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STUDY OF INTERANNUAL AND INTRA-SEASONAL VARIABILITY OF SUMMER MONSOON CIRCULATION OVER INDIA

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ABSTRACT

In this study satellite derived Outgoing Long wave Radiation (OLR) and National Centre for Environmental Prediction (NCEP) reanalysis zonal wind (U-850 and U-200 hPa levels) datasets for 27-years are used to examine important and unique characteristics of summer monsoon circulation variability across India. Among mean 73 pentads of annual cycles for OLR and zonal wind components, large scale monsoon convective activity, monsoon westerlies at 850 hPa and strengthening of easterlies at 200 hPa levels are conspicuously represented by P-30 to P-55 pentads over India. More details of monsoon circulation change are inspected in spatial distribution of OLR and wind fields for the climatological annual cycles. The OLR field is inversely related with U-850 hPa, while it is directly related with U-200 hPa levels; both are statistically significant at 0.1% level in this study. Annual cycles of the OLR and wind fields (anomaly) reveal striking interannual monsoon circulation variability in El Nino (2002) and La Nina (1998) years. The monsoon seasonal circulation changes in above contrasting years are highlighted and they reveal that U-850 hPa is almost a mirror image of U-200 hPa distribution of wind fields over the monsoon region. Finally the strength of ISO index in terms of Monsoon Hadley Index (MHI) and Madden and Julian Oscillation (MJO) index are evaluated to study year-to-year monsoon variability across India. Above ISO indices are related with Indian summer monsoon rainfall and the relationships are statistically significant.

Keywords: Convective activity, circulation changes, variability.

INTRODUCTION

The interannual variability of combined atmosphere-ocean system is manifest in changes of the atmospheric, oceanic circulations and extreme events like monsoon rainfall in the regional climate. Strong seasonality in terms of rainfall over the tropical monsoon region is observed due to interannual variability in the form of the mean annual cycle (Mooley and Parthasarathy, 1984). Goswami (1997) opined that modulation of the Intra-Seasonal Oscillations (ISO) by the annual cycle could give rise to an internal quasi-biennial oscillation in the tropical atmosphere. It is well documented that the most dominant feature in the tropics is the ISO, which is a naturally occurring component of both coupled ocean-atmospheric phenomenon. ISOs represent an entire cycle of 30-50 days and fluctuations in tropical rainfall, which is driven by internal feedback mechanism between convection and dynamics (Madden and Julian, 1971). It is also called as Madden-Julian Oscillation (MJO) or 40-day wave. They have originated from western Indian Ocean, which propagate quite vigorously in eastward or northward direction and exhibits remarkable interannual and intra-seasonal variability of rainfall (Ramamurthy, 1969). The ISO moves northward across India resulting in wet and dry spells within the Indian monsoon season, which is known as active and break monsoon conditions. It is, however, varied its activity from year-to-year over Southeast Asia in general and India in particular. Northward propagation of ISO using convective fields during Indian summer monsoon is studied by (Yasunari, 1979 and 1980; Sikka and Gadgil, 1980) with a limited data. Singh and Kripalani (1990) and Singh *et al*. (1992) used long records of daily rainfall data over the Indian continent and examined the 30-50 day oscillation. They, however, could not come to a clear conclusion regarding relationship between the ISOs and the interannual variability of the Indian summer monsoon rainfall. Fenessey and Shukla (1994) showed that the spatial structures of the interannual variability and intraseasonal variability are quite similar, while Goswami (1994) proposed a conceptual model of how the ISOs influence the seasonal mean and interannual variability of the Indian monsoon. Later Annamalai *et al*. (1999) examined the relationship between intraseasonal oscillations and interannual variability using NCEP and European Centre for Medium range Weather Forecast (ECMWF) reanalysis and they concluded that there was not a common mode that described the intraseasonal and interannual variability. Apart from the above, several studies have indicated that the 30-50 day oscillation is a dominant phenomenon in the interannual variability of Indian summer monsoon rainfall (Julian and Madden, 1981; Krishnamurthi *et al*., 1985; Wang and Rui, 1990; Goswami and Mohan, 2001; Annamalai and Slingo, 2001; Kemball-Cook and Wang, 2001; Goswami *et al*., 2003; Rao and Sikka, 2007; Susmitha *et al*., 2008; Bhanu Kumar *et al*., 2008). Several modeling studies showed

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that a significant fraction of the interannual variability of the seasonal mean Indian summer monsoon is governed by internal chaotic dynamics (Goswami, 1998; Hazarallah and Sadourny, 1995; Rowell *et al*., 1995; Stern and Miyakoda, 1995). Most of these studies, however, do not provide any detailed insight regarding the origin of the internally generated interannual variability. Recently a few studies of course made use of MJO and Monsoon Indices to express Asian monsoon circulation variability with limited data (Webster and Yang, 1992; Degtyarev *et al*., 2007; Manoel *et al*., 2006; Goswami *et al*., 1999; Li and Zeng, 2002). So far there are no detailed studies to explain variability of monsoon circulation based on convection, circulation changes and above said indices. Hence the aim of this paper is to investigate interannual and intra-seasonal monsoon variability over India.

MATERIALS AND METHODS

We know that marked interannual and intra-seasonal variations of the atmosphere-ocean system are an essential characteristic of tropical climate. In this study satellite derived daily OLR and NCEP zonal wind fields (2.5°x2.5°) at 850 and 200 hPa levels are downloaded from the NOAA website (www.cdc.noaa.gov) to study interannual and intra-seasonal variability of Indian monsoon circulation changes for the period, 1979-2005 and the study region (50°-100°E and 0°-38°N) is shown in figure 1. These datasets are used to prepare mean 73 pentads in order to examine climatological annual cycles in the form of histograms and spatial distribution formats over the study region. Anomaly annual cycles of OLR and wind fields are also prepared for El Nino (2002) and La Nina (1998) years to find out contrasting convection and circulation changes if any. Mean convective and circulation changes over study region during monsoon season (June-September) are also prepared for above contrasting years. The MJO index is obtained from the Climate Prediction Centre (http://www.cpc.noaa.gov) at 70°E, 80°E and 100°E longitudes for the monsoon period, which is evaluated from pentad velocity potential at 200 hPa level using extended empirical orthogonal function analysis across Indian longitudes for intra-seasonal variations. And mean MJO index variations are calculated for the study period and related with monsoon rainfall. Similarly MHI is evaluated by taking the difference between U-850 and U-200 hPa wind flow over the study region during the monsoon season and above indices are related with monsoon rainfall, which is downloaded from IITM website for the study period. The connection between them is promising. To find out the relationship between any two variables used in this study is correlation and regression analyses.

RESULTS AND DISCUSSIONS

Study of climatological annual cycle

The mechanisms of interannual variability of circulation and climate are related to the functioning of the annual cycle and the annual cycle over a region has a significant year-to-year variations. Anomaly climatological annual cycle of large scale organized convection in 73 pentads from 27-year mean is presented in figure 2a. The most salient features of the mean annual pentad OLR march of convection shows extrema of annual OLR cycle reached minimum in August and maximum in February. Out of these 73 pentads, P-30 to P-55 pentads show large scale monsoon convective activity, which relates to Indian monsoon rainfall. Similarly figures 2b and 2c represent anomalous annual cycle of winds at U-850 and U-200 hPa levels respectively. They depict that trade winds are replaced by monsoon westerlies (850 hPa) and got strengthened from pentad P-25 to P-55, while easterlies (jet stream) at 200 hPa have attained maximum strength during the above period. Further OLR field is inversely related with the U-850 hPa, while it is positively related with U-200 hPa levels for the study period. Both are statistically significant. Thus OLR field has profound influence on wind fields to relate mean interannual variability of monsoon circulation.

To further examine climatological annual cycle of convection and circulation features across India, the OLR and wind fields for typical pentads of P-1 (3^{rd}-7^{th} January), P-26 (8^{th}-12^{th}May), P-31 (2^{nd}-6^{th}June), P-55 (30^{th} Sept.- 4^{th} Oct.) P-60 (4^{th}-8^{th} Nov.) and P-72 (24^{th}-28^{th} Dec.) are presented (Fig. 3a-c). Details of convection and circulation changes are discussed as follows. Pentad (P-1) in figure 3a shows a maximum OLR of about 280W/m^2, which is centered over central India. This is the slowly emerging part of annual cycle of monsoon circulation. Later there is a dramatic change in convective activity in the pentad P-26 and this is the beginning of fast intra-seasonal cycle of Indian summer monsoon, which coincides with the Onset of monsoon over Kerala in extreme south India. Above intense convective activity continued till the pentad P-55 due to planetary scale monsoon activity over study region. The value of OLR of P-26 to P-55 is negatively correlated with rainfall during June through September over India and it amounts to -0.6 and hence OLR is a good proxy for monsoon rainfall. Next pentads, P-56 to P-68 represent the post-monsoon season with low OLR field due to seasonal disturbances like tropical cyclones and easterly waves etc. In December, the climatological annual cycle of OLR fields again represents 280 W/m^2. Thus the convective activity is very interesting in climatological annual cycle, which reveals both summer and post-monsoon convection across India. As OLR is related with zonal wind, climatological annual circulation changes at U-850 and U-200 hPa levels are discussed. The figure 3b represents pentads of mean annual cycle of circulation changes at U-850 hPa. Pentad, P-1 of above figure shows a strong anti-cyclonic circulation over central India with a dominant easterly component over India. There is a spectacular change in circulation changes by migrating above anti-cyclone at the end of May/early June (P-26) by the appearance of strong southwesterlies. Somali jet is also appeared over the Arabian Sea and maintained its strength till the end of September (P-31 to P-55). Later southwesterlies are replaced gradually by northeasterlies with a commencement of post-monsoon from the Siberian high (P-60). At the end of the mean annual cycle these easterlies are weakened and conditions are favourable for the formation of anti-cyclone over central India (P-72). The figure 3c shows corresponding circulation changes at U-200 hPa for the above pentads. Pentad P-1 of above figure reveals the axis of Sub-Tropical Ridge (STR) at 10°N and westerly jet stream (28°N). Later easterly jet stream is fully established rather abruptly over south Bay of Bengal and south India by early June (P-31), while existing westerly jet stream disappeared. In September (P-55), the axis of STR shifts southwards (15°N) and week low level easterlies begin to appear over north Bay, which is a beginning of post-monsoon season. Later easterly jet stream has disappeared in P-60 and P-72 with the weakening of easterlies and the STR is shifted towards south. Thus above studies conclude that the climatological interannual variability in the tropics is dominated by changes in cloudiness and circulation changes caused by the Indian monsoon.

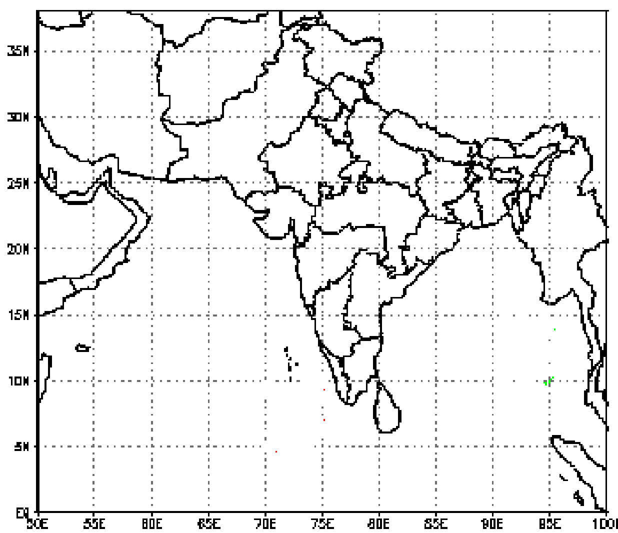

Fig. 1. Study region (0°-38°N and 50°-100°E).

Anomaly annual circulation changes over India

In tropics extreme atmospheric circulation changes are generally attributed with El Nino and its counter part La Nina episodes through Walker circulation. So it is of interest to know how monsoon convective activity and its related circulation changes are varying during anomaly annual cycles using OLR and wind datasets instead of precipitation criteria in this study. Figure 4a depicts composite annual cycle of OLR for El Nino (2002) and La Nina (1998) years, when monsoon rainfall amounts received were 81% and 108% respectively over India. Negative OLR anomalies were highly dominant over the most parts of Arabian Sea, Indian sub-continent and the Bay of Bengal in La Nina period, while reverse convection was observed in El Nino period during June through September in composite annual cycle (not shown). Thus there is a striking contrast in monsoon convection in El Nino and La Nina periods, but there is no change noticed in the pre-monsoon period in the above two cases. During active phase of the Indian monsoon, typically there is more rain over central India and a stronger monsoon trough. Thus the variations of Indian summer monsoon convection are better seen in the anomaly annual cycles of above contrasting years.

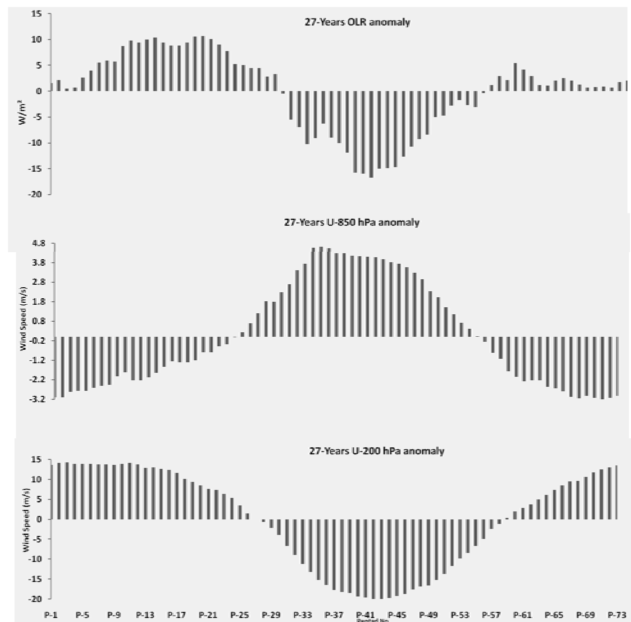

Fig. 2. Anomaly annual cycles of (a) large scale organized cumulus convention (OLR); (b) zonal wind at 850 hPa; (c) Zonal wind at 200 hPa over the study region during 1979 -2005 in 73 pentads.

Similarly interannual monsoon variability in El Nino and La Nina years are also examined through a composite anomaly annual cycle of zonal wind at 850 and 200 hPa levels (Fig. 4b) and curves indicate variation of zonal wind in terms of direction and speed. At the time of Indian summer monsoon though both the low level westerlies and upper level easterlies are considerably strong in both contrasting years. However there is a striking difference in strength of winds at 850 and 200 hPa levels in the above years. This figure also explains that the signal associated with El Nino and La Nina years extends backward some seasons before an anomalous monsoon. Thus this study explains that significant variations may be due to ISOs during Indian monsoon season.

Above interannual monsoon variability studies have clearly indicated that OLR and circulation changes are more predominant during the Indian summer monsoon due to ISOs. And the variations in convective activity and circulation changes for the monsoon period of above El

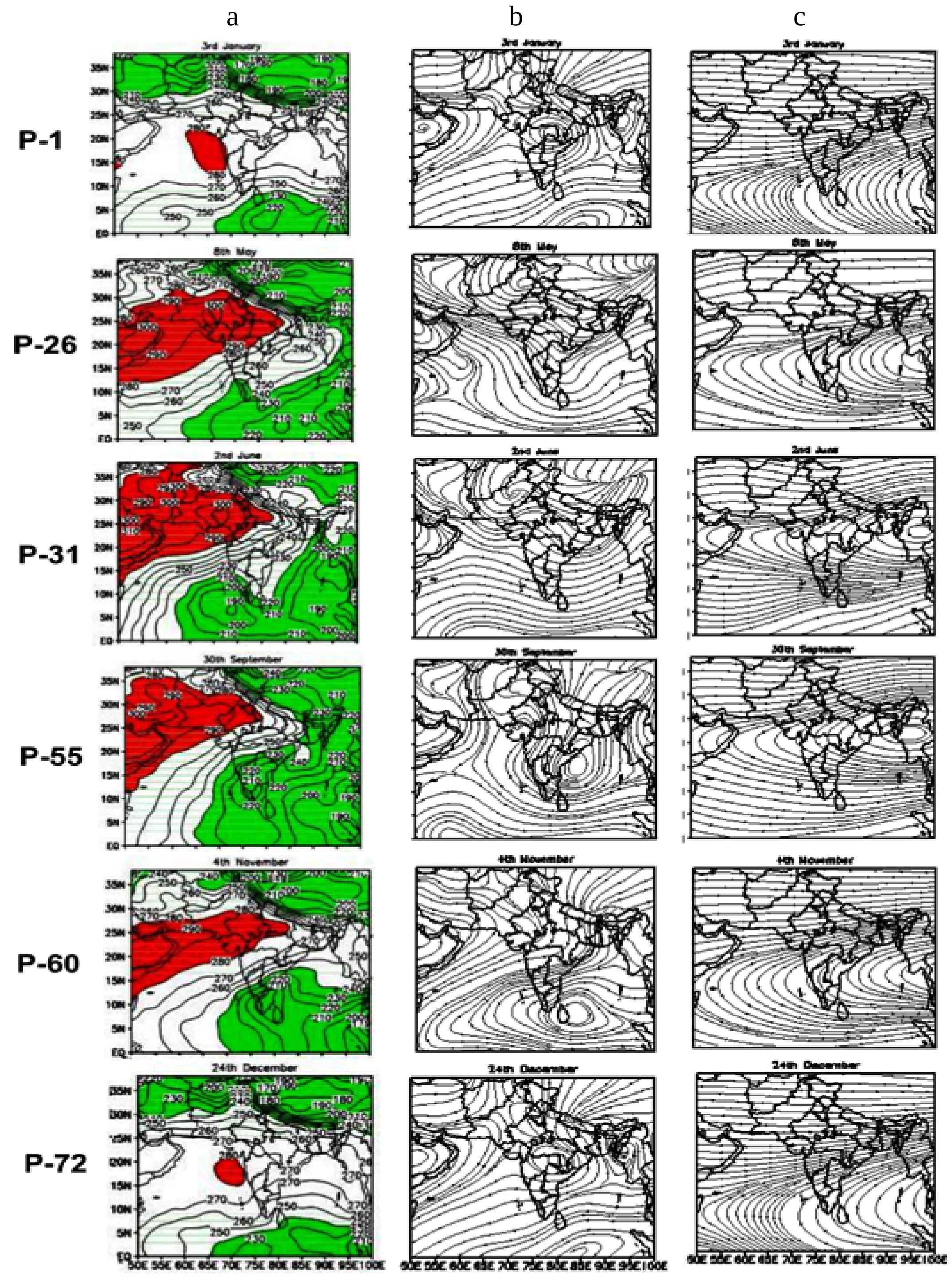

Fig. 3. Mean annual cycles of (a) OLR and wind at (b) U-850 hPa (c) U-200 hPa levels in typical pentads.

Nino and La Nina periods are also discussed in detail (Figs. 5a & b). The large scale phenomenon are often associated with changes with atmospheric circulation that encompass areas for larger than a particular affected region. There is a distinct pattern of low level and upper-level atmospheric anomalies, which accompany ISO related pattern of monsoon rainfall. In this study figure 5 a & b shows composite anomaly OLR and wind fields at U-850 hPa and U-200 hPa levels relative in 1998 and 2002 respectively for the monsoon period. The strength of OLR is different in 1998 and 2002 in terms of large scale cumulus convection. Negative OLR anomalies lie over most of the Indian sub-continent, central Arabian Sea and southeast Bay of Bengal, which extends across the

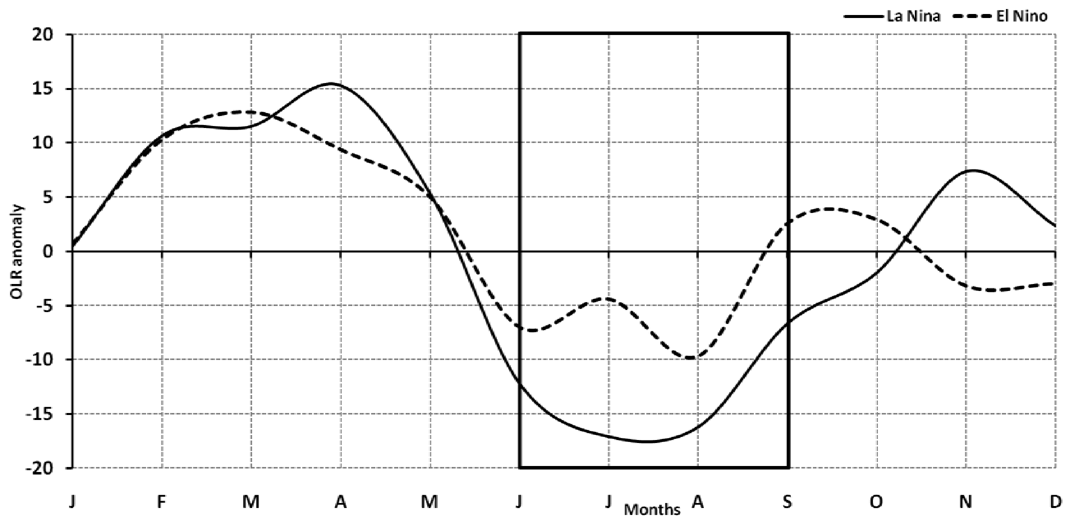

Fig. 4a. Interannual variation of the anomalous OLR relative to El Nino and La Nina years.

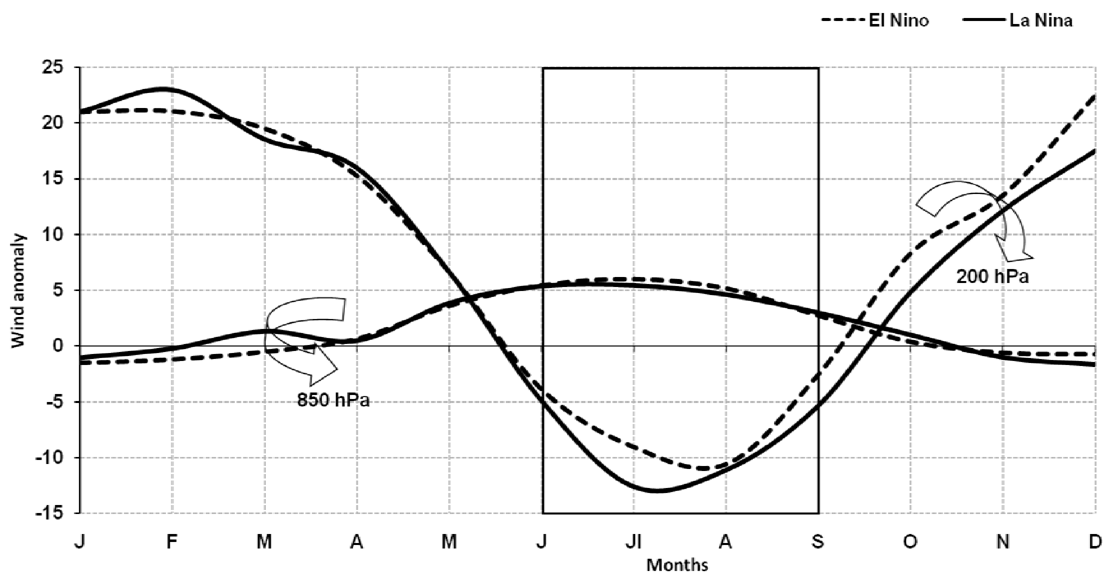

Fig. 4b. Same as above figure except for zonal wind at 850 hPa and 200 hPa levels.

equator in 1998, while in 2002 reverse situation is shown. Thus there is a spectacular contrast in the enhanced and depressed convection during La Nina and El Nino periods respectively. Next the wind strength at U-850 hPa shows much stronger (2 m/s) in 1998, while the wind strength was relatively weak in 2002. Similar differences are also observed at the anomaly wind at U-200 hPa in terms of strength of easterly jet stream. Anomalous easterly wind speed of -1.5 m/s is observed in the region of tropical easterly jet in 1998, while relatively weak wind appeared in the year 2002. Over the monsoon region, U-850 hPa is almost a mirror image of U-200 hPa distribution of wind fields. Thus these circulation changes clearly indicate that stronger monsoon westerlies in the La Nina period influence Indian monsoon rainfall through Walker circulation.

Influence of ISOs on monsoon circulation

Above studies indicate that OLR and wind fields are very potential to examine interannual circulation variability and spectacular changes due to ISOs in monsoon season. The strength of ISO is determined in terms of MJO index, which is positively related with OLR (r = 0.54) and MJO index is also statistically related (r = -0.5) with monsoon rainfall in this study. Year-to-year variation of mean MJO index (June-September) clearly shows El Nino, La Nina and neutral periods (Fig. 6a). There are six El Nino (1979, 1982, 1987, 1992, 1997 and 2002) and five La Nina

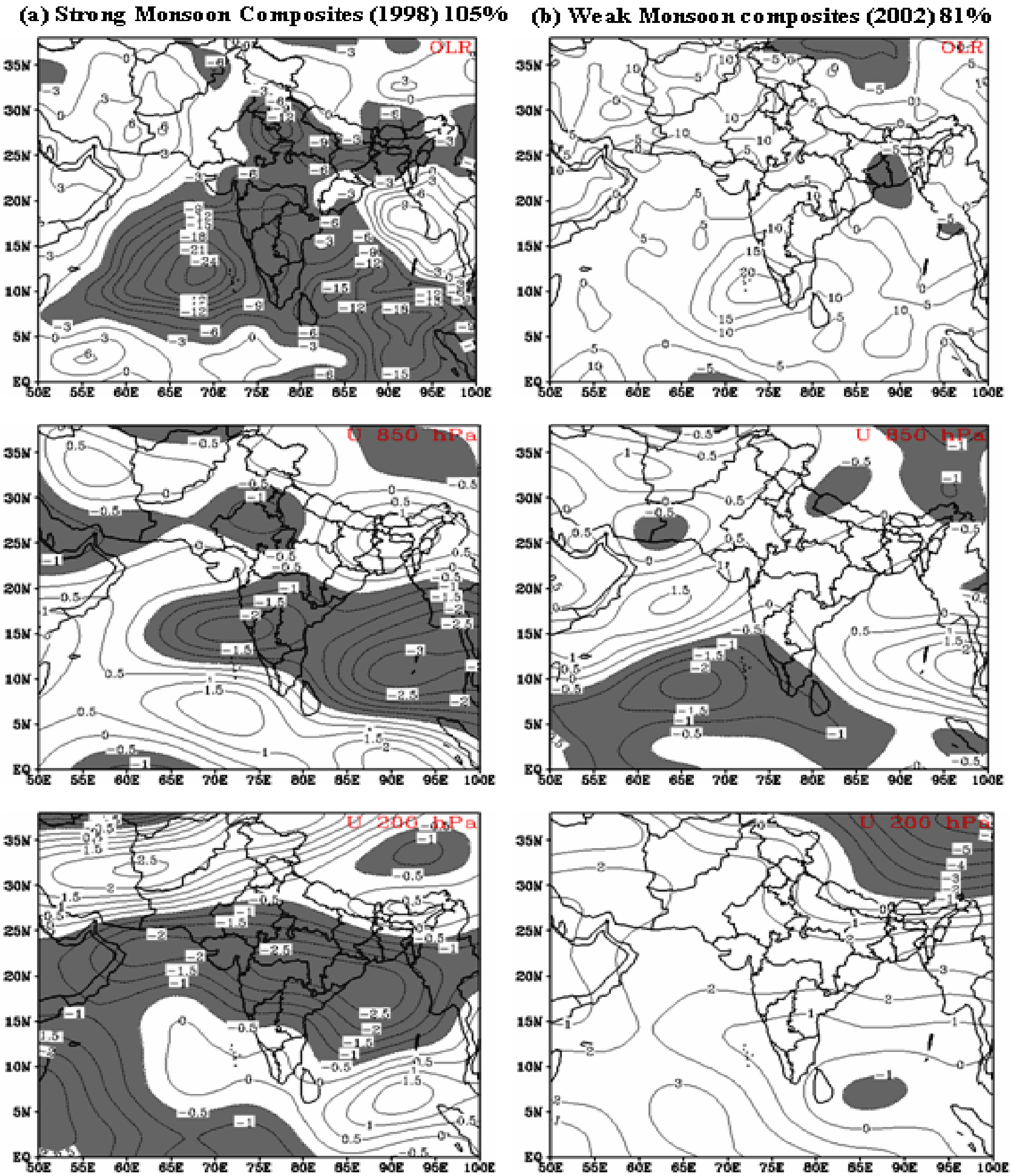

Fig. 5. a & b. Composite anomaly OLR and zonal wind fields for (a) La Nina (1998) and (b) El Nino (2002) monsoon years (shaded regions represent negative anomalies; percentage denote all India rainfall).

periods (1981, 1984, 1991, 1998 and 2005). Similarly monsoon Hadley index is also evaluated to define the strength of ISO, which also represents the same El Nino and La Nina periods (Fig. 6b). The relationship between MHI and monsoon rainfall is 0.6. In the year 2002, MJO and MHI are 0.31 and -1.2 respectively, while in 1998 they are -0.91 and 0.26. Thus year-to-year variability of Indian summer monsoon activity (rainfall) can be identified using above indices.

CONCLUSIONS

The analysis of datasets of satellite derived OLR and NCEP winds over the study region for 27-years reveals some interesting facts of variability of Indian monsoon.

The mean annual cycle of OLR in the tropics is dominated by changes in cloudiness caused by the Indian monsoon. Out of 73 pentads, P-30 to P-55 pentads show marked large scale monsoon convective activity. Mean

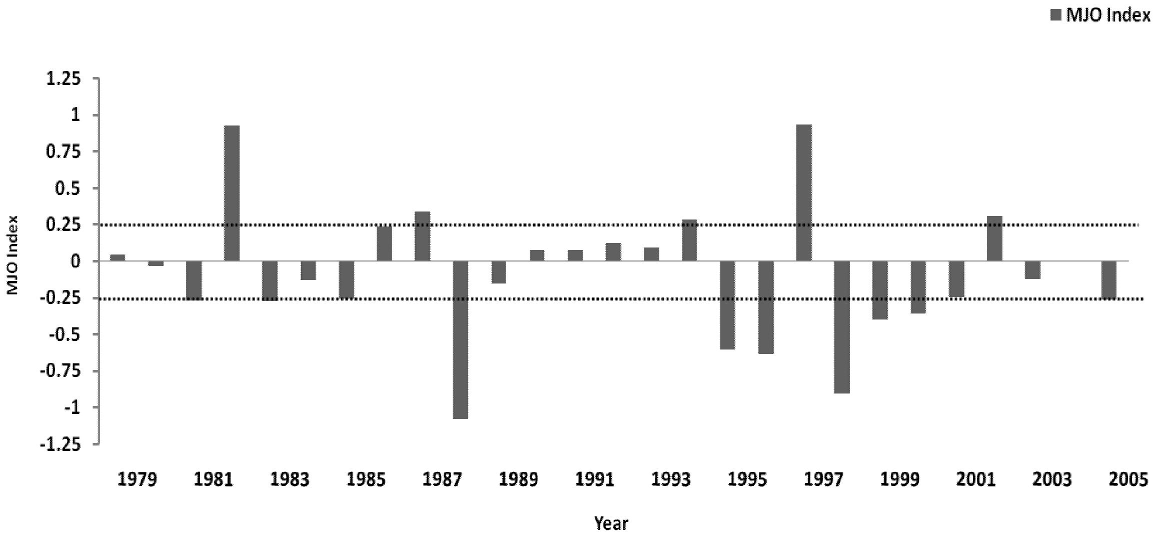

Fig. 6a. Inter annual variation of MJO Index during 1979-2005.

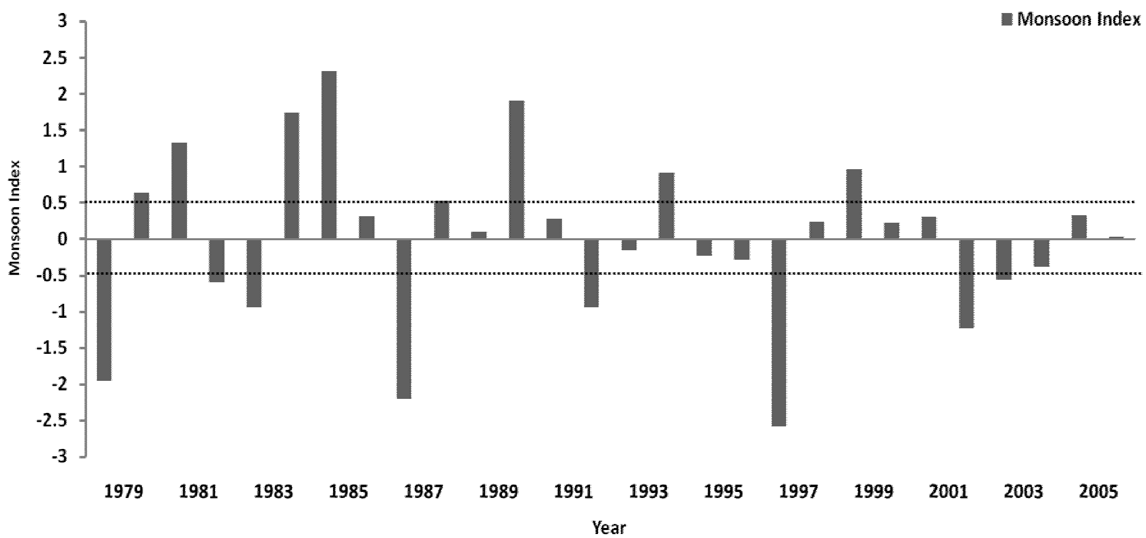

Fig. 6b. Inter annual variation of monsoon Hadley index during 1979-2005.

annual cycle of wind field supported above monsoon variability. The Interannual variability of ISO is partly linked to ENSO cycle. Strong ISO activity is often observed with La Nina.

Indices of MJO and monsoon indicate year-to-year variation of summer monsoon rainfall.

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