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# *The importance of moving tropical disturbances over the Indian Ocean during the summer monsoon*

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ABSTRACT. In this paper, some results are given which help support the idea that the tropical disturbances propagating over the Indian Ocean during the northern summer, are an important phenomenon of the broad-scale Indian monsoon.

Time-longitude sections of cloudiness over the Indian Ocean during one month and a half of the 1975 summer monsoon stress the existence of moving disturbances : eastward-moving ones in the northern Indian Ocean and westward-moving ones in the southern Indian Ocean. These perturbations as well as their zonal propagation are also evidenced at ground level. From a comparative analysis with balloon trajectories, it is shown that they can have an influence on the low-level air flow circulation over the Indian Ocean.

The intensity of the Mascarene High Pressure, located near 30°S, 50°E, is studied in relation with the occurrence of the westward-moving disturbances. It is shown that these disturbances modulate the anticyclone intensity of the broad-scale monsoon system with a quasi-biweekly period.

The relationship found by Findlater (1969) between the low-level cross-equatorial winds over Kenya and rainfall over the western coast of India is investigated with focus on the tropical disturbances propagating eastwards over the northern Indian Ocean. An increase of the intensity of the Somalia jet occurs each time a perturbation originates over the western Arabian Sea and begins moving eastwards. The rainfall mechanism over the south part of the western coast seems to be linked to these perturbations and rainfall maxima occur a few days before the pressure minima. The relationship, with a 3-4 day lag between wind maxima over Kenya and rainfall maxima over the western coast can be well explained with the eastward-moving tropical disturbances.

## 1. Introduction

The southwest monsoon rainfall which accounts for major part of precipitation in India occurs in pulses evidenced by the alternations of strong and weak monsoon conditions, called "active" and "break" monsoons. The physical phenomenon which could explain these large-time variations still remains greatly unknown. Tentative explanation has often been given by meteorologists which focus on mechanisms occurring over the Indian region itself or at the mid-latitudes of the northern hemisphere (Ramaswamy 1962). Little emphasis has been placed in phenomenon occurring over the oceanic areas of the broad-scale monsoon system (Malurkar 1960). However, tropical disturbances propagate over the Indian Ocean as recently shown by Zangvil (1975) from time-longitude sections of satellite-derived data on cloud brightness as well as space-time spectrum analyses. Disturbances, with a nearly 9-day period, were found propagating eastwards in the northern Indian Ocean and westwards in the southern Indian Ocean. However, the role of these perturbations as well as the relationship with monsoon activity was not investigated. During the period of the balloon experiment presented in a companion paper, an analysis of cloudiness coverage was made to study the perturbations as well as their influence on the low-level air flow circulation, using the balloon trajectories. This study is presented in sections 2 and 3.

Krishnamurti and Bhalme (1976) have recently studied some elements of the broad-scale monsoon system. They showed that all the elements exhibit an oscillation in the quasi-biweekly period range of 14±2 days. It seemed interesting to study the relationship between the tropical disturbances occurring during the summer monsoon and the quasi-biweekly oscillation of some elements of the monsoon system. This relationship between the westward-moving disturbances and the quasi-biweekly oscillation of the Mascarene High Pressure (the anticyclone of the monsoon system) is investigated in section 4.

Another intriguing phenomenon of the summer Indian monsoon is studied in section 5 : the strong correlation found by Findlater (1969) between the low-level cross-equatorial winds over Kenya and rainfall over the western coast of India. Findlater's findings, however challenged by Raghavan *et al.* (1975), showed that rainfall was maximum over the western coast 2 or 3 days after the winds reached their maxima at Garissa (0·3°S, 49·4°E) in Kenya. This relationship is studied during the 1975 summer monsoon with focus on the eastward-moving disturbances.

## 2. The tropical disturbances over the Indian Ocean during the summer monsoon

Mercator mosaic of the NOAA-4 satellite composite visible images is used to perform a nephanalysis. The geographic sector extends from 20°N to 20°S and from 40°E to 90°E. The cloud amount of this area is estimated in every square of 2·5-degree long in longitude and latitude. Each square is evaluated from 0 to 9 according to the cloud amount. This analysis is made every day from June 25, 1975 to August 10, 1975. Time-longitude sections extending from 40°E to 90°E are then displayed from 10°N to 15°S at a 2·5-degree latitude interval to stress the existence of organized features propagating over the Indian Ocean. This approach is quite well appropriate to identify and separate disturbance types in cloud brightness, and to discriminate between various zonally propagating waves on the basis of phase speed.

Fig. 1 (a) shows the existence of organized and moving features in the latitude band 2·5°N-5°N. During the period studied, three perturbations cross the Indian Ocean from 40°E to 90°E; the first one from July 5 to July 16, the second one from July 15 to July 25 and the last one from July 31 to August 9. Very clear sky conditions prevail before the occurrence of the first two perturbations and before the last one. The cloud cover at a given longitude is modulated by the passage of the perturbations. The maximum cloudiness region is associated with the trough of the waves. These perturbations move eastwards with phase speed of 5°-6° longitude per day. The main periodicity of these perturbations lies between 10 and 14 days and zonal wavelength is at least 7000 km.

No feature is crossing the ocean near 5°S as revealed by Fig. 1 (b). Thus during the most part of July, large amount of clouds extends from about 55°E to 80°E. They correspond to the equatorial trough often found at this latitude during the summer monsoon.

More southwards, two moving features are noticed in the bands 7·5°S-10°S (Fig. 1 c) and 10°S-12·5°S (Fig. 1 d). They cross the ocean from July 17 to July 25 and from July 30 to August 9. They are moving westwards with phase speed of about 5°-6° longitude per day. The second disturbance occurs about 14 days after the first one and the horizontal wavelength reaches at least 7000 km.

Fig. 2 gives a schematic view of all these tropical disturbances crossing the Indian Ocean during the 1975 summer monsoon. It gives the maximum cloudiness lines estimated from the time-longitude sections. There can be some inaccuracy on the estimated date of the passing over of a disturbance at a given longitude.

At ground levels, the "wavy" perturbations can be seen on a pressure record and also on a surface wind record if the wind field is steady when no wave occurs. Equatorial waves can have a latitudinal extent of 15° and can be detected polewards from the latitude where their influence is maximum. Fig. 3 gives the pressure records at Amini (11°N, 72·5°E) and Minicoy (8·5°N, 73°E). According to Fig. 2, large cloud clusters are crossing the meridian of these island stations on July 12, 21 and August 6. The disturbances are clearly visible on the pressure data and the passing over of a disturbance is associated with a decrease of pressure. The lag of the coincidence is about one or two days. Fig. 4 gives the pressure records at the Seychelles Islands (4·7°S, 55·5°E), Iles Glorieuses (11·5°S. 47°E) and Diego Garcia (7·2°S, 72·2°E). The last two pressure minima correspond to the passing over of the two westward-

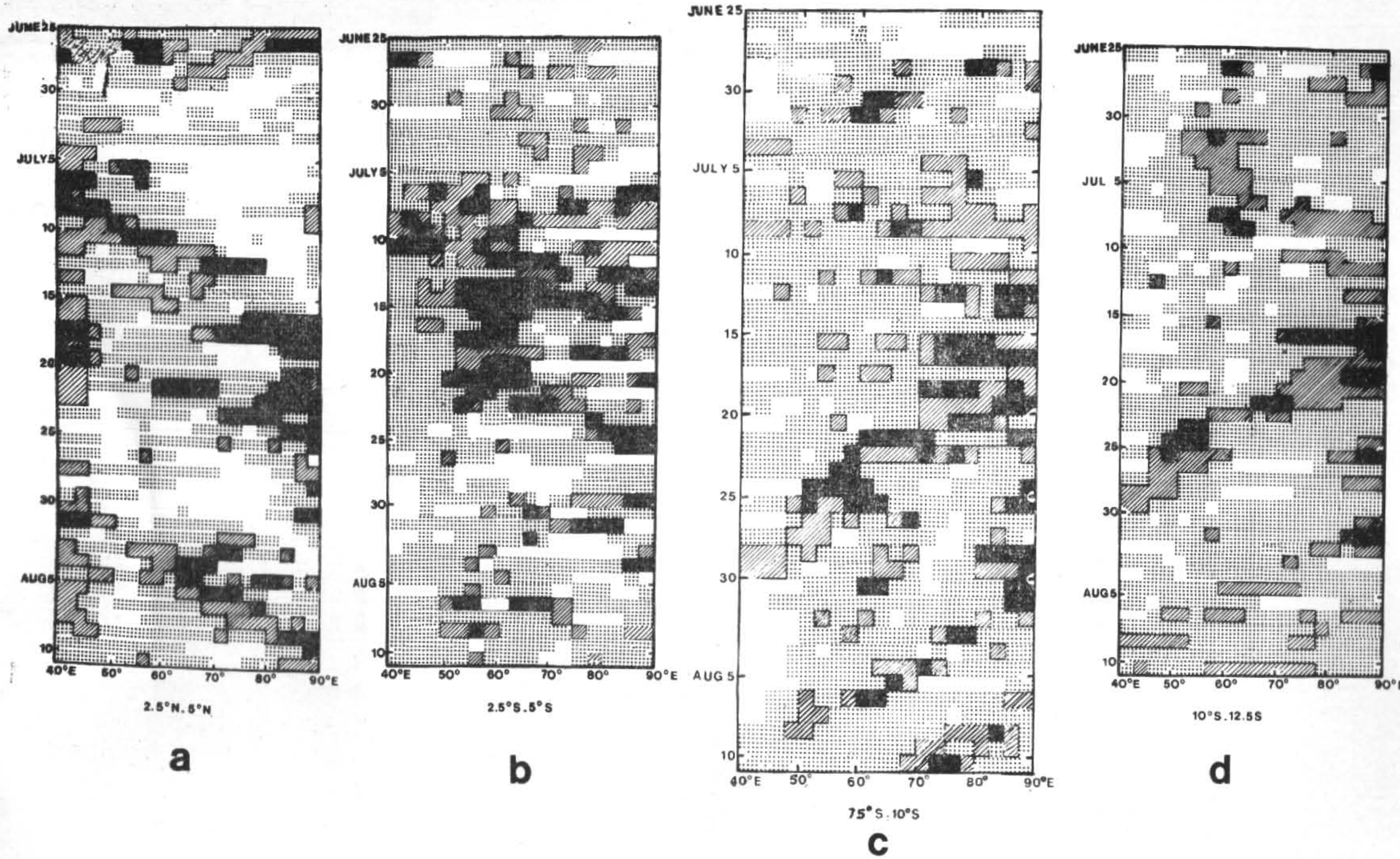


Fig. 1. Time-longitude sections of cloud cover of the Indian Ocean for the period from June 25 to August 10, 1975. Cloudiness coverages ⩾70% are shaded, cloudiness coverages <70% and ⩾50% are hatched, cloudiness coverages <50% and ⩾30% are dotted and blank parts correspond to cloudiness coverages <30%

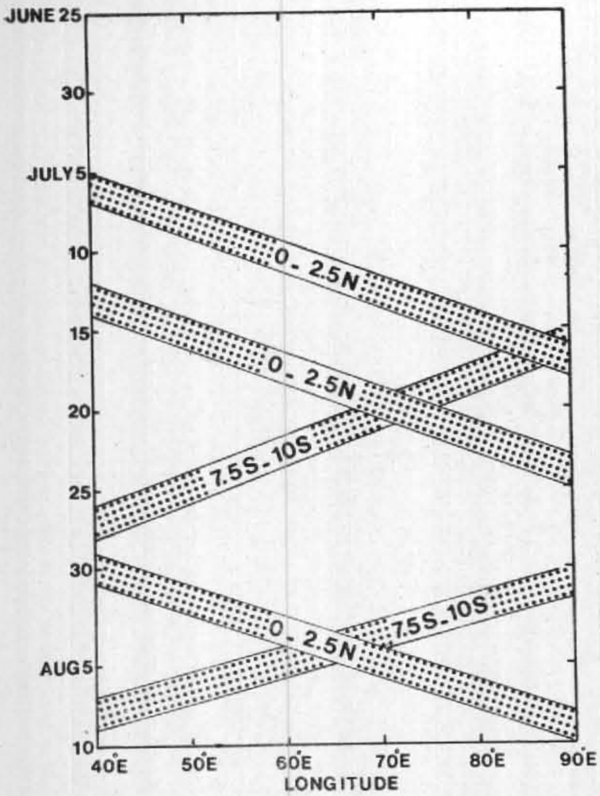


Fig. 2. Schematic view of the different tropical disturbances travelling over the Indian Ocean during one month and a half of the 1975 summer.

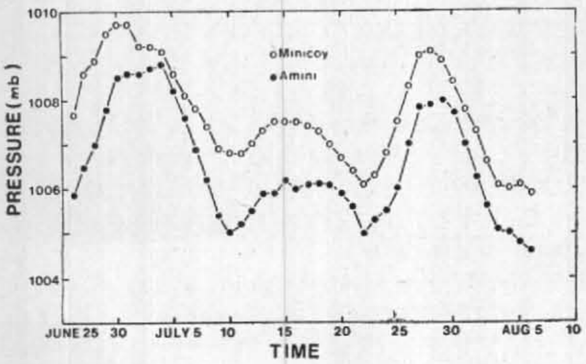


Fig. 3. Pressure records at Amini (11°N, 72·5°E) and Minicoy (8·5°N, 73°E). The raw data are smoothed with running 5-day means.

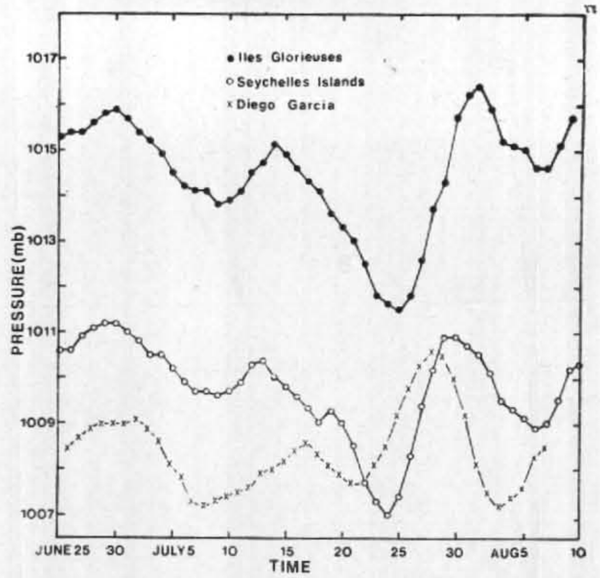


Fig. 4. Pressure records at the Seychelles Islands (4·7°S, 55·5°E); Iles Glorieuses (11·5°S, 47°E) and Diego Garcia (7·2°S, 72·2°E). The raw data are smoothed with running 5-day means.

moving disturbances and their propagation is easily evidenced when looking at the records of these islands located at different longitudes.

### 3. The influence of the tropical disturbances on the low-level air flow circulation

As the cloud cover analysis is made during the same period as the balloon experiment (Cadet and Ovarlez 1976), a study can be carried out to determine the influence of the tropical disturbances on the low-level air flow circulation.

Cadet and Olory-Togbe (1976) show that the passing over of a disturbance can sometimes be seen on surface wind records. This is particularly evident for the first westward-moving disturbance propagating in the southern Indian Ocean and which provokes an important change of the direction of winds at the Seychelles Islands. At the same time, a reversal of the monsoonal flow is evidenced by the balloon trajectories: the balloons are drawn towards Madagascar (*see* companion paper). The influence of the second westward-moving disturbance is not noticeable on the balloon trajectories.

The influence of the eastward-moving disturbances is less evident perhaps due to the presence of an intermittent equatorial trough between 60°E and 80°E during most of the balloon experiment. However, during the third launching period a change in the direction of the air flow crossing the equator is noticed (Cadet and Ovarlez 1976). This is due to the third eastward-moving disturbance. The veering is evident from Fig. 5 which gives the directions of the tangents to the balloon trajectories at the point where they cross the equator : it exceeds 60°E. However, when the first disturbance is crossing the ocean, the veering

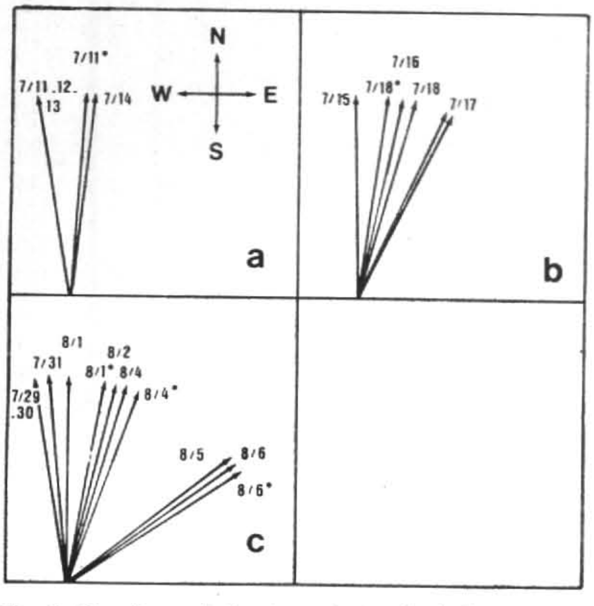


Fig. 5. Directions of the tangents to the balloon trajectories at the longitude point where the balloons cross the equator, a : First eastward-moving disturbance, b : Second disturbance and c : Third disturbance.

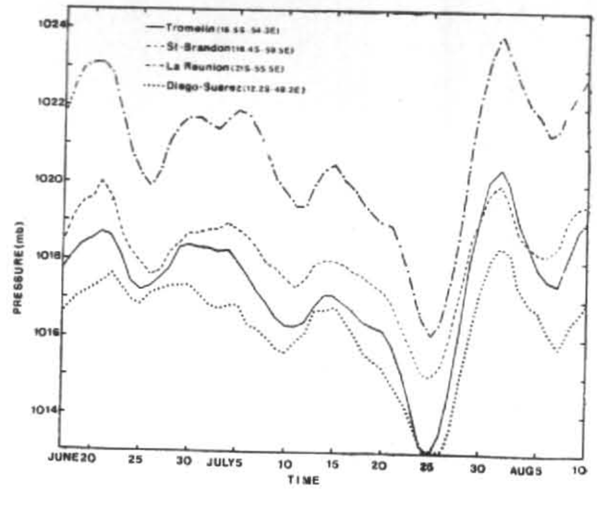


Fig. 6. Pressure records at some island stations in southern Indian Ocean near the Mascarene High Pressure. The raw data are smoothed with running 5-day means.

is not noticeable, but it reaches 30° for the second depression. Just after the passing over of this disturbance the direction resumes its initial value. The time-longitude sections show that the first "waves" are not well time-separated and the sky is cloudy between them. This corresponds to the presence of large amount of clouds over the equatorial part of the ocean.

These results show that disturbances propagating over the equatorial Indian Ocean can influence the low-level air flow circulation, causing occasionally a reversal of the monsoonal flow.

## 4. The quasi-biweekly modulation of the Mascarene High Pressure by westward-moving disturbances

Fig. 6 gives pressure records at some island stations located in the southern Indian Ocean near the Mascarene High. A quasi-biweekly oscillation appears on all the records and the minima occur around June 26, July 11 and 25 and August 6. The last two minima (the most important ones) are well related to the occurrence of the two westward-moving disturbances which are in the vicinity of 55°E on July 25 and August 6 (Fig. 2). The first two minima are also certainly due to the passing over of disturbances which are not noticed on time-longitude sections of cloudiness. In both cases, the pressure fluctuation due to the passage of the depression is less important, the associated trough is less intense, cloud activity is not sufficient and no moving feature can be seen from an analysis of cloud cover.

The quasi-biweekly oscillation of the Mascarene High is not provoked by the passage of mid-latitude winter hemisphere disturbances as shown by Cadet (1977a). Thus this periodic intensification and weakening of the anticyclone of the broad-scale monsoon system are due to westward-moving tropical disturbances propagating over the southern Indian Ocean.

## 5. The eastward-moving disturbances and the relationship between the cross-equatorial flow over Kenya and rainfall over the western Indian coast

Fig. 7 gives the wind index at Mombasa (Kenya) according to Findlater (private communication). Three major increases occur during the studied period, on July 4, 16 and 28, and the intensity oscillates with a quasi-biweekly period (about

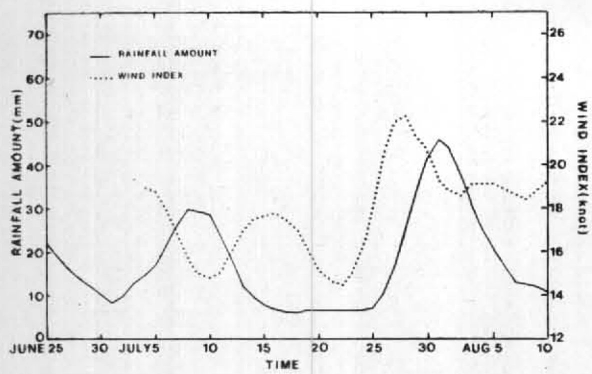


Fig. 7. Wind index at Mombasa (4°S, 39·5°E) and rainfall in western India. The wind index is the mean of the south components at 1000, 2000, 3000, 4000 and 5000 feet above sea level. Rainfall is the mean value of ten stations along the western coast of India. All the raw data are smoothed with 7-point filter (*After* Findlater, private communication).

12 days). When comparing to Fig. 2, these increases are well related to the occurrence of the eastward-moving tropical disturbances which originate over the western Arabian Sea. Thus the eastward-moving disturbances modulate the intensity of the East African low-level jet with a quasi-biweekly period. This influence of the tropical disturbances on the intensity of the jet can be understood. When a depression locally intensifies, before the disturbance starts moving eastwards, a convergence zone is created and the intensity of the winds around that zone increases, particularly near the East African coast where the air flow is laterally bounded by orographic features.

The tropical disturbances can be detected at ground level on pressure records as previously shown. Fig. 8 (a) and (b) gives the pressure records at some stations along the southern part of the western coast of India. The pressure minima are well related to the passing over of the eastward-moving tropical disturbances as shown by Fig. 2. Thus the influence of these perturbations seems important over a large part of the coast but is less evident northwards as shown by Cadet (1977b).

Fig. 8 (c) and (d) gives rainfall amount for the stations previously studied. For those located in the southern tip of India (Fig. 8 c), the rainfall maxima occur roughly during three periods : July 8-9-10-11-12, July 22-23-24 and July 30-31—August 1-2-3. The second relative maximum is is not quite well stressed and corresponds to a "break" in the activity of the monsoon (Cadet and Olory 1976). For these stations, large rainfall rates are correlated within a few days with pressure minima and consequently are linked to the occurrence of eastward-moving tropical disturbances. For the other two stations which lie in the heavy rainfall belt on the windward side of the Western Ghats, the correlation is far from perfect (Fig. 8 d). Thus, for Mangalore no correlation can be found: the rainfall rate is always important. For Honavar, the rainfall maxima occur a few days before the pressure minima. Thus one can notice that intense precipitation rates occur slightly ahead of the disturbance. This is evidenced from the analysis of the data of stations located more northwards along the coast (Cadet 1977b).

The lag of 2-3 days between the maxima of winds over Kenya and the maxima of rainfall over the western coast is taken by Findlater (1969) as an indication of an intimate relation between the two phenomena. In this study the lag is sometimes larger but its importance is largely dependent on the simultaneity of pressure minimum with rainfall maximum. Thus, in the southern part of the western coast, the lag is larger and can reach 6 days. However, Fig. 7 also gives mean rainfall rate at 10 stations scattered along the western coast; the correspondence is good and the lag is about 3-4 days. This relationship seems understandable with the tropical disturbances propagating eastwards over the Indian Ocean. When a tropical disturbance originates over the western Arabian Sea, the intensity of the low-level jet increases. Since the mean phase speed of the perturbations is about 5°/day, it reaches the western coast of India after 5-6 days. Increased rainfall rate is associated with such a perturbation but can occur about 1-2 days before the pressure minimum. This gives the time-lag of a few days between the two phenomena. Thus the correspondence between the trend of rainfall over western India and the trend of wind index over eastern Kenya can be quite well explained by tropical disturbances propagating eastwards over the Indian Ocean.

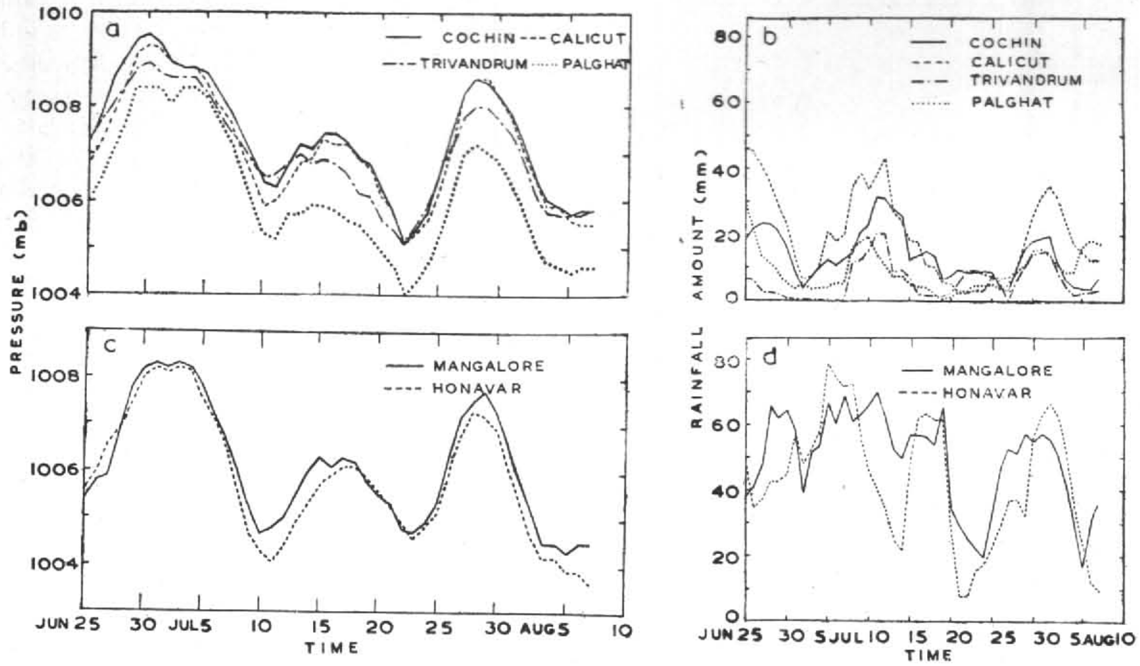


Fig. 8. Pressure and rainfall records at some selected stations along the western coast of India. The raw data are smoothed with running 5-day means.

## 6. Concluding remarks

All the results presented in this paper suggest that tropical disturbances propagating over the Indian Ocean during the summer monsoon are an important phenomenon. They are related to the quasi-biweekly oscillation of some elements of the broad-scale monsoon system and they can explain relationships which were not previously understandable. Further work must be done to investigate their importance, structure as well as relationship with monsoon activity over India. A climatological study of these perturbations over a few years is now under way at the Laboratoire de Meteorologie Dynamique as well as further study of their structure. It will be hopeful that special efforts might be done during MONEX-79 to study these perturbations.

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