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Fluctuations of precipitable water over the Indian Ocean during the 1979 summer monsoon

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ABSTRACT

Fluctuations of precipitable water (PW) over the Indian Ocean during the 1979 summer season are studied. Time series of space average PW over the Arabian Sea show the existence of a well-marked oscillation of humidity related to the active/break cycle of the monsoon. This cycle around 30–50 days was the major feature of the 1979 monsoon. It also appeared on the pressure and zonal wind fields. This oscillation resulted from perturbations originating over the equatorial eastern Indian Ocean and propagating northward toward India. The arrival over India of a trough-ridge characterized by humid/dry conditions gave rise to an active/break monsoon. It is also suggested that this type of oscillation might be related to the date of the onset of the monsoon. Another periodicity around 10–12 days is also found in the PW and meridional wind fields. This fluctuation appears to be associated with a westward propagating mode north of the equator.

1. Introduction

The present paper is the second part of a work dealing with the problem of water vapour content of the atmosphere, its fluctuations and its transport over the Indian Ocean during the 1979 summer. In Cadet (1983a), the method used to derive fields of precipitable water (called PW thereafter) was presented. TIROS-N derived PW in three layers (surface–700 mb, 700–500 mb and 500–300 mb) over the Indian Ocean were merged with similar fields computed from the FGGE Level III-b data set. When compared to PW obtained from dropsonde humidity profiles, the final fields reached a relative accuracy of 13%. In Cadet (1983a), the monthly evolution of the mean fields was presented and discussed. Fields during active and break phases of the monsoon showed that important intraseasonal variations exist in the fields of PW during the Indian summer monsoon. The aim of this paper is to analyze the fluctuations of the humidity fields over the Indian Ocean.

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Summer rainfall over India exhibits large fluctuations during the same season. The Indian summer monsoon has two basic synoptic patterns: the active and break (weak) phases. These patterns alternate with a typical period of about 30–50 days. Yasunari (1981) suggested that this cycle is due to the meridional propagation of perturbations from the equatorial eastern Indian Ocean. Northward propagation of maximum cloud zones over the same area was noted by Sikka and Gadgil (1980) in relationship with the activity of the monsoon. Using the MONEX data set, Krishnamurti and Subrahmanyam (1982) demonstrated the northward propagation of troughs/ridges in the lower troposphere preceding active/break monsoons. Cadet (1983b) also studied similar perturbations using surface fields based on ship observations during the 1975 monsoon. Murakami et al. (1984) analyzed the Level III-b data set and focused on the 40–50 days mode of the 1979 summer monsoon. Although this data set has some deficiencies, these authors were able to reveal some details of this mode.

During the 1979 summer monsoon, the active/break cycle was well marked (see Fig. 2 displaying the rainfall along the western coast of India). The onset was largely delayed till mid-June and the monsoon was very active for about 20 days. Then a major break occurred around mid-July followed by a revival during the first half of August. The decrease of activity which followed augured the end of the 1979 season (Fein and Kuettner, 1980).

The monsoon also exhibits another periodicity around 2 weeks which appears during the active phase. In this frequency range, studying a certain number of elements of the monsoon, Krishnamurti and Bhalme (1976) found meridional teleconnections between the two hemispheres. Their hypothesis of a natural oscillation of the monsoon system due to cloud feedback and associate large-scale radiative effects was tested by Webster and Chou (1980) who were able to reproduce these fluctuations of rainfall with a model. Krishnamurti and Ardanuy (1980) investigating zonal interaction in the lower troposphere, found the existence of a 10–20 day westward propagating mode. In 70% of the cases studied, the association of the ridge passage of this mode was associated with a reported date of a break. Murakami (1980) also showed the existence of westward propagating 20–30 day perturbations in the outgoing long-wave radiation fields over the Northern Indian Ocean. Cadet (1983b) suggested a strong relationship between the meridional propagating modes around 30 days and the zonal propagating mode around 10–15 days. Goswami and Shukla (1984) recently simulated these two major periodic oscillations. They suggested that they result from interactions between moist convective and dynamical processes.

2. Time series over different domains

In Cadet (1983a), biweekly and monthly mean fields of PW in the three layers were presented to show changes occurring during the onset of the monsoon and its break/active phases. In order to study the fluctuations of PW, time series were determined over four different domains representing key areas over the Indian Ocean (Fig. 1). The first one is located over the Arabian Sea characterized by a westerly flow and convergence of moisture in its eastern part. Another domain is defined along the coast of East Africa where the strong cross-equatorial Somali jet is a prominent feature. The eastern equatorial Indian Ocean is

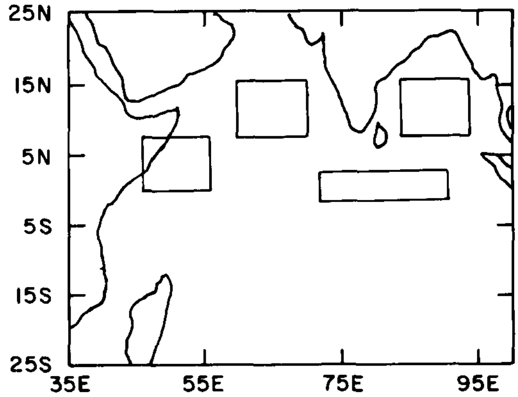


Fig. 1. The four domains over the Indian Ocean over which time series have been estimated.

characterized by the existence of a secondary convergence zone whose intensity is out of phase with the activity of the monsoon (Sikka and Gadgil, 1980). The last domain is located over the Bay of Bengal where monsoon depressions form.

On Fig. 2, the time series of PW over the Arabian Sea in the three layers are presented as well as rainfall along the west coast of India obtained from the Indian Meteorological Department as an index of the activity of the monsoon. The large time-scale oscillation characterized by large humidity around mid-June and the beginning of August is related to the active/break cycle of the monsoon. The same features can be seen in the two higher layers. Relatively dry air prevailed over the Arabian Sea before the onset when northerlies were flowing. Build-up of moisture over the Arabian Sea took place at least a week before the first intense rainfall over southwestern India. After the onset, moisture content dropped by 40–50%. A moisture build-up took place a few days before the revival after mid-July. During the early withdrawal of the 1979 monsoon, moisture decreased.

Fig. 3 presents PW in the lowest layer over the three other domains. Along the Somali coast, the onset was characterized by a decrease of moisture when the zone of convergence shifted rapidly northward. Short time-scale fluctuations ($\simeq 10$ days) are noted. Over the equatorial eastern Indian Ocean, no large fluctuation can be seen. Humidity was nearly constant and there is no evidence of an onset phase. The different phases of the 1979 monsoon can be seen over the Bay of Bengal. One

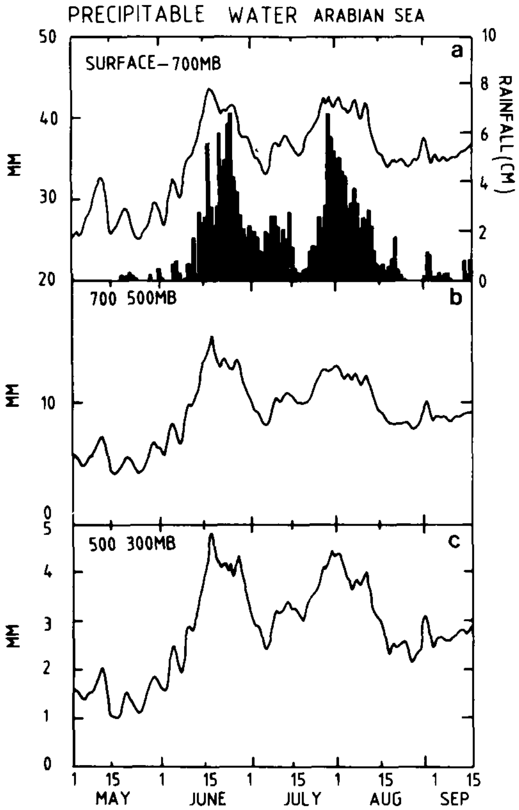


Fig. 2. Time series of PW over the Arabian Sea domain in the three layers. (a) surface–700 mb; (b) 700–500 mb; (c) 500–300 mb.

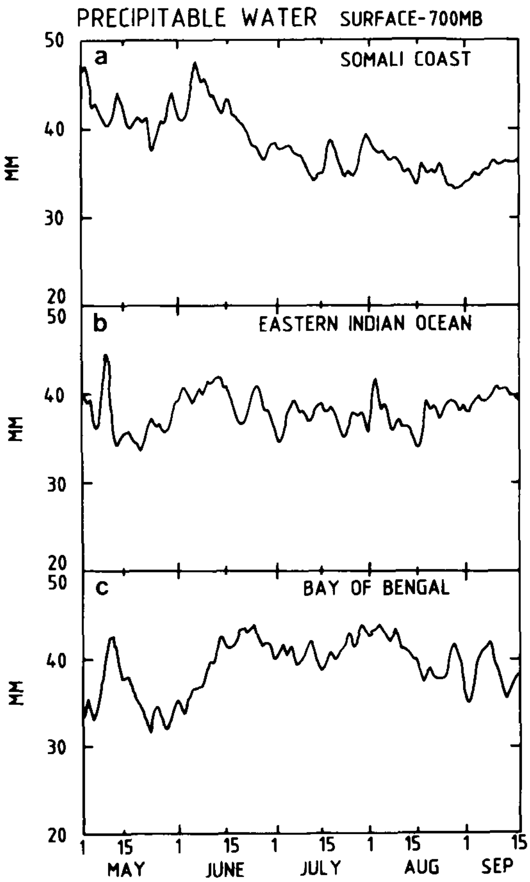


Fig. 3. Time series of PW in the first layer. (a) Somali coast; (b) eastern equatorial Indian Ocean; (c) Bay of Bengal.

interesting feature is the increase of moisture which took place around May 10 during the decrease of humidity along the African coast. As will be seen below, this is part of the oscillation of the tropical atmosphere giving rise to the break/active cycle of the monsoon and related to its onset.

3. Main periodicities

As stated in Section 1, two main periodicities are known to prevail over the Indian Ocean around 10–15 days and 20–50 days. The time series of PW at each grid point has been spectrally analyzed to find any evidence of these periodicities in the humidity fields. Fig. 4 represents the entire domain with 12 spectra of PW in the first layer. Each spectra is the average of 121 spectra computed at the 121 grid points of each subdomain of 10° × 10°. A lag-correlation method has been used with a maximum lag of 50 days. The time series at two adjacent grid points are not independent because the raw data were objectively analyzed to obtain the final fields. Confidence intervals have been estimated as follows. The number of degrees of freedom is equal to 5 for each individual spectrum. The radius of influence of the last scan of the objective analysis was 2·5°. Some geometric consideration shows that during the objective analyses, each grid point is influenced by about 20 other grid points, i.e., there are roughly 6 independent estimations of spectra in each 10° × 10° box. Thus, the final number of degrees of freedom

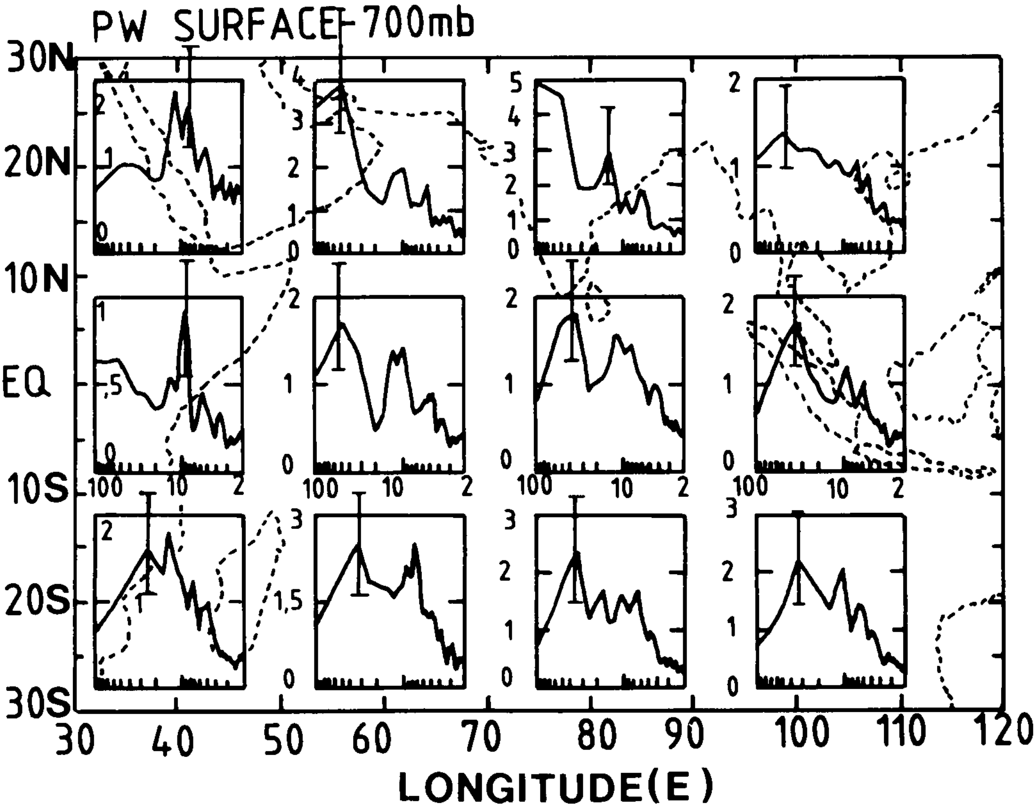


Fig. 4. Spectral analysis of PW time series in the layer surface–700 mb. Each spectra is the average of 121 spectra computed at each grid point. Confidence intervals at the 90% level are given.

is estimated to be 30. 90% confidence limits are indicated on the graph.

Two main periodicities can be seen on the spectra: 10–12 days and 30–50 days. The first existed all over the domain, whereas the latter, related to the break/active cycle of the summer monsoon, mainly prevailed east of 60° E. Confidence intervals show that these peaks are significant. The 30–50 day mode resulted from the succession of the different phases (activity) of the 1979 monsoon as revealed by Figs. 2, 3. Similar results were obtained for PW in the layer 700–500 mb, whereas weaker fluctuations seemed to exist in the upper layer.

Fig. 5 shows the geographical distribution of power spectral density between days 25 and 50 ($\int_{25\,\text{days}}^{50\,\text{days}} P(f)\,\mathrm{d}f$). The fluctuations related to the activity of the monsoon mainly existed over the Arabian Sea and at the longitudes of the Bay of Bengal from about 20° S northward. This latter domain is the area of major activity of northward moving perturbations studied by Yasunari (1979), Sikka and Gadgil (1980) and Krishnamurti and Subrahmanyam (1982). The fluctuations over the Arabian Sea are forced by these perturbations when they reach the Indian trough as shown by Cadet (1983b).

In Krishnamurti and Subrahmanyam (1982), the spectrum of the average zonal wind over the Arabian Sea was computed. It depicted the existence of a strong fluctuation of the circulation around 30–50 days. Fig. 6 gives the spectra of the zonal component of the wind at 850 mb from the Level III-b data set. The 30–50 day period was the major feature of the circulation north of the equator east of 50° E. It can be noted that the 10–12 day period is rather weak on the zonal wind and the peaks are not significant except in the southern

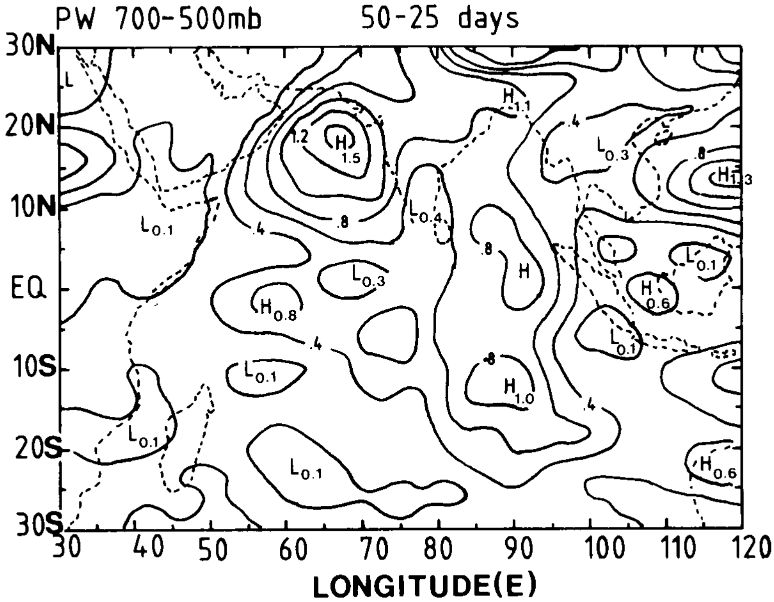


Fig. 5. Power density (mm^2) between 25 and 50 days of the PW in the layer 700–500 mb.

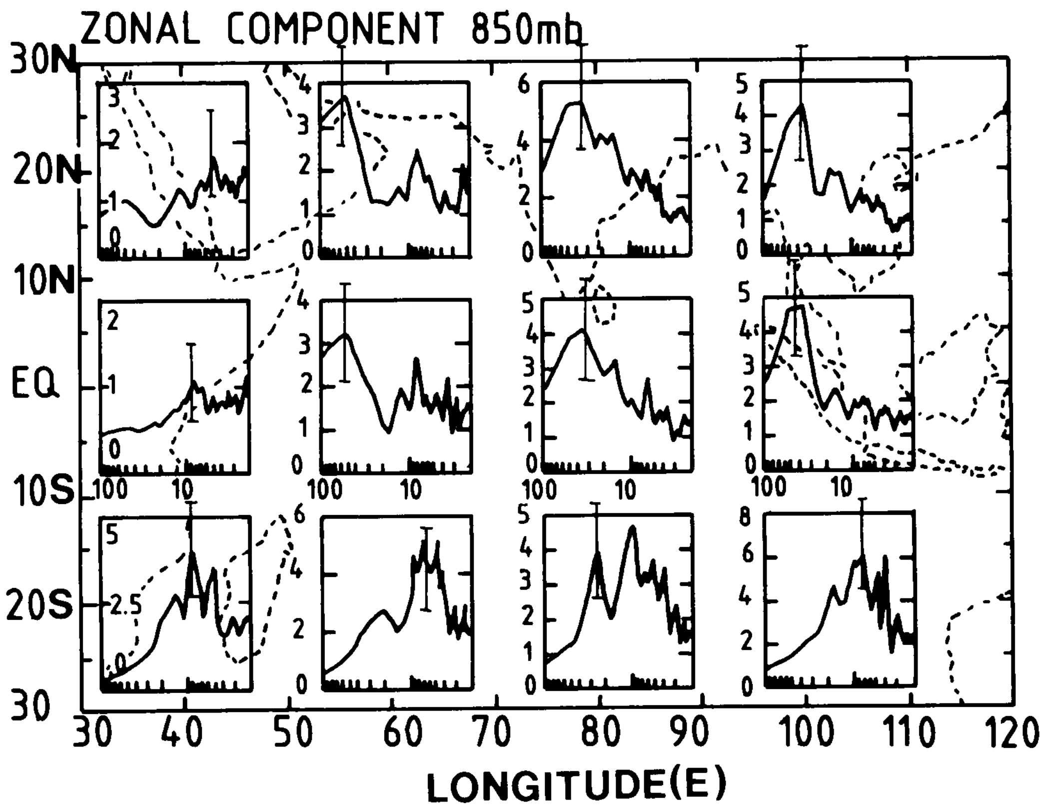


Fig. 6. Spectral analysis of the zonal component of the wind. Each spectra is the average of 121 spectra computed at each grid point. Confidence intervals at the 90% level are given.

hemisphere where they are related to eastward-moving perturbations. Spectra of the meridional component of the wind (not shown) exhibit only the fluctuations around 10–15 days with a rather weak 30–50 day signal except in the Bay of Bengal. This was also noted by Murakami et al. (1984).

4. Propagation of perturbations

Krishnamurti and Subrahmanyan (1982) have shown the northward propagation of ridges and troughs from the equatorial Indian Ocean during the summer 1979. In order to further document these perturbations, time-latitude diagrams of filtered PW and wind components were made at different longitudes. A butterworth filter was used to retain fluctuations with periods between 20 and 60 days (half response of the filter at these periods) (Murakami, 1979).

Fig. 7a gives the filtered PW in the layer surface–700 mb at 80° E. Northward propagation of dry and humid perturbations from the equator can be noted, whereas similar perturbations were propagating southward in the southern hemisphere. Before the onset (1–15 June) and the revival phase (15–31 July) of the 1979 monsoon above, normal humid conditions were prevailing over the equatorial domain whereas drier conditions existed north of 20° N. This corresponds to a well-known feature of the activity of the monsoon (Sikka and Gadgil, 1980): when break conditions are prevailing over India, convection is enhanced near the equator. These moist systems started to

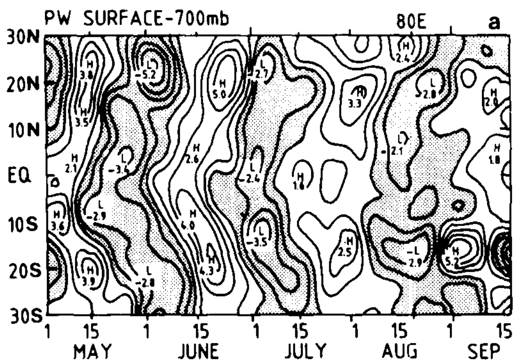
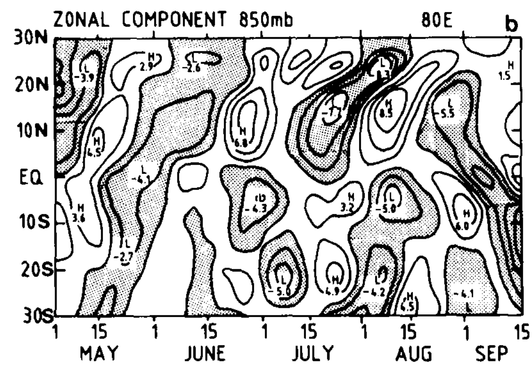


fig.7a



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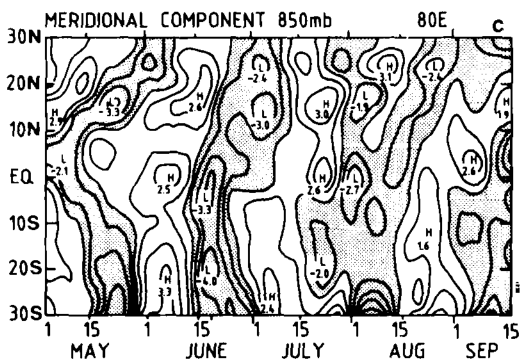

fig.7c

Fig. 7. Time-latitude diagrams of the filtered (a) PW in the layer surface–700 mb (contour interval in 1 mm); (b) zonal wind (contour inverval is 2 m s^{-1}); (c) meridional wind (contour interval is 1 m s^{-1}) at 80° E. The filter half-response frequencies are 20–50 days. Shaded areas correspond to negative anomalies.

propagate northward and by the time they reached Central India, the activity of the monsoon was maximum. Dry conditions existed over the equatorial area before the break period and when this dry perturbation reached India, a break started.

On Figs. 7b, c, the time-latitude sections of the filtered zonal and meridional components of the wind at 850 mb are displayed. North of the equator, there are some indications of a northward propagation. Comparing these figures to Fig. 7a, it can be seen that high humid conditions are associated with negative zonal and positive meridional winds, i.e., a trough (there was some lag between the wind components and the humidity as was noted by Murakami et al., 1984), whereas dry conditions are associated with a ridge. Thus the activity of the monsoon is associated with the arrival of ridges/troughs over central India originating from the equatorial area. After the onset, this cycle of the monsoon is associated with large fluctuations of the intensity of the circulation north of 10° N. No propagation similar to that found in the PW time-latitude diagrams can be noted on Figs. 7b, c in the southern hemisphere. This may result from the poor data coverage over that domain which does not allow a good description of a weak signal. On Fig. 7c, there is some indication of a southward propagation from the equator in the southern hemisphere during the two first oscillations.

It is interesting to note the existence of similar patterns prior to the onset of the monsoon. This suggests the possibility that the onset may be linked to these northward-propagating perturbations. A trough moved from the equatorial Indian Ocean during the second week of May. When this trough reached Central India, an onset did not take place, since several other conditions were not met. Then in 1979, the onset had to wait for the arrival of the next perturbation. This may explain the delay of the 1979 onset. The dates of the onset of the monsoon are known to fluctuate by about 15–20 days (Fieux and Stommel, 1977). This number is about half the period of the northward-propagating perturbations. Multiple onsets separated by about 30 days have also been noted over the Arabian Sea and may be related to the 30–50 day mode (Fieux and Stommel, 1977). This is rather speculative based on one event, and this hypothesis deserved further study.

The different parameters were also filtered in the spectral range 8–20 days to study the shorter oscillation. Time-longitude sections were constructed. Fig. 8 gives the section of the filtered meridional component of the wind at 10° N. There is a westward-propagating mode with its major peak around 10 days, which was also apparent in the pressure field (not shown). This mode is similar to the perturbations studied by Krishnamurti and Ardanuy (1980) and Murakami (1980).

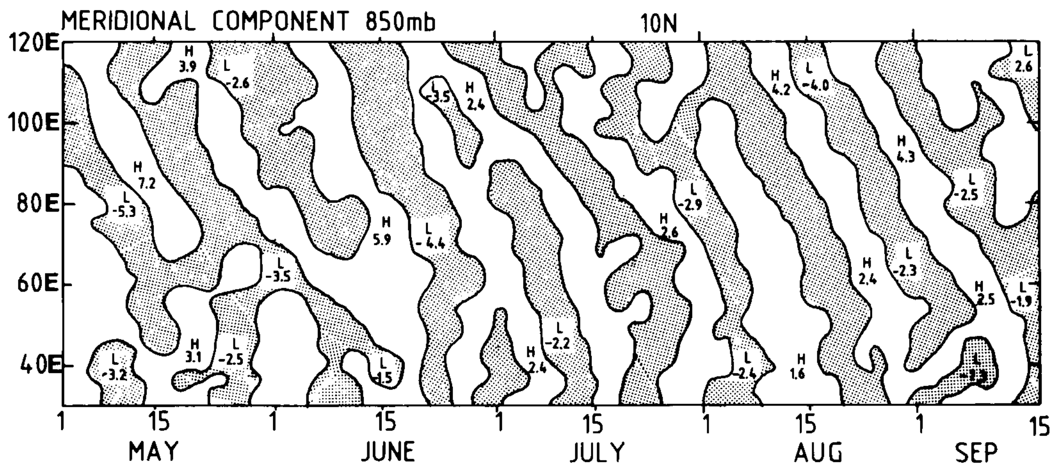

Fig. 8. Time-longitude diagram of the filtered meridional wind at 10° N. The filter half-response frequencies are 8 and 20 days.

5. Conclusions

The fluctuations of precipitable water over the Indian Ocean during the 1979 summer have been studied. The analysis has particularly focused on the 30–50 day cycle related to the active/break cycle of the monsoon. The cycle is due to northward propagating perturbations originating over the equatorial eastern Indian Ocean. We suggest the existence of a link between these perturbations and the onset of the monsoon.

The existence of this very strong signal in the 30–50 day spectral range and its relationship to the activity of the monsoon might allow some forecasting of the break/active periods over India and possibly the date of the onset.

6. Acknowledgements

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