Intra-seasonal oscillations during monsoon 2002 and 2003

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Features of the intra-seasonal oscillations during monsoon 2002, a drought year, and monsoon 2003, a normal year, have been examined by applying a frequency filter and the technique of wavelet analysis to rainfall data. Analysis reveals that while the faster 10–20 days mode dominated monsoon 2003, the slower 30–60 days mode dominated monsoon 2002.

THE summer monsoon rainfall from 1 June to 30 September for India as a whole during 2002 (2003) was 81 (102)% of its long period average (LPA). Thus, while the southwest monsoon of 2002 was a severe all-India drought, monsoon of 2003 was marked by near-normal rainfall over the country, distributed equitably over both space and time (source: India Meteorological Department website, www.imd.ernet.in).

This monsoon rainfall variability is partly due to the external surface boundary forcing and partly due to its internal dynamics. Slowly varying surface boundary conditions such as the sea surface temperature, land-surface temperature, snow cover, soil moisture, etc. in the preceding winter and the pre-monsoon season are believed to constitute a major forcing on the inter-annual variability of the monsoon rainfall – these provide the handle for seasonal prediction. The diverse nature of the forecasts varying from 85 to 113% (of its LPA) of the all-India summer monsoon rainfall for 2003 suggests the complexity of the problem[1]. This complexity may due to the fact that variability associated with the internal dynamics within the monsoon system is inherently unpredictable. The intra-seasonal variability dominant during the monsoon season constitutes this internal dynamics. Thus the inter-annual changes in the intra-seasonal variability (i.e. within the season) are an important potential source of inter-annual (from one year to the other) fluctuations of Indian summer monsoon rainfall strength[2–6].

It is well known that the rainfall distribution over India varies considerably from day to day. Over major parts, rain occurs in spells under the influence of favourable circulation conditions. This intermittent behaviour of rainfall is associated with an hierarchy of quasi-periods, namely 3–7 days, 10–20 days and 30–60 days. While the 3–7 days periodicity is associated with oscillations of the monsoon trough, the 10–20 days periodicity or the quasi-biweekly oscillations are associated with the westward moving waves or the synoptic-scale convective systems generated over the warm Bay of Bengal, propagating inland and contributing substantial rainfall. Active spells of monsoon are characterized by a sequence of time-clustering development of such disturbances, whereas no such systems occur during breaks[7,8].

The 30–60 days periodicity is linked with the globally eastward-moving wave numbers 1 and 2 in the tropics, in particular the equatorial regions. These eastward-moving 30–60 days or 40–days oscillations are now designated as the Madden–Julian oscillations[9]. These two periods, the 10–20 days[10] and the 30–60 days[11], have been related with the active and break cycles of monsoon rainfall over the Indian region. The 30–60 days oscillations are also characterized by northward movement of weather anomalies, including rainfall and outgoing long-wave radiation[12–16]. However, these northward-moving 30–60 days oscillations show considerable variation in this period within the same season or year-to-year[17–20]. Besides, certain summers exhibit regular northward progressions of convection, whereas during other summers the northward propagation is irregular or absent entirely[14,17]. More details of this mode, its mechanism of northward propagation and its role in the active–break cycles of monsoon rainfall over India can be found elsewhere[7,21].

From the above it is clear that the seasonal monsoon strength may depend on the frequency and duration of spells of break or active periods associated with these intra-seasonal oscillations. The reasons for the fluctuations between the active and weak spells, and the processes which could trigger a change from one state to another, within the monsoon season still need understanding[7]. Hence to understand the role of the intra-seasonal oscillations in the active–break cycles and in the seasonal monsoon strength, characteristic features of these oscillations, in particular the 10–20 days and the 30–60 days have been investigated by applying a frequency filter and the technique of wavelet analysis to the rainfall data for the summer months during the monsoon drought of 2002 and the normal monsoon of 2003.

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Data

The description of datasets for monsoons of 2002 and 2003 used in this study are as follows:

(i) Daily station (approximately 50) rainfall data and the daily rainfall data for India as a whole (day-to-day rainfall based on approximately 100 to 150 stations) are collected from All-India weather summary prepared by the India Meteorological Department (IMD).

(ii) Weekly rainfall data for India as a whole and the subdivisional rainfall data are downloaded from the website of IMD, www.imd.ernet.in

(iii) The CPC (Climate Prediction Center, USA) merged rainfall data are downloaded from the website www.cpc.ncep.noaa.gov. Data for southern Asia are available for the region 70–110°E, 5–35°N since 1 May 2001 at a resolution of 0.1° × 0.1°. Inputs to estimate this rainfall include GTS station data, geostationary infrared cloud top temperature fields, polar orbiting satellite precipitation estimate data from SSM/I and AMSU-B microwave sensors. More details are available from the website.

Daily rainfall distribution

Year-to-year changes in the behaviour of the intra-seasonal oscillations in rainfall can be demonstrated by displaying the time series of precipitation. Hence daily time series for India as a whole for the monsoons of 2002 and 2003 are shown in Figure 1 along with the seasonal cycle (average daily rainfall).

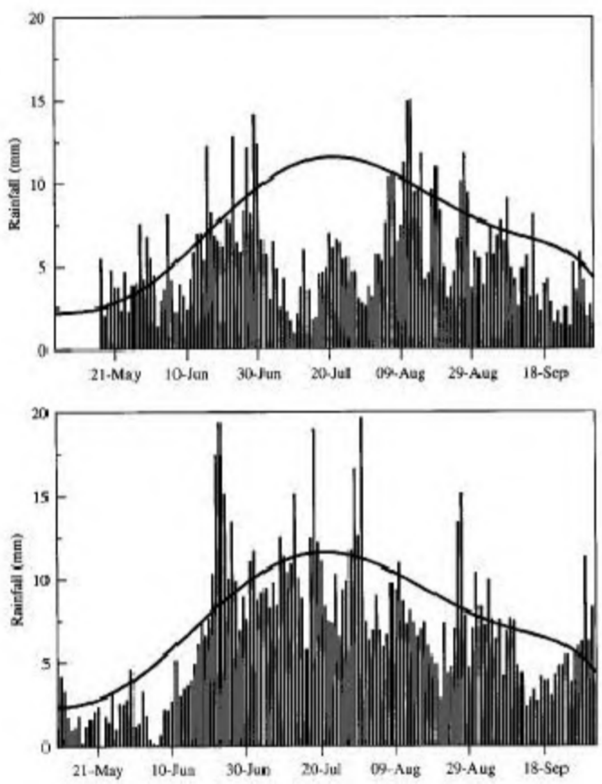

Figure 1. Time series of daily precipitation for India as a whole for monsoon 2002 (upper panel) and monsoon 2003 (lower panel). Solid curve represents daily normal smoothened values (details on website www.tropmet.res.in).

The 2002 summer monsoon is marked by a long break, i.e. below normal rainfall throughout the month of July. In fact, precipitation on most of the days during this month is less than half the normal value. The rainfall during July 2002 was deficient by about 50% (www.imd.ernet.in)[22]. Except during the last week of June and second week of August, no clear active periods are noticed.

Conversely, during 2003 summer season, no well-defined break periods are discernible. Instead the precipitation time series is marked by relatively steady rainfall from one day to the next throughout the season. In particular, the 2003 summer is devoid largely of low rainfall days. Some distinct active periods are seen around 20 June, 15 July, 30 July, and the first and last week of September.

Subjecting the daily time series to some statistical/mathematical techniques can derive more inferences. The techniques normally applied to examine periodicities are band-pass filter, spectrum analysis, harmonic analysis and more recently, wavelet analysis. While the first three techniques give no information on how the periodicities may have varied with time, i.e. within the monsoon season, wavelet analysis is becoming a common tool for analysing localized variation of power within a time series. Hence in this article we have applied the techniques of band-pass filter and wavelet analysis.

Inferences from band-pass filter

We investigate the spatial and temporal characteristics of the 10–20 days and 30–60 days oscillations in monsoon rainfall. For examining the intensity of these oscillations and their spatial and temporal variations, Butterworth band-pass filter is applied[23]. The actual calculation consists of two steps. At the first step, the tentative output is calculated. Then this output is reversed in time and processed again to obtain the final output. This procedure results in zero phase shift for all frequencies, hence the frequency bands are not overlapping. The filter with half-power points at 10 and 20 for the quasi-biweekly oscillations and at 30 and 60 days for the so-called 40-days oscillations is applied to the rainfall time series. The percentage of the original variance retained by the filtered time series is determined. Before the band-pass filter is applied to the rainfall time series, the seasonal cycle is removed by subtracting the mean rainfall for that particular day.

All-India daily rainfall time series

To begin with, the band-pass filter is applied to the anomalies of the daily precipitation time series displayed in Figure 1. The filter is applied to retain variances in 3–7, 10–20 and 30–60 days band (Table 1).

Table 1 reveals that the variances in the faster modes (3–7, 10–20 days) are more during monsoon 2003 than 2002, while the variance in the slower mode (30–60 days) is more during 2002 than 2003.

The differences in the filtered variances for 2002 and 2003 have been tested by applying the F-test. The values of F-statistics are 1.43, 1.9 and 1.36 for 3–7, 10–20 and 30–60 days filtered variances respectively. These values are highly significant at 5% level. The critical value of $F_{121,121}$ is 1.25. Also Monte-Carlo simulations with 1000 random samples confirm the significance of differences in these variances for 2002 and 2003.

Figure 2 shows the daily rainfall anomalies, the filtered 10–20 days and 30–60 days time series super-imposed on the same diagram. The filtered time series for 2002 (2003) are displayed in top (bottom) panel. While the amplitude of the 10–20 days oscillation during monsoon 2003 is enhanced, it is suppressed during monsoon 2002. On the other hand, the amplitude of the 30–60 days oscillation is enhanced during 2002 and suppressed during 2003. Further, the active (break) monsoon spells are strengthened when the positive (negative) phases of both these oscillations appear simultaneously, i.e. they are phase-locked; for example, around 10 August 2002 and 21 June 2003 (July 2002 and around 15 September 2003).

This suggests that during the monsoon drought of 2002, the 30–60 days mode was predominant, while during 2003, the 10–20 days mode was prevalent.

Table 1. Percentage of variances retained by the filtered series

	Filter		
Year	3–7	10–20	30–60
2002	11.5	7.9	12.4
2003	16.5	15.3	9.1

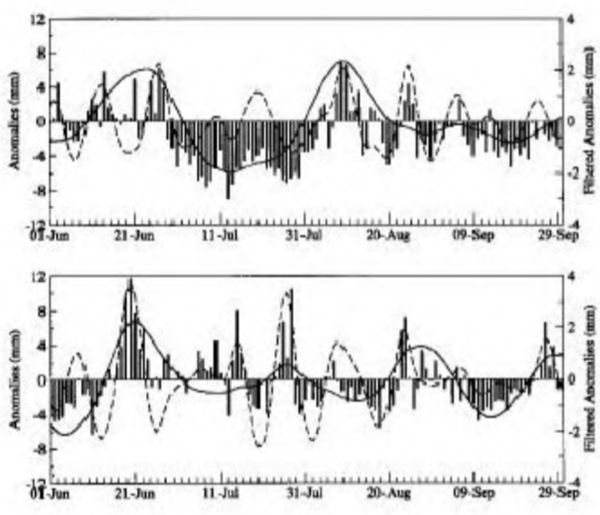

Figure 2. Time series of daily precipitation, filtered 10–20 days (dashed line) and filtered 30–60 days (solid line) for monsoon 2002 (upper panel) and 2003 (lower panel).

Spatial distribution of variance

To examine how the intensity of these modes may have changed over various parts of India, we first need to know the spatial rainfall distribution. Hence we present the subdivisional rainfall information. On a meteorological subdivisional level, rainfall between – 19 and + 19% of LPA is regarded as normal. A rainfall deficit/surplus of more than 25 (50)% of LPA is defined as a moderate (severe) meteorological drought/flood (IMD).

Maps showing the spatial distribution of rainfall in terms of percentage departures from normal are shown in Figure 3. The most striking difference of this rainfall distribution is over northwest India. While this region witnessed moderate to severe drought during 2002, it witnessed moderate to severe floods during 2003. In general, the rainfall distribution over the country is on the negative (positive) side during 2002 (2003). The main deficient areas during 2003 are from south Maharashtra through Karnataka to Kerala (IMD).

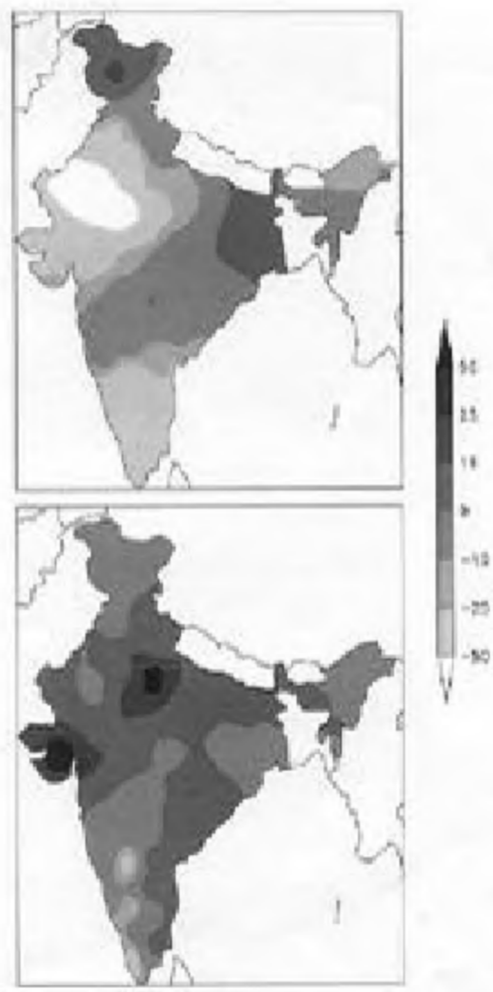

Figure 3. Spatial distribution of percentage departure from normal rainfall for monsoon 2002 (upper panel) and monsoon 2003 (lower panel).

To examine whether the intensity of the intra-seasonal oscillations had any role to play in the above rainfall distribution, band-pass filter was applied to rainfall time series of stations shown in Figure 4. Since daily point rainfall data can be highly variable, 5-day (pentad) rainfall has been considered for these stations.

The spatial distribution of variance contained in the 10–20 days band is shown in Figure 5. Over most of the area the variances vary from 10 to 30% during 2002 and 30 to 50% during 2003. Again suggesting that the intensity of the 10–20 days mode was more during 2003 than during 2002. It is interesting to note that the deficient areas during 2003 (south Maharashtra to Kerala) show relatively less variance (20–30%) in this band compared to variance distribution over other parts of the country.

A similar spatial distribution for the 30–60 days band is shown in Figure 6. Over major parts of the country, the variances vary from 15 to 30% during 2002 with maximum over northwest India – the region of severe rainfall deficiency. During 2003 it varies from 5 to 20%. Thus over most of the country, the 30–60 days mode was more dominant during 2002 than 2003.

The F-test shows that 55 (42)% stations have significantly more 30–60 (10–20) days filtered variance in 2002 (2003) than in 2003 (2002). Monte-Carlo simulations with 1000 random samples show significant differences only in 4% cases, supporting the results obtained through F-test.

In summary, regions with deficit rainfall are more likely to be dominated by the 30–60 days mode, while the surplus areas are likely to be dominated by the 10–20 days mode.

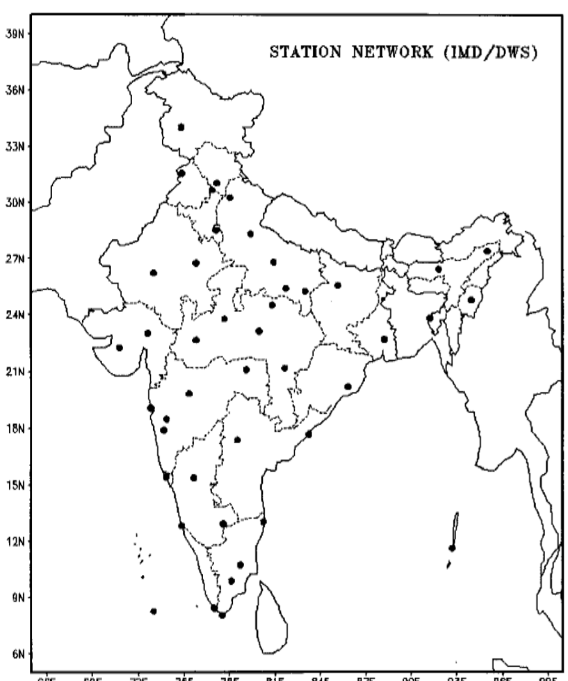

Figure 4. Location of stations (represented by dots) used to compute spatial distribution of variances in pentad rainfall.

Inferences from wavelet analysis

In the above analysis, the dominant intra-seasonal mode during the entire season has been identified. However, it gives no knowledge of the change in the intensity of the mode during the season nor does it give any clue whether one mode changes to another.

Wavelet transform (WT) or wavelet analysis is a powerful mathematical analysis method well suited to the study of multi-scale non-stationary processes occurring over finite spatial and temporal domains. Mathematically, WT of any function h is defined as the integral inner product between h and wavelet function ω. The wavelet functions ω are those functions satisfying certain criteria[24,25]. The wavelet function used in the present study is the 'Mexican hat' function, which is a second derivative of the Gaussian function.

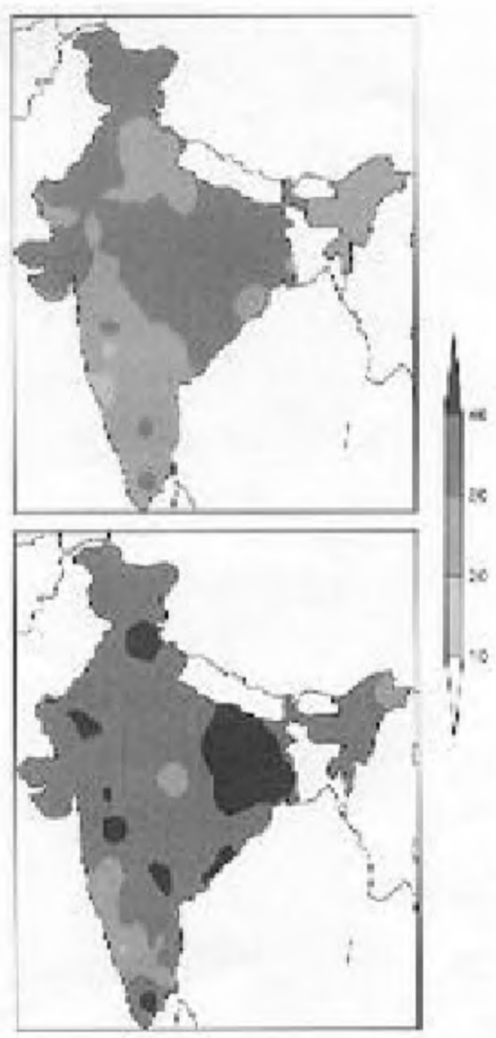

Figure 5. Spatial distribution of variances (%) contained in the 10–20 days band for monsoon 2002 (upper panel) and monsoon 2003 (lower panel).

WT is a common tool for analysing localized variation of power within a time series. By decomposing a time series into time–frequency space, one is able to determine both the dominant modes of variability and how those modes vary in time. It involves a transform from a one-dimensional time series (or frequency spectrum) to a diffused, two-dimensional time–frequency image[26]. Computational procedure for WT is available on website http://ion.research-systems/IONscript/wavelet.

The week-by-week rainfall departures and the wavelet spectrum determined from the daily rainfall time series for monsoon 2002 are depicted in Figure 7. Except for a few weeks the rainfall departures are below normal, in particular during July. The wavelet spectrum for monsoon 2002 reveals that during June the maximum variance (red colour) is centred in periods less than 20 days, in particular during the last week of June. There is a clear indication that the period of oscillation increases to around 60 days in July, with maximum variance centred around day 50 (i.e. July 20) in the 40–80 days band. Thereafter the period of oscillation monotonically decreases with periods less than 25 days centred around day 70 (i.e. August 10), and those less than 10 days between days 80 and 90 (second half of August). During mid-September, the variance again shifts to the 30–60 day period around day 110, but with reduced power.

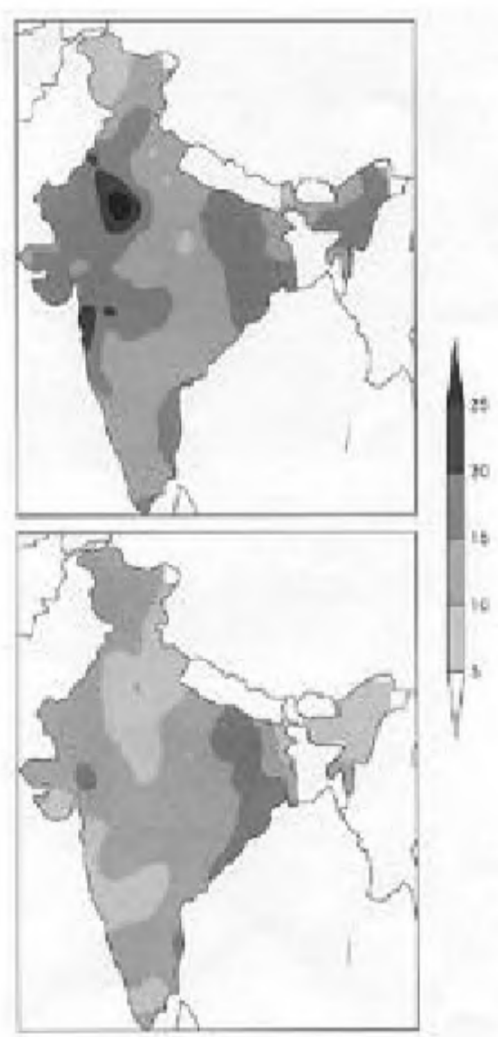

Figure 6. Same as Figure 5, but for the 30–60 days band.

Thus there is a clear synchronization between the weekly rainfall departures and the wavelet spectrum, with negative rainfall departures dominated by the slower 30–60 day mode and positive departures by the faster mode having periodicity less than 20 days.

A similar weekly rainfall departure diagram with the wavelet spectrum for monsoon 2003 is shown in Figure 8. At the beginning of June, the maximum variance is centred around the 30–60 days periodicity; thereafter, in general, over the season the maximum variance is centred in periods less than 20 days, in agreement with the rainfall departures fluctuating around the normal value after July.

Hence weeks of subdued rainfall activity are dominated by the 30–60 days mode, while weeks with active rainfall periods are dominated by the 10–20 days mode.

Propagation characteristics

As mentioned earlier, a dominant characteristic of the intraseasonal fluctuations during summer in the monsoon re-

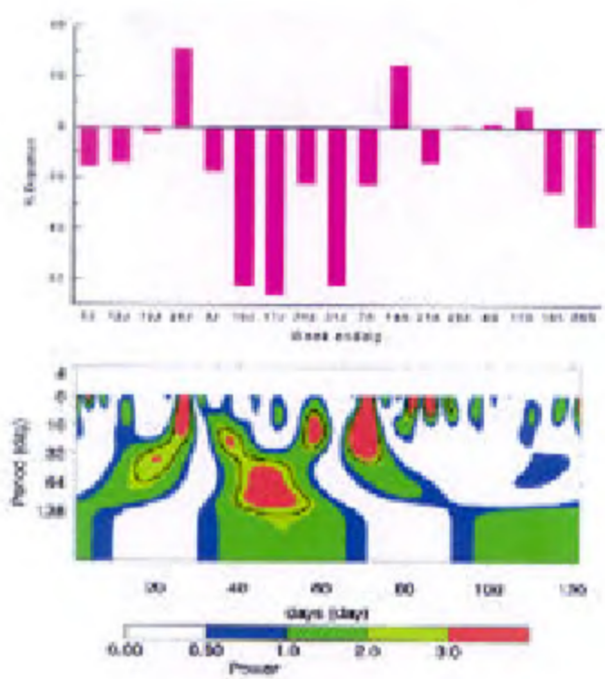

Figure 7. Percentage departures of week-by-week rainfall (upper panel) and wavelet spectrum (lower panel) computed from daily rainfall for monsoon 2002. For the wavelet spectrum, the x-axis denotes days from 1 June to 30 September and y-axis the period in powers of 2.

gion is the active–break cycles of precipitation over India that exhibit periods of 30–60 days[7,11]. The active–break cycles are linked to observed northward propagation of convection from the equatorial Indian Ocean[11,27,28].

Thus a fundamental and unique characteristic of the summer 30–60 days mode is a northward movement of convection, beginning in the central equatorial Indian Ocean and ending near the foot of the Himalayas in north India. Hence in this section we examine the northward propagations using the CPC-merged rainfall data. Hovmoller diagrams are probably the best and simplest means for studying the propagation characteristics of weather anomalies along a particular latitude or longitude belt.

Meridional propagations

To examine the south-to-north progressions, time–latitude sections of the unfiltered CPC precipitation estimated over the Indian longitudes 70–85°E are depicted in Figure 9. One episode of coherent northward movement is clearly visible for monsoon 2002. This episode commences at the beginning of July and propagates barely till 20°N by the first week of July and thereafter up to 25°N till mid-July. From mid-July up to mid-September, hardly any precipitation is visible.

On the other hand, evidence of coherent northward movement of envelopes of precipitation is largely absent during monsoon 2003; however active rainfall periods dominate from July till mid-September. This period is associated with rainfall anomalies fluctuating around the normal period (see Figure 8, weekly anomalies for 2003).

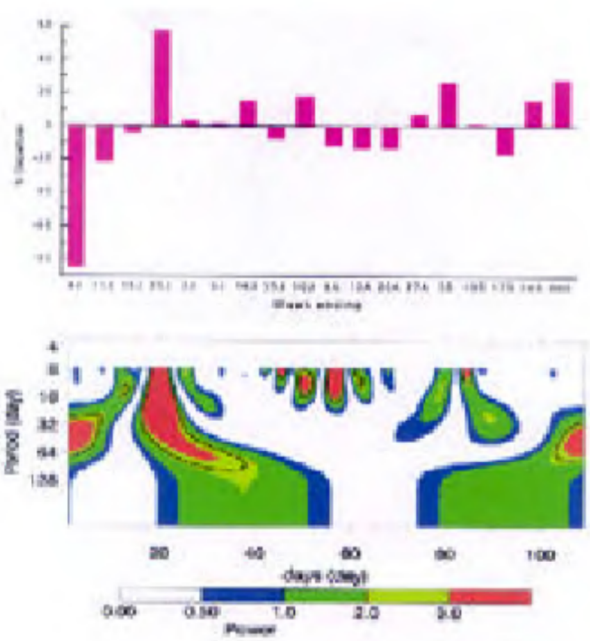

Figure 8. Same as Figure 7, but for monsoon 2003.

In summary, while the monsoon 2002 reveals one northward progression associated with the slow 30–60 days mode, no meridional progressions are seen for monsoon 2003.

Discussion and summary

Intra-seasonal oscillations during the monsoon of 2002, a drought year, and during the monsoon 2003, a normal monsoon year, have been examined by applying the techniques of band-pass filter and wavelet analysis. While the monsoon of 2002 was dominated by the slower 30–60 days mode, monsoon 2003 was dominated by the faster 10–20 days mode. Even within the monsoon season, a change from active to weak spell clearly reveals that the period of oscillation increases from less than 20 days to more than 50 days. This was obvious during the long dry spell of July 2002. In contrast, a change from weak to active spell shows a decrease in periodicity length. Several earlier studies have shown that intra-seasonal (10–20) 30–60 days activity is (directly) inversely related to the Indian monsoon strength[29–31].

Thus the inverse (direct) relationship of the Indian monsoon strength with the 30–60 (10–20) days mode should have some implications for forecasting. However, it is difficult to estimate whether changes in intra-seasonal variabilities force changes in monsoon strength or vice versa. No clear relationship between the 30–60 days activity and global sea surface temperature has been found,

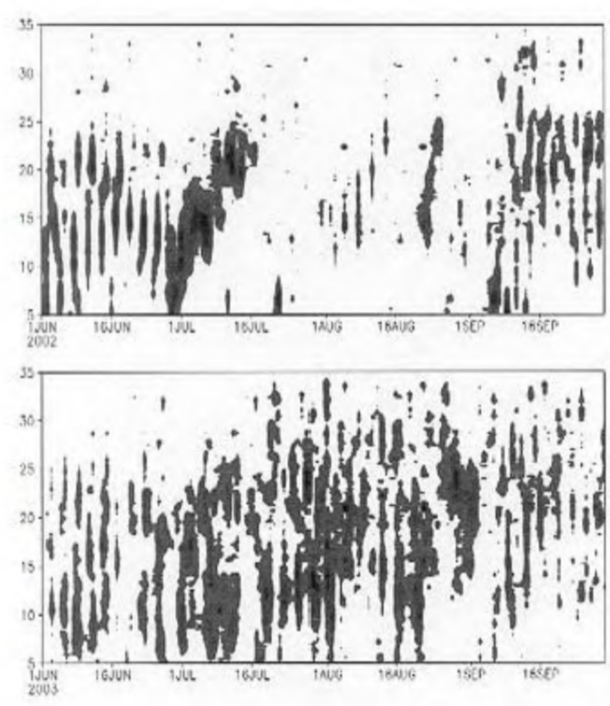

Figure 9. Time (x-axis) – latitude (y-axis) sections of CPC daily precipitation estimates over the longitude belt 70–85°E for monsoon 2002 (upper panel) and monsoon 2003 (lower panel).

suggesting that the 30–60 days variation may be internally or chaotically generated or due to unidentified boundary conditions[20]. However, since these oscillations play a significant role in seasonal monsoon strength, if some statistical/dynamical scheme could foreshadow the behaviour of these oscillations, it will go a long way in serving as a guiding tool for extended range forecasting.

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