Water Vapor Transport over the Indian Ocean during the 1979 Summer Monsoon.  
Part I: Water Vapor Fluxes

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ABSTRACT

Water vapor transport over the Indian Ocean during the 1979 summer monsoon season is studied. The analysis is based on wind fields from the European Centre for Medium Range Weather Forecasts and humidity fields derived from a three-layer predictable water dataset. Fields of zonal and meridional water vapor fluxes show significant variations over the north Indian Ocean in association with the different phases of the 1979 monsoon. Whereas after the onset, the cross-equatorial water vapor flux west of 50°E does not vary much; it undergoes significant fluctuations east of that longitude. The bulk of water vapor crossing the western coast of India comes from the Southern Hemisphere. The latitude band between 10° and 20°S appears as a major source of moisture during the northern summer. The major moisture supply for the western coast of Burma and Thailand is advected over the Bay from the Arabian Sea branch of the monsoon. The water vapor flux across the west coast of India undergoes large amplitude variations in relation with the active/break cycle of the 1979 monsoon (onset, active, break and revival periods). During active periods, the moist flow over the Arabian Sea strengthens and deepens. The water vapor flux across the west coast of India is well related to rainfall along the coast. The early retreat of the 1979 monsoon is associated with a decreasing trend in moisture transport over the Arabian Sea. In the Bay of Bengal, the cross-equatorial flux is not affected by the break/active cycle of the monsoon. There are strong surges of northward flux into the Bay. Some of them are related to the formation of Bay depressions.

1. Introduction

This paper is the continuation of a work on atmospheric water vapor content, fluctuations and transport over the Indian Ocean during the 1979 summer. In Cadet (1983), the method used to derive fields of precipitable water (PW) from Tiros-N moisture data, subjective estimates of PW from cloud images and the relative humidity FGGE Level III-b dataset was presented. Mean fields were also analyzed. In a companion paper, Cadet (1986) studied the fluctuations of the fields of PW. Meridionally propagating perturbations related to the break/active cycle of the 1979 monsoon were investigated. In the present paper, we are studying water vapor transport using as an initial data basis the fields of PW presented and discussed in the previous two papers, and the Level III-b wind fields from the European Centre for Medium Range Weather Forecasts (ECMWF).

The summer monsoon is characterized by a large cross-equatorial low-level air flow over the Indian Ocean. This flow is particularly intense along the coast of East Africa because of the existence of the low-level Somali jet (Findlater, 1969). Along with evaporation over the Arabian Sea, this water supply from the Southern Hemisphere is an important source of moisture for the Indian monsoon. Due to the lack of wind and humidity data over the ocean, there is an uncertainty about the source of moisture for monsoon rainfall.

Using data collected during the International Indian Ocean Expedition (IOE) in 1963–64, Pisharoty (1965) computed the water budget in a volume covering the Arabian Sea during July 1963 and 1964. He concluded that the influx of water vapor across the equator was small compared to evaporation over the Arabian Sea. However, in that study only a few upper air stations were used and the bulk of the cross-equatorial flux associated with the then unknown Somali Jet was missed. Using the same dataset and additional upper air soundings, which captured the influence of the Somali jet, Saha (1970) found that the cross-equatorial flux accounted for 60%–80% of the net total flux across the west coast of India. For the same period, Saha and Bavadekar (1973) computed water vapor budgets over the Arabian Sea and found that the interhemispheric flux was 30% larger than Arabian Sea evaporation. Ghosh et al. (1978) using data gathered during the MONEX-73 (MOnsoon Experiment) experiment in May–July 1973 found that the moisture flux across the west coast of India was more than twice the moisture flux across the equator from the Southern Hemisphere. This result, stressing the importance of evaporation

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over the Arabian Sea, was in opposition to Saha’s findings. Using climatological data from ship observations, Hastenrath and Lamb (1980) concluded that the cross-equatorial flux of moisture was the dominant source of moisture for southern Asia rainfall. Cadet and Reverdin (1981a,b) studied the water vapor transport over the Indian Ocean during the 1975 summer using ship observations and some upper air soundings. They found that over the Indian Ocean, 80% of the total interhemispheric flux of moisture entered the Arabian Sea with the bulk taking place west of 60°E (50%) whereas 20% of this total entered the Bay of Bengal. Their water vapor budget estimates showed that about 70% of the water vapor crossing the western coast of India came from the Southern Hemisphere. The intensity of cross-equatorial moisture fluxes along the African coast determined by Van de Boogard and Rao (1984) using some of the aircraft measurements obtained during MONSOON-77 agreed with the estimation of Cadet and Reverdin (1981b).

Most of the previous studies were based on the analysis of ship observations, few irregularly spaced upper air soundings and concentrated on mean monthly fields or during specific periods without any reference to the break/active cycle of the monsoon. This may explain the disagreement between the results. During recent years, the large amount of good quality data gathered during FGGE (December 1978–79) resulted in investigations of water vapor transport with a finer time and space resolution than previous studies. Howland and Sikdar (1983) performed a detailed investigation of water vapor transport over the Arabian Sea during a few days before and during the onset of the 1979 monsoon based on dropsondes, ship and island radiosondes, and satellite-derived winds. They observed important changes between the premonsoon and monsoon onset periods in both the mean kinematic and moisture fields.

Mohanty et al. (1983) used the FGGE level III-b dataset to study the heat and moisture budgets over a large domain of Asia and the Indian Ocean north of the equator and west of 75°E. They observed a moisture build-up before the onset of 1979 monsoon and large variations of moisture fluxes entering the domain in association with the different phases of the 1979 monsoon. Pearce and Mohanty (1984) studied the mean tropospheric (100–10 kPa) moisture flux during biweekly periods of May and June 1979 over a large scale MONEX area (40°N, 40°S; 0°, 150°E). They showed that a major part of the moisture necessary to provide the latent heat release over India is supplied by evaporation from the Indian Ocean south of the equator and off the horn of Africa. This latent heat release, in turn, maintains the strong cross-equatorial flow.

In a comprehensive study of the 40–50 day fluctuations over the summer monsoon domain, Murakami et al. (1984) investigated the water vapor transport and moisture budget over the Indian Ocean and the western Pacific Ocean during the 1979 summer. In July the net moisture flux from the Southern Hemisphere corresponded to 88% of the moisture flux across the west coast of India. They concluded that the flux from the Southern Hemisphere was not large enough to maintain the rainfall over southern Asia and that evaporation over the Arabian Sea constituted a key contribution to the moisture supply for monsoon rains.

In this paper, a detailed study of water vapor transport during the entire 1979 monsoon season is presented. The initial data basis is made of twice-daily wind (Level III-b dataset) and PW fields. This work is reported in two parts. This paper (Part I) is devoted to the presentation of the data and the analysis of biweekly fields of zonal and meridional water vapor fluxes and of the time series of fluxes across different sections in the Indian Ocean. The results of water vapor budget studies will be presented in Part II.

2. The data

In this study, horizontal wind and specific humidity fields at different pressure levels at 00 and 12 UTC are used. The analysis covers the period from 1 May to 15 September 1979. The spatial domain is 30°S–30°N and 30°E–120°E. A two-degree latitude by two-degree longitude grid system is used at the surface, 100, 85, 70, 50, 40 and 30 kPa pressure levels.

a. Horizontal wind fields

The wind fields are the Level III-b wind dataset produced by the European Centre for Medium Range Weather Forecasts (ECMWF) and described by Bengtsson et al. (1982). Since this data is on a grid with a resolution of 1.875°, a two-dimensional cubic-spline routine is used to transfer the Level III-b fields onto a 2° × 2° grid system.

b. Specific humidity fields

The specific humidity fields at the pressure levels mentioned before are determined from the PW dataset compiled by Cadet (1983) to which the reader is referred for a complete description. The PW dataset is defined for three layers: Sf–70 kPa, 70–50 kPa and 50–30 kPa. From a comparison with dropsonde humidity data obtained during MONEX, a relative accuracy of about 13% for the PW data was estimated. To determine the specific humidity at each pressure level from the three-layer PW data, a prescribed decrease with height of specific humidity is assumed. The vertical profile is fit to a second-order polynomial evaluated at each grid point.

The accuracy of the specific humidity fields derived from the PW data is determined by making comparisons with specific humidity values obtained from off synoptic time dropsondes and ship upper air reports.
The specific humidity values are spatially interpolated at the location of the sounding with a nine-point Lagrangian interpolation scheme and linearly interpolated at the time of the soundings from the fields at 0000 and 1200 UTC. It is found that the derived specific humidity fields underestimate the dropsonde and ship soundings in accordance with the study of the accuracy of the PW fields (Cadet, 1983). Gruber and Watkins (1979) found a similar result when comparing humidity values obtained from Tiros-N to upper-air sounding data over the United States. Table I gives some statistics of the comparison below 70 kPa where the bulk of water vapor transport is taking place. The mean difference is defined as the average of the ratio of the absolute difference between the radiosonde specific humidity and specific humidity from the fields to the radiosonde specific humidity. These comparisons reveal a systematic error so the specific humidity fields are modified with the coefficients of the regression equation determining the line of best fit between the PW fields and the dropsonde and ship values of specific humidity. The modified specific humidity shows an improvement in all the comparison statistics (Table I). Below 70 kPa the accuracy is better than 10%.

3. Mean fields of horizontal water vapor fluxes

To follow the broad evolution and fluctuations of the water transport during the monsoon season, layer averages of water vapor flux for the onset, break and active periods are now presented.

The layer averaged horizontal water vapor flux at each grid point is estimated using the following equation:

\[ F = -\frac{1}{g} \int_{P_b}^{P_l} q v dp \]

with \( g \) the acceleration of gravity, \( p \) the pressure, \( P_l \) the pressure at the top of the layer, \( P_b \) the pressure at the bottom of the layer and \( qv \) the water vapor flux (zonal or meridional) at each pressure level (a linear vertical variation is assumed) and \( F \) the vertically integrated flux of water vapor at a specific grid point.

The atmospheric layers for which the water vapor transports are determined are Sfc–70 kPa and 70–50 kPa. These two layers were chosen because it has been shown by Bavadekar and Mooley (1978) that at least 80% of the water vapor flux across the west coast of India occurs below 70 kPa.

a. The onset phase

Due to the late establishment of the 1979 monsoon circulation over the northern Indian Ocean and the onset of the monsoon rainfall around mid-June, the first half of June was rather typical of premonsoon conditions whereas the second half described a post-onset period (Fein and Kuettnner, 1980; WMO, 1981).

Figures 1a and 1b give the mean meridional and zonal water vapor flux for 1–15 June in the Sfc–70 kPa layer. Compared to May (not shown), the low-level northward transport across the equator into the western Arabian Sea has increased by about 20%–40%. The eastward flux between the Equator and 10°N also increased significantly between May and the first half of June (100%–200%) and is strongest between the equator and 6°N. At the beginning of June, anticyclonic conditions still prevailed over the Arabian Sea with a southward flux along the western coast of India as shown in Fig. 1a. A split in the low-level flow indicated in the mean flux field may be due to the intense shear line existing over the southeastern Arabian Sea from about 13 to 15 June (Krishnamurti et al., 1980). A sustained northward flux up the Mozambique channel can be also noted.

The development of the onset vortex which characterized the onset of the 1979 monsoon and its displacement from the western coast of India toward the northwestern sector of the Arabian Sea was associated with the strengthening and deepening of the southwest flow over the western Arabian Sea and the westerlies over the central and eastern Arabian Sea. Figures 2a and 2b, which show the horizontal water vapor flux in the Sfc–70 kPa layer for 16–30 June, illustrate the strengthening of the cross-equatorial flux west of 60°E and the moisture transported by the low-level Somali jet. Off the coast of East Africa, the increase was over 100% between the first and the second halves of June. The eastward flux over the Arabian Sea also strengthened dramatically. There was a similar increase in eastward water vapor transport over India and the Bay of Bengal. Whereas in May and the first half of June there was some significant interhemispheric flux into the Bay of Bengal (Fig. 1a), the maximum northward flux during the second half of June was located near the head of the Bay of Bengal. This was due to the presence of two depressions in the Bay of Bengal and the west-southwest flux from the Arabian Sea and India which fed into them. In the Southern Hemisphere, no increase in the strength of the trade winds can be noticed between the two halves of June. The latitude belt between 10° and 20°S appears as a major moisture source during the northern summer confirming studies of Ramage and Raman (1970) and Murakami et al.
(1984). There is once again a significant northward transport of water vapor up the Mozambique channel.

Figures 3a and 3b give the horizontal water vapor fluxes for 16–30 June in the layer 70–50 kPa. Compared to the first half of June (not shown) there was a deepening of the monsoon flow during the second half of June. The eastward flux over the Arabian Sea intensified and was located more south and east than the Sfc–70 kPa maximum. This resulted from the deepening of the monsoon flow as it moved eastward. Northerly flux prevailed over the northern Arabian Sea indicative of shallow monsoon flow topped with drier northerly air from the continent. Mainly east of 60°E, a large part of the Indian Ocean was characterized by southward flux. Figures 2 and 3 indicate the origin of the major moisture supply for the western coast of Burma and Thailand; water vapor was advected from the west and was part of the large-scale cross-equatorial flow in the Arabian Sea.

b. Break and active periods

The monsoon flow during 1979 was characterized by four different epochs: strong monsoon, break, revival and the last break from which the 1979 monsoon never revived (Fein and Kuettnner, 1980; WMO, 1981). In the middle of July break conditions were prevailing over the Arabian Sea, India and the Bay of Bengal. The break was characterized by weaker circulation and rainfall amount well below normal for most of the Indian land mass except the foothills of the Himalaya and extreme Southern India.

Figures 4a and 4b give the meridional and zonal flux for the break period (14–25 July) in the layer Sfc–70 kPa. In terms of water vapor transport, the break is best shown in the zonal field (Fig. 4b). Compared to the active period (Fig. 2b), the decrease of zonal flux over the central and southern Arabian Sea was about 30%–40% while the decrease reached 50%–100% in the southeastern Arabian Sea near the west coast of India. A slight increase of the eastward water vapor flux existed over the northern Arabian Sea and northern India in association with the northward shift of the monsoon trough during the break. Significant decreases of 100%–150% were also found in the eastward water vapor flux over the central and southern Bay of Bengal.

The changes in the meridional flux field between late June and the break period were not as striking as the zonal component changes over the Arabian Sea except for a significant increase in the northward flux.
in the south Bay of Bengal. The strongest cross-equatorial flux during the break period was still located around 45°–50°E, but there was a general decrease in the intensity of the interhemispheric flux between 40° and 70°E.

One important change in the Sfc–70 kPa water vapor transport field which may also be related to the break and active periods of the monsoon occurred in the flux up the Mozambique channel. Compared to the active period of late June, the flux was much weaker. Along with this feature, there was a decrease in the water vapor transported by the southeast trades in the Southern Hemisphere. The coexistence of the weaker transport by the southeast trade winds and up the Mozambique channel may be one of the factors contributing to the weak monsoon flow across the Equator and over the Arabian Sea during break periods.

After the break, the monsoon circulation began to re-intensify in late July and early August. To capture the revival over most of the domain, the period chosen was 26 July–5 August (Figs. 5a and 5b). During the revival period, there was a dramatic increase in eastward water vapor flux south of 15°N, which ranges from 30%–50% over the central Arabian Sea to 50%–100% over the eastern Arabian Sea, southern India and the Bay of Bengal. In relationship with the southward shift of the monsoon trough back to its normal position, easterly flux was quite reduced over the northern Arabian Sea and an easterly flux can be noticed over most of the northern India and the head of the Bay of Bengal.

During the revival period, the Southern Hemisphere trades between 40° and 55°E strengthened and took on a more southerly component. The stronger northward flux south of the equator led to a stronger cross-equatorial water vapor transport so that there was a 20%–50% increase in interhemispheric flux. The return of a significant northward flux up the Mozambique channel can also be noted.

4. Water vapor flux across different sections

To further document the fluctuations of the monsoon water vapor transport, time series of the fluxes across different sections have been determined. The following equation was used:

$$F_v = -\frac{1}{g} \int_{P_b}^{P_s} \int_0^L q v_n dp dl$$

where $L$ is the horizontal length of the section and $v_n$ is the wind component normal to the horizontal section. The fluxes were computed for four different layers: Sfc–85 kPa, 85–70 kPa, 70–50 kPa and Sfc–50 kPa. The time series were low-pass filtered with a 24-hour moving average to reduce short time-scale fluctuations such as the diurnal variations.

fig 3. as in fig 2 except for the 70-50 kPa layer. Contour intervals are 20 kg m⁻¹ s⁻¹.

fig 4. as in fig 1 except for 14-25 july (break period).
Most of the previous studies on water vapor transport over the Arabian Sea were concerned with the role interhemispheric flux played in determining the transport of water vapor across the west coast of India. Consequently, equatorial sections were chosen as 42°–50°E, 50°–60°E, 60°–70°E, 70°–80°E, 80°–90°E and 90°–100°E. Another section is also taken along the west coast of India. In addition, water vapor transports were also computed across four-degree long sectors, which were normal to the direction of the mean low-level (85 kPa) Somali jet. Figure 6 shows the location and the length of the equatorial and Indian sections and the cross-jet sections. The mean position of the jet was determined by finding the location of the 85 kPa wind maximum for each latitude on every observation from 1 June to 31 August.

a. Arabian Sea equatorial sections

The time series of the cross-equatorial water vapor flux (×10^7 kg s⁻¹; a unit) in the Sfc–85 kPa layer for 42°–50°E, 50°–60°E and 60°–70°E is shown in Fig. 7. Between 42° and 50°E the flux remained about the same during the first month. No dramatic onset in the water vapor transport across the equator can be seen. At the beginning of June, the cross-equatorial flux began to gradually increase until it reached a maximum value of 17.5 units. After mid-June, the flux across 42°–50°E was quite constant until mid-August when it began to decrease. In the 70–50 kPa layer (Fig. 8a), the flux between 42° and 50°E was mainly southward up to the beginning of June, indicating that the northward interhemispheric flux was shallow before the onset of the monsoon and capped by drier air flowing from...
land as discussed in section 3a. Afterwards, the flux became positive. An estimate indicates that the 70–50 kPa flux contributed less than 15% to the total flux across the most western section in the Sfc–50 kPa.

During the entire month of May, the cross-equatorial flux was rather weak across the 50°–60°E section (Fig. 7b) with a gradual increase in the cross-equatorial flux associated with the strengthening of the monsoon around 5 June. The onset near the equator was characterized by the sudden increase of water vapor flux beginning around 10 June and reaching a maximum value of 25 units on 22 June. This is primarily due to the well-known increase in surface winds around 10 June (WMO, 1981). A minimum value occurred on 16 July which may be associated with a major break period. The revival period of 26 July to 5 August was marked by an increase of moisture flux.

This revival period was followed by a break characterized by a dramatic reduction of the cross-equatorial flux. After 15 August the intensity of the water vapor fluxes in the two layers were typical of premonsoon conditions. This break period never revived and gave the way to an early withdrawal which was the main reason for the failure of the 1979 monsoon.

As with the increase between preonset and onset periods, the fluctuations in the cross-equatorial water vapor transport associated with the break, revival and withdrawal phases of the monsoon were much larger across 50°–60°E than they were across 42°–50°E. The flux in the 70–50 kPa layer (Fig. 8b) underwent large amplitude fluctuations during the preonset period when anticyclonic conditions were prevailing over the Arabian Sea. The positive flux after mid-June indicates that the post-onset phase was characterized by a deepening of the moist layer whereas the layer was shallower during the break period.

Since the temporal variations of the cross-equatorial flux were much larger across 50°–60°E than across 42°–50°E, we conclude that the flux associated with the Somali jet located along the Horn of Africa was relatively steady compared to the interhemispheric flux between 50°–60°E. Due to the larger fluctuations across 50°–60°E associated with the various phases of the monsoon, the relative difference between the amount of water vapor transported across the equator between 50°–60°E and 42°–50°E also changed depending on the phase and strength of the monsoon. During the active phase of the monsoon following the onset (15 June–7 July), the total amount of water vapor transported between the surface and 50 kPa was about 20% larger across 50°–60°E than across 42°–50°E, whereas it was of equal magnitude across the two sections from 7 to 27 July, which includes the break. At the height of the break (17–18 July), the cross-equatorial flux across 42°–50°E was larger than across the other section. The revival period was characterized by a flux across the 50°–60°E section about 20% larger than the flux across the most western section.

The cross-equatorial flux across 60°–70°E was basically southward between 1 May and 13 June for the Sfc–85 kPa layer (Fig. 7c) as well as for the higher layer (Fig. 8). There was a lag of a few days between the increase of the flux associated with the monsoon onset across that section and the increase across the sections to the west. After mid-June, the trend of the flux across 60°–70°E was similar to the trend of the fluxes across the other sections even though the magnitude was very much reduced. Another interesting feature of the 60°–70°E interhemispheric flux was the southward transport of water vapor between 5 July till the end of July in the 70–50 kPa layer indicating that the cross-equatorial monsoon flow became very shallow during the break.

b. India west coast section

After the water vapor is transported across the equator, a certain amount of water vapor is picked up by evaporation over the Arabian Sea and advected towards the west coast of India. Figure 9 displays the time series of the water vapor flux across the west coast of India between 8°N and 20°N for the Sfc–85 kPa, 85–70 kPa and 70–50 kPa layers.

The different phases of the 1979 monsoon are all well defined by the fluxes across the west coast of India. The time series in the three layers were very similar in terms of shape and trends. This is consistent with a
deepening of the moist layer as the cross-equatorial air approaches the western coast (Grossman and Durrnan, 1984). Before the onset the flux was weakly positive in the lowest layer and negative in the 70–50 kPa layer. A preonset maximum was reached on 14 May. As discussed by Cadet (1986), this increase was related to a meridionally propagating perturbation originating over the equatorial eastern Indian Ocean which when reaching India produced a larger interhemispheric pressure gradient. This increase of water vapor flux can also be seen on Fig. 7 and was associated with a temporary increase in the cross-equatorial winds (Schott and Partagas, 1981). Afterwards, the water vapor transport decreased and then gradually increased until it explosively strengthened around 15 June, lagging by five days the increase noted in Fig. 7. In the Sfc–85 kPa layer, the maximum eastward flux across the west coast of India was reached one week after, four days after and at the same time as the maximum northward cross-equatorial flux across, respectively, the 42°–50°E, 50°–60°E and 60°–70°E sections. This suggests that during the onset phase the establishment of the monsoon flow over the Arabian Sea starts in the western Arabian Sea.

The flux minimum across the equatorial sections preceded the coastal section minimum by one week. These minima were associated with the 16 to 24 July break in the 1979 monsoon. As for the onset, the changes in water vapor transport associated with this mid-July break and the subsequent revival were more drastic than across the equator.

During the onset, active and revival periods of the monsoon, the strength and depth of the monsoon westerlies increased and more water vapor was transported by the layer above 70 kPa. During these periods, the flux in the 70–50 kPa layer can contribute from 15% to 25% of the total eastward flux. During preonset and weak periods this contribution is much less than 15%. Thus, as mentioned previously the active periods do not correspond only to an increase of the eastward flux over the Arabian Sea but also to a deepening of the layer over which it occurred. Comparison of Fig. 9c and Figs. 8a and 8b shows the deepening of the layer of the eastward flux from the western to the eastern Arabian Sea.

c. Water vapor transport and west coast rainfall

The large increase of water vapor flux across the west coast of India during mid-June fueled the onset of the monsoon rains over western India. Figure 10 gives the histograms of the average rainfall over the subdivisions along the west coast of India (Konkan, coastal Karnataka and Kerala) as given by the supplement to the Indian Daily Weather Report as well as the time series of the water vapor transport in the Sfc–85 kPa layer across the southern-half coastal section (Fig. 10a), and across the equator between 50° and 60°E (Fig. 10b).

The trends between rainfall and water vapor flux across the west coast of India were similar. The different phases of the 1979 monsoon as seen on the rainfall

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Fig. 9. Time series of the water vapor flux (10^7 kg s^-1) across the west coast of India in the (a) Sfc–85 kPa layer, (b) 85–70 kPa layer and (c) Sfc–50 kPa layer.

Fig. 10. Time series of the water vapor flux (10^7 kg s^-1) across the southern section of the west coast of India and across the equator between 50° and 60°E(b) along with precipitation over the subdivisions of the western coast of India.
record are clearly identified on the time series of the water vapor flux. The large increase of water vapor flux was associated with the first large rainfall. The break in the activity of the monsoon just after mid-July was associated with a weak water vapor flux across the west coast of India. The revival phase was marked by an increase of water vapor flux which stayed at high values even when precipitation had decreased.

Figure 10b displaying the flux across the equatorial section between 50° and 60°E shows that rainfall fluctuations were in phase with cross-equatorial flux variations. The break in rainfall corresponded well to a minimum value of water vapor flux.

d. Bay of Bengal sections

The time series of cross-equatorial flux across 70°–80°E, 80°–90°E and 90°–100°E for the Sfc–85 kPa and 70–50 kPa layers are presented in Figs. 11 and 12.

Up to mid-June, the flux in the 70°–80°E section was on the average northward in the first layer and southward in the upper layer. After mid-June, the cross-equatorial flux was southward in both layers. During the monsoon season when the westerlies were well established over the Arabian Sea, the winds were deflected by the mountains forming a lee trough (Gadgil, 1977) and giving rise to a northwest flow which contributed to the southward flux. In the 80°–90°E section, the flux was mainly northward in the lowest layer except during the onset period. The cross-equatorial flux became southward in the higher layer after mid-June, thus indicating a shallower cross-equatorial flux after the onset. In the most eastern section, the flux in the lowest layer was southward before the onset became northward afterwards. The opposite seemed to take place in the 70–50 kPa layer.

While the moisture flux into the Arabian Sea and across the western coast of India (Figs. 7, 8 and 9) were for the most part positive, most of the cross-equatorial fluxes into the Bay of Bengal were nearly zero. This suggests that the cross-equatorial flow into the Bay barely contributed as a moisture source for the subcontinent monsoon. The Bay cross-sections do not give evidence of the break and active cycle of the monsoon. This indicates the difference in the dynamics of cross-equatorial flow between the Arabian Sea and the Bay of Bengal.

Some fluctuations can be associated with depressions. They are mainly seen in the 80°–90°E and 90°–100°E equatorial sections. One depression formed in the southern Bay by May 5 and moved northwestward and hit land by May 12. The associated surge can be seen first across 90°–100°E where maximum values were reached by 10 May. As the depression moved westward, the surge was found two days later across the 80°–90°E section and three days later across the 70°–80°E section. After the onset, some surges were associated with depressions—after mid-June, beginning.
of July and August and after mid-August. The surge just after mid-July resulted from break conditions over India and the Bay of Bengal. The southward turning of the flow south and east of the southern tip of India was much reduced and there was an enhancement of the northward flux.

e. Section perpendicular to the low-level jet stream

Figure 13 gives an $x$–$t$ diagram of the mean weekly water vapor flux across the different cross-jet sections in the Sfc–85 kPa layer. Four surges of water vapor flux occurred in the southern Indian Ocean near the beginning of June, July, August and September without any counterpart in the Northern Hemisphere. The onset, break and active phases of the monsoon were barely noticeable in the Southern Hemisphere but very well defined north of the equator. The downstream propagation of surges during the onset and the revival phases is seen by the later arrival of strong flux along each successive cross-jet sector between the equator and the west coast of India as indicated by the tilted dashed lines. The mid-July and end of July–beginning of September breaks were well defined over the northern Indian Ocean.

The water vapor transport in the 85–70 kPa layer (not shown) was very similar to the Sfc–85 kPa flux in regards to both temporal variations and relative changes. However, while the moisture transported across the Southern Hemisphere sectors in the Sfc–85 kPa layer was generally 60%–70% of the total flux between the surface and 70 kPa, this percentage was typically 50%–60% north of the equator. This smaller percentage was the result of a deeper monsoon flow over the Arabian Sea which, during the active periods, extended up to 60 kPa. Figure 13 also shows that maximum moisture transport occurred over the southwestern and south-central Arabian Sea. The decrease in the eastern part of the Arabian Sea can be attributed to moisture convergence due to the decrease in wind intensity near the west coast of India.

f. Spectral analysis

Power spectral analysis of the flux across the west coast of India in the Sfc–85 kPa layer is displayed on Fig. 14. The Maximum Entropy Method was used. The dominant period of the water vapor flux lies around 40–50 days. The same major periodicity is found for the time series of the fluxes across the equator. It suggests that the changes in the water vapor transport across the equator and over the Arabian Sea have the same periodicity as from changes in the planetary scale monsoon (Murakami et al., 1984).

5. Conclusion

This paper is the first part of a detailed investigation of the water vapor transport over the Indian Ocean during the 1979 summer monsoon. Wind fields from ECMWF and humidity fields derived from precipitable water fields were used as the basic datasets. Fields of horizontal water vapor flux during different phases of the monsoon and water vapor fluxes across different sections have been discussed.

Mean fields of meridional and zonal water vapor flux in the Sfc–70 kPa layer during preonset, post-onset, break and revival periods show that major changes were found in the northward transport up the Mozambique channel, the cross-equatorial flux and the eastward flux across the Arabian Sea, India and the Bay of Bengal. The largest changes occurred in the eastward transport over the Arabian Sea.

Time series of water vapor flux across the equator have shown that the bulk of the cross-equatorial flux into the Arabian Sea occurred west of 60°E. After the onset, the interhemispheric water vapor flux west of
50°E did not vary much due to the relative steadiness of the Somali jet whereas the flux east of 50°E underwent significant fluctuations during the monsoon season in association with the active/break cycle of the monsoon.

The time series of water vapor flux across the west coast of India were very similar to those across the equator emphasizing the important influence of interhemispheric flux in determining the flux across the west coast of India. However, the fluctuations of the flux across the coast had a much larger amplitude stressing the important changes in circulation and evaporation taking place over the Arabian Sea. The analysis of the flux across sectors perpendicular to the low-level circulation emphasized these results. It is also found that during active periods the monsoon moist flux was not only stronger but it was also deeper. A good relationship was also found between the flux across the west coast of India and rainfall there. In the Bay of Bengal, the cross-equatorial flux was modulated by the occurrence of Bay depressions.

In part II, a detailed investigation of water vapor budget over the Arabian Sea and the Bay of Bengal will be reported.

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