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Active and Break Spells of the Indian Summer Monsoon

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Abstract

Sub-seasonal rainfall fluctuations, characterized as active and weak spells during the Indian monsoon season (June to September) is an important component of the variability of the Indian monsoon rainfall. In this paper, we suggest criteria for identification of active and break events of the Indian summer monsoon on the basis of the recently derived high resolution daily gridded rainfall data set over India (1951-2007). Active and break events are identified from the average rainfall data over a critical area, called the core monsoon zone within which the monsoon trough/ Continental Tropical Convergence Zone (CTCZ) normally fluctuates in the peak monsoon months of July and August. Active and break events are defined as periods in which the normalized anomaly of the rainfall over the monsoon zone exceeds 1 or is less than -1.0 respectively, provided the criterion is satisfied for at least three consecutive days. The active and break events using this criterion are found to be comparable to those identified by using the traditional IMD criteria based on low level pressure and wind patterns. The criteria suggested here can be used to monitor the active and break events of the Indian summer monsoon on a real time basis.

On an average, there are 7 days of active and break events during the period July and August. Breaks tend to have a longer life-span than active spells. While, almost 80% of the active spells lasted 3-4 days only 40% of the break spells were of such short duration. A small fraction (9%) of active spells and 32% of break spells lasted for a week or longer, of these, almost 30% break spells persisted for more than 10 days. Active events are more common than breaks. While active events occurring almost every year, not a single break occurred in 26% of the years. There are no significant trends in either the days of active events or break events during the monsoon season.

The space-time evolution of the rainfall composite patterns suggests that the revival from breaks seems to occur primarily from northward propagations of the convective cloud zone. We also show that there are important differences between the spatial patterns of the active/ break spells and those characteristic of interannual variation, particularly those associated with the link to ENSO. Hence the interannual variation of the Indian monsoon cannot be considered as primarily arising from the interannual variation of intraseasonal variation. However, the signature over the eastern equatorial Indian Oceans on intra-seasonal time-scales is similar to that on the interannual time-scales. With the help of NCEP/NCAR reanalysis data, for the first time, the present study has elucidated the difference in the meridional circulation between the active spells with moist convection and intense break events with a heat trough type circulation.

Introduction

Indian summer monsoon, which is a part of the Asian monsoon system, exhibits a wide spectrum of variability, on daily, sub-seasonal, inter-annual, decadal and centennial time scales. During the summer monsoon season (June to September), a substantial component of this variability of convection and rainfall over the Indian region arises from the fluctuation on the intra-seasonal scale between active spells with good rainfall and weak spells or breaks with little rainfall. The inter-annual variability of the sub-seasonal fluctuations during the monsoon season is large. Long intense breaks are known to have an impact on the seasonal monsoon rainfall over the country (e.g.. Fig. 1 depicting the variation of the daily rainfall over central India during the excess monsoon season of 1975 and the drought of 2002). Frequent or prolonged breaks during the monsoon season, such as the break in July 2002, can lead to drought conditions. Long breaks in critical growth periods of agricultural crops lead to substantially reduced yield (Gadgil et al 2003). Even in normal monsoon years, an uneven spatial and temporal distribution of rains has an adverse effect on agriculture. Therefore, prediction of intraseasonal variation and of the occurrence of breaks, their duration and intensity in particular, is very important.

Blanford (1886) first described this fluctuation in the rainfall over the monsoon trough zone between spells \`during the height of rains' and \`intervals of drought', and elucidated the nature of the pressure distribution and circulation associated with these phases of contrasting rainfall conditions. Blanford's (1886) "intervals of droughts", during which the large-scale rainfall over the Indian monsoon zone is interrupted for several days in the peak monsoon months of July-August, have been called 'breaks' in the monsoon (e.g., Ramamurthy 1969, Alexander et al 1978, Raghavan 1973, Krishnamurti & Bhalme 1976, Sikka 1980 etc.). Although interruption of monsoon rainfall is recognized as the most important feature of the 'break', the criteria used by India Meteorological Department (IMD) and by several meteorologists for identifying a 'break', are the low level pressure and wind patterns associated with such a rainfall anomaly, rather than the rainfall distribution itself (Rao 1976). In Ramamurthy's (1969) comprehensive study of breaks during 1888 – 1967, a break situation was defined as one in which the surface trough (the "monsoon trough') is located close to the foothills, easterlies disappear from the sea level and 850hpa charts (similar to the situation described by Blanford 1886) , provided the condition persisted for at least two days. Subsequent to the classic work of Ramamurthy's (1969), De et al (1998) have identified the breaks during 1968-1997 using the same criteria. The break composite of Ramamurthy (1969) shows large negative anomalies over a belt around the normal position of the monsoon trough and positive anomalies near the foothills of the Himalayas and southeastern peninsula (Fig 2). During active monsoon conditions, the monsoon trough is either near the mean position or a little to the south of its normal position and the rainfall anomaly pattern is the opposite of that for breaks.

The break phase is characterized by a marked change in the lower tropospheric circulation over the monsoon zone, with the vorticity above the boundary layer becoming anticyclonic (Ramamurthy 1969, Sikka & Gadgil 1978). It should be noted that whereas active-weak cycles in the fluctuation of the monsoon rainfall occur every year, breaks do not (Ramamurthy 1969), and long breaks such as the one in 2002 (Fig.1) occur only in a few years. During long intense breaks, the surface temperature increases rapidly and a heat-trough type circulation gets established over the monsoon trough zone with subsidence over most of the troposphere and no disturbances are generated (Raghavan 1973). The occurrence of a heat trough type circulation in the peak monsoon months of July and August over the monsoon zone in place of a TCZ, implies a major transition. Revival of the monsoon from a break occurs with a transition to a moist convective regime either with northward propagation of the equatorial TCZ (Sikka & Gadgil 1980) or with westward propagation of synoptic scale systems generated over the warm waters of the Bay of Bengal (Sikka & Dixit 1972, Sikka & Gadgil 1980).

The dominant time-scales of intra-seasonal variation are 10-20 days and 30-60 days with comparable contributions to the total intra-seasonal variability in the Indian region (Goswami 2005 and references therein). While the quasi biweekly (10-20 days) scale is characterized by westward propagations (Krishnamurti and Bhalme 1976, Krishnamurti and Ardanuy 1980 and Yasunari 1979), the 30-50 day scale is associated with northward propagations from the near-equatorial region.

Since the study of Ramamurthy (1969), active spells and weak spells/breaks of the Indian summer monsoon have been extensively studied, particularly in the last decade (e.g. Magana & Webster 1996, Rodwell 1997, Webster et al 1998 Krishnan et al. 2000, Krishnamurthy and Shukla (2000,2007,2008), Lawrence and Webster 2001, Annamalai and Slingo 2001, De and Mukhopadhyay 2002, Kripalani et al. 2004, Goswami and Ajayamohan 2001, Goswami et al. 2003, Waliser et al 2003, Gadgil and Joseph 2003, Wang et al 2005, Mandke et al. 2007 and recent reviews by Goswami 2005 and Waliser, 2006). However, different scientists have used the same term ‘break’, to denote different features of convection and/or circulation over different regions. Webster et al (1998) used the term ‘break’ as defined by Magana & Webster (1996) to denote weak spells of convection and 850 hPa zonal winds over a larger scale region (65-95°E, 10-20°N). On the other hand, Goswami & Ajaya Mohan (2001) defined ‘breaks’ on the basis of the strength of the 850 hpa wind at the single grid-point 15°N, 90°E. Krishnan et al (2000) defined break days as days with positive OLR anomalies over northwest and central India (i.e. only over the western part of the monsoon trough zone), provided the average OLR anomaly over 73-82°E, 18-28°N exceeds $10Wm^{-2}$.

Since it is recognized that rainfall is the most important facet of the monsoon and has a direct socioeconomic impact, it has been the basis for identification of active spells and breaks in many studies. However, even when the "breaks" are identified in terms of rainfall or convection over the Indian region, a variety of definitions are used. Rodwell (1997), and Annamalai & Slingo (2001) used the term 'break' to denote weak spells of the daily all-India average rainfall calculated operationally by the IMD. Annamalai and Slingo (2001) used the daily all-India rainfall based on data at more than 200 stations representing the whole country. Mandke et al. (2007) identified the active/break days on the basis of the precipitation anomaly over an area $73\text{-}82^0$ E, $18\text{-}28^0$ N, which they called the Indian core region. The periods were identified as active (break) when the standardized rainfall anomaly over the Indian core region exceeds (less than) 0.7 (-0.7) for three consecutive days during 15 June to 15 September. Krishnamurthy and Shukla (2000, 2007) used the all-India daily rainfall index (IMR) from the 1^0 by 1^0 rainfall data for 1901-70, prepared from the IMD raingauge data (Hartmann and Michelson 1989) and Krishnamurthy and Shukla (2008) used the IMD gridded 1^0 by 1^0 rainfall data (Rajeevan et al 2006) for identifying the active and break spells. The threshold used for identifying the spells was one-half of the standard deviation of the IMR index. Gadgil & Joseph (2003) have defined breaks (and active spells) on the basis of the daily rainfall over the monsoon trough zone. They defined a break (active) day as a day on which the rainfall is below (above) specified thresholds for western and eastern parts of the monsoon zone. The thresholds for defining a break were chosen so as to have maximum possible overlap with breaks identified by Ramamurthy (1969) and De et al (1998) on the basis of the synoptic situation as per the IMD definition (Rao, 1976). The break composite of rainfall of Gadgil and Joseph (2003) is very similar to that of Ramamurthy (1969) with positive anomalies over the Himalayan foothills and southeastern peninsula.

Since different criteria are used for identification of breaks and active spells in different studies, there are differences in the breaks identified and the associated circulation and convection patterns. Krishnamurthy and Shukla (2008) show (their Fig.1) that the OLR anomaly patterns over the Indo-West Pacific longitudes for active spells and breaks identified by them differ considerably from those of Goswami and Ajay Mohan (2001) and Webster et. al.(1998). The OLR anomaly patterns for the break and active composites over the Indo-West Pacific longitudes of Krishnamurti and Shukla (2008) shown in their figure 1, are rather similar to those of Gadgil and Joseph (2003).

The relationship of the interannual variation of the monsoon with intraseasonal variation between active spells and breaks has been extensively studied. It has been shown that the major difference between the rainfall variation in good and some poor monsoon seasons is the occurrence of a long dry spell (break) in the latter (e.g. The comparison of the weekly rainfall over central India during the excess monsoon season of 1917 with the deficit year of 1918 (Normand 1953) and comparison of the daily rainfall over central India during the excess monsoon season of 1975 and the drought of 2002 in Fig. 1). While it is recognized that intraseasonal variation and particularly, long intense breaks can have an impact on the seasonal total rainfall of the Indian monsoon, there is no consensus as yet on the extent of the contribution of the intraseasonal variation to the interannual variation. Ferranti et al (1997), Goswami et al. (1998) and Goswami (2005) suggest that the intraseasonal and interannual variability are governed by a common spatial mode of variability. According to Goswami and Ajay Mohan (2001), a higher probability of active (break) conditions within a season is associated with a stronger (weaker) than normal monsoon. On the other hand, Krishnamurthy and Shukla (2000) showed that the nature of intraseasonal variability is not different during the years of major droughts or major floods. The multi-channel singular spectrum analysis of Krishnamurthy and Shukla (2008) using OLR data reveals two dominant intraseasonal oscillatory modes and two large-scale standing patterns, one over the equatorial Pacific and the other over the equatorial Indian Ocean. They show that seasonal rainfall is determined mainly by two persisting large-scale standing patterns, without much contribution from the oscillatory modes.

Under the Indian Climate Research Programme (ICRP) (DST, 1996), a major programme on the Continental Tropical Convergence Zone (CTCZ) is planned with the aim of understanding and hence predicting the space-time variation of the CTCZ and the large-scale monsoon rainfall. The Asian Monsoon Years (AMY 2007-2011) programme is a cross-cutting initiative as part of the International Monsoon Study under the World Climate Research Programme (WCRP) in coordinated observation and modeling effort. One of the major science themes is multi-scale interaction over the tropical convergence zone. The planned activity of CTCZ and AMY consists of field experiments which can generate the kind of observations required for testing the hypotheses proposed for mechanisms, and modelling studies for simulation and prediction. A major focus of the CTCZ programme is the intraseasonal variation of the CTCZ. The problem of transition between the heat trough regime characterizing long intense dry spells/breaks and the moist convective regime of the TCZ will be addressed under the CTCZ programme. An important objective is unravelling the factors that determine the life-span of active and weak spells of the CTCZ and mechanisms/ processes involved in the transition between these states.

Since different criteria are used for definitions of breaks in the different studies, there are differences in the breaks identified, hence in their duration, their frequency of occurrence as well as the associated circulation and convection patterns. Clearly it is important to decide on a reasonable and objective criterion for identifying breaks and active spells. In our view,the criteria should be based on rainfall as it is the critical facet of the monsoon (Krishnamurthy and Shukla (2002, 2007) and Gadgil and Joseph 2003). In this paper, we suggest criteria for identification of active and break spells on the basis of the recently derived daily gridded rainfall data set (Rajeevan et al. 2006), which is routinely updated by the India Meteorological Department (IMD). Active and break events are identified from the average rainfall data over the core monsoon zone, within which the monsoon trough/ CTCZ normally fluctuates, and over which large negative anomalies have been observed in the traditionally defined (Ramamurthy 1969) breaks. Active spells and breaks are defined as periods in which the normalized anomaly of the rainfall over this region exceeds 1.0 or is less than -1.0 respectively, provided the criterion is satisfied for at least three consecutive days. The active and break events using this criterion are found to be comparable to those identified by Ramamurthy (1969) and De et al (1998), using the IMD definition and those of Gadgil and Joseph (2003).

In section 2, details of the data used for this study are discussed. Section 3 deals with the criteria adopted for defining the active and break events, comparison with earlier studies and description of the important characteristics of these spells. In Section 4, the relationship of the active spells and breaks, we have identified, with interannual variation of the Indian summer monsoon rainfall (ISMR) is investigated. The major features of intense long breaks in terms of the increase in surface temperature and the heat-trough type meridional circulation are elucidated in section 5.

2. Data

For the present study, we have used an updated version of the high resolution gridded daily rainfall data developed by Rajeevan et al. (2006). The original data set was developed by Rajeevan et al. (2006) for the period 1951-2003 using 1803 stations. The daily rainfall data were interpolated into grids of 1^0 X 1^0 degree resolution using the Shepard (1968) interpolation method. Standard quality controls were made on the data before interpolating the data into regular grids. In the interpolation method, interpolated values are computed from a weighted sum of the observations. Given a grid point, the search distance is defined as the distance from this point to a given station. The interpolation is restricted to the radius of influence. We have also considered the method proposed by Shepard to locally modify the scheme for including the directional effects and barriers. In this method, no initial guess is required. More details of the development method are given in Rajeevan et al (2006).

In the original data analysis, there were many data gaps, especially over the northern parts of India. We have therefore updated this analysis by considering more stations (total 2140 stations instead of 1803 stations) from northern parts of India and thus improving density of station network. We have further extended the rainfall analysis to 2007, thus making 57 years of daily rainfall data for the present study. IMD now compiles the daily data from more than 2000 stations on real time mode. Therefore, availability of daily rainfall data is now assured on real time basis for the daily gridded rainfall analysis. The stations considered in this analysis were selected such that these stations have minimum 90% data availability during the analysis period. The network of stations considered for the analysis is shown in Fig.3.

For examining the characteristics and circulation anomalies associated with the active/break events, we have used the daily re-analysis data of NCEP/NCAR (Kalnay et al. 1996). The daily data of mean sea level pressure, wind data at 850 hPa and 200 hPa levels were used for the analysis. In addition, we have also used the daily OLR data measured from Advanced High Resolution Radiometers (AVHRR) aboard NOAA polar orbiting satellites. These data were obtained from Climate Diagnostics Centre, http://www.cdc.noaa.gov/.

3. Active and Break Events based on rainfall

A large number of studies on monsoon breaks are based on the all-India average rainfall. However, Krishnamurthy and Shukla's (2000) analysis showed that the dominant mode in the daily rainfall has anomalies of one sign over central India and anomalies of the opposite sign over the foothills of the Himalayas and over southeastern peninsula. Thus, the intraseasonal variations are not coherent over the entire Indian region and all-India average cannot be considered to be representative of the different subregions. The most conspicuous feature of the rainfall anomaly pattern of the monsoon breaks as obtained by Ramamurthy (1969) is the large negative rainfall anomaly over the plains of northwest and central India (Fig 2). Positive rainfall anomalies occur over northeast India, and also over southeastern peninsula. This rainfall pattern is similar to the dominant intraseasonal mode of Krishnamuthy and Shukla (2000).

Our identification of active spells and breaks is based on the updated version of the IMD gridded rainfall data set, as discussed above. The criteria we adopt are derived from the rainfall over the region over which significant rainfall fluctuations between the active and break spells are observed viz. the core monsoon zone (Fig.4). The spatial variation of the mean (1951-2006) rainfall during July –August is also shown in Fig. 4. While choosing this zone, care was taken not to include the foothills of Himalayas, where substantial amount of rainfall is received during the monsoon breaks. This core monsoon zone is very similar to the geographical area considered by Gadgil and Joseph (2003) for identifying active and break spells.

The average of zonal rainfall is significantly correlated with the rainfall over different grids (Fig. 5a) showing that the intraseasonal variation is coherent over this zone and the average rainfall over this zone is indeed representative of the rainfall within sub-regions of the zone. It is seen that the rainfall over northeast India and southeast peninsula shows negative correlation with the rainfall over the core monsoon zone. The correlation based only on the rainfall during the active and break spells is much higher throughout the core monsoon zone (Fig 5b).

The variation of the mean daily rainfall over the core monsoon zone and that over the country as a whole, from 1 May to 30 October based on the data for 1951-2004 is shown in Fig. 6a. . The variation of the average all-India rainfall is seen to be very similar to the variation of the core monsoon zone rainfall and during August, the average all-India rainfall is almost the same as that of the core monsoon zone. The interannual variation of the all-India summer monsoon rainfall (ISMR) is highly correlated (correlation coefficient: 0.91) with that of the summer monsoon rainfall over the core monsoon zone (Fig. 6b) suggesting that it is a critical region for interannual variation as well as intraseasonal variation of the monsoon.

Active and break events were identified by averaging the daily rainfall over this core monsoon zone and standardizing the daily rainfall time series by subtracting from its long term normal (1951-2000) and by dividing by its daily standard deviation. From Fig.3, it can be seen that sufficient stations (803 stations) are available in this zone for averaging and preparing daily rainfall data. The break spell has been identified as the period during which the standardized rainfall anomaly is less than –1.0, consecutively for three days or more. Similarly the active periods are identified as the periods during which the rainfall anomaly is more than +1.0 times the standard deviation, consecutively for three days or more.

The break spells identified in this study using the above method (Table1) are comparable with those defined by Ramamurthy (1969), De *et al*. (1998) and there is a very large overlap with those identified by Gadgil and Joseph (2003). There are minor variations in the break spells identified by these methods. However, for the long breaks such as those in 1965, 1966, 1968, 1972, 1979 and 1982, there is a maximum overlap of break days among the three methods. It appears that the criterion based on the rainfall over the core monsoon zone for occurrences of breaks are somewhat more stringent than the one used by Ramamrthy (1969) and De et al (1998). Thus during 1951-89, no breaks occurred in 3 summer monsoon seasons as per the criterion of Ramamurthy (1969) and De et al. (1998) whereas breaks did not occur in 10 monsoon seasons as per the present criteria and in 8 monsoon seasons as per the Gadgil and Joseph's (2003) criterion . On the other hand, breaks identified according to the criteria adopted by Krishnan et al (2000) and Webster et al. (1998), occur every year. These 'breaks' are thus weak spells of the active-weak fluctuations of the monsoon which occur every year.

The active spells identified by using our criteria are shown in Table 2. Active spells occur in almost every monsoon season, with only two seasons, being without even a single active event. On an average, during July and August, there are 7.2 and 7 days of active and break days respectively. The standard deviation of break spells (6.5 days) is much larger than the standard deviation of active spells (4.7 days). The average number of active days in July (3.8) is somewhat larger than in August (3.4); whereas the average number of break days in July (3.2) is smaller than that of August (3.8). The frequency distribution of the duration of breaks is similar to that of the breaks identified by Ramamurthy (1969) and Gadgil and Joseph (2003) (Table 3). The frequency distribution of active spells (Table 4) shows that breaks tend to have a longer life-span than active spells. While, almost 80% of the active spells lasted 3-4 days only 40% of the break spells were of such short duration. A small fraction (9%) of active and 32 % of break spells lasted for a week or longer, of these, almost 30% break spells persisted for more than 10 days. Active events are more common than breaks occurring almost every year, whereas not a single break occurred in 26% of the years.

The variation of the number of active and break days during the summer monsoon for the period 1951-2007 is shown in Figs 7 a and b respectively. During the period 1951-2007, the maximum number of break days occurred in 2002 (25 days in July) while the maximum number of active days (22 days) occurred in 2006. The longest break spell (16 days) occurred in 1979 from 14-29 August. During 2002, two separate break spells occurred, from 4-17 July and then from 21-31 July.

Joseph and Simon (2005) have reported that the number of break days (defined as those with mean zonal wind at 850 hPa from the NCEP/NCAR reanalysis in the box 10-20^{o}N, 70-80^{o} E, equal to or less than 9/11 m/s during June-September), increased by 20-30% during the period 1950-2002. However, we find no statistically significant trends during 1951-2007, either in the number of break or active days during the monsoon season (June to September) each year identified by using the rainfall criterion for active and break spells used in this study. It is possible that the trend they observed in the number of break days based on wind data, could have arisen from combining the data from pre-satellite era to the recent period.

4. Rainfall composites and evolution of active and weak spells

The rainfall anomaly composite over the Indian region for breaks (Fig. 8a) is similar to that of Ramamurthy (1969). The composite for active spells (Fig. 8b) is almost a mirror image of the break composite. During breaks and active spells, the rainfall anomaly is seen to be homogenous over the core monsoon zone and also along the west coast. However, the anomalies over northeast India and southeast Peninsula are of the opposite sign.

The evolution of the active and break phases is elucidated with lagged composites of daily rainfall anomalies for lags ranging from –12 to +12 days (Fig. 9 and b). Lag-0 refers to the midpoint of the break/active period. Evolution of the active spells has some interesting features. Twelve days before the active spell (at lag -12) a large part of the monsoon zone has negative rainfall anomalies whereas there is a belt just to the south of about 20^{0}N with positive anomalies and the west coast also has positive anomalies of rainfall. In the next ten days, this zonal band of positive anomalies shifts northwards, intensifies and expands and at lag 0, the pattern is the mirror image of the break spell with negative anomalies over the foothills and positive anomalies over the monsoon zone as well as the west coast. By lag +4 days, the region of positive anomalies shrinks and moves northward and by lag +8, negative anomalies occur over most of the peninsular region, including the west coast.

Eight days before the break (at lag-8 days), negative rainfall anomalies appear over the western part of the monsoon zone and the west coast, which increase and slowly expand northwestwards. At lag-4, the negative rainfall anomalies cover the entire monsoon zone whereas positive anomalies are seen along the foothills of the Himalayas (associated with the shift in the monsoon trough over that region) and over southeastern peninsula. The same pattern (albeit with more intense negative anomalies) characterizes the break (lag 0). From lag +2 days, positive anomalies over the peninsula spread northward and westward and subsequently cover the monsoon zone and the west coast by lag +12. At lag+12, negative anomalies are restricted to the foothills of the Himalayas and large positive anomalies are observed along the west coast. Thus, from the evolution of the composite patterns, it appears that the revival from breaks seems to occur primarily from northward propagations. This feature is also seen in the evolution of breaks and active spells of Krishnamurthy and Shukla (2008).

5. Intraseasonal and interannual variations

The variation of the ISMR with the number of break days and active days in July-August of that year is shown in Figs. 10 a and b respectively. It is seen that ISMR is significantly negatively correlated with the number of break days. Although the magnitude of the correlation is high (0.61) there is considerable scatter. Note that even in the absence of breaks, the rainfall was deficit by almost 10% in one year (1991) and with only 3 break days, the season of 1974 was a drought. The correlation with the number of active days is relatively poor. Thus, it is not surprising that the ISMR was near the average value for monsoon season with the largest number of active days viz. 2006. The low correlation with the number of active days is consistent with the result that the all-India rainfall is not well correlated with the number of depressions or depression days but is largely determined by the lower intensity systems (Sikka 1980, Mooley and Shukla 1987).

The active and break composites of the OLR anomaly patterns are shown in Fig.11. The break composite is characterized by large positive OLR anomalies over the core monsoon zone and the equatorial west Pacific and central Pacific and large negative OLR anomalies over the eastern equatorial Indian Ocean and northern west Pacific (120-130^0 E, 20-30^{0}N). Thus, over 70-130^0 E, the quadrapole pattern described by Annamalai and Slingo (2001) is seen. The active composite has large negative OLR anomalies over the core monsoon zone and over the equatorial central and west Pacific. Positive anomalies are seen over the eastern equatorial Indian Ocean.

The relationship of the interannual variation of ISMR with the convection over the Indian and Pacific Oceans is shown in Fig. 12a. It is seen that ISMR is negatively correlated with the convection over the central Pacific, which is a. manifestation of the well known ENSO-monsoon relationship on the interannual scale (Sikka 1980, Rasmusson and Carpenter 1983 and several subsequent studies). This is clear from the correlation of OLR with ENSO index (which is defined as the negative of the normalized Nino 3.4 SST anomaly, so that it is positive when ENSO index is favourable for the monsoon) depicted in Fig 12b. It is seen that the impact of ENSO is suppression/enhancement over the equatorial and north Indian Ocean as well as the Indian region.

ISMR is positively correlated with convection over the western equatorial Indian Ocean and negatively correlated with convection over the eastern equatorial Indian Ocean. The equatorial Indian Ocean Oscillation (EQUINOO, Gadgil et al 2004) is characterized with convection anomalies of opposite signs over the western and equatorial Indian Ocean. The correlation of OLR with the index EQWIN of EQUINOO (Gadgil et. al. 2004), which is again defined so that it is positive when favourable for the monsoon, is shown in Fig. 12c. It is seen that the large positive correlation of ISMR with convection over the western equatorial Indian Ocean is a manifestation of the link of the interannual variation of ISMR with EQUINOO (Gadgil et. al 2004, 2007). The two standing persistent modes over the Indian-west Pacific region identified by Krishnamurthy and Shukla (2008) are the ENSO and EQUINOO modes of Figs 12 b and c. Gadgil et. al. (2004) showed that there is a strong relationship between the extremes (droughts and excess monsoon seasons) and a composite index which is a linear combination of the ENSO index and EQWIN. Using a longer data set (from 1881 to 1998), Ihara et. al. (2007) showed that the variation of ISMR is better described by use of indices of ENSO as well as EQWIN than by ENSO index alone. The inference of Krishnamurthy and Shukla (2008) on the importance of these two modes for interannual variation of the monsoon is consistent with these studies demonstrating the importance of ENSO and EQUINOO.

Comparison of Figs. 11 a and b with 12 a and b a shows that the pattern of convection anomalies over the central Pacific associated with breaks and active spells is opposite to that characteristic of the interannual variation of ISMR associated with the ENSO. On the other hand, Figs 11 a and b and 12 a and c show that the intraseasonal anomaly patterns over the eastern equatorial Indian Ocean are similar to those on the interannual scale associated with the link to EQUINOO.

Thus, there are important differences between the spatial patterns of the active/ break spells and those characteristic of interannual variation, particularly those associated with the link to ENSO. Hence the interannual variation of the Indian monsoon cannot be considered as primarily arising from the interannual variation of intraseasonal variation. However, over the eastern equatorial Indian Ocean, the signature of breaks is similar to that of droughts.

6. Long intense breaks and heat troughs

Let us consider first the seasonal patterns. The analysis of Trenberth et al (2000) on the global divergent circulations derived from NCEP and ECMWF reanalysis data shows that the first mode (i.e. complex empirical orthogonal function, CEOF1) explains about 60% of the variance, while the second mode (CEOF2) explains about 20% of the variance. The vertical structure functions of the mass weighted divergent velocity field of these modes is shown in Fig. 13 (after Trenberth et al 2000). The first mode has a simple vertical structure with a maximum in vertical motion around 400 hPa, convergence in the lower troposphere and divergence in the upper troposphere. Thus, the vertical structure of the first mode corresponds to that of the TCZ. The second mode is characterized by relatively shallow overturning with maximum vertical velocities near 800 hPa and outflow from 750 hPa to 350 hPa. This structure corresponds to a heat trough (Ramage 1971).

The surface low pressure belt over the Indian region during the summer monsoon comprises a well marked heat low over the northwestern region and a low pressure belt associated with the moist convective regime characterizing the CTCZ, extending westward from the head of the Bay of Bengal (Fig.14a). Consistent with this, the vertical velocity at 400 hPa for the CEFO1 of Trenberth et al (2000) is upward only over the moist convective regime over the eastern sector. The observed vertical profile of the mean meridional circulation for July (Fig. 14b) over the western (65-70^{0}E) and eastern (78-88^{0}E) sectors clearly brings out the shallow cell associated with the heat low in contradistinction to the deep over turning associated with the CTCZ over the eastern sector.

During long intense breaks, the surface temperature increases rapidly and a heat-trough type circulation gets established over the monsoon trough zone (Raghavan 1973). The variation of the maximum temperature anomaly averaged over the monsoon zone, during June-August 2002 is shown in Fig.15a. .It is seen that the surface temperature increases rapidly during the break of 4-17 July with the day time temperature anomaly exceeding 3^{0}C, for many days. The spatial variation of the temperature anomaly for the peak break days (12-15 July) is shown in Fig. 15b. The meridional wind, averaged over the longitudes 78-88^{0}E, for the peak break days is shown in Fig.16a. It is seen that a shallow meridional cell characteristic of a heat low prevails with convergence restricted to below 800 hPa and northerlies prominent around 700 hPa. The occurrence of a heat trough type circulation in the peak monsoon months of July and August over the monsoon zone in place of a TCZ, implies a major transition. Revival from such breaks involves a transition to a moist convective regime with convergence up to the mid-troposphere and northerlies aloft. This is illustrated in Fig 16b which shows the vertical variation of the meridional wind, averaged over 78-88^{0}E, for the active spell after revival from the break with northerlies only above 300 hPa. The difference between the peak phase of long and intense breaks, weak spells and active spells are clearly brought out in Fig 17 in which the vertical velocity at 850 and 700hpa is shown for a day in the peak break phase (28 July), a weak spell (5 August) and an active spell (24 August) in 2002. Large scale subsidence is observed over the monsoon zone during the peak break phase, which is substantially reduced in the weak spell. During the active spell, large scale ascent is observed over the core monsoon zone.

7. Summary and conclusions

We have proposed criteria to identify and monitor the active and break events during the Indian summer monsoon season on the basis of operationally derived rainfall data, which are available on real time basis. The identification of active and break events is based on the daily rainfall data averaged over the monsoon core zone which is coherent with respect to intraseasonal variation and over which large fluctuations of rainfall occur on this scale. . The interannual variation of the all-India summer monsoon rainfall (ISMR) is highly correlated with that of the summer monsoon rainfall over the core monsoon zone suggesting that it is a critical region for interannual variation as well as intraseasonal variation of the monsoon. The break (active) spell has been identified as the period during which the standardized rainfall anomaly is less (more) than –1.0 (+1.0), consecutively for three days or more. The break periods identified in this study are comparable with those defined by Ramamurthy (1969), De *et al*. (1998) and there is a very large overlap with those identified by Gadgil and Joseph (2003). During the drought years like 1965, 1966, 1968, 1972, 1979 and 1982, there is a maximum overlap of break days among the three methods discussed.

On an average, there are 7 days of active and break events during the period July and August. Number of break days is significantly correlated with the ISMR. However, even in the absence of breaks, the rainfall was deficit by almost 10% in 1991 and with only 3 break days, the season of 1974 was a drought. The correlation with the number of active days is relatively poor. The time series analysis shows no significant trends in either the days of active events or break events during the monsoon season. This is in contradiction to the Joseph and Simon (2005)'s conclusion of an increasing trend in the number of break days. Possible reason for the difference could be their use of wind data (which forms the basis of their definition of breaks) from pre-satellite period up to the recent time for deriving the trend.

The evolution of the lagged rainfall composites associated with the break and active spells suggests that the revival from breaks seems to occur primarily from northward propagations of the maximum rainfall zone. We have shown that there are important differences between the spatial patterns of the active/ break spells and those characteristic of interannual variation, particularly those associated with the link to ENSO. Hence the interannual variation of the Indian monsoon cannot be considered as primarily arising from the interannual variation of intraseasonal variation. However, the signature over the eastern equatorial Indian Oceans on intra-seasonal time-scales is similar to that on the interannual time-scales.

For the first time, the present study has elucidated the difference in the vertical meridional circulation between the active spells with moist convection and intense break events with a heat trough type circulation with the help of NCEP-NCAR reanalysis data. It is important to unravel the factors that determine the transitions in space and time from a heat low type circulation to a moist convective regime characterizing the Continental Tropical Convergence Zone (CTCZ) and vice versa for developing suitable prediction tools.

Previous research studies have shown there is a high potential predictability of the phases of the intra-seasonal oscillation beyond medium range prediction (Goswami and Xavier 2003 and Waliser et al 2003). However, experiments with the weather/climate GCMs are not that encouraging. Waliser et al (2003) analyzed 10 AGCMs that participated in the CLIVAR/AAMP AGCM inter-comparison project and found that the most problematic feature is the overall lack of variability in the equatorial Indian Ocean. Nanjundiah and Krishnamurti (2007) have also discussed the studies of prediction of ISOs. Waliser et al (2006) discussed the prediction of MJOs using both dynamical and statistical methods. They conclude that considerable research is required for prediction of intraseasonal scales to attain levels of skill currently available in short term forecasts. There are uncertainties associated with the simulation of the intra-seasonal variability and with how to carry out sub-seasonal predictions in terms of supplying initial conditions and modeling surface boundary conditions (Waliser et al. 2003). On the other hand, prediction efforts using empirical methods (Goswami and Xavier 2003, Webster and Hoyos 2004 and Xavier and Goswami 2007) showed some encouraging results. However, more research and development work is required to establish useful extended range prediction system and to help bridge the gap between weather and seasonal-to-interannual climate predictions.

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Table - 1
MONSOON BREAK SPELLS

YEAR	PRESENT STUDY	GADGIL AND JOSEPH(2003)	Ramamurthy (1969) up to 1967. De et al. (2002) from1968 to 1989
1951	24-29A	14-15J, 24-30A	1-3 J, 11-13 J, 15-17 J,24-29A
1952	9-13J.28-3QA	1-3J, 10-13J, 27-30A	9-12J
1953	-	-	24-26J
1954	22-28A	22-29A	18-29J, 21-25A
1955	24-26J	24-25J	22-29J
1956	-	23-30A	23-26A
1957	-	28-29J	27-31J, 5-7A
1958	-	-	10-14A
1959		-	16-18A
1960	18-23J	20-24J, 30-31A	16-21J
1961	-	-	-
1962	27-29J	27-28J, 1-2A, 7-8A, 25-26A	18-22A
1963	13-19J, 21-23J	18-19J, 22-23J	10-13J, 17-21J
1964	29J-4A	-	14-18J, 28J-3A
1965	6-11J, 1-14A	7-11J, 4-14A	6-8J, 4-15A
1966	2-12J, 21-31A	2-12J, 22-31A	2-11J, 23-27A
1967	7-14J	6-15J	7-10J
1968	25-31 A	25-31A	25-29A
1969	-	27-31A	17-20A, 25-27A
1970	13-19J	14-19J, 23-26J	12-25J
1971	8-10J, 5-7A, 17-20A	8-10J, 5-6A, 18-19A	17-20A
1972	18J-3A	19J-3A	17J-3A
1973	24-26J, 31J-2A	24-26J, 30J-1A	23J-1A
1974	29-31A	24-26A, 29-31A	30-31A
1975	-	-	24-28J
1976	-	3-4J, 21-22A	-
1977	15-20A	15-19A	15-18A
1978	-	-	16-21J
1979	2-6 J, 14-29A	2-6J, 15-31A	17-23J, 15-31A
1980	17-20J, 13-15A	17-20J, 14-15A	17-20J
1981	24-27A	19-20A, 24-31A	26-30J, 23-27A
1982	1-8J	1-8J	-
1983	23-25A	8-9J, 24-26A	22-25A
1984	27-29J	-	20-24J
1985	23-25A	2-3J, 23-25A	22-25A
1986	22-31A	1-4J, 31J-2A, 22-31A	23-26A, 29-31A
1987	23-25J, 30J-4A, 8-13A, 16-18A	16-17J, 23-24J, 31J-4A, 11-13A	28J-1A
1988	14-17A	14-17A	5-8J, 13-15A
1989	18-20J, 30J-3A	30-31J	10-12J, 29-31J

MONSOON BREAK SPELLS	
YEAR	**PRESENT STUDY**
1990	-
1991	-
1992	4-11 J
1993	20-23J, 7-13A, 22-28A
1994	-
1995	3-7J, 11-16A
1996	10-12A
1997	11-15J, 9-14A
1998	20-26 J, 16-21A
1999	1-5J, 12-16A, 22-25A
2000	1-9A
2001	31J-2A, 26-30A
2002	4-17J, 21-31 J
2003	-
2004	10-13J, 19-21J, 26-31A
2005	7-14A, 24-31A
2006	-
2007	18-22J, 15-17A

Table - 2
MONSOON ACTIVE SPELLS

YEAR	ACTIVE SPELLS
1951	25-27J
1952	23-31J
1953	3-5A, 12-19A
1954	9-12A
1955	29-31A
1956	2-8J, 11-14J, 1-5A
1957	20-23A
1958	8-11 J
1959	12-14J, 26-29J
1960	1-4J, 15-17A
1961	6-10J, 16-18J, 24-26A
1962	16-18J, 12-14A
1963	10-12A
1964	5-7J, 15-17A, 23-25A
1965	26-29J, 24-26A
1966	-
1967	1-3J, 24-29J
1968	5-10J, 29-31 J, 4-6A
1969	29J-1A
1970	1-3J, 17-20A, 27-29A
1971	19-21J, 26-31A
1972	5-7J
1973	7-9 J, 13-15J, 12-14A,18-20A,26-31A
1974	17-20A
1975	13-16J, 12-15A
1976	16-18J, 28-31A
1977	5-7J
1978	7-10J, 15-17A, 24-30A
1979	3-5A, 7-12A
1980	1-3J
1981	7-10J
1982	12-14A, 17-23A
1983	18-21J.18-20A
1984	3-6A, 9-11 A, 15-19A
1985	15-17J, 30J-3A.6-9A
1986	21-24J, 13-15A
1987	24-29A
1988	26-28J
1989	-
1990	21-24A, 29-31A

YEAR	MONSOON ACTIVE SPELLS
1991	29-31J
1992	26-29J, 16-18A
1993	7-9J, 15-18J
1994	2-4J, 9-17J, 18-20A, 25-27A
1995	18-25J
1996	24-28J, 19-22A
1997	30J-1A.20-26A
1998	3-6J
1999	-
2000	12-15J, 17-20J
2001	9-12 J
2002	-
2003	26-28J
2004	30J-1A
2005	1-4J, 27J-1A
2006	3-6J, 28J-2A, 5-7A, 13-22A
2007	1-4J, 6-9J, 6-9A

<u>Table- 3</u>
Frequency Distribution of the duration of Break spells in Per cent

Duration	Monsoon breaks		
	Present Study	Gadgil & Joseph	Ramamurthy
3-4	40	44.8	49.5
5-6	28	22.8	19.8
7-8	19	14.3	16.2
9-10	3	6.7	6.3
11 -12	4	4.8	4.5
13-14	3	3.8	1
>15	3	2.8	2.7

<u>Table- 4</u>
Frequency Distribution of the duration of Active spells in per cent

Duration	Present Study
3-4	79
5-6	12
7-8	6
9-10	3
> 10	0

Legends to Figures

Fig. 1		Variation of the daily rainfall over central India during June – September 1975 (excess monsoon year) and 2002 (drought year).
Fig. 2		Mean rainfall anomaly during the break spells (after Ramamurthy, 1969)
Fig. 3		Network of stations considered for the development of high resolution gridded data set.
Fig. 4		Monsoon core zone considered to identify the active and break events. Mean (1951-2007) rainfall (mm/day) during the period July and August is also shown.
Fig. 5	**a)**	Correlation coefficient of 5-day average rainfall over the monsoon zone with rainfall at all grid points. Rainfall during only July and August months have been considered
	b)	The same as (a) but only rainfall during the active and break spells was considered.
Fig. 6	**a)**	Variation of average (1951-2004)daily rainfall averaged over the monsoon zone and the country as a whole (all-India).
	b)	Scatter plot between the average rainfall over the monsoon core zone (June to September) and ISMR. Period: 1951-2007.
Fig. 7		Time series of a) Active days and b) Break Days during July and August. Period: 1951-2007.
Fig. 8	**a)**	Composite of rainfall anomaly (mm/day) for the break spells (1951-2004)
	b)	Composite of rainfall anomaly (mm/day) for the active spells (1951-2004)
Fig. 9	**a)**	Lagged rainfall composites during the break spells (1951-2004)
	b)	Lagged rainfall composites for the active spells (1951-2004)
Fig. 10		Scatter plot between (a) number of break days and ISMR and (b) number of Active days and ISMR. Period: 1951-2007.
Fig. 11		Composites of OLR anomalies during **a)** Break and **b)** Active spells. Period of analysis: 1979-2007.
Fig. 12	**a)**	Correlation (X 100) between OLR and ISMR during June to September
	b)	ENSO index is the negative of the normalized SST anomaly of Nino 3.4 so that positive values are favorable for the monsoon
	c)	Correlation (X 100) between OLR and EQWIN during June to September
Fig. 13		The first two modes of global divergent circulation (after Trenberth et. al. 2000)
Fig. 14	**a)**	Mean sea level pressure and surface winds for July (from IMD)
	b)	Latitude –height section of meridional wind climatology during July
Fig. 15	**a)**	Variation of day time temperature anomaly from 1 July to 15 August, 2002, averaged over central India.
	b)	Maximum Temperature anomaly during the period 12-15 July 2002.
Fig. 16		Latitude- Height section of meridional wind averaged over 78-88^0 E.
Fig. 17		Spatial plot of Omega (Pa/sec) for (a) break phase (28 July2002), (b) Weak Spell (5 August 2002) and (c) Active Spell (24 August 2002).

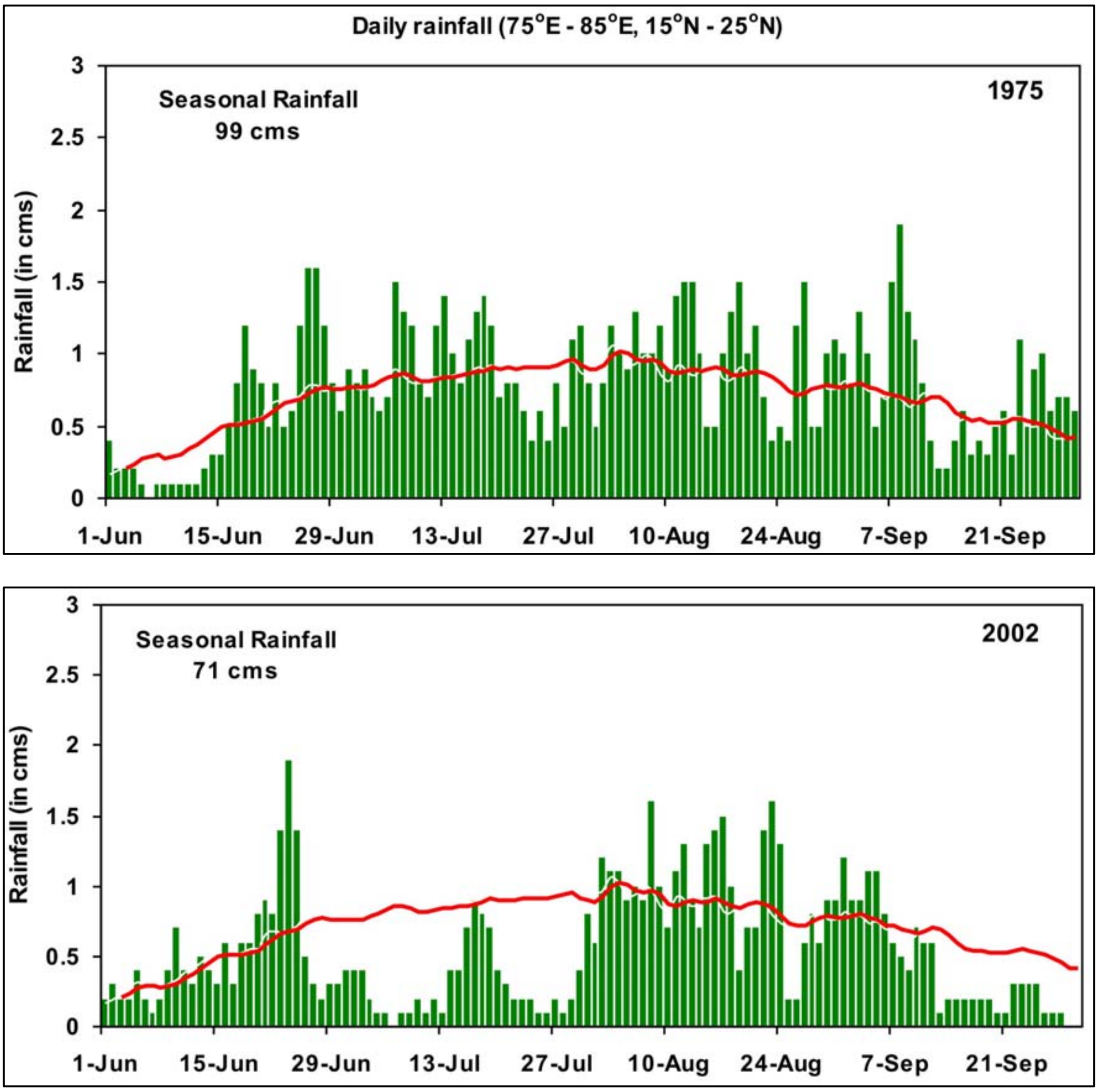


Fig. 1: Variation of the daily rainfall over central India during June – September 1975 (excess monsoon year) and 2002 (drought year).

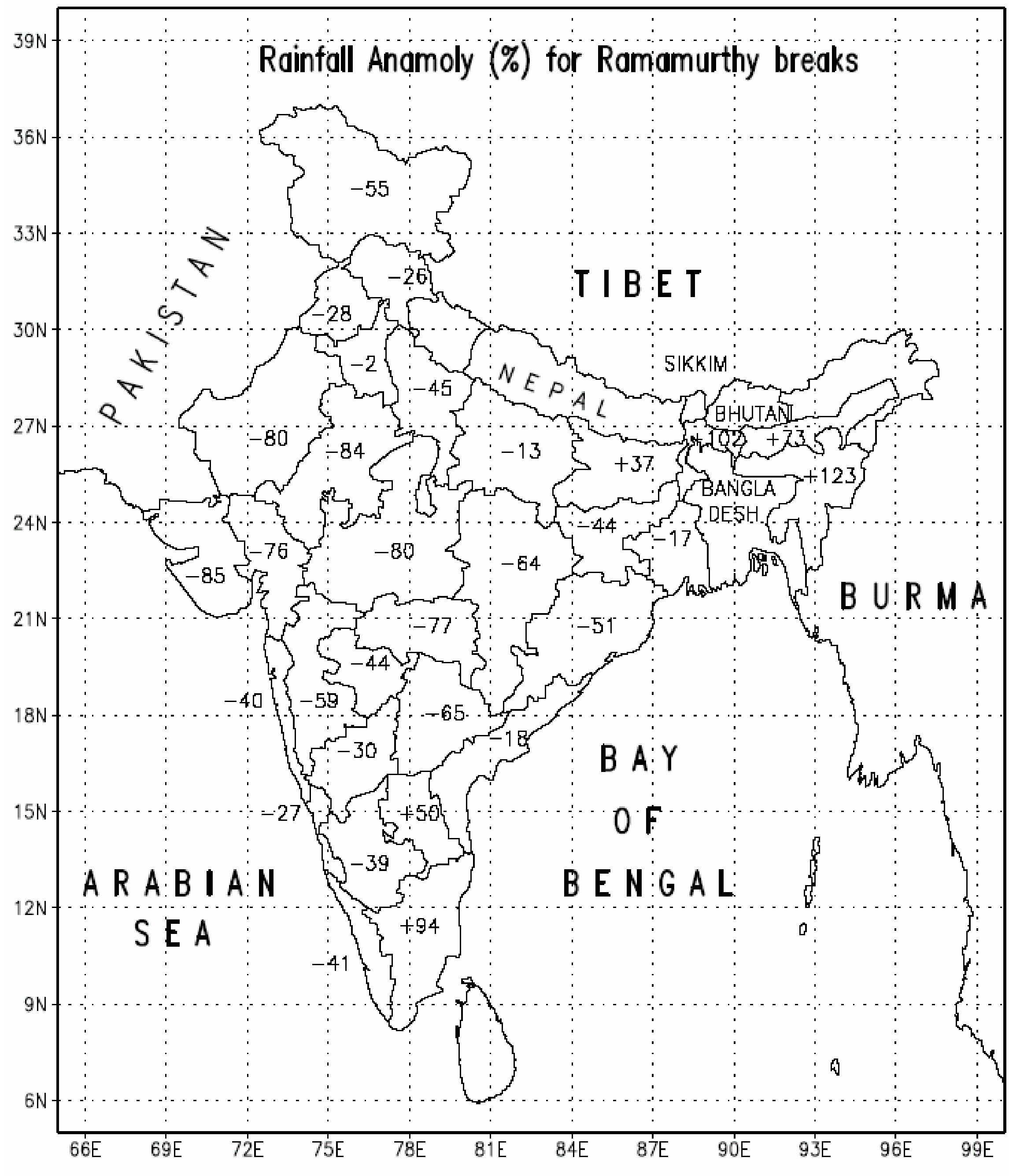


Fig. 2. Mean rainfall anomaly during the break spells (after Ramamurthy, 1969)

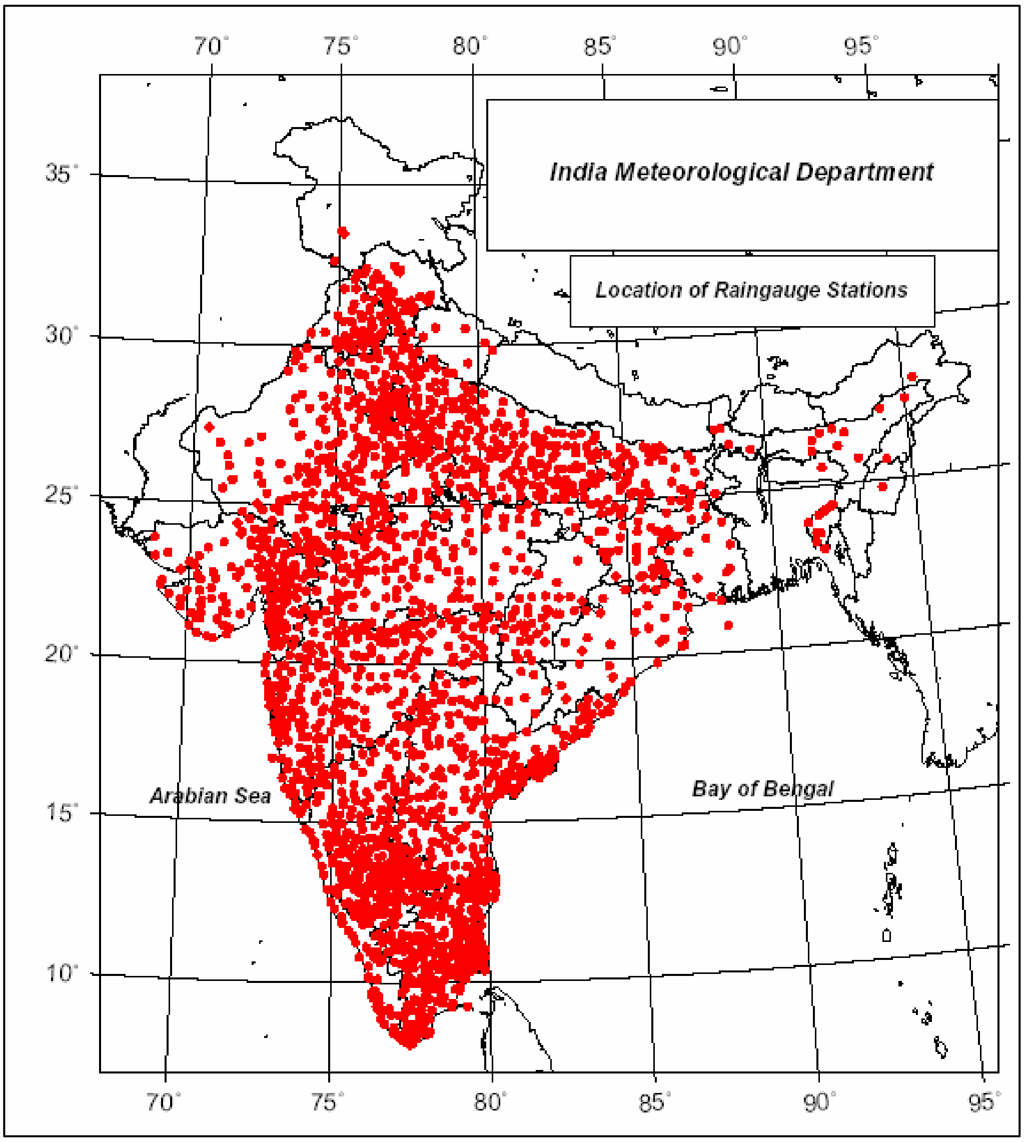


Fig. 3: Network of stations considered for the development of high resolution gridded data set.

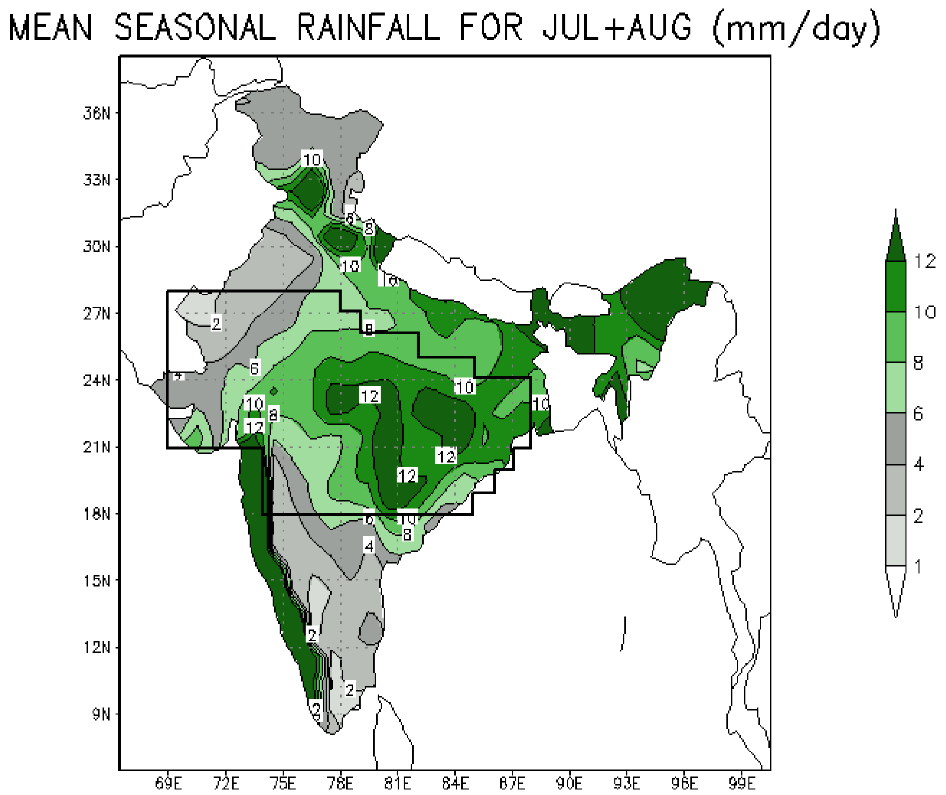


Fig.4: Monsoon core zone considered to identify the active and break events. Mean (1951-2007) rainfall (mm/day) during the period July and August is also shown.

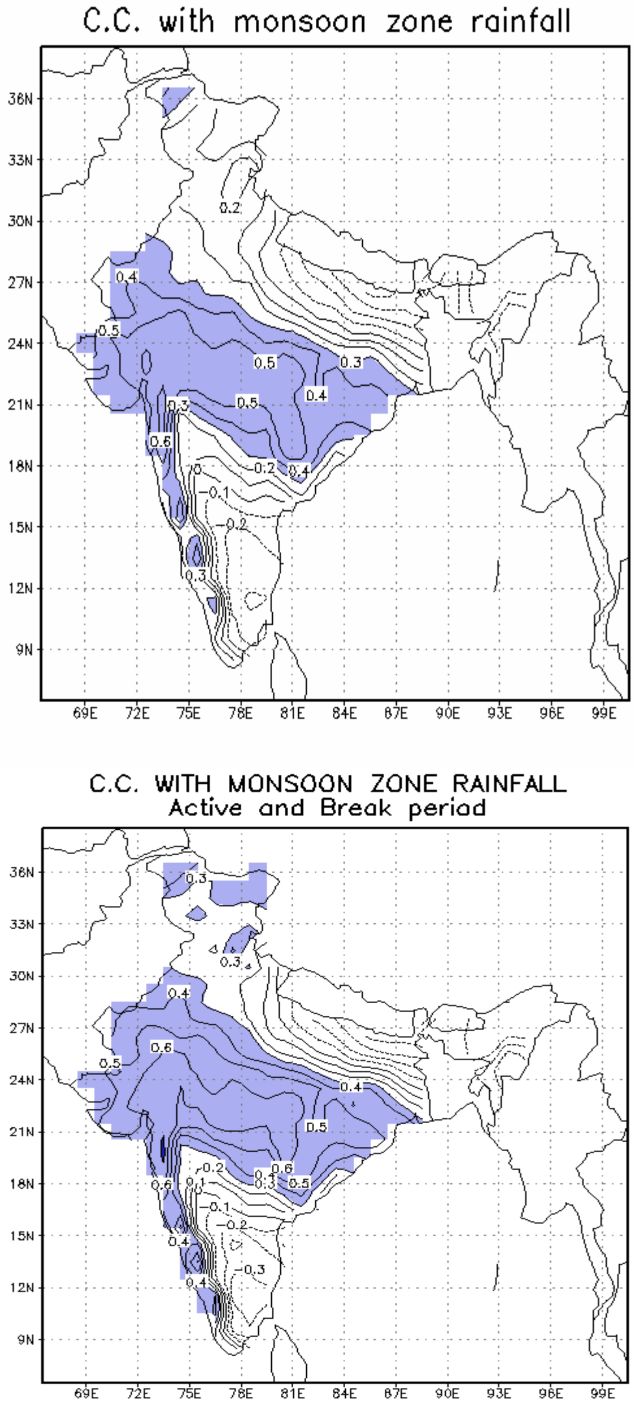


Fig. 5. (a) Correlation coefficient of 5-day average rainfall over the monsoon zone with rainfall at all grid points. Rainfall during only July and August months have been considered and (b) the same as (a) but only rainfall during the active and break spells was considered.

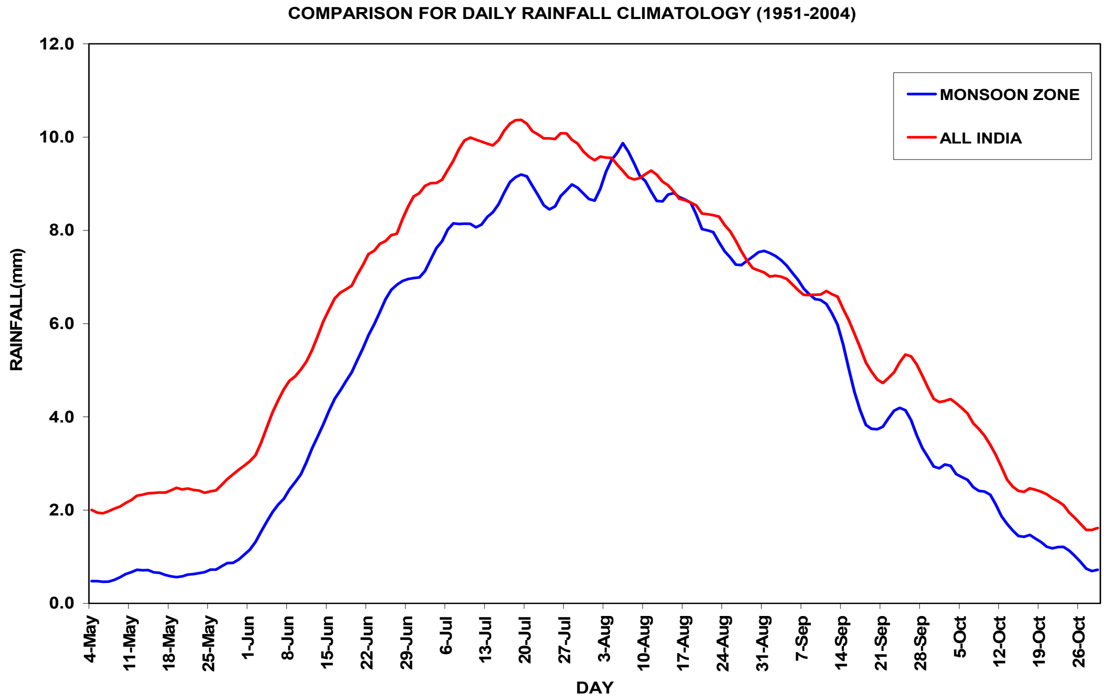


Fig. 6 a : Variation of average (1951-2004) daily rainfall averaged over the monsoon zone and the country as a whole (all-India).

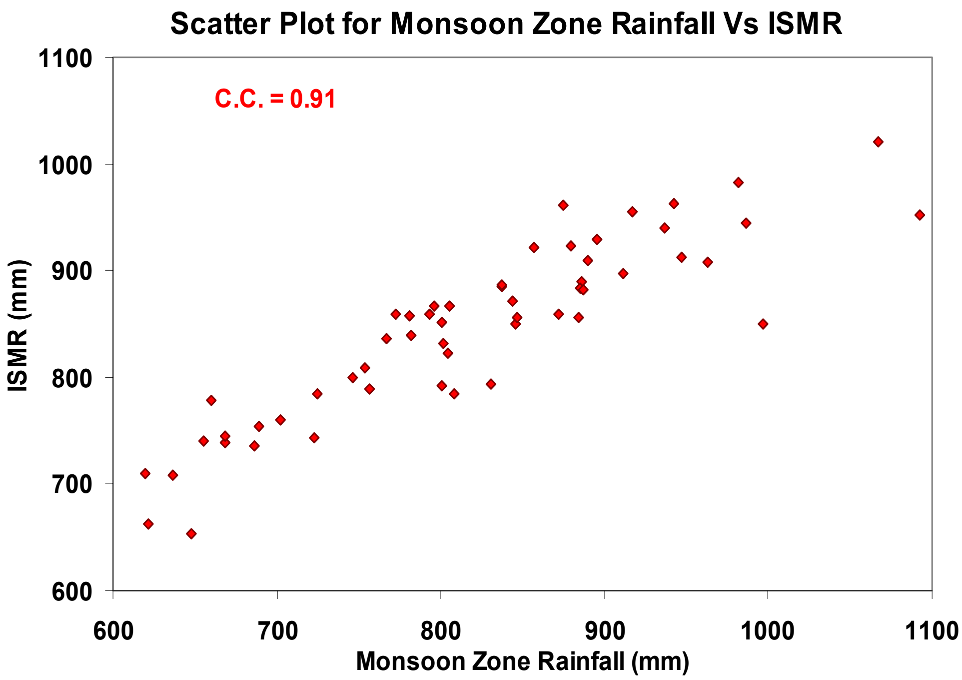
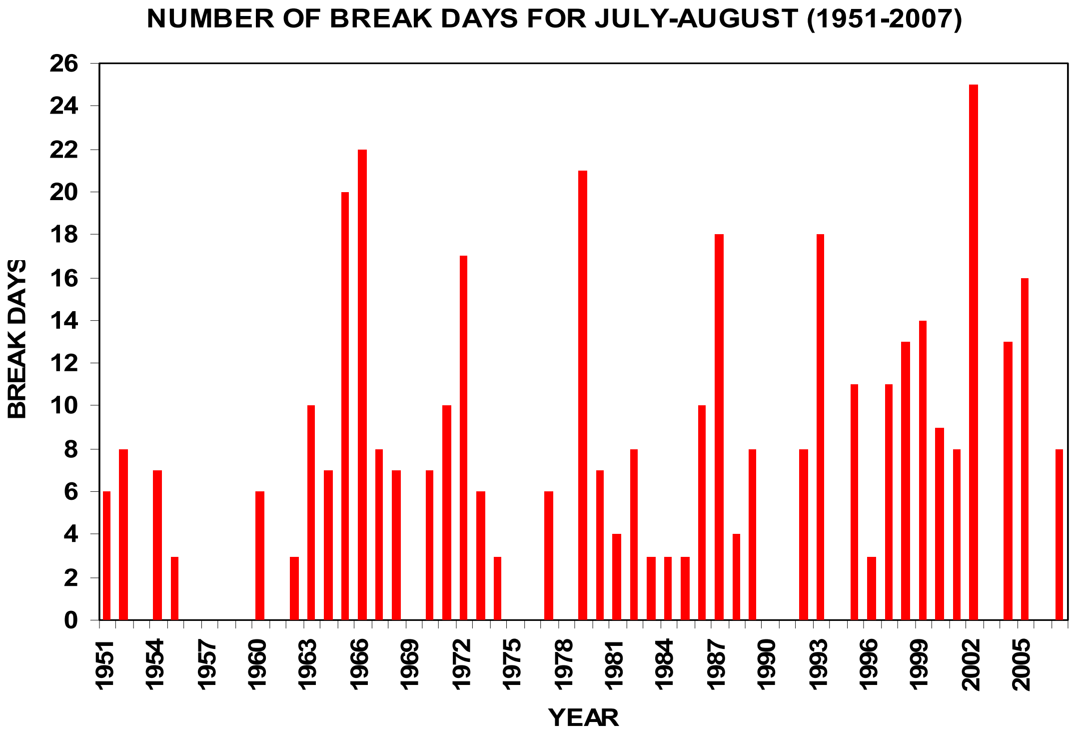


Fig. 6 b : Scatter plot between the average rainfall over the monsoon core zone (June to September) and ISMR. Period: 1951-2007.



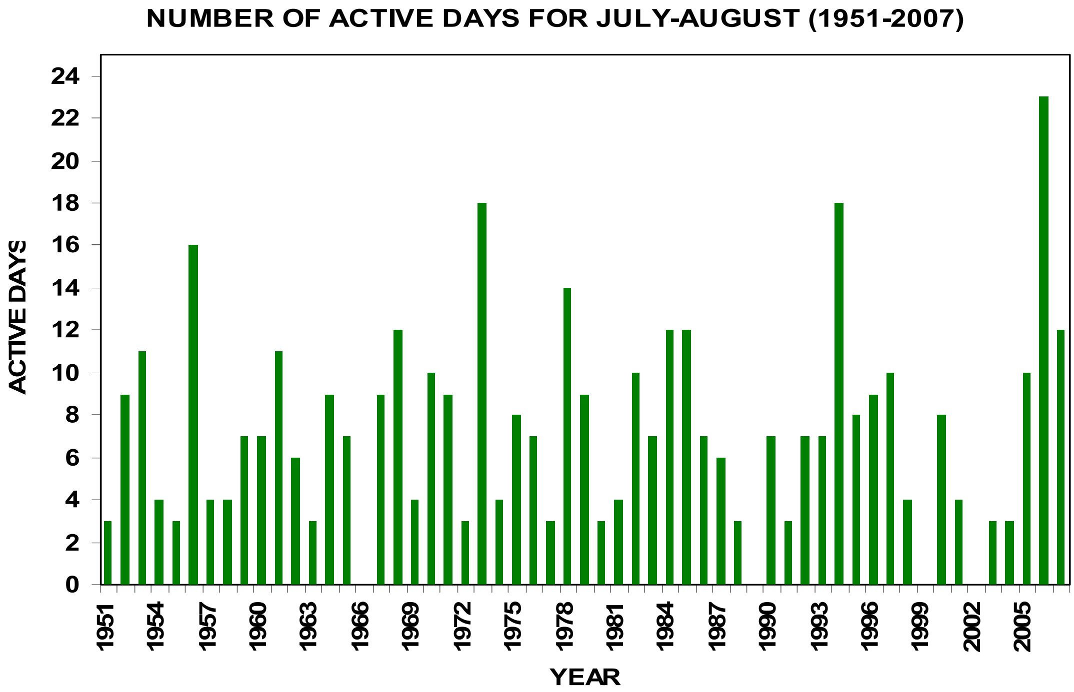


Fig 7: Time series of a) Active days and b) Break Days during July and August. Period: 1951-2007.

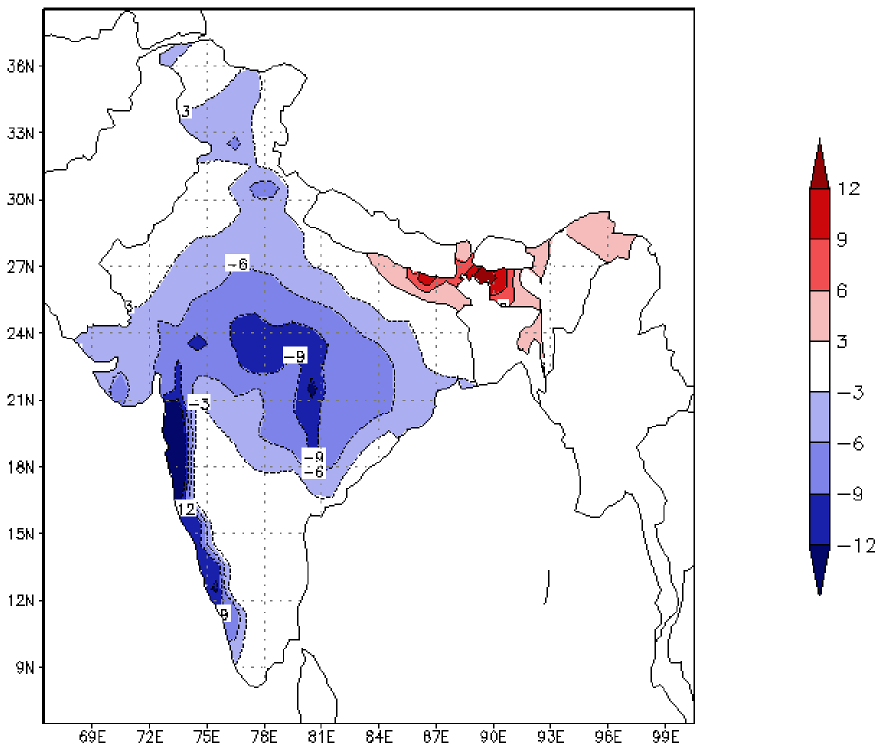


Fig 8. a: Composite of rainfall anomaly (mm/day) for the break spells (1951-2004)

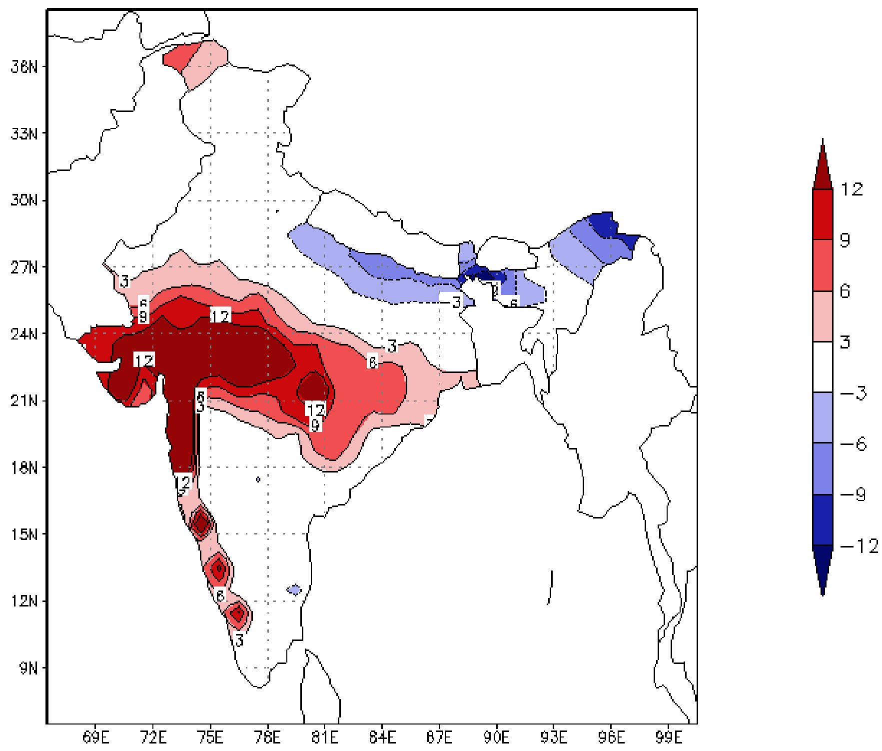


Fig 8. b**:** Composite of rainfall anomaly (mm/day) for the active spells (1951-2004)

LAGGED COMPOSITES FOR DAILY RAINFALL ANOMALIES FOR BREAK PERIOD

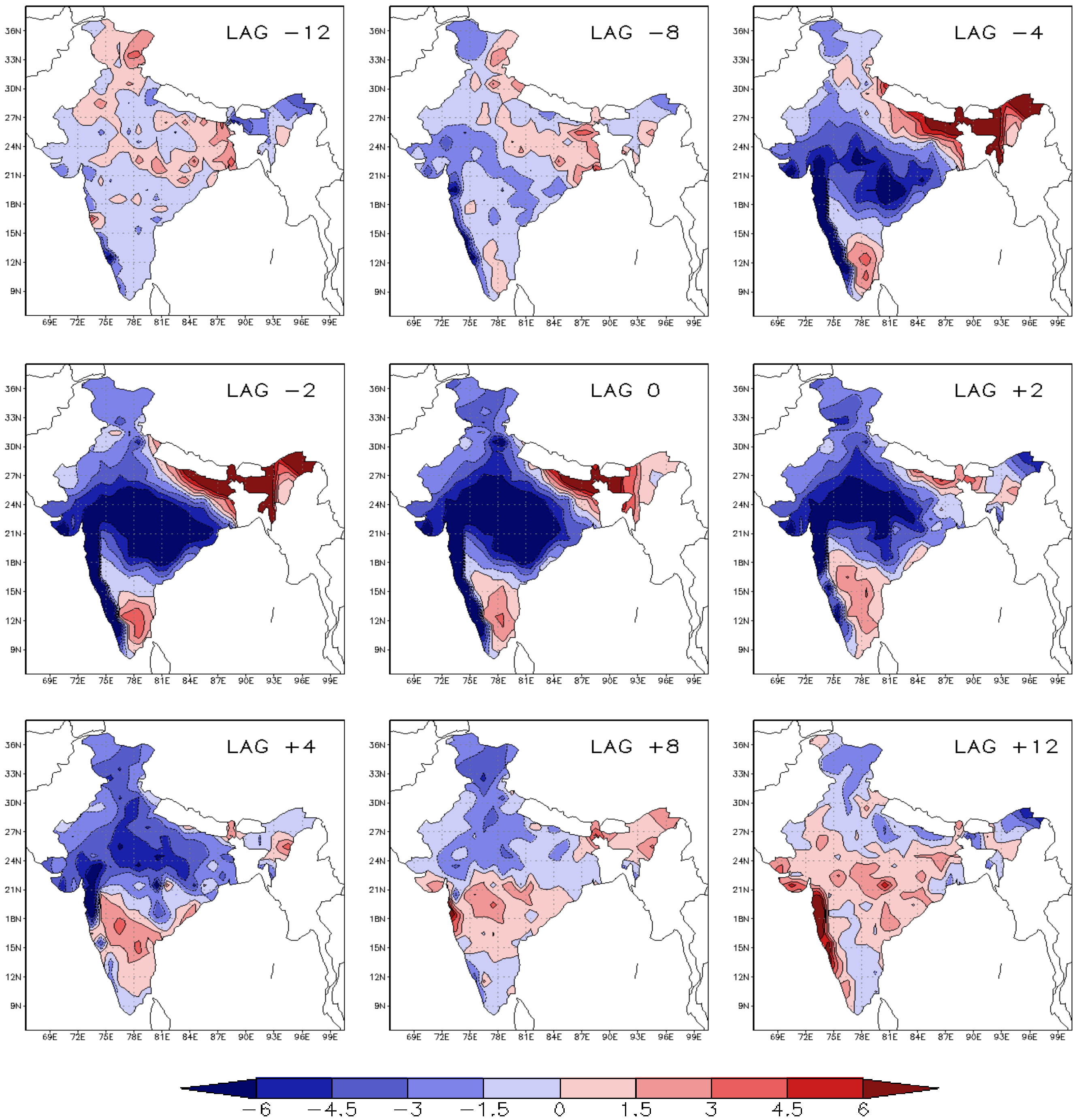


Fig 9 a : Lagged rainfall composites during the break spells (1951-2004)

LAGGED COMPOSITES FOR DAILY RAINFALL ANOMALIES FOR ACTIVE PERIOD

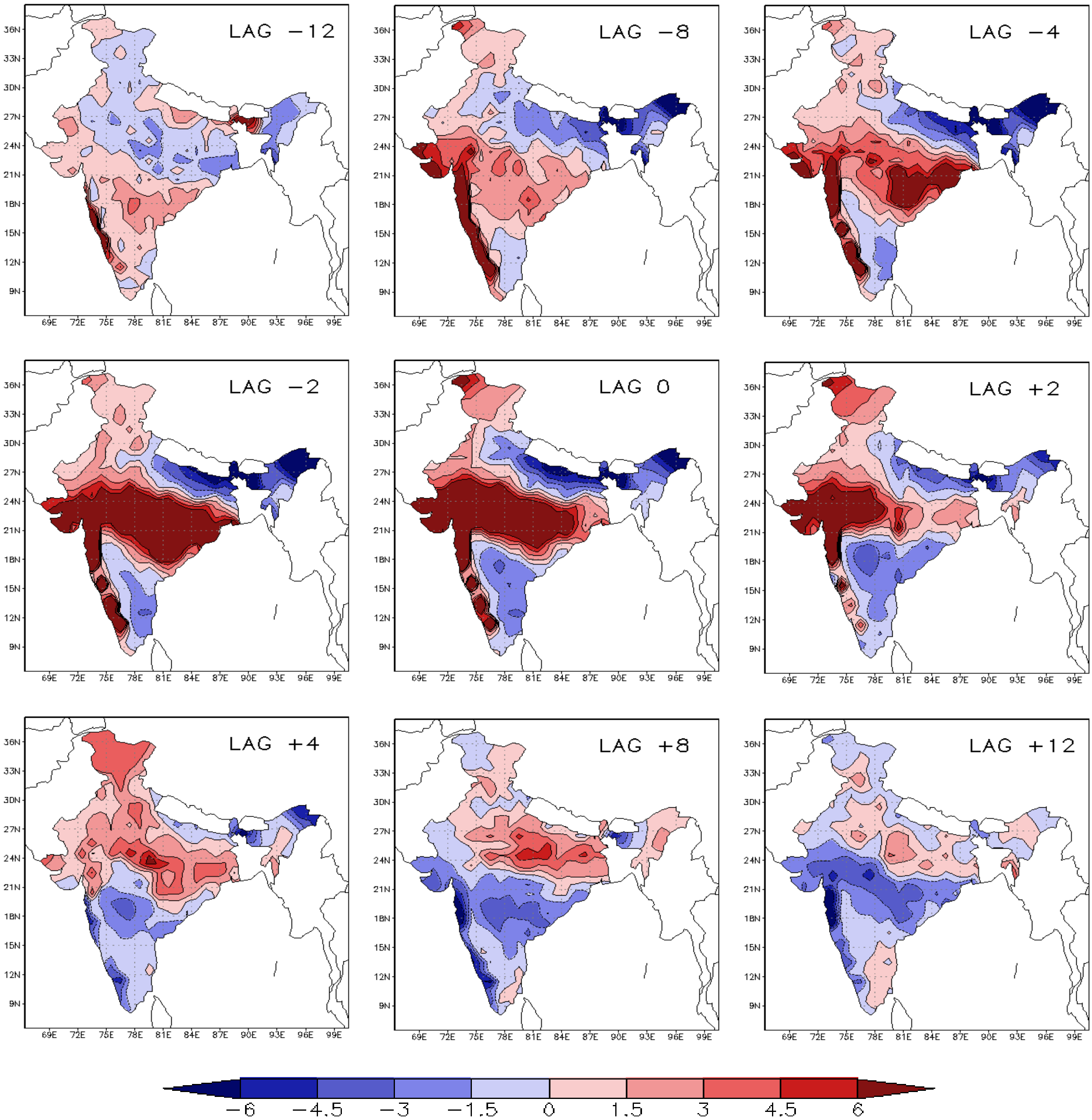
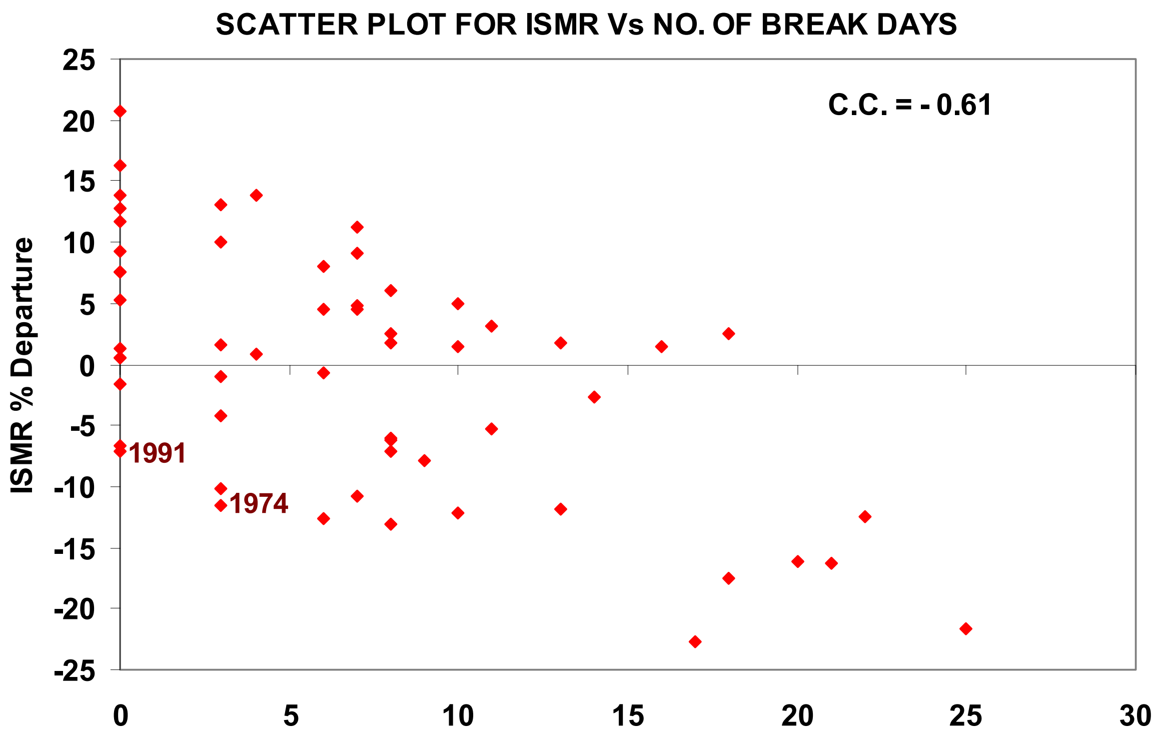


Fig 9 b : Lagged rainfall composites for the active spells (1951-2004)



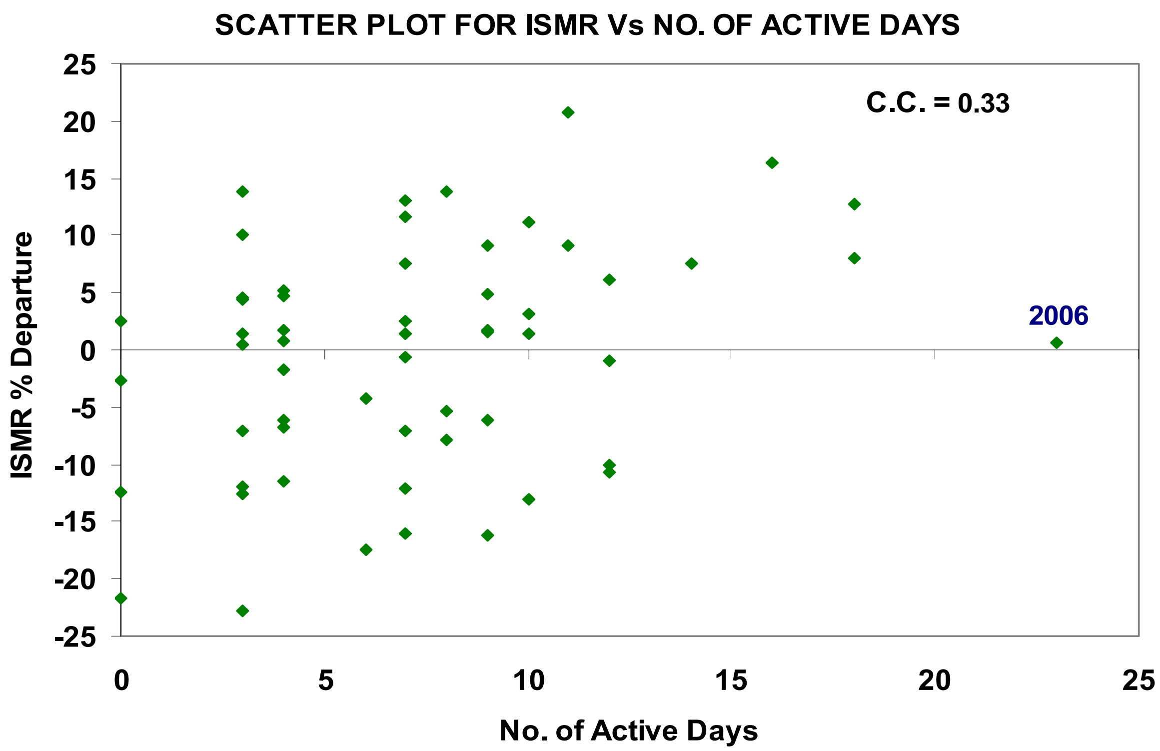


Fig. 10. Scatter plot between (a) number of break days and ISMR and (b) number of Active days and ISMR. Period: 1951-2007.

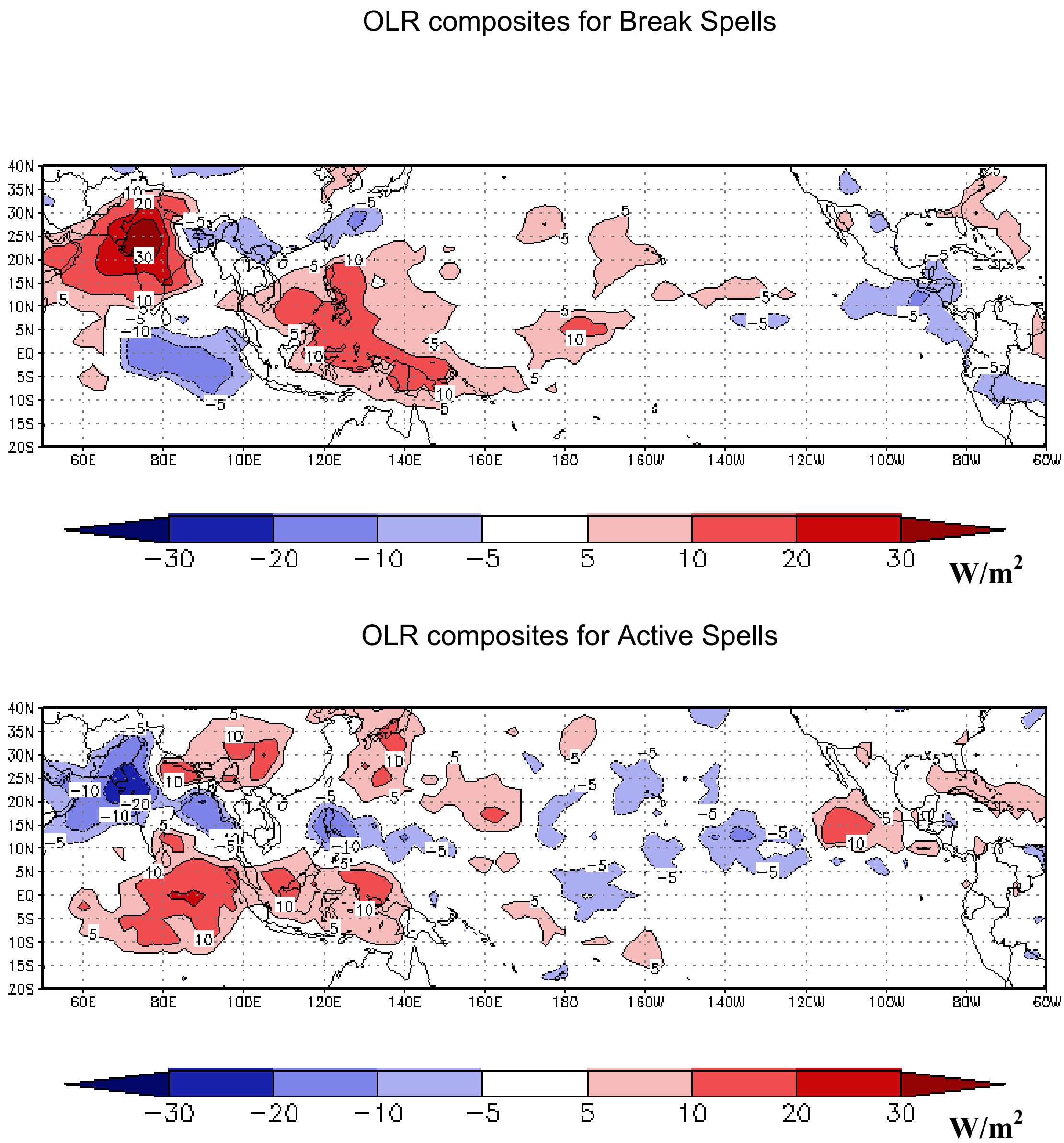


Fig. 11: Composites of OLR anomalies during (a) Break and (b) Active spells. Period of analysis: 1979-2007.

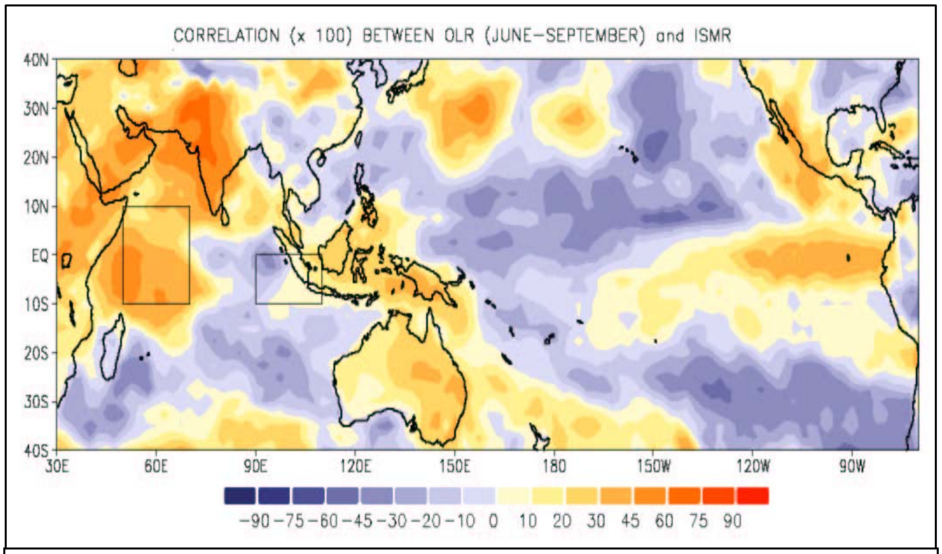


Fig. 12 a: Correlation (X 100) between OLR and ISMR during June to September

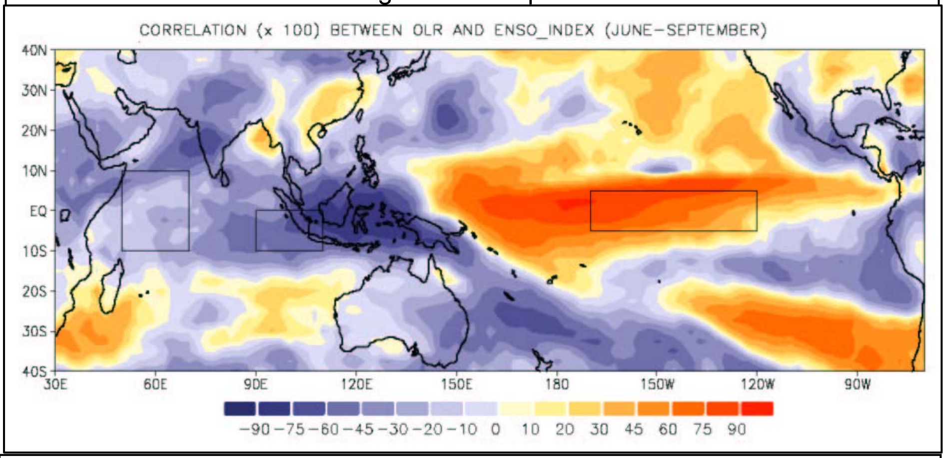


Fig. 12 b: ENSO index is the negative of the normalized SST anomaly of Nino 3.4 so that positive values are favorable for the monsoon

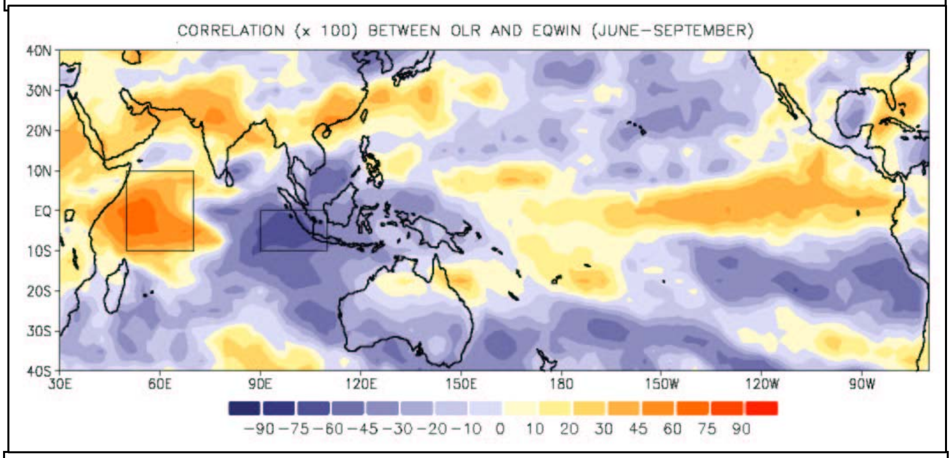


Fig. 12 c: Correlation (X 100) between OLR and EQWIN during June to September

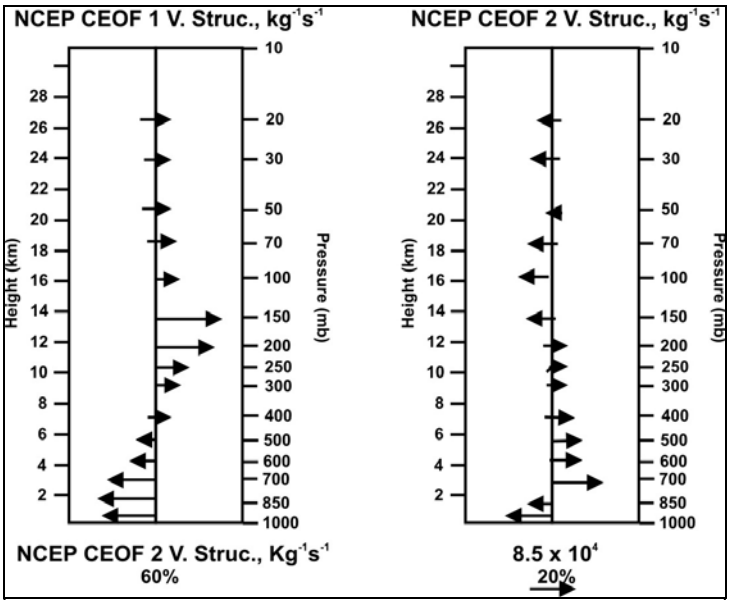


Fig. 13: The first two modes of global divergent circulation (after Trenberth et. al. 2000)

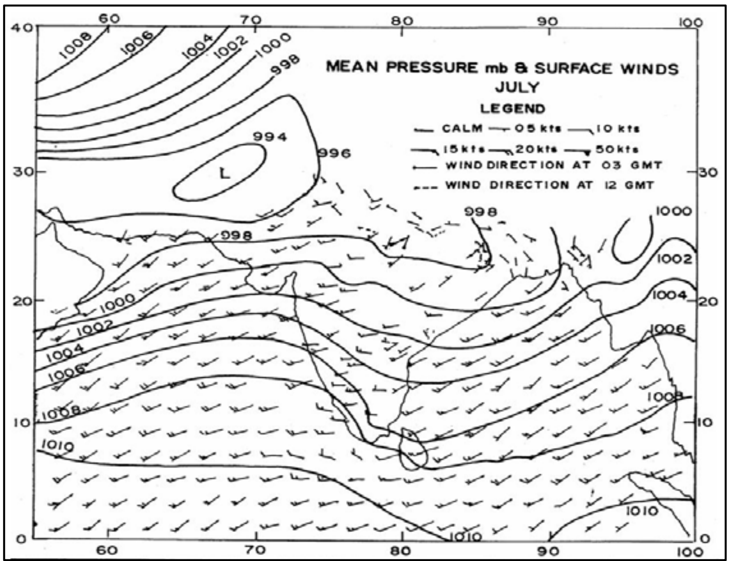


Fig. 14 a : Mean sea level pressure and surface winds for July (from IMD)

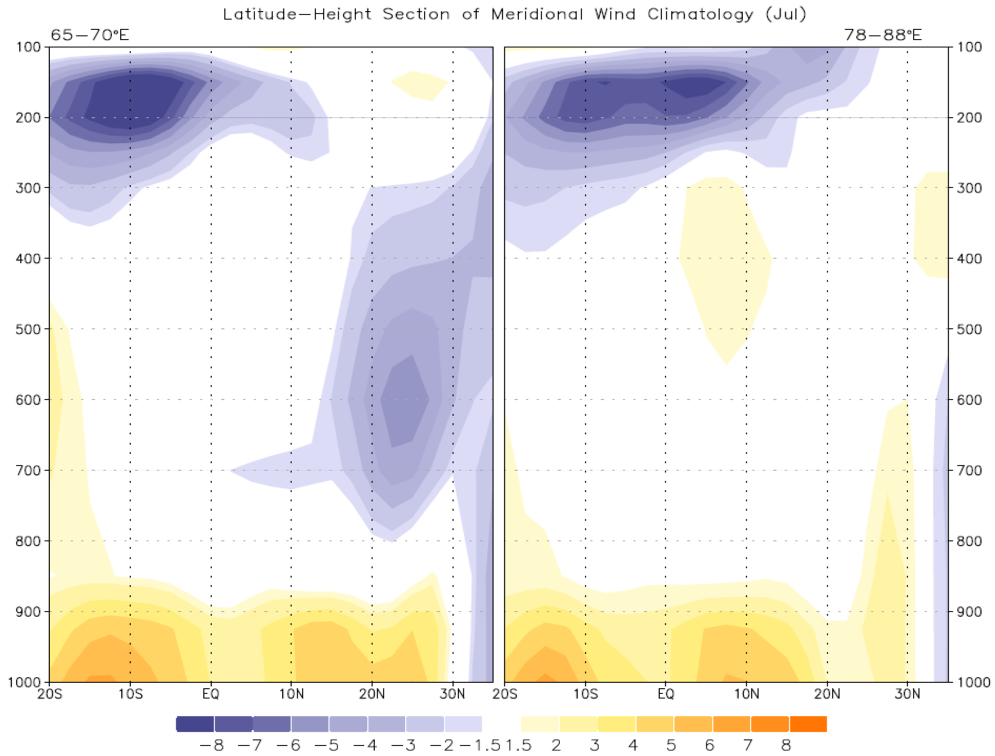


Fig 14. b : Latitude –height section of meridional wind climatology during July along 65-70^0 E (left) and 78-88^0 E (right).

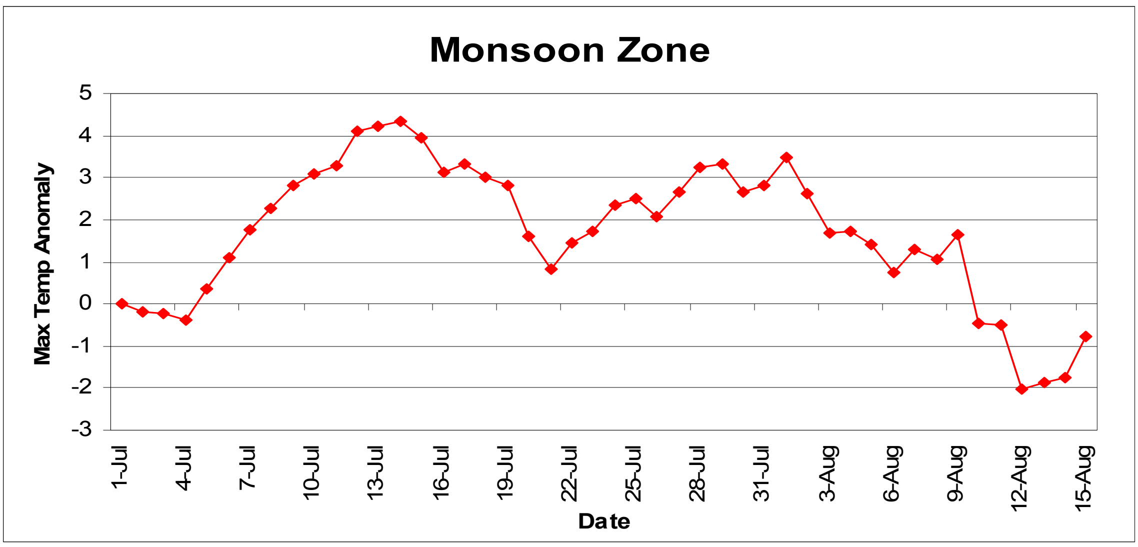


Fig 15 a: Variation of day time temperature anomaly from 1 July to 15 August, 2002, averaged over central India.

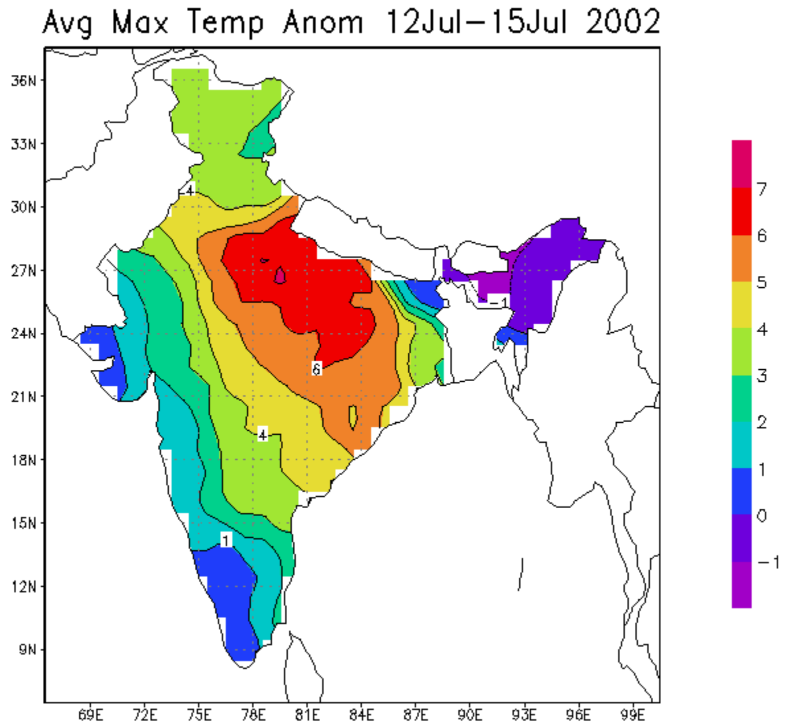


Fig 15 b: Maximum Temperature anomaly during the period 12-15 July 2002.

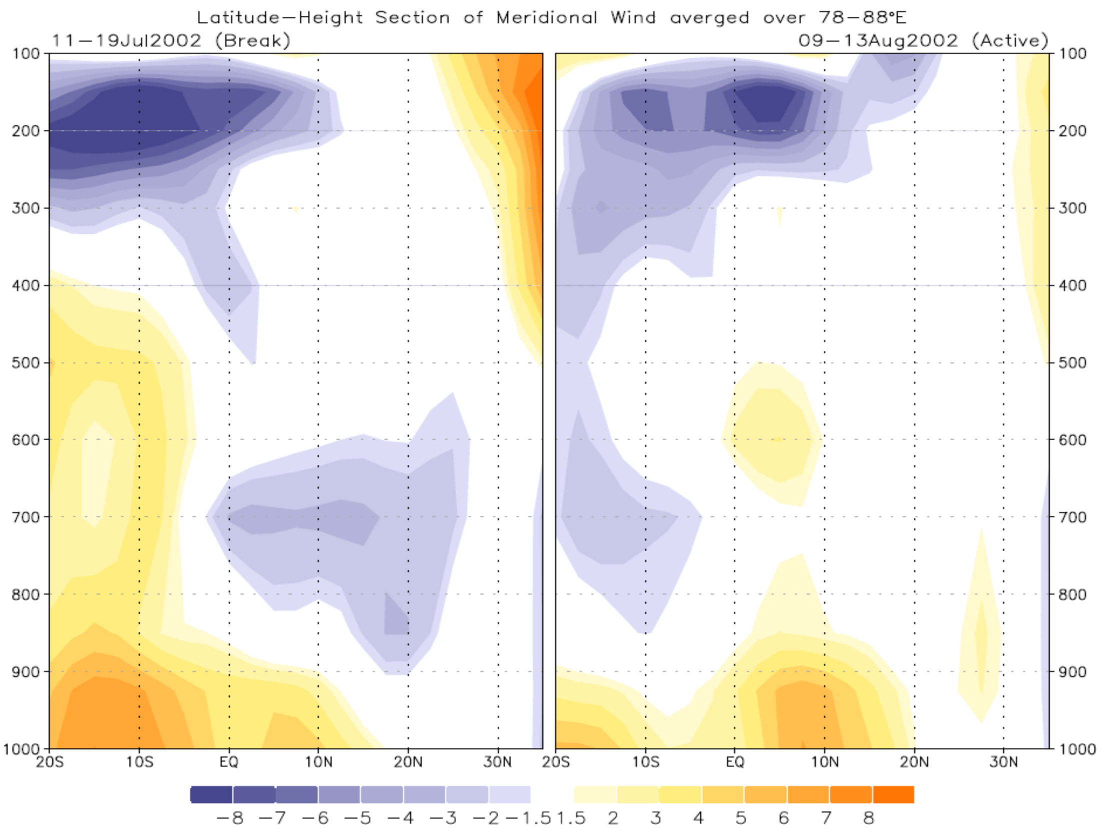
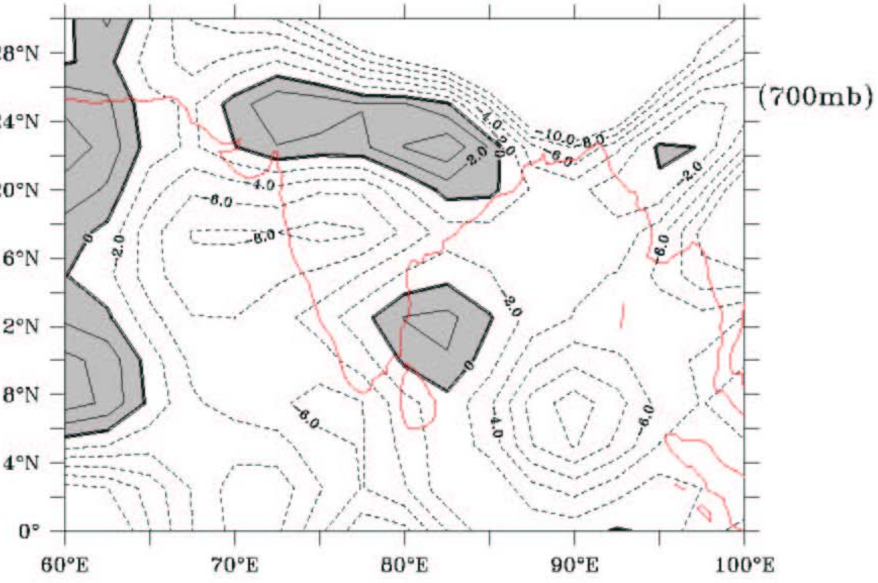
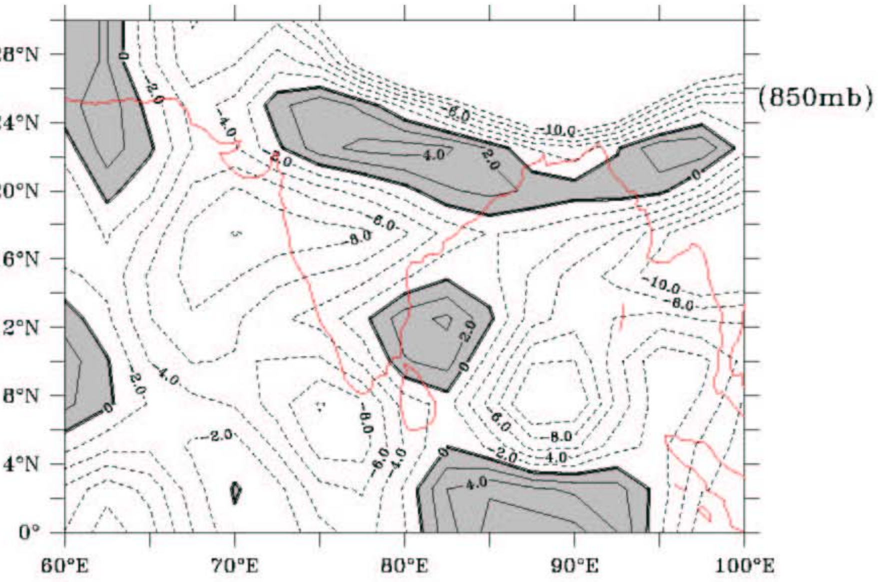


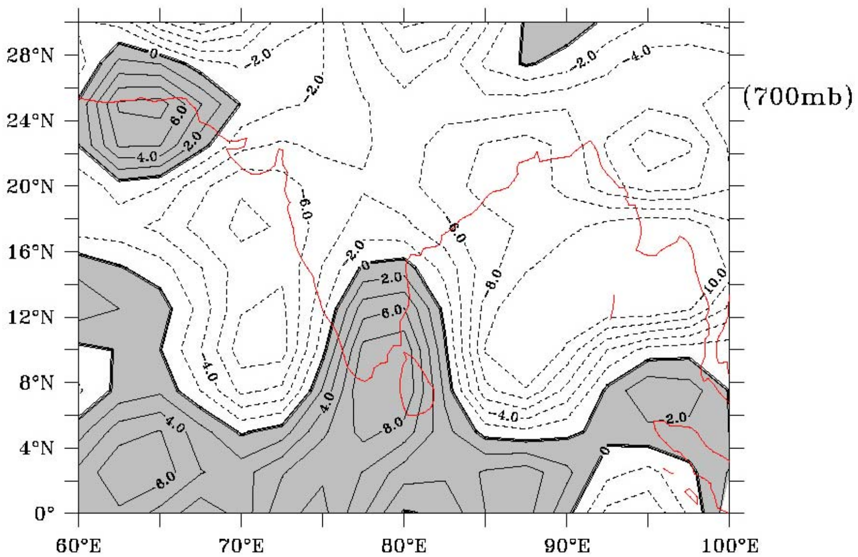
Fig. 16: Latitude- Height section of meridional wind averaged over 78-88^0 E.

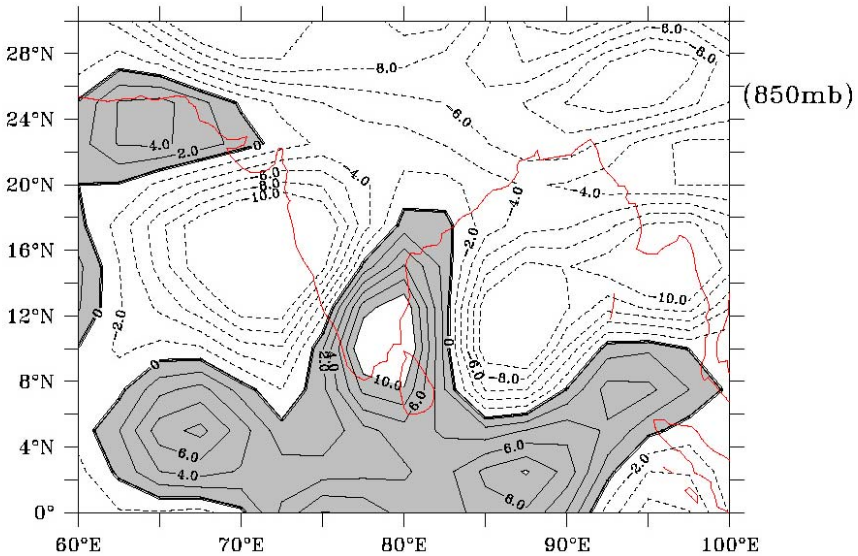
28-JUL-2002 00:0





05-AUG-2002 00:00





24-AUG-2002 0

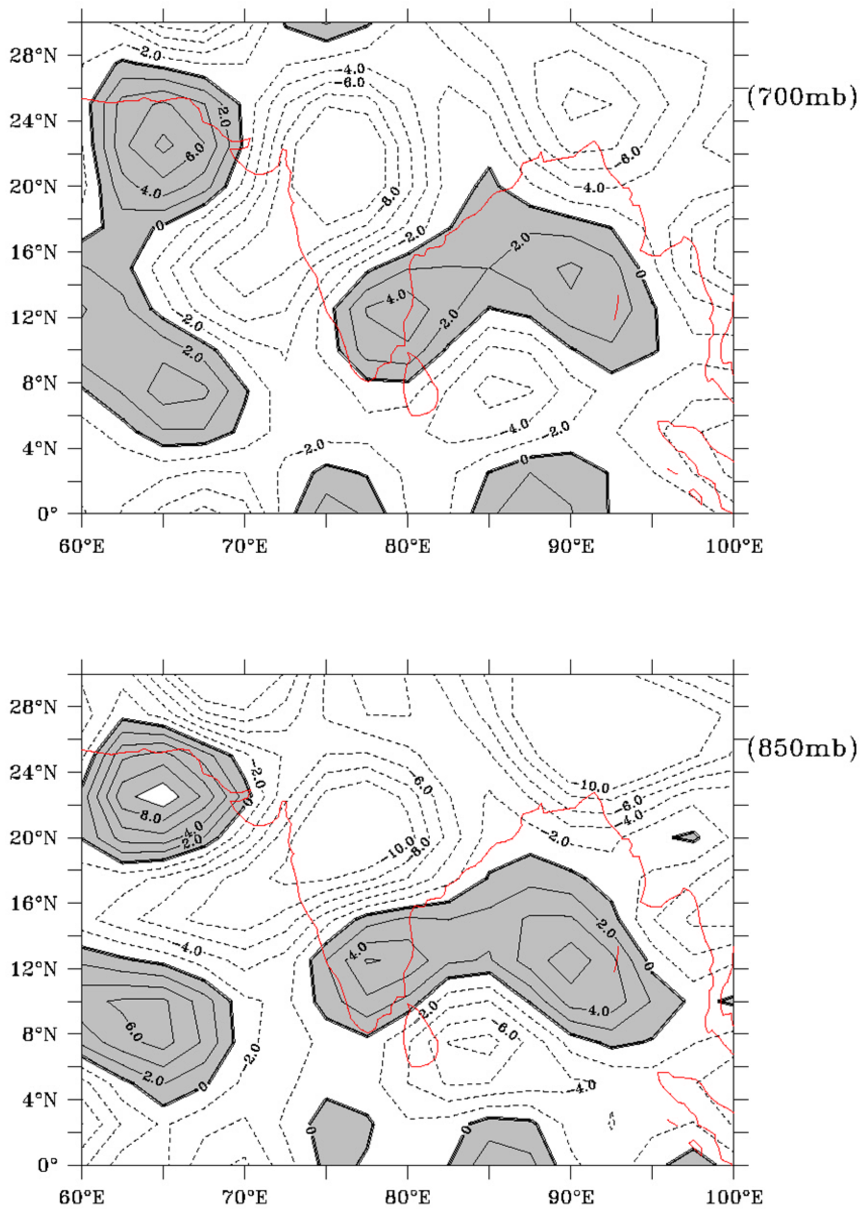


Fig. 17: Spatial plot of Omega (Pa/sec) for a) break phase (28 July2002), b) Weak Spell (5 August 2002) and c) Active Spell (24 August 2002).