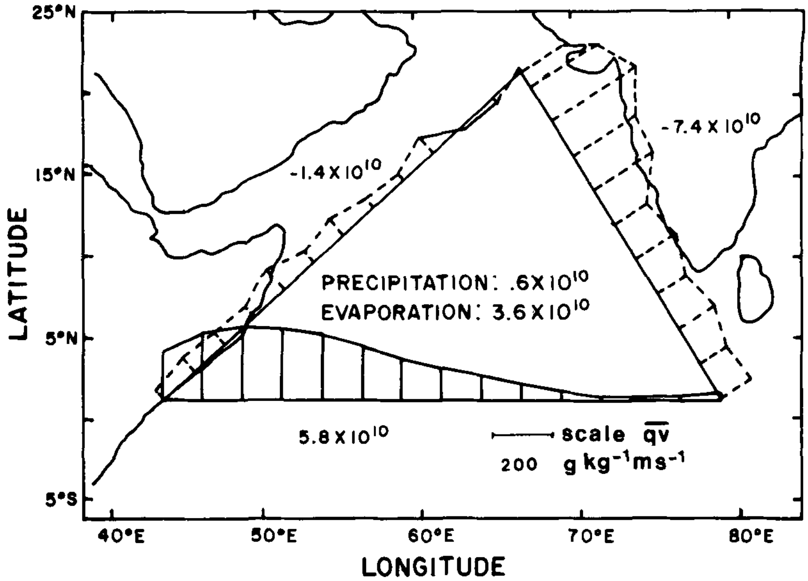

Fig. 8. Water vapour budget over the Arabian Sea. Unit: metric ton day^{-1}. July 1975. The surface water vapour flux ($g\ kg^{-1}\ m\ s^{-1}$) at the grid points across the different boundaries and the scale of these fluxes are given. Solid lines indicate input fluxes whereas dashed lines refer to output fluxes.

that about 30% of the moisture supplied by the southwesterly flow across the Indian coast is picked up over the Arabian Sea.

For July, the evaporation is found to be equal to 3.6 10^{10} metric ton day^{-1} which gives 0.2 10^{10} metric ton day^{-1} for the precipitation, i.e. a mean height of 0.45 mm day^{-1} over the total surface of the triangle. This result is in good agreement with observations and analysis of cloud cover, which suggests that precipitation is weak over the Arabian Sea except off the west coast of India.

Table 3 gives the fluxes, evaporation and precipitation during the different months. The larger fluxes across the southern and eastern boundaries occur in July. The monsoon months are characterized by a large increase of the flux across

Table 3. *Water vapour budgets over the Arabian Sea and the Bay of Bengal (output flux positive, input flux negative). Unit: 10^{10} metric ton day^{-1}*

	May	June	July	August	Sept.
Arabian Sea					
Southern boundary	−3.9	−6.9	−5.8	−5.8	−5.3
Eastern boundary	+4.5	+9.2	+7.4	+8.7	+7.2
Western boundary	+0.6	+0.8	+1.4	+0.6	+0.9
Flux divergence	+1.2	+3.1	+3.0	+3.5	+2.8
Evaporation	+3.0	+3.9	+3.6	+3.4	+3.3
Precipitation	+1.8	+0.8	+0.6	−0.1	+0.5
Bay of Bengal					
Southern boundary	−1.1	−2.3	−1.3	−1.8	−1.4
Eastern boundary	+2.7	+5.2	+2.2	+4.2	+3.3
Northern boundary	−0.5	+0.7	+0.9	+0.7	+0.7
Western boundary	−1.5	−2.5	−2.1	−2.4	−1.8
Flux divergence	−0.4	+1.1	−0.3	+0.7	+0.8
Evaporation	+1.6	+2.0	+2.0	+1.7	+1.8
Precipitation	+2.0	+0.9	+2.3	+1.0	+1.0

the eastern wall: compared to May, the value in June has doubled. The flux across the western boundary has always the same value except in June where it is stronger. This latter flux is smaller compared to the fluxes across the other boundaries. The percentage ratio of total northward flux to total eastward flux lies between 60% and 75% during the monsoon months whereas in May this ratio rises up to 88%, but this stronger value could reflect the different vertical structure of the lower troposphere during May. These results suggest that 70% of moisture crossing the west coast of India is supplied by the southern hemisphere and 30% is picked up by evaporation from the Arabian Sea.

Evaporation has nearly the same value during all the months except in September whereas precipitation is weak in June, July, August, and September. In May, precipitations are important and as evaporation is also high, it means that during that month water evaporated from the Arabian Sea serves locally for the development of the weather. This is in good agreement with the location of intense convective activity, associated with ITCZ, over central Arabian Sea before the onset of the monsoon. In August, negative precipitation is found: this wrong value results from the inaccuracy in the estimations of the different fluxes.

4.3. *Bay of Bengal*

Fig. 9 gives the fluxes for June 1975 across the different walls. Input fluxes with comparable intensities take place through the southern and the western boundaries. This latter one is due to the southwesterly flow over western India. A large output flux takes place through the eastern wall, i.e. about twice as large as the input flux through the southern wall. The total net flux divergence is positive, i.e. a part of the output flux comes from evaporation. The intensity of net flux divergence is weak compared to the intensity of the fluxes across the different walls. Evaporation was computed over the polygon and reaches 2 10^{10} metric ton day^{-1} in June. Only a small part of this water is transported across the boundaries of the polygon. Nearly 75% is used locally for the development of the weather. It is well known that during the monsoon, this region is very cloudy and the precipitations are important (Sadler, 1969; Rao et al., 1976). Monsoon depressions also propagate across the Bay of Bengal and bring important precipitation along their path.

Table 3 gives the different fluxes as well as the evaporation and the precipitation for the different months. The flux divergence is very weak and precipitation is important. Water vapour picked up by evaporation over the ocean seems to be used largely for local weather development.

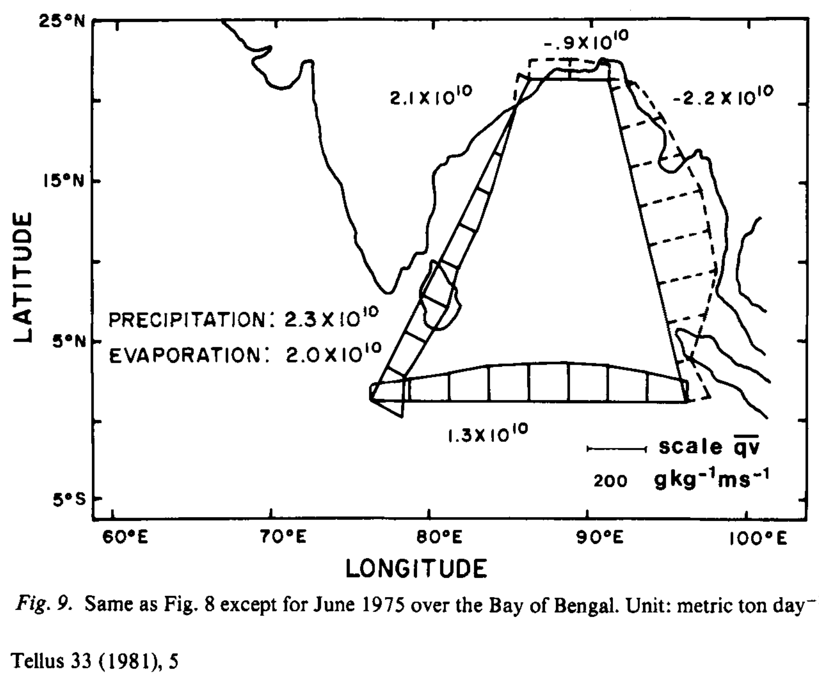

Fig. 9. Same as Fig. 8 except for June 1975 over the Bay of Bengal. Unit: metric ton day^{-1}.

5. Conclusions

Water vapour transport over the Indian Ocean during the 1975 Indian summer monsoon has been studied using twice daily assimilated fields at surface level and upper air data at meteorological stations. The main results of this study are:

(1) There is a large increase of surface water vapour fluxes over the Arabian sea during the onset of the monsoon along the western coast of India.
(2) Surface fluxes of water vapour are characterized by large amplitude variations with a typical period around 10 days. Periodic variations with a 10-day period can also be noted on time series of wind components, water vapour mixing ratio and rainfall over India.
(3) Correlation studies between different sections perpendicular to the intense low-level flow in the western Indian Ocean suggest that the forcing of these oscillations is located in India.
(4) Water vapour budgets over the Arabian Sea show that about 70% of the water vapour that crosses the western coast of India originates from the Southern Hemisphere whereas 30% comes from evaporation over the Arabian Sea.
(5) In the Bay of Bengal, the fluxes across the Burma coast are important and water vapour picked up be evaporation over the ocean is used mostly for local weather development.

Much more needs to be done to estimate more accurately the transport of water vapour over the Indian Ocean, to understand its variations and their relationship with rainfall over India. This investigation is now underway, thanks to the 1979 MONEX effort which has provided the most comprehensible data coverage over the area, especially the Arabian Sea and the Bay of Bengal.

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ПЕРЕНОС ВОДЯНОГО ПАРА НАД ИНДИЙСКИМ ОКЕАНОМ

Изучается перенос влаги над Индийским океаном в период летнего муссона в Индии. При этом используются метеорологические поля на поверхности на сетке размером 2,5° за два срока в сутки и данные по свободной атмосфере. Представлены суточные изменения потоков влаги у поверхности через различные разрезы. В Аравийском море начало муссона характеризуется большим увеличением потоков влаги у поверхности. Основной особенностью этих потоков является наличие колебания с главным периодом в 10 ± 2 дня. Это колебание приводит в основном к колебанию компонент скорости ветра, а не к периодическим флуктуациям отношения смеси. Это колебание, замеченное также в осадках, может быть связано с колебанием крупномасштабной системы муссона. Анализ коэффициентов корреляции между потоками через различные разрезы в Аравийском море дает основание полагать, что периодические вариации интенсивности ветра и, следовательно, потоков влаги вызываются эффектами вниз по направлению ветра.

Над Аравийским морем и Бенгальским заливом были оценены среднемесячные бюджеты влаги. Результаты показывают, что около 70% влаги, пересекающей западный берег Индии, приходит из Южного полушария, в то время как 30% набирается путем испарения над океаном к сереву от экватора. В Бенгальском заливе влага, испарившаяся над океаном, в основном используется, по всей видимости, для локального развития погоды.