Clustering of Synoptic Activity by Indian Summer Monsoon Intraseasonal Oscillations

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Short title: MODULATION OF SYNOPTIC ACTIVITY BY ISO

Abstract. Active and break phases of the Indian summer monsoon are characterized by enhancement and decrease of precipitation over the monsoon trough region. Using genesis data of monsoon low pressure systems (LPS) and circulation data for the period 1954 to 1993, it is shown that the frequency of occurrence of LPS is nearly 3.5 times higher in the active phase of monsoon as compared to the break phase. In addition, the tracks of these synoptic systems are also strongly spatially clustered along the monsoon trough during the active phase of the monsoon. The enhanced (decreased) frequency of occurrence of LPS during active (break) phases is due to modulation of meridional shear of zonal winds and cyclonic vorticity along the monsoon trough by the intraseasonal oscillations (ISO).

1. Introduction

Active and break episodes, characteristic of subseasonal variations of the Indian summer monsoon, are associated with enhanced (decreased) rainfall over central and western India and decreased (enhanced) rainfall over the southeastern peninsula and eastern India [*Singh et al. 1992; Krishnamurthy and Shukla 2000*]. The intraseasonal variations of rainfall (active-break cycles) are strongly coupled to the intraseasonal variations of circulation [*Hartmann and Michelson* 1989; *Webster et al.* 1998; *Sperber et al. 2000; Goswami and Ajayamohan 2001*]. How large scale intraseasonal variations of circulation result in enhancement or decrease in rainfall over the Indian subcontinent?

The main rain producing systems over the Indian monsoon region are the synoptic scale lows and depressions, collectively referred to here as low pressure systems (LPS) with typical time and length scales of 3-5 days and 2000 km. The maximum wind speed associated with lows is less than 8.5 m/s while the maximum wind speed in depressions is between 8.5 m/s and 16.5 m/s. Lows and depressions are shear instabilities energized by moist convection [*Shukla* 1987; *Goswami et al.* 1980; *Mak* 1987]. Large meridional shear of the eastward component of winds and high cyclonic vorticity at low levels over the monsoon trough region favor growth of these instabilities. Recent studies [*Webster et al.* 1998; *Goswami and Ajayamohan* 2001; *Sperber et al. 2000*] have shown that the spatial structure of monsoon ISO is such that they strengthen the seasonal mean circulation in one phase while weakening it in the opposite phase. Therefore, the monsoon ISO has the potential to modulate the frequency of occurrence of LPS by alternately enhancing and weakening the zonal wind shear and low level cyclonic vorticity in the monsoon trough (MT). Indication of association between ISO regimes and synoptic activity during the Indian summer monsoon was presented in some previous studies [*Murakami et al.* 1984; *Murakami et al.* 1986; *Yasunari* 1981]. Murakami et al.(1986) show an approximate inverse relationship between the low frequency ISO anomalies and energy of synoptic disturbances over the Indian monsoon region during 1979. However, the number of years of data used in these studies were rather small and the robustness of the signal not established. Moreover, the spatial clustering was not addressed. Liebmann et al. (1994) demonstrated modulation of storms and tropical cyclones over the Indian Ocean and western Pacific by the Madden-Julian Oscillation (MJO) [*Madden and Julian* 1994], but excluded weaker systems (such as lows) from their study. The question of clustering of synoptic disturbances during the Indian summer monsoon season was not addressed adequately in this study as hardly any tropical cyclone forms during the summer monsoon season (June-Sept) because they excluded the important rain producing events during this season namely lows. Here, using circulation data and LPS genesis data for 40 years, we show that the dry and wet spells of the Indian monsoon indeed arise from a space-time clustering of the LPS and that this clustering is caused by a modulation of the large scale monsoon circulation by the monsoon ISO.

2. Data Used

Daily NCEP/NCAR reanalysed winds [*Kalnay et al.* 1996] at 850 hPa level for the period 1954-1993 are used for studying the large scale intraseasonal variability of circulation. Pentad Climate Prediction Center Merged Analysis of Precipitation (CMAP) for the period 1979-2000 [*Xie and Arkin* 1997] are used to describe the large scale monsoon intraseasonal oscillations in rainfall. Daily anomalies are obtained by removing the annual cycle (annual mean and the first three harmonics) from daily (or pentad) observations every year. History of genesis and tracks of all lows and depressions formed during June-September over the Indian monsoon region (50°E-100°E, 0°-30°N) for 40 years (1954-1993) were collected. The data for the first 30 years (1954-1983) were taken from *Mooley and Shukla* [1989] who compiled a comprehensive history of genesis and tracks of all lows and depressions between June and September for the period 1888-1983 by careful examination of Daily Weather Reports and annual summary of tracks of storms and depression published by the India Meteorological Department (IMD). The information for the period 1984 to 1993 was collected from the Seasonal Weather Summary (June-September) published by IMD [*e.g. IMD* 1985].

3. Results

The frequency of occurrence of the monsoon synoptic systems as a function of phase of the ISO is examined in this section, using an index of ISO activity. The relative vorticity at 850 hPa represents monsoon activity quite well on intraseasonal time scales [*Webster et al.* 1998; *Goswami and Ajayamohan* 2001; *Sperber et al. 2000*]. Therefore, we define a monsoon intraseasonal index (MISI) as the 10-90 day filtered relative vorticity at 850 hPa averaged over 80°E-95°E, 12°N-22°N, which represents the core region of the MT. The index is constructed each year from 1 June to 30 September for the 40 years under consideration and normalized by its own standard deviation. A sample of normalized MISI for 10 years is shown in Fig.1. As is characteristic of monsoon ISO [*Goswami and Ajayamohan* 2001], MISI contains two dominant range of periodicities, 10-20 days and 30-60 days (not shown). Normalized MISI > +1 represents active conditions while MISI < -1 represents break conditions. These phases of monsoon ISO are associated with enhanced and decreased rainfall respectively (Supplementary Fig.S1) over the MT region.

Figure 1 Figure 1

Figure 2 Figure 2

The total number of LPS during the 40-year period is 510, with a seasonal average of 12.5. The frequency distribution of genesis of LPS as a function of phase of the ISO is obtained by putting the genesis dates of all the LPS during the 40 year period (1954-1993) into bins of MISI of size 0.25 (Fig.2). The skewness of the distribution towards the positive MISI is evident. Out of the 510 LPS, 350 occur in the positive phase of the ISO and 160 occur in the negative phase. The birth of an LPS is approximately 3.5 times more likely in the active phase (147 systems for MISI > +1) than in a break phase (42 systems for MISI < -1). The tracks of lows and depressions are important in determining the rainfall distribution over the MT region. Therefore, it is important to examine if the tracks are also clustered in space during active conditions. Detailed track information of LPS is available for 1954-1983 [*Mooley and Shukla* 1987]. The tracks of all LPS during active and break conditions as defined by MISI during the 30 year are shown in Fig.3. The genesis as well the tracks of LPS are strongly clustered along the

MT during an active phase. During a break phase, almost no LPS forms and move along the MT. Few LPS that are born during a break are confined to the foothills of Himalaya, or form in the Arabian sea off the western coast and move westward. A few LPS also form in the southern Bay of Bengal during a break. Since lows and depressions are the main rain-bearing systems of the monsoon [*Mooley and Shukla* 1989], the spatial and temporal clustering of LPS is essentially responsible for increasing (decreasing) rainfall over the central India during active (break) conditions.

Figure 3 Figure 3

To understand how the ISO achieves this clustering, we examine the modulation of the low level circulation at 850 hPa by the ISO. The climatological seasonal (JJAS) mean 850 hPa winds and corresponding relative vorticity are shown in Fig.4a, while a difference between active and break composites (as defined by MISI for the 40 year period) of wind anomalies and corresponding relative vorticity is shown in Fig.4b. It may be noted that the vorticity in the monsoon trough may increase (decrease) by 50% during an active (break) spell. The enhancement of shear and low level cyclonic vorticity in this region in the positive phase of the ISO increases the probability of genesis of LPS. Similar mechanism is responsible for clustering of tropical cyclones and hurricanes in Gulf of Mexico [*Maloney and Hartmann* 2000a], eastern Pacific [*Maloney and Hartmann* 2000b] and western Pacific [*Liebmann et al.* 1994], through modulation of circulation by the MJO.

Figure 4 Figure 4

How do different frequencies of monsoon ISO contribute to the clustering? To answer this question, MISI was reconstructed with 30-60 day, 10-20 day and less than 10 day filtered vorticity and frequency distribution of genesis of LPS (similar to Fig.3) were calculated and the results are summarized in Table-I. Ratio between active and break conditions as defined by different frequency bands is noteworthy. Its is seen that both 10-20 day and 30-60 day oscillations result in some clustering. However clustering is enhanced significantly when they are combined (i.e 10-90 day). Probability of genesis is significantly enhanced when phases of both 10-20 day and 30-60 day modes cooperate. Also, high frequencies (period less than 10 days) by themselves do not give rise to any clustering.

4. Conclusions

What leads to the increase (decrease) in rainfall over the MT region during active (break) conditions? To gain insight to this question, we hypothesize that the monsoon ISO achieve this by modulating the genesis of LPS through modulation of the large scale monsoon flow. An index of monsoon intraseasonal circulation is constructed for 40 summer monsoon seasons using 850 hPa vorticity from NCEP/NCAR reanalysis. Using LPS genesis data for this period and the index of intraseasonal variability of circulation, the frequency distribution corresponding to different phases of ISO is found. It is shown that the genesis of an LPS is more than three times as likely in an active phase than in a break phase. Increase (decrease) in the meridional shear of zonal wind and low level cyclonic vorticity along the MT during active (break) phase lead to enhanced (decreased) cyclogenesis and higher (lower) frequency of occurrence of

LPS. The modulation of large scale flow by the ISO during an active phase not only increases the frequency of occurrence of LPS, but also spatially clusters the track of the LPS along the MT. The increase (decrease) in rainfall over central India during active (break) condition results from spatial and temporal clustering of LPS by monsoon ISO.

The slow evolution of the monsoon ISO on account of its 30-60 day dominant periodicity's may make it potentially predictable up to about three weeks in advance. Since the monsoon ISO affect clustering of the LPS, an extended range prediction of the ISO could be used for extended range prediction of the dry and wet spells. Skillful prediction of the winter-time east-ward propagating ISO with similar periodicity (the MJO) up to three weeks in advance have been demonstrated [*Lo and Hendon* 2000; *Waliser et al.* 1999; *Mo* 2001] using statistical technique. We envisage the monsoon ISO to have similar predictability. Work in this direction is expected to lead to extended range prediction of the dry and wet spells of the Indian summer monsoon. To explore this possibility, we have constructed an empirical technique that is successful in predicting the dry and wet spells of Indian monsoon rainfall about 15 days in advance [*Xavier* 2002].

Acknowledgments. This work is partially supported by a grant from the Department of Science and Technology, Government of India. R. S. Ajayamohan is supported by a fellowship from Council of Scientific and Industrial Research (CSIR), India.

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Received December 6, 2002

Figure 1. Normalized Monsoon Intraseasonal Oscillation Index (MISI) for 10 years (each year has 122 days starting from 1954). Thin solid line corresponds to ± 1 normalized unit.

Figure 2. Histogram of genesis of LPS (lows & depressions) for the Indian monsoon region (50°E-100°E, Eq-30°N) during June to September for the period 1954-1993 as a function of normalized MISI.

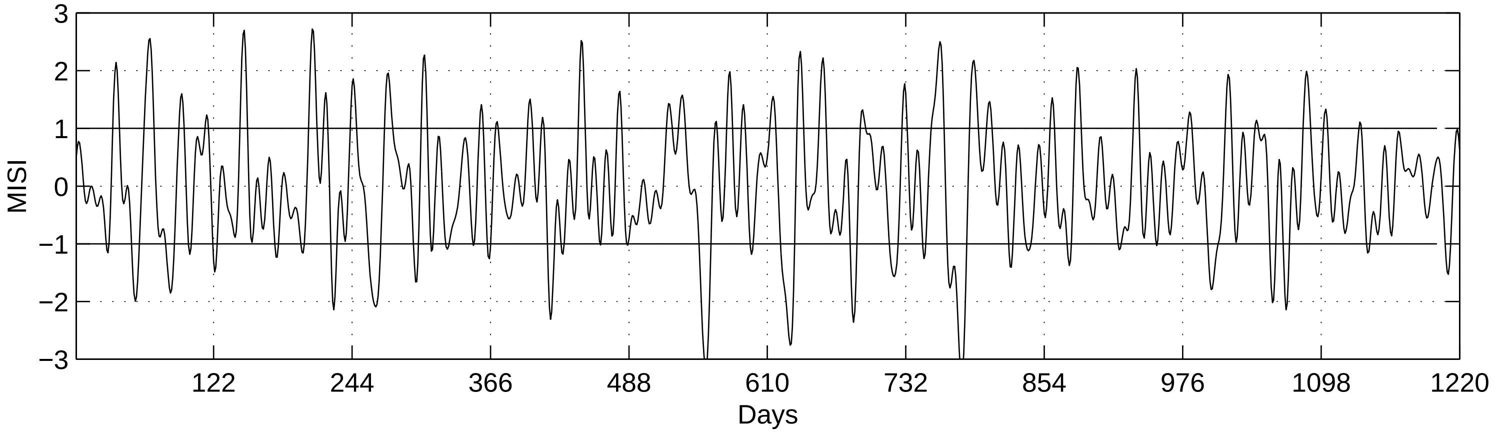
Figure 3. Tracks of LPS for the period 1954-1983 during extreme phases of monsoon ISO. **(a)** 'Active' ISO phase (MISI $> +1$) and **(b)** 'Break' ISO phase (MISI $<$ -1). Dark dots represent the genesis point and their lines show the tracks.

Figure 4. (a) Long term seasonal (June-September) mean vector winds (ms^{-1}) at 850 hPa and associated relative vorticity ($10^{-6}s^{-1}$). Thick line indicates the approximate location of the monsoon trough.**(b)** Active minus break composite wind anomalies (ms^{-1}) and associated relative vorticity ($10^{-6}s^{-1}$) at 850 hPa during the 40 year period (1954-1993). The region of positive vorticity is shaded with minimum contour of 1 units and contour interval of 5 units in both panels.

Supplementary Figure: Active minus break composite precipitation of ISO filtered anomalies (mm day^{-1}) during 1979-2000 based on active and break days as defined by MISI.

Table 1.: Contribution of different frequency bands to clustering. Count of LPS for MISI >0 (< 0) and active (MISI > +1) and break (MISI < −1) conditions. MISI is constructed from vorticity filtered with different bandpass filters.

MISI →	> 0	< 0	Ratio	> 1	< 1	Ratio
10-90 days	350	160	**2.18**	147	42	**3.50**
30-60 days	316	194	**1.62**	115	42	**2.74**
10-20 days	330	180	**1.83**	152	50	**3.04**
0-10 days	259	255	**1.01**	86	87	**0.98**


MISI
Days
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0
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−2
−3
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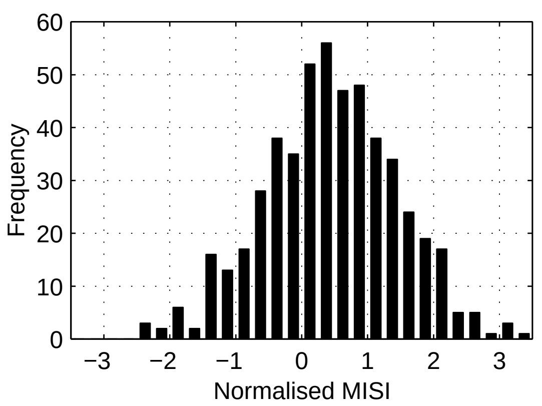
244
366
488
610
732
854
976
1098
1220



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20
10
0
Frequency
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−2
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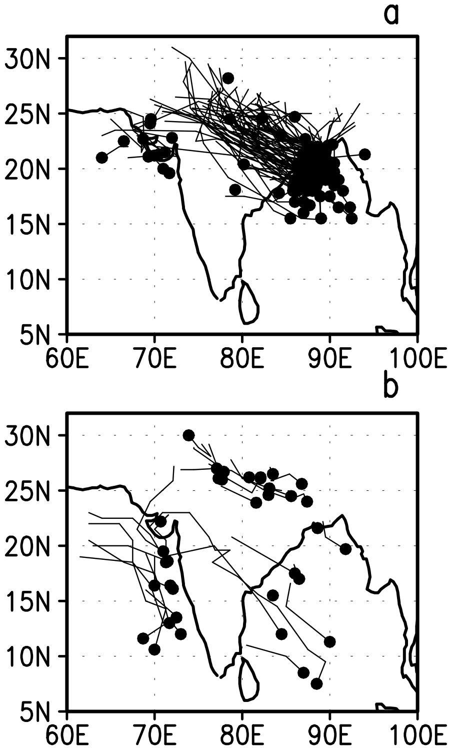
0
1
2
3
Normalised MISI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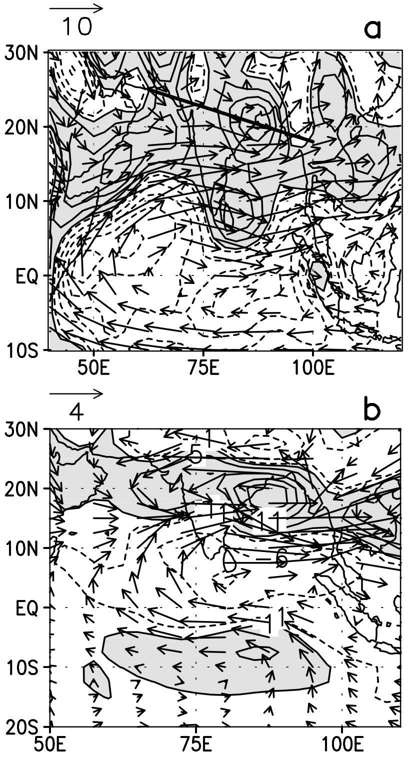
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