Tellus (1988), *40A*, 133–150

Long-range forecast of the break and active summer monsoons

By DANIEL L. CADET and PIERRE DANIEL,* *Laboratoire de Météorologie Dynamique du CNRS, Ecole Polytechnique, 91128 Palaiseau Cedex, France*

(Manuscript received 8 May; in final form 23 July 1987)

ABSTRACT

Ship observations along the major shipping route from Sri Lanka to Sumatra have been processed over a 23-year period from January 1954 to December 1976. Daily time series of the zonal and meridional components of the wind, pressure, cloudiness, air temperature and SST have been constructed over the southern Bay of Bengal. The zonal wind component, the pressure and the cloudiness exhibit a well-defined 30- to 50-day mode. The fluctuations of these parameters are physically consistent. The period of the low-frequency mode varies over the 23-year period, but does not show a seasonal or annual cycle. The low-frequency variations of the surface parameters can be associated with the break and active cycle of the Indian summer monsoon.

The low-frequency relationship established between the surface meteorological parameters over the southern Bay of Bengal and the activity of the summer monsoon (rainfall at stations in India) is used to forecast the occurrence of the active and inactive periods. The forecast is based on the fitting of an auto-regressive moving average process over a 4-month period of the time series to extrapolate it over 30, 40 or 50 days. During years when the 30- to 50-day mode is well-defined, high-quality forecasts can be obtained. The forecasts fail during years when the phase of the low-frequency mode varies rapidly during spring and summer. On the average, the dates of the peak of the active/inactive monsoons can be predicted with an accuracy of about a week. This study offers new perspectives for the long-range forecast of fluctuations of the activity of the summer monsoon.

1. Introduction

The last few years have seen the publication of a large number of papers discussing the 30- to 50-day oscillation of the atmosphere. Madden and Julian (1971, 1972) discovered the existence of an oscillation of the tropical atmosphere with a period of around 40 days. The phenomenon was described as a global scale zonally oriented circulation cell that propagates eastward with the largest amplitude in the Pacific Ocean. Following FGGE (First GARP Global Experiment) and the production of a good quality global data set for 1979, some other aspects of the 30- to 50-day mode have been revealed (see, for example, T. Murakami et al., 1984; Krishnamurti and Gadgil, 1985; Krishnamurti et al., 1985; T. Murakami and Nakazawa, 1985; Nakazawa, 1986, T. Murakami et al., 1986a). Some information on the oscillation has also been obtained from the analysis of data sets covering several years (Knutson et al., 1986).

Rainfall over India during the summer monsoon is characterized by inactive spells between active periods. They are weak periods when the monsoon trough is located close to the foothills of the Himalaya mountains which leads to a decrease of rainfall over most of India, but increases along the Himalayas and the Southern Peninsula. The typical period of the active/break cycle of the monsoon lies between 30 and 50 days, depending on the year. The relationship between the 30- to 50-day mode and the activity of the

* Also Ecole Nationale de la Météorologie, 42 avenue Coriolis, 31057 Toulouse Cedex, France.

Indian summer monsoon was pointed out in the pioneering works of Yasunari (1979, 1980) and Sikka and Gadgil (1980). On that time scale, systems of troughs and ridges propagate northward from the equatorial zone at the longitudes of the Bay of Bengal. Alexander et al. (1978) showed for the period 1965 to 1973 that a strong (weak) monsoon epoch was preceded by the northward shift of an east–west anomaly trough (ridge) over the Peninsula. The analysis of the 1979 FGGE data set has confirmed the dependence of the active/break cycle of the Indian summer monsoon for a meridional propagation of 30- to 50-day oscillation (Krishnamurti and Subrahmanyam, 1982; T. Murakami et al., 1984; M. Murakami, 1984). The dependence of the date of the onset of the monsoon on the phase of the mode was also suggested by Cadet (1986), Lau and Chan (1986) and others. Singh and Kripalani (1985) analyzed the intraseasonal evolution of 5-day mean monsoon rainfall over India. They showed south to north progression of rainfall anomalies with a recurrence period of about 40 days. In a companion paper, Singh and Kripalani (1986) examined the relationship among the mean sea-level pressure, 700 mb height and rainfall over India, and found a similar northward progression of anomalies.

Because breaks last on the average 6 days, the longest ones lasting from 17 to 20 days, and a late break in August often means the end of the monsoon season, they have an impact on the economy of the countries affected by the Indian summer monsoon. A late or an early onset can also have important consequences. Forecasting the arrival of a break a few weeks in advance appears to be very useful. Only a few attempts have been made to forecast some of the major elements of the monsoon (onset, break and active periods). Kung and Sharif (1980, 1982) proposed a forecast scheme of the onset date based on antecedent upper air conditions over India in April and seasonal rainfall in central India based on upper air conditions over India and Australia and sea surface temperature in the Indian region. Krishnamurti and Ardanuy (1980) used the steady variations of phase of the 10- to 20-day westward propagating mode over India to forecast the arrival of a break epoch 10 days in advance. The forecast was successful in over 70% of the cases examined during the period 1943–1972. Although the question of forecasting the different phases of the monsoon is an important one, these are the only published attempts.

The existence of a strong relationship between the phase of the northward propagating 30- to 50-day mode and the activity of the summer monsoon offers a way to forecast the break/active cycle of the monsoon. In this paper, we present the results of a study on the potentiality of the 30- to 50-day mode to forecast the dates of minimum and maximum activity of the monsoon.

To assess the statistical significance of the results, the analysis must be based on a long-data set. In this paper, the data set consists of 23 years of ship reports available over the southern Bay of Bengal along the main shipping route from Sri Lanka to Sumatra in the Indian Ocean. Although the quality of ship observations is questionable, it is the only data set available on a very long basis. The purpose of the study is to forecast the 30- to 50-day oscillation in the southern Bay of Bengal from ship reports available during the first few months of the year well before the establishment of the summer monsoon. Then a forecast of the dates of maximum and minimum activity of the monsoon is made.

After presenting and discussing the data in Section 2, the 30- to 50-day oscillation and its relationship to the activity of the monsoon is studied in Section 3. After establishing the relationship between the phase of the 30- to 50-day mode in the southern Bay of Bengal and the activity of the monsoon, a 30- to 60-day forecast is performed for each year starting with the data available during the period from January to April. Section 4 is devoted to a presentation of the results of this forecasting exercise. Finally, in Section 5, the results are discussed and some conclusions are drawn.

2. The data

To test the significance of the proposed method, the forecast must be tested on a large number of cases. Long records of observations on a daily basis in the Indian Ocean and, in particular, in the Bay of Bengal where the relationship between the phase of the 30- to 50-day mode and the activity of the monsoon has been clearly established, are rather rare. The latitude

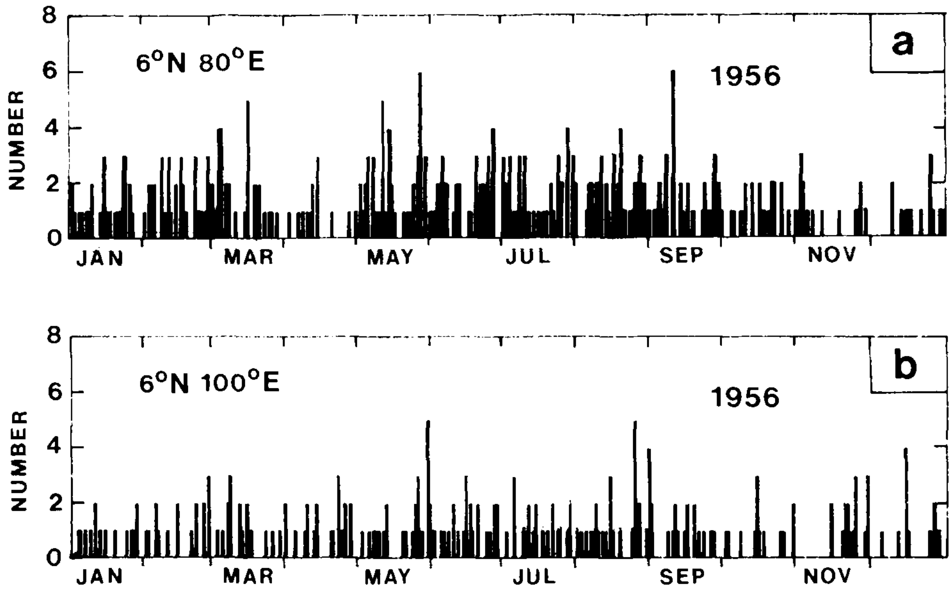

Fig. 1. Number of data per day during 1956 in the quadrangle (1° in longitude and 4° in latitude) centered at 6° N, 80° E (a) and 6° N, 100° E (b).

band around 5° N, located within the area where the northward propagating perturbations are formed, is well sampled by ships of opportunity travelling along this main shipping route from Sri Lanka to Sumatra. We decided to use that data set for the study. Although the quality of observations obtained from ship reports has been largely discussed and is sometimes questionable, they can be used along heavily sampled shipping routes to study a rather low-frequency quasi-periodic signal. This point will be demonstrated later on. Note that ship reports along main shipping routes can be used to study short-term phenomenon. The first pioneering effort was made by Fieux and Stommel (1977), who analyzed the structure and variability of the onset of the Indian monsoon along two shipping routes from the horn of Africa to Sri Lanka and along the coasts of East Africa and Arabia. They showed that the date of the onset of the monsoon (establishment of a strong southwest circulation) can be determined with an accuracy of about 2 days.

Ship reports were collected from the meteorological services of three nations (the United States, the United Kingdom and the Netherlands) for the period 1954–1976. The quality and density of these data during that period were discussed by Cadet and Diehl (1984). The route from Sri Lanka to Sumatra was divided into 20 quadrangles of 1° in longitude and 4° in latitude centered at 6° N from 80° E to 100° E. Ship reports from the three sources were merged and duplicate reports were rejected. Fig. 1 gives an example of the data density for 1956 in two quadrangles centered at 80° E and 100° E. It is very rare to have no observations for more than 5 days which is only 1/8 of the period of the oscillation to be studied. Daily values of the following parameters were determined in each quadrangle: zonal and meridional components of the wind, surface pressure, air temperature, sea surface temperature and total cloudiness. In order to fill the gaps (days without observation), some interpolation was performed. First, a time interpolation was made if there were data during the two days preceding and following the data void day. Then a space interpolation was performed not extending beyond two quadrangles to the west and to the east of the data void quadrangle. Finally, if data void days still existed, a time interpolation with no restriction was made. Figs. 2, 3 give two examples of the time series. They will be discussed in Section 3.

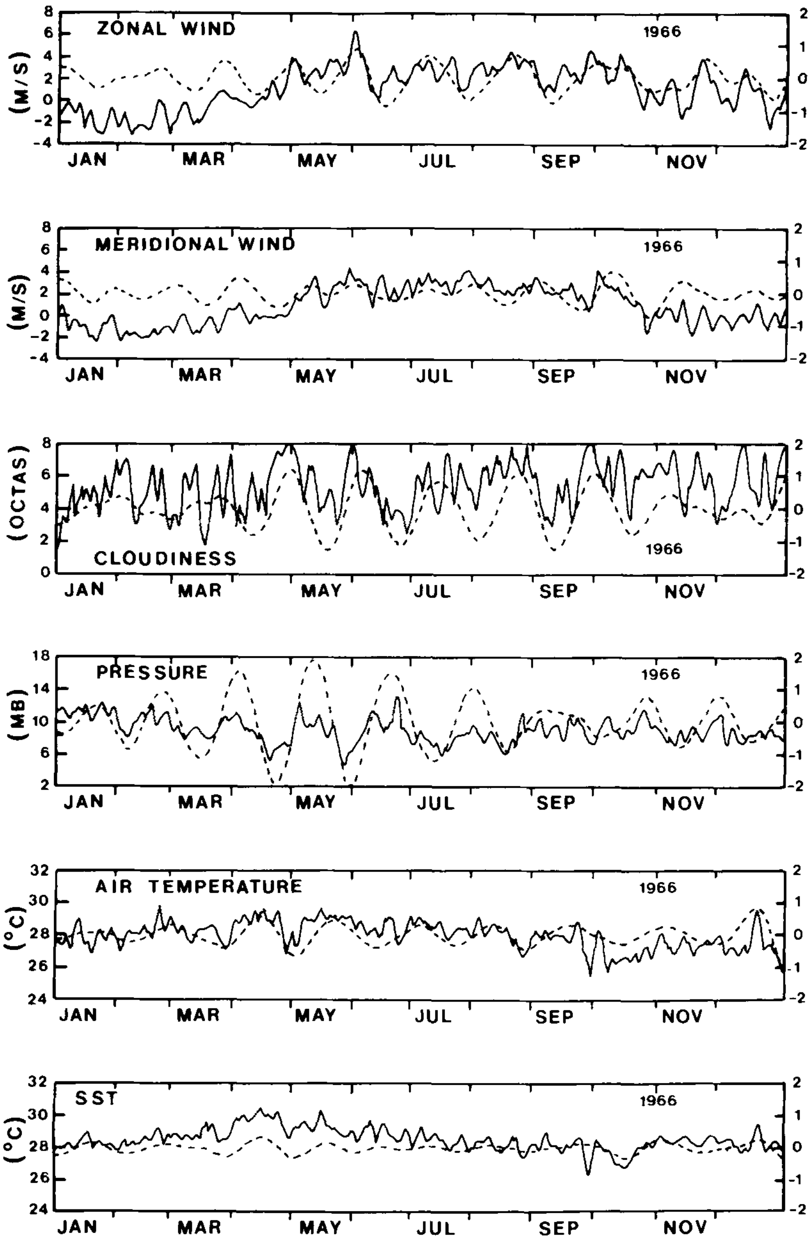

Fig. 2. Time series of the zonal (a) and meridional (b) components of the wind, total cloudiness (c), sea level pressure (d), air temperature (e) and SST (f) for 1966 in the quadrangle located at 6°N and 87°E. Solid lines: raw data. Dashed lines: 30–50 days filtered data. Units on the left ordinate are for raw data and on the right ordinate for the filtered data.

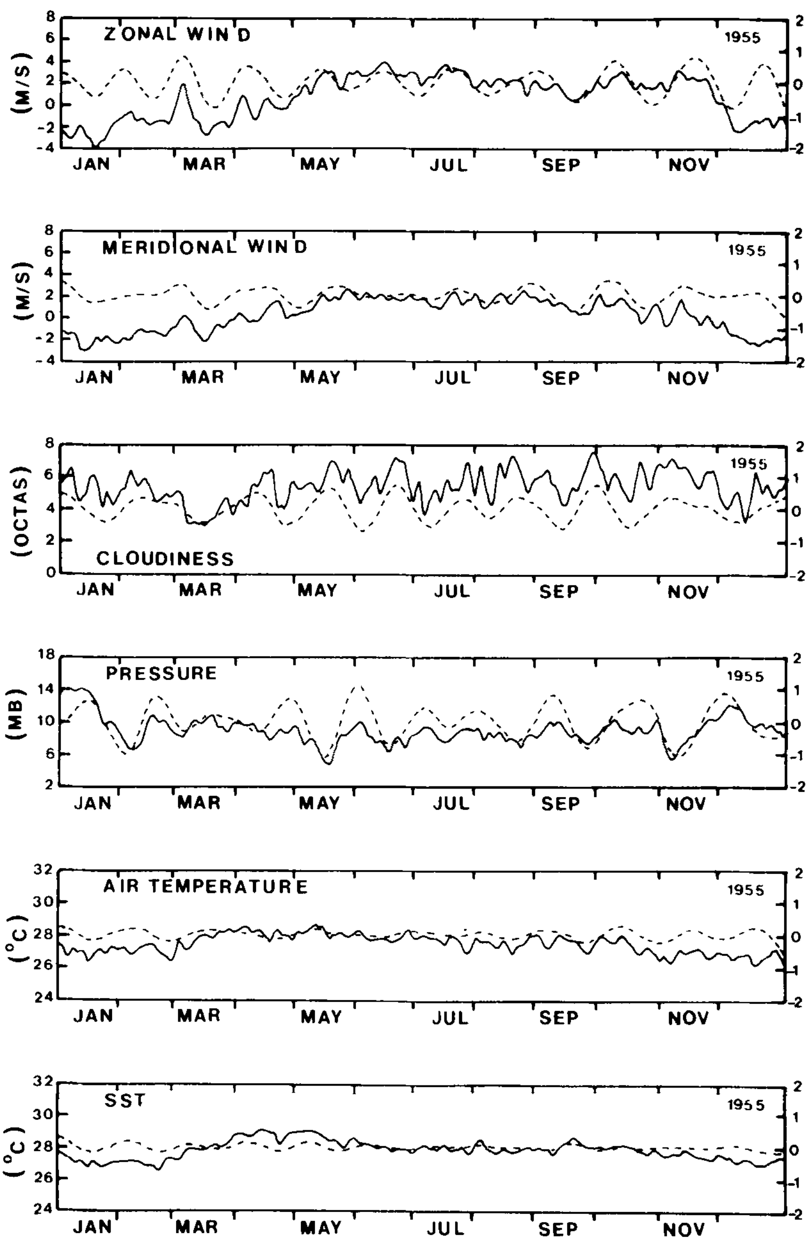

Fig. 3. Time series of the same parameters as in Fig. 2 averaged over the 20 quadrangles extending from 80°E to 100°E, but for 1955.

To determine the activity of the summer monsoon, daily rainfall amounts were extracted from the Indian Daily Weather Report at 15 stations scattered throughout India starting from the southern tip of India to Central India. These stations are: Trivandrum, Cochin, Mangalore, Bangalore, Hyderabad, Jagdalpur, Bombay, Bhopal, Ahmedabad, Allahabad, Bénarès (Varanasi), Gwalior, Kanpur, Agra and New Delhi. The rainfall data were not available during the entire period and only 14 years of entire records of the stations were obtained.

3. The 30- to 50-day mode

3.1. Oceanic data

Fig. 2 presents the daily fluctuations of the different parameters during 1966 in the quadrangle centered at 6°N and 87°E. Fig. 3 presents the average time series over the 20 quadrangles during 1955. The major annual events taking place over the Indian Ocean are well described by the time series. Although there is no sudden onset of the monsoon in the Bay of Bengal, the northeasterly flow prevailing during the first months of the year is replaced around the beginning of May by a southwesterly flow which lasts till October. Cloudiness does not present an annual signal but rather strong intraseasonal fluctuations. The time series of sea-level pressure reveals the annual cycle as well as strong intraseasonal fluctuations. The time series of air temperature and SST are typical of the northern Indian Ocean, rising during the first few months of the year, decreasing after the establishment of the summer monsoon circulation due to strong turbulent mixing and significant evaporation at the surface of the ocean, starting to increase at the end of the summer monsoon and decreasing during the last few months of the year due to less solar heating and the establishment of the northeast monsoon.

The spectra of the time series of the different parameters were estimated with the maximum entropy method (MEM). Before analyzing the data, an 11-day moving average filter was used to reduce the high frequency noise and the importance of the 10- to 12-day fluctuations of the summer monsoon (Krishnamurti and Bhalme, 1976). The number of degrees of freedom for the spectra can be estimated using the formula given by Bennett (1979, p. 184). The number of degrees of freedom for an auto-regressive process is $2N/P$ where N is the number of independent observations in the record and P the order of the auto-regressive process. The 11-day moving average reduces the number of independent observations such that:

$$N \text{ dof} = NB_{\text{eff}},$$

with

$$B_{\text{eff}} = \frac{1}{2\Delta t} \int_f R(f)\,\mathrm{d}f,$$

where $R(f)$ is the transfer function of the filter, Δt the time interval and N the number of points of the original record. Confidence intervals at the 5% level are given on the spectra.

Because some of the time series reveal a strong annual cycle, a fast Fourier transform was performed and the annual cycle was removed. Then each time series was normalized by its standard deviation. Fig. 4 gives some spectra of the time series of the different parameters during different years in some quadrangles. The pressure, the cloudiness and the wind components are the parameters exhibiting a significant peak in the 30- to 50-day range for most of the time series. The SST and the air temperature also show the existence of a low-frequency mode in some quadrangles. Spectra of the space-average time series reveal that the peaks are less defined except for the pressure and the total cloudiness. A characteristic of the tropical 30- to 50-day oscillation is the non-seasonal variation of its frequency near the equator (Anderson et al., 1984). These authors found changes in period from 32 days to 55 days. Such fluctuations in the period of the 30- to 50-day mode in the southern Bay of Bengal may give rise to some problems when a forecast based on the existence of a constant period is made. In order to document the variations of the period of maximum energy, these periods have been computed for all seasons (4 months) from 1954 to 1976 for the pressure and total cloudiness time series averaged over the 20 quadrangles. The period of maximum energy oscillates between 60 and 25 days (Fig. 5). During certain years, the periods for the pressure and the cloudiness are very close, whereas, for example, in 1955 and 1966, they differ. There is no clear

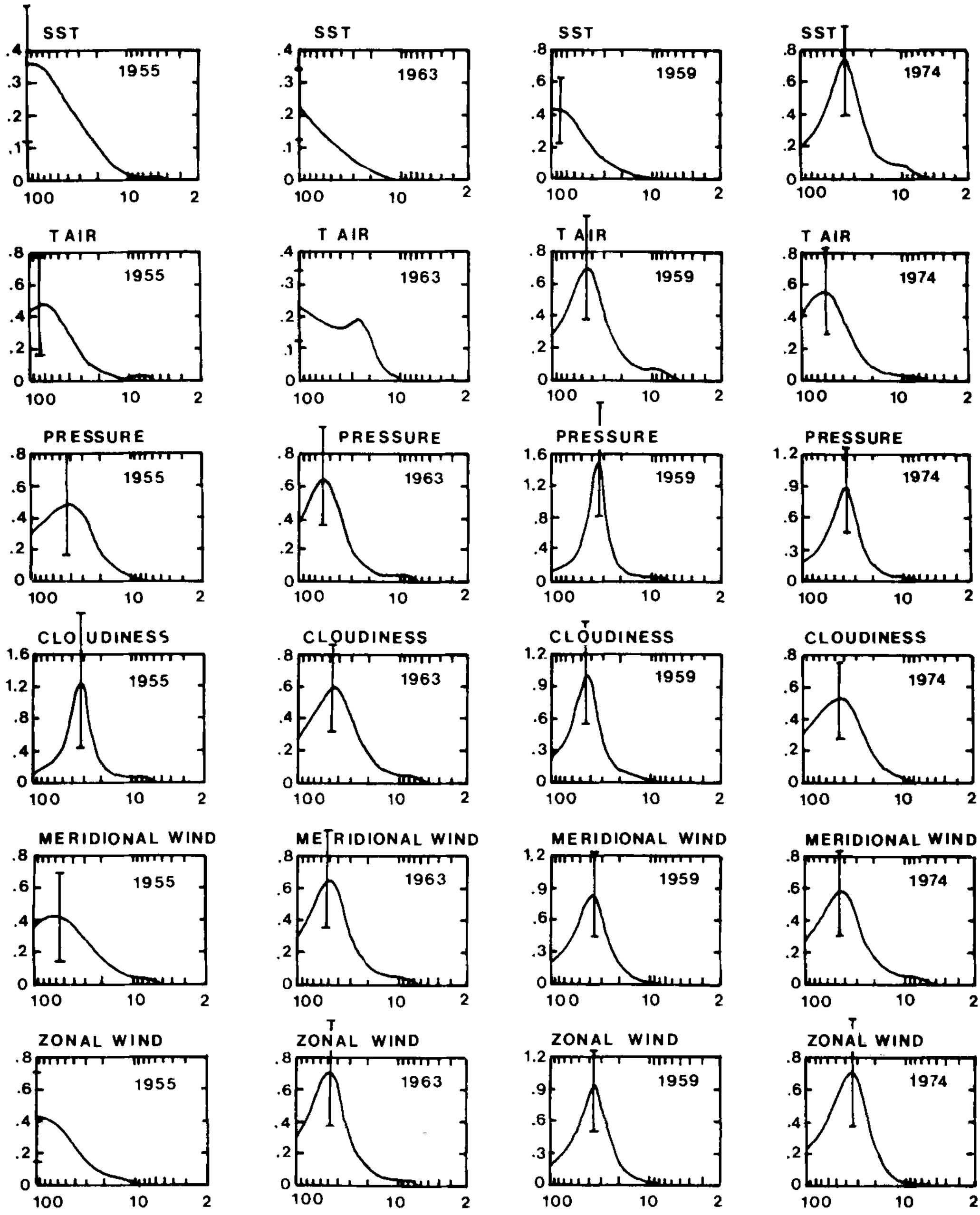

Fig. 4. Examples of spectra (maximum entropy method) of the different parameters during certain years in some quadrangles. The annual cycle has been removed and an 11-day running average is performed to remove high-frequency noise. The vertical bars indicate the 5% significant level which takes into account the reduction of the number of degrees of freedom due to the moving average process. The ordinate corresponds to power density times the frequency.

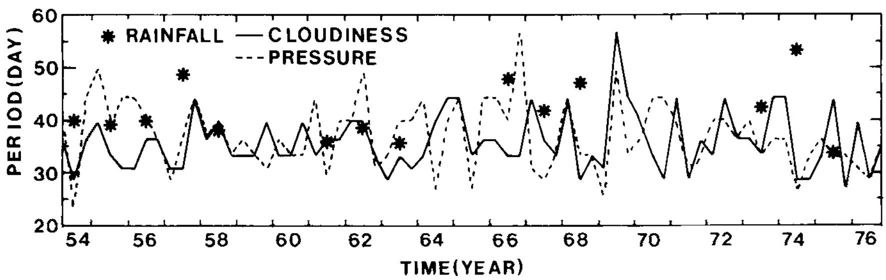

Fig. 5. Interannual variations of the period of maximum energy during the 23 years. One estimate of the main periodicity is obtained for every 4 months. The solid lines corresponds to the cloudiness, the dashed line to the pressure and the stars indicate the period for the Indian rainfall time series during the summer.

Table 1. *Average period of the low-frequency mode (between 2 and 100 days) during the 23 years, and standard deviation*

Parameter	Zonal wind (m/s)	Meridional wind (m/s)	Cloudiness (octas)	Pressure (mb)	Air temperature (°C)	SST (°C)
average period (days)	39.8	37.4	37.4	38.2	42.9	64.0
standard deviation (days)	6.8	3.6	3.6	3.7	7.6	23.8

indication of a seasonal cycle of the period of the low-frequency mode. The average periodicity and its standard deviation of the major peak between 2 and 100 days during the 23 years is given by Table 1. The wind components, cloudiness, pressure and air temperature oscillate with a periodicity in the spectral range 30–40 days with a reasonable standard deviation. The existence of a major low-frequency mode on SST is more questionable. This may result from the quality of the measurements and its weak amplitude.

After establishing the existence of a major periodicity around 25 to 60 days, the 6 different parameters have been band-pass filtered with a Butterworth filter (M. Murakami, 1979) retaining fluctuations with periods between 30 and 50 days (half response of the filter at these periods). The filtered time series are shown in Figs. 2, 3 (dashed lines). In 1966 in the quadrangle located around 87°E, the signal is quite well-defined on the pressure, cloudiness and zonal wind time series. Its amplitude is weaker on the air temperature and the meridional wind and the SST signal is flat. For the cloudiness, the oscillation can be easily detected during spring, summer and part of fall. For the pressure, the signal exists during the entire year, but with maximum amplitude during spring and summer suggesting a seasonality of the amplitude of the low-frequency mode in 1966. T. Murakami et al. (1986b) analyzed OLR data and found that the low-frequency fluctuations are more pronounced over the northern and southern hemisphere monsoon regions during the summer (wet season) than winter (dry season), respectively.

In 1955 (Fig. 3), the amplitude of the time series averaged over all the quadrangles is weaker than in 1966 with a rather flat signal on the SST, air temperature and meridional wind, whereas the oscillation appears quite markedly on the zonal wind, cloudiness and pressure. It is interesting to note that the seasonal dependence of the amplitude is weaker in 1955 than in 1966. The analysis of the 23-year data set tends to indicate that the seasonal dependence is particularly strong when the 30- to 50-day mode is well-defined.

Figs. 2, 3 also reveal the phase relationship existing between the different parameters. Cloudiness and zonal wind appear to be in phase but they are out of phase with the pressure. Fig. 6 gives some examples of the lag-cross correlation between the pressure and cloudiness filtered time series averaged along the shipping route. The

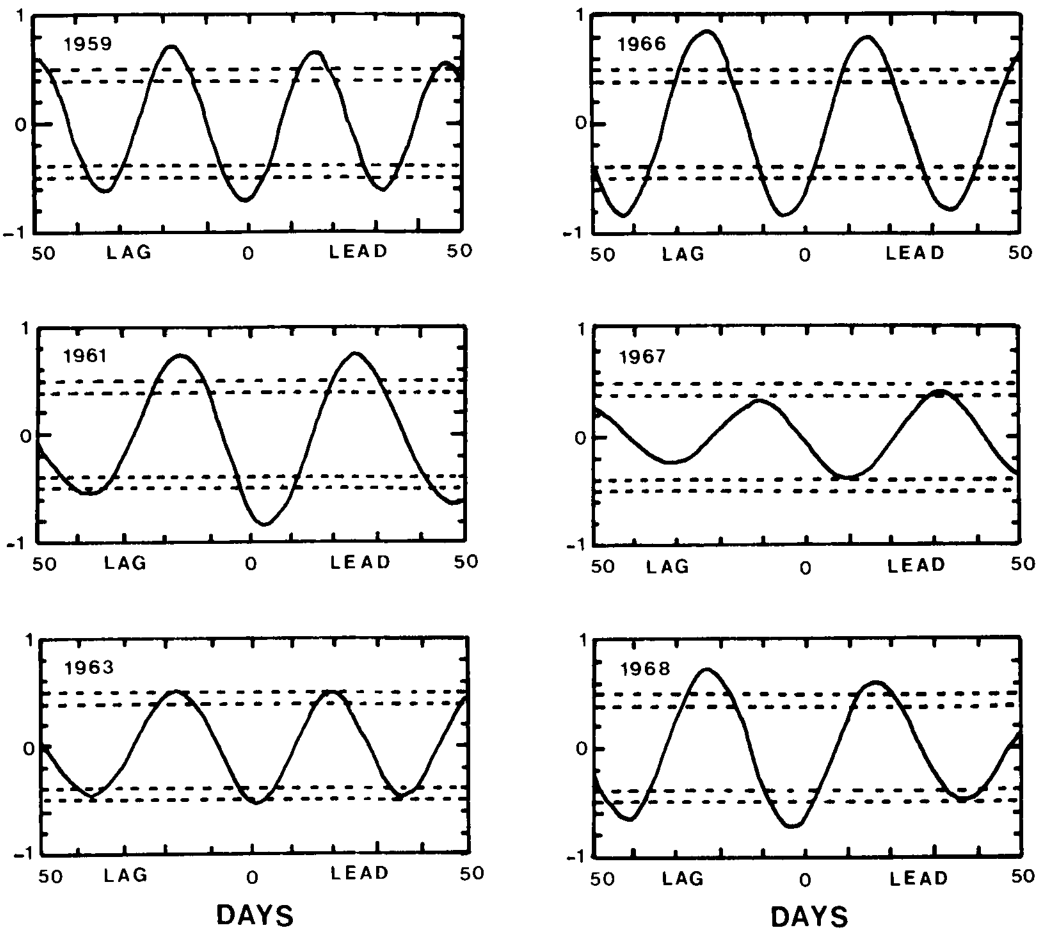

Fig. 6. Lag-cross correlation between the pressure and cloudiness time series filtered between 30 and 50 days. The original time series represent the averaged values along the shipping route. The 1% significance level is given and has taken into account the reduction of the number of degrees of freedom due to the Butterworth filter. Lag/lead means that the pressure is lagging/leading the cloudiness.

cross correlation is well above the 1% significance level (which takes into account the reduction of the number of degrees of freedom introduced by the filtering process) in 1959, 1961, 1966 and 1968. However, the correlation is not significant in 1963 and 1967. For nearly all the years (except 1961) when the correlation is significant, the minimum (maximum) cloudiness leads the maximum (minimum) pressure by a few days (about 5 days). Cross spectral analysis (not shown) confirms these results. The out-of-phase relationship between pressure and cloudiness is physically consistent. Note that the different parameters have been processed independently. Lower (higher) pressure associated with higher (lower) wind is also consistent with the analysis of Krishnamurti and Subrahmanyam (see their Fig. 3 of streamlines and isotachs of the 30- to 50-day filtered wind fields over the Indian Ocean during the 1979 summer).

Because the 30- to 50-day mode appears quite clearly on the pressure and the cloudiness, these two parameters have been selected for the rest of the study.

3.2. Rainfall

As discussed in Section 1, the activity of the monsoon fluctuates at low frequency in relation-

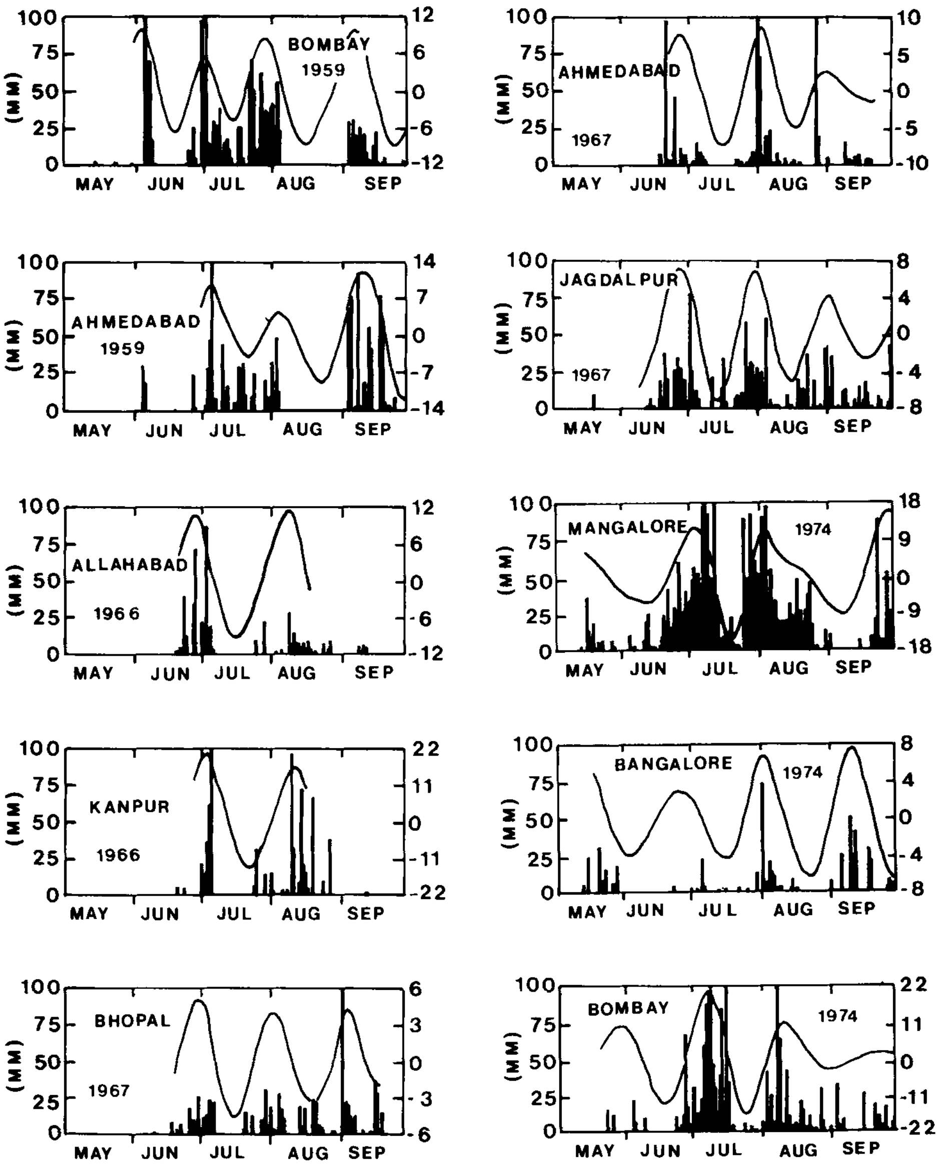

Fig. 7. Rainfall records at some stations during certain years. The raw data as well as the filtered time series are plotted to emphasize the break/active cycle. Units on the left ordinate are for the raw data and on the right ordinate for the filtered data.

ship to the 30- to 50-day mode (Metha and Ahlquist, 1986). As an example, Fig. 7 gives the rainfall time series at some stations in India during certain years. These rainfall records clearly show the pulsatory nature of the monsoon. The filtered time series (same Butterworth filter as previously defined) is superimposed on the raw data. The break and active episodes occur quasi-simultaneously throughout India. Fig. 8 gives some spectra of the rainfall time series. Three main periodicities exist for rainfall records: around 3–5 days corresponding to monsoon depressions (M. Murakami, 1976), around 10–12 days induced by the quasi-biweekly oscillation of

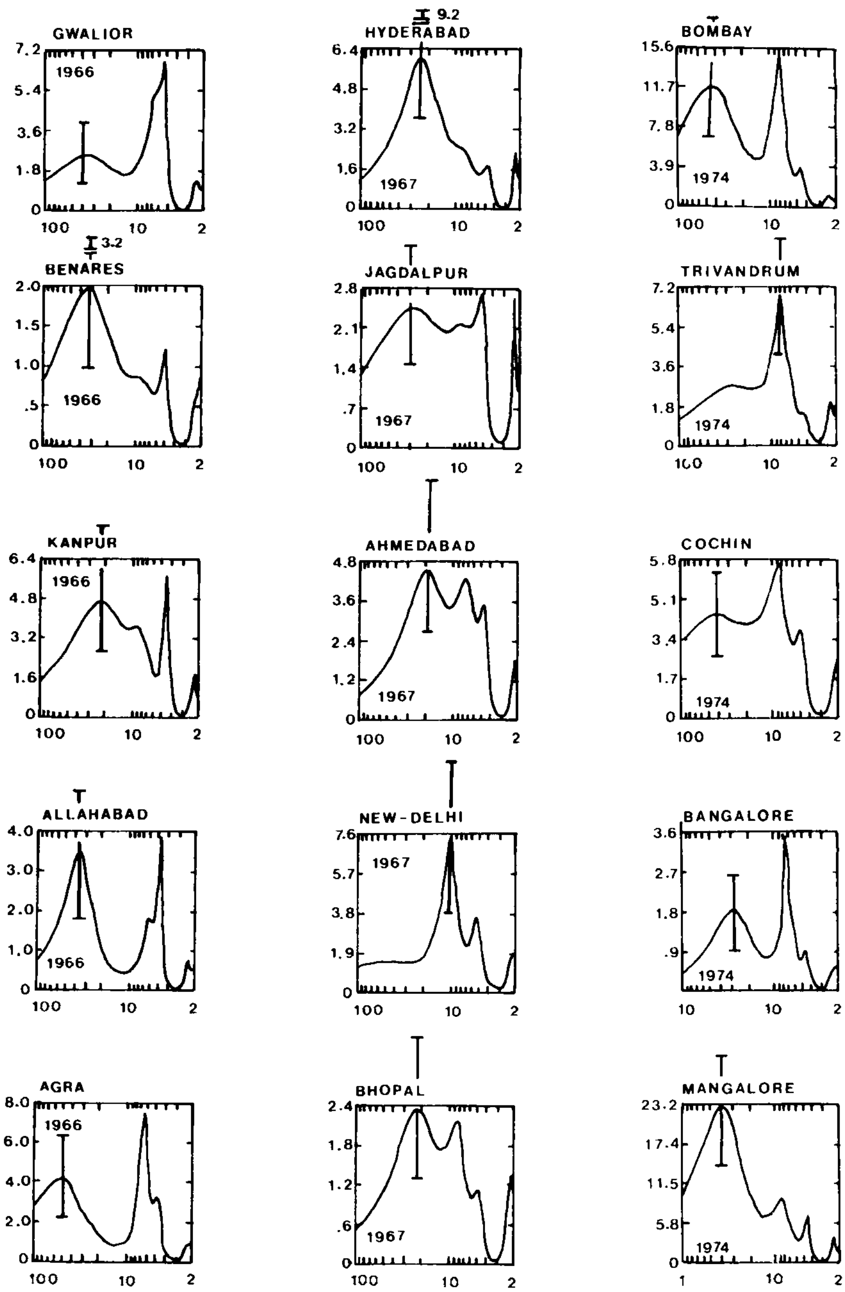

Fig. 8. Examples of spectra of the rainfall time series during certain years at some stations. Confidence intervals at the 5% level are given. The ordinate corresponds to power density times the frequency.

the monsoon (Krishnamurti and Bhalme, 1976) and the low-frequency mode in the 30- to 50-day spectral range. Table 2 gives some statistics on the low-frequency mode for the 15 stations. The periods lie within the range from 30–50 days. At the stations where the mode is well-defined, the typical standard deviation is about 10 days. However, the variability is greater than for the

Table 2. *Statistics on low-frequency fluctuations of rainfall time series at different stations in India: average summer precipitation, average period of the low-frequency mode and its standard deviation*

Station	Average summer precipitation (mm)	Average period (days)	Standard deviation (days)	No. years	Lag (days) with pressure (σ)	Lag (days) with cloudiness (σ)
Trivandrum	1285	39.2	10.4	14	9.0 (5.5)	3.3 (6.3)
Cochin	2073	50.0	18.1	14	11.8 (8.8)	6.9 (6.7)
Bangalore	562	42.0	11.2	14	11.8 (10.5)	6.2 (10.9)
Mangalore	2882	56.4	24.5	14	18.1 (7.4)	7.5 (7.6)
Hyderabad	546	41.9	14.9	11	9.9 (10.4)	8.8 (8.0)
Jagdalpur	1001	41.7	11.9	14	11.2 (7.8)	10.6 (8.4)
Bombay	1679	39.5	8.9	14	9.8 (3.4)	7.8 (3.6)
Bhopal	885	39.2	9.8	11	17.4 (5.1)	16.1 (4.6)
Ahmedabad	676	36.1	8.3	10	19.6 (7.4)	17.1 (9.9)
Allahabad	620	33.4	10.8	7	26.0 (6.7)	24.7 (8.1)
Bénarès	470	31.7	2.2	3	26.0 (10.3)	24.2 (10.7)
Gwalior	708	36.9	10.3	9	24.0 (8.2)	26.2 (8.7)
Kanpur	458	30.9	1.7	4	23.8 (11.4)	25.7 (9.3)
Agra	289	35.4	4.6	2	23.3 (8.3)	27.1 (9.2)
New Delhi	508	35.2	5.8	6	26.3 (8.2)	27.6 (13.9)

The 4th column gives the number of years used at each station to construct the statistics. The last 2 columns give the lag (days) between maxima/minima of rainfall at the stations and maxima/minima of pressure and minima/maxima of cloudiness along the shipping route in the southern Bay of Bengal. In parentheses, the standard deviation of the lag is indicated. Stations are ordered in latitude from south to north.

cloudiness and pressure in the southern Bay of Bengal. The periods at the northern stations appear shorter than those at the southern stations. Periods at Mangalore and Cochin are the longest ones but the standard deviation is also large. The value of the periods of the low-frequency mode averaged over the 15 stations are indicated on Fig. 5. The low-frequency periods of rainfall time series are close to the periods found for the pressure and cloudiness for most of the summers, but there are some discrepancies (1957, 1968 and 1974).

Lag cross-correlation functions and cross-spectra between the filtered rainfall time series at the different stations have been determined. Rainfall at Bombay has been taken as a reference, because the low-frequency mode is well-defined at that station. Fig. 9 shows the lag cross-correlation functions in 1962 between rainfall at Bombay and at other stations. In the 30- to 50-day range, Bombay rainy and dry spells lag behind those at the southern stations such as Bangalore, Cochin, Trivandrum but leading those at the northern stations such as Ahmedabad, Delhi and Agra. This is in accordance with recent results of Singh and Kripalani (1985) on the northward progression of rainfall anomalies over India.

Lag cross-correlation functions have been determined between the filtered time series of rainfall at Indian stations and the filtered time series of cloudiness and pressure along the shipping route. Because the low-frequency troughs and ridges and associated wet and dry spells propagate northward, the maxima/minima of rainfall at India stations lag behind the maxima/minima of cloudiness and the minima/maxima of pressure over the southern Bay of Bengal. Table 2 gives the statistics for the lag. It tends to increase from the south to the north in accordance with the northward propagation. The cloudiness seems to give better results than the pressure, especially for the southern stations. Bombay, which is located around 18.5°N, appears to behave differently because its lag is similar to those of the southern stations. This result is inconsistent with conclusions drawn from the analysis of Fig. 9. This similar lag between monsoon activity at Bombay and at the southern stations and pressure/cloudiness fluctuations in the southern Bay of Bengal may be due to the fact that they are all located along the western coast of India. At the

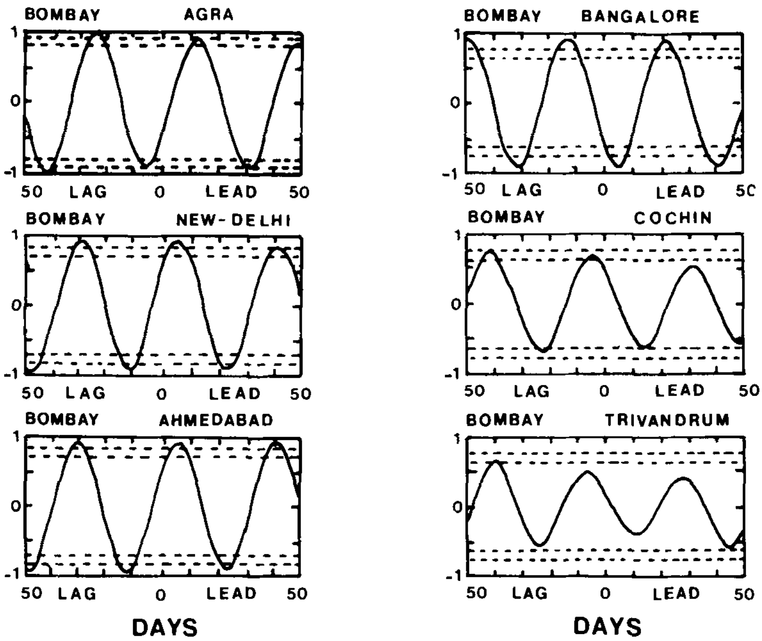

Fig. 9. Lag–cross correlation between the filtered time series at Bombay and at other stations during 1962. The 5% confidence interval is given and takes into account the reduction of the number of degrees of freedom due to the filtering. Lag/lead means that rainfall time series in Bombay lags/leads rainfall time series at the other stations.

northern stations, the lags determined with the pressure and the cloudiness agree quite well, whereas there is less agreement at the southern stations. From these lags, we can infer an average latitudinal progression of 0.8° lat/day which is about the value given by Krishnamurti and Subrahmanyam (1982), but is larger than the estimate obtained by Singh and Kripalani (1985).

4. Forecasting the break/active cycle of the monsoon

After demonstrating the existence of low-frequency oscillations in the surface data time series over the Bay of Bengal and rainfall time series over India and establishing the relationships between the different parameters, we attempt a 30- to 70-day forecast of the activity of the monsoon.

We proceed as follows. The method is identical for the pressure and the cloudiness. First, the time series of the parameter averaged along the shipping route are filtered between 30 and 50 days for the entire year. Second, the first 4 months of data (January to April) are taken and an auto-regressive (AR) process (Box and Jenkins, 1976) is fitted to this 4-month time window. Using the AR model, an extrapolation is made for the next 30, 40, 50 or 70 days, depending on the range which is aimed at. Third, the 4-month time window is shifted by one day, another AR process is fitted and the extrapolation is made for the next 30, 40 or 50 days. This process is repeated till the forecast reaches the end of the year. For a better presentation of the results, the forecast time series is band-pass filtered by the same Butterworth filter to remove the small amount of random component introduced by the AR model.

To assess the quality of the forecast, some statistics are constructed on the difference between the predicted minima/maxima of pressure and maxima/minima of cloudiness and the observed maxima/minima of the activity of the monsoon. To determine this difference, the average time lag, determined for each station, between the occurrence of a perturbation in the southern Bay of Bengal (maximum/minimum of cloudiness and minimum/maximum of pressure)

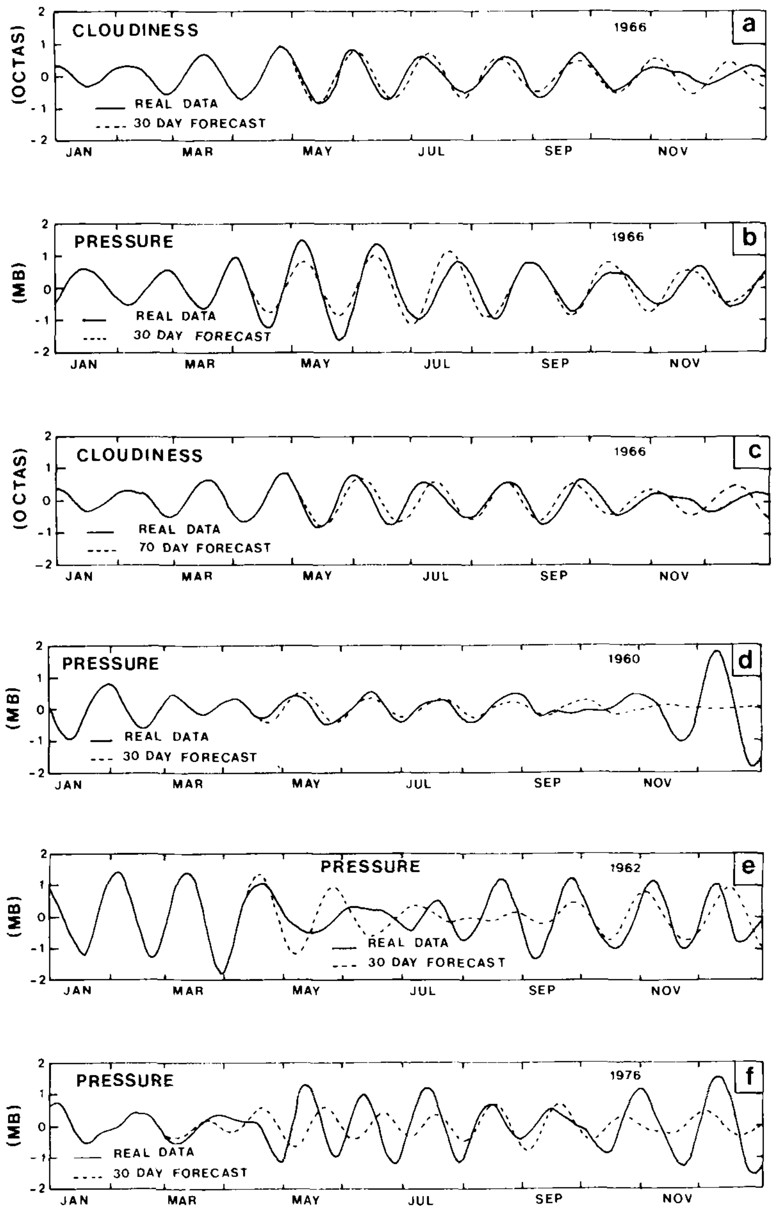

Fig. 10. Examples of the forecast time series at different ranges (30 and 70 days) for certain years. The solid line represents the band-pass filtered time series. The dashed line gives the forecast time series (see text for details on the procedure used to obtain the forecast).

and the maximum/minimum phase of activity of the monsoon is taken into account.

The approach used here relies on the Box–Jenkins method, which offers a way to develop a model of a time series and to forecast its future evolution. An auto-regressive process (AR) is fitted to the data. This method is very popular and has been applied in meteorology to model rainfall time series (Delleur and Kavvas, 1978) or any other meteorological time series (Katz and

Skaggs, 1981). In this study, the order of the AR has been taken equal to 9. This is also the order of the auto-regressive moving average process used in the spectral analysis of the time series (MEM).

In this method, developed to forecast the activity of the monsoon, an important hypothesis is made. The forecast relies on the phase of the low-frequency mode. Its quality depends on the knowledge of the phase of the phenomenon during the 4-month period during which an AR process is fitted onto the time series. As discussed previously, the period of the mode is not constant with time. The forecast of the timing of the maxima/minima of the activity of the monsoon will be affected by any change in the period of the mode during the forecast period.

The 30-, 40-, 50-, 60- and 70-day forecasts have been made for the years during which daily rainfall data are available at the 15 selected stations. Fig. 10 gives some examples of the forecast time series at the 30- and 70-day range. During certain years when the low-frequency mode is well-defined such as in 1966 when the amplitude is weak but the period constant, a forecast up to 70 days can be made with a certain degree of accuracy. However, during other years, such as 1962, when the mode is well-defined during the first 4 months of the year and then fades away before reappearing in August, the forecast fails because there is a rapid change in the characteristics of the phenomenon. This change may be due to a problem in the data because the active/break cycle is well-defined on the rainfall time series at the stations, as can be inferred from the filtered rainfall time series at different stations (not shown). Another example of a failing forecast is given by the 1976 pressure time series. A well-defined low-frequency mode exists during the summer season, but does not appear during the first few months of the year. As a consequence, the forecast which is based on an AR model fitted to the previous 4 months of data fails during the beginning of the summer season. Better results are obtained in July, August and September when the AR model is fitted to a well-defined mode.

For the different forecast range, some statistics have been made. They are presented in Table 3, which gives the mean error (days) of the forecast of the 1st, 2nd and 3rd active and inactive periods at the 15 selected stations. The statistics are given for the 30-, 40- and 50-day forecasts. These statistics have been obtained as follows. The dates of maxima and minima of the filtered forecast pressure and cloudiness time series are determined over the southern Bay of Bengal. Then the lag existing between the minimum (maximum) of pressure/maximum (minimum) of cloudiness and the peak of the active (inactive) monsoon is added for each station. These final dates are compared to the dates of occurrence of the peak of the active and break monsoons obtained from the filtered time series of rainfall at each station. For the first two active and inactive periods for most of the stations, the statistics are based on 14 years, whereas for the third active and inactive monsoons, the statistics are typically based on 7 and 8 years, because during certain years, only two active and break periods take place. Note that the date of the onset is not really predicted, because no universal definition of that date exists: establishment of a strong low-level circulation over the Arabian Sea, first sustained rainfall along the southern part of the west coast of India, etc. The date of the maximum intensity of the first active period which starts the monsoon season is forecast.

At most rainy stations, for example those along the western coast of India where the 30- to 50-day cycle is well marked, the average error is about a week. The error is larger at other stations. The error is about the same when using the pressure or the cloudiness time series. Note that the statistics incorporate some years when the forecast fails (Figs. 10e–f). For the years exhibiting a well-defined and nearly invariant low-frequency mode, the error reaches about 4 days. The error generally increases with increasing length of forecast. At stations with a rather short rainy season, i.e., some northern stations such as Agra or New Delhi, the error on the forecast date of third active and inactive period is very large, because during certain years, there are really no observed third active and inactive spells.

5. Conclusions

In this study, ship observations along the well-sampled shipping route from Sri Lanka to Sumatra have been processed to determine the daily fluctuations of zonal and meridional

Table 3. *Statistics on the quality of the forecast of the dates of the peak of the active and inactive periods of the monsoon at the different stations*

	1st active period			1st inactive period			2nd active period			2nd inactive period			3rd active period			3rd inactive period		
Stations	30	40	50	30	40	50	30	40	50	30	40	50	30	40	50	30	40	50
Bombay	7.9	7.9	9.1	8.9	8.4	9.9	8.7	9.7	8.8	6.9	7.7	7.8	8.1	8.3	9.6	8.4	9.8	9.9
	8.1	8.1	9.9	10.7	10.9	10.6	9.0	8.5	9.4	8.9	9.5	9.5	7.2	6.2	8.8	6.4	6.5	7.8
Trivandrum	9.9	10.1	10.4	10.0	9.0	10.6	8.1	7.8	9.6	6.4	7.1	7.9	8.9	9.2	10.9	9.9	9.6	10.7
	8.1	7.9	7.9	9.6	9.1	9.1	9.1	9.1	10.4	8.0	8.4	9.1	10.4	10.1	10.2	8.4	8.6	8.3
Cochin	9.2	9.4	9.2	8.9	8.6	8.9	12.1	11.4	11.9	12.0	11.8	12.6	8.1	8.1	11.6	8.9	8.8	9.4
	10.1	10.2	9.4	10.8	10.6	10.5	11.1	11.4	11.3	11.2	11.3	10.7	8.0	8.6	7.6	6.7	7.4	7.4
Bangalore	8.4	7.4	7.0	11.1	8.9	9.3	10.7	11.0	11.1	10.8	11.3	10.6	12.5	12.6	12.5	10.4	11.2	12.8
	9.6	9.7	9.7	10.6	10.3	9.4	12.4	12.5	11.1	12.5	13.1	11.7	11.8	11.9	11.5	8.6	10.1	10.0
Mangalore	9.0	8.7	8.8	9.0	7.1	8.4	6.9	7.3	9.7	7.5	8.1	9.3	12.2	11.5	10.3	10.6	10.9	11.5
	8.2	8.1	8.0	8.9	8.6	8.9	10.2	10.5	9.4	8.6	9.1	8.8	10.0	9.9	9.0	8.4	10.1	9.8
Hyderabad	13.2	12.3	12.1	11.1	9.0	10.3	10.4	10.4	11.0	10.4	11.1	10.8	9.6	10.6	9.8	10.5	10.5	11.0
	11.6	11.1	12.0	11.1	11.1	11.1	10.9	11.1	11.6	9.8	9.8	10.8	9.0	8.5	8.8	9.4	8.8	9.9
Jagdalpur	11.1	11.2	11.8	12.9	12.1	12.2	10.8	11.3	12.1	9.3	10.1	11.1	9.0	8.2	10.1	9.1	8.6	10.3
	11.7	11.5	11.6	12.8	12.4	12.0	9.4	9.1	11.0	8.9	9.2	10.8	8.2	7.0	7.8	7.3	6.9	7.5
New Delhi	11.0	11.2	12.4	12.1	11.1	11.8	11.8	11.4	13.2	11.0	11.9	12.1	17.5	17.6	19.0	19.0	19.3	20.4
	9.4	9.4	10.4	7.2	7.8	8.2	10.1	9.8	10.1	10.5	12.1	10.3	17.8	17.8	15.4	18.3	19.5	19.3
Agra	8.6	8.4	9.6	7.5	7.6	7.1	12.4	12.6	11.7	9.4	12.8	13.3	22.4	21.8	22.3	23.0	23.0	23.8
	9.9	10.2	11.6	12.4	9.7	9.4	11.2	10.8	11.8	11.8	12.8	12.9	16.4	17.3	16.7	19.2	20.2	20.3
Allahabad	7.6	7.7	10.1	11.0	11.2	10.7	11.4	11.1	9.4	6.5	6.5	7.8	12.7	13.2	14.0	10.5	11.6	11.2
	9.7	9.5	9.9	10.1	10.3	10.6	10.7	10.9	10.7	8.6	7.5	8.1	11.6	11.8	10.7	13.1	13.3	12.8
Gwahoi	9.1	9.4	9.3	9.0	9.7	9.7	9.8	10.8	10.4	10.5	10.3	10.0	15.7	14.3	15.5	13.8	14.9	16.1
	9.2	9.1	9.4	9.4	9.1	8.6	9.9	10.0	9.2	11.3	12.3	11.6	14.7	15.5	15.0	14.3	15.5	15.2
Kanpur	9.6	9.2	8.5	9.0	9.1	8.2	13.2	12.4	11.6	14.4	14.7	14.7	18.2	18.7	20.7	16.9	17.2	18.1
	10.0	9.6	9.7	10.9	9.4	9.9	10.9	10.1	9.8	12.2	13.1	11.8	14.4	15.6	15.8	15.6	15.8	15.6
Bénarès	7.0	6.6	7.3	9.4	7.7	7.9	11.2	10.7	9.6	10.3	11.2	13.1	11.9	12.8	13.5	19.1	19.3	19.7
	8.6	8.8	9.3	9.0	9.1	8.9	9.8	9.8	9.6	11.5	12.7	12.2	15.0	13.9	12.5	20.3	21.0	20.4
Bhopal	9.4	9.7	10.7	8.1	8.6	8.6	10.9	10.1	9.1	8.4	8.9	9.8	8.8	10.3	12.2	9.6	10.5	10.9
	9.2	8.9	9.9	8.9	8.9	8.9	8.9	9.2	9.1	8.3	9.1	9.6	6.9	6.4	8.6	9.0	9.5	9.1
Ahmedabad	10.4	10.9	11.4	10.9	11.4	11.0	11.5	10.3	11.4	10.4	10.9	10.1	11.4	12.2	11.5	12.8	12.8	13.5
	11.3	11.1	10.9	11.0	10.6	10.0	8.5	9.1	8.5	10.8	10.8	11.2	12.8	12.6	10.8	14.4	14.8	13.5

The first line gives the average error (day) for the cloudiness and the second line for the pressure. The statistics of the 30-, 40- and 50-day forecasts are given.

components of the wind, pressure, cloudiness, air temperature and SST over a 23-year period from 1 January 1954 to 31 December 1976. The time series of pressure and cloudiness exhibit a well-defined 30- to 50-day oscillation. Low (high) pressure events are associated with above (below) normal cloudiness. They correspond to the perturbations propagating northward during the summer monsoon which give rise to the low-frequency fluctuations of the monsoon activity.

The strong relationship existing between these northward propagating perturbations which are noted on the cloudiness and surface pressure data while passing over the southern Bay of Bengal and the activity of the monsoon over India has been used to forecast the break and active periods of the summer monsoon. The results indicate that the activity of the monsoon can be predicted a month in advance with an average error of about a week for most of the stations over India. In particular, the method offers a way to forecast the onset of the summer monsoon at the 30-day range.

When the low-frequency mode is well-defined during the first few months of a year and its characteristics (mainly its period) do not change very much during the spring and summer seasons, a quite accurate timing of the active and inactive periods can be forecast. However, during certain years, the 30- to 50-day mode is not well-defined and/or its characteristics are changing rapidly. Then it seems hazardous to use the mode to forecast the activity of the monsoon, especially when there is an unexpected collapse in the amplitude of the 30- to 50-day mode during the summer season.

It can also be noted that the data set used in this study is not of the best quality, but it offers the advantage of being available for many years allowing the determination of some significant statistics. Some other data sets covering many years are also available (for example outgoing longwave radiation). They clearly show the evidence of the low-frequency mode and its relationship with the activity of the summer monsoon. It should be interesting to use these other data sets to forecast the activity of the monsoon.

6. Acknowledgements

This study has been performed during the post-graduate visit of Pierre Daniel to LMD. Computations have been performed at CIRCE (CNRS Computing Center).

REFERENCES

Alexander, G., Keshavamurty, R. N., De, U. S., Cheppala, R., Das, S. K. and Pillai, P. V. 1978. Fluctuations of monsoon activity. *Indian J. Meteorol. Hydrol. Geophys. 29*, 76–87.

Anderson, J. R., Stevens, D. E. and Julian, P. R. 1984. Temporal variations of the tropical 40–50 day oscillation. *Mon. Wea. Rev. 112*, 2431–2438.

Bennett, R. J. 1979. *Spatial time series. Analysis. Forecasting*. Control. Pion Limited, London, 674 pp.

Box, G. E. and Jenkins, G. M. 1976. *Time series analyses. Forecasting and control*. Holden-Day Editor, 575 pp.

Cadet, D. L. and Diehl, B. C. 1984. Interannual variability of surface fields over the Indian Ocean during recent decades. *Mon. Wea. Rev. 112*, 1921–1935.

Cadet, D. L. 1986. Fluctuations of precipitable water over the Indian Ocean during the 1979 summer monsoon. *Tellus 38A*, 170–177.

Delleur, J. W. and Kavvas, M. L. 1978. Stochastic models from monthly rainfall forecasting and synthetic generation. *J. Appl. Meteorol. 17*, 1528–1536.

Fieux, M. and Stommel, H. 1977. Onset of the southwest monsoon over the Arabian Sea from marine reports of surface winds: structure and variability. *Mon. Wea. Rev. 105*, 231–236.

Katz, R. W. and Skaggs, R. H. 1981. On the use of autoregressive-moving average processes to model meteorological time series. *Mon. Wea. Rev. 109*, 479–484.

Knutson, T. R., Weickmann, K. M. and Kutzbach, J. E. 1986. Global-scale intraseasonal oscillations of outgoing long wave radiation and 250 mb zonal wind during northern hemisphere summer. *Mon. Wea. Rev. 114*, 605–623.

Krishnamurti, T. N. and Bhalme, H. N. 1976. Oscillations of a monsoon system. Part I: observational aspects. *J. Atmos. Sci. 33*, 1937–1954.

Krishnamurti, T. N. and Ardanuy, P. 1980. The 10 to 20 day westward propagating mode and "breaks in the monsoons". *Tellus 32*, 15–26.

Krishnamurti, T. N. and Subrahmanyam, D. 1982. The 30–50 day mode at 850 mb during MONEX. *J. Atmos. Sci. 39*, 2088–2095.

Krishnamurti, T. N., Jayakumar, P. K., Sheng, J., Surgi, N. and Kumar, A. 1985. Divergent circulations on the 30 to 50 day time scale. *J. Atmos. Sci. 42*, 364–375.

Krishnamurti, T. N. and Gadgil, S. 1985. On the structure of the 30 to 50 day mode over the globe during FGGE. *Tellus 37A*, 336–360.

Kung, E. C. and Sharif, T. A. 1980. Regression forecasting of the onset of the Indian summer monsoon with antecedent upper air conditions. *J. Appl. Meteorol. 19*, 370–380.

Kung, E. C. and Sharif, T. A. 1982. Long-range forecasting of the Indian summer monsoon onset and rainfall with upper air parameters and sea surface temperature. *J. Meteorol. Soc. Japan 60*, 272–281.

Lau, K.-M. and Chan, P. H. 1986. Aspects of the 40–50 day oscillation during the northern summer as inferred from outgoing longwave radiation. *Mon. Wea. Rev. 114*, 1354–1367.

Madden, R. A. and Julian, P. R. 1971. Detection of a 40–50 day oscillation in the zonal wind in the tropical Pacific. *J. Atmos. Sci. 28*, 702–708.

Madden, R. A. and Julian, P. R. 1972. Description of global-scale circulation cells in the tropics with a 40–50 day period. *J. Atmos. Sci. 29*, 1109–1123.

Murakami, M. 1976. Analysis of summer monsoon fluctuations over India. *J. Meteorol. Soc. Japan 54*, 15–31.

Murakami, M. 1979. Large-scale aspects of deep convective activity over the GATE area. *Mon. Wea. Rev. 107*, 994–1013.

Murakami, M. 1984. Analysis of deep convective activity over the western Pacific and southeast Asia. Part II: seasonal and intraseasonal variations during northern summer. *J. Meteorol. Soc. Japan 62*, 88–108.

Murakami, T., Nakazawa, T. and He, J. 1984. On the 40-50 day oscillation during the 1979 northern hemisphere summer. Part I: phase propagation. *J. Meteorol. Soc. Japan 62*, 440–468.

Murakami, T. and Nakazawa, T. 1985. Tropical 45 day oscillations during the 1979 northern hemisphere summer. *J. Atmos. Sci. 42*, 1107–1122.

Murakami, T., Chen, L.-X., Xie, A. and Shrestha, M. L. 1986a. Eastward propagation of 30–60 day perturbations as revealed from outgoing longwave radiation date. *J. Atmos. Sci. 43*, 961–971.

Murakami, T., Chen, L.-X. and Xie, A. 1986b. Relationship among seasonal cycles, low-frequency oscillations and transient disturbances as revealed from outgoing longwave radiation data. *Mon. Wea. Rev. 114*, 1456–1465.

Nakazawa, T. 1986. Intraseasonal variations of OLR in the tropics during the FGGE year. *J. Meteorol. Soc. Japan 64*, 17–34.

Sikka, D. R. and Gadgil, S. 1980. On the maximum cloud zone and the ITCZ over Indian longitudes during the southwest monsoon. *Mon. Wea. Rev. 108*, 1840–1853.

Singh, S. V. and Kripalani, R. H. 1985. The south to north progression of rainfall anomalies across India during the summer monsoon season. *PAGEOPH 123*, 624–637.

Singh, S. V. and Kripalani, R. H. 1986. Application of extended empirical orthogonal function analysis to interrelationships and sequential evolution of monsoon fields. *Mon. Wea. Rev. 114*, 1603–1610.

Yasunari, T. 1979. Cloudiness fluctuations associated with the northern hemisphere summer monsoon. *J. Meteorol. Soc. Japan 57*, 227–242.

Yasunari, T. 1980. A quasi-stationary appearance of 30 to 40 day period in the cloudiness fluctuations during the summer monsoon over India. *J. Meteorol. Soc. Japan 58*, 225–229.