Interactions between the summer mean monsoon and the intraseasonal oscillation in the Indian monsoon region

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The relationship between interannual variations of the seasonal mean monsoon and intraseasonal oscillation (ISO) during boreal summer over the Indian monsoon region is investigated. The result shows a negative correlation between all-India summer monsoon rainfall and the ISO intensity. It is argued that the negative correlation is primarily attributed to the impact of the mean state of Indian summer monsoon on ISO. A strong Indian monsoon leads to the weakening of convection over the equatorial eastern Indian Ocean. The latter may further suppress the eastward and northward propagating ISO variances over the Indian Ocean and lead to a weakened intraseasonal activity over the Indian monsoon region. The ISO may feed back to the Indian summer mean monsoon through nonlinear eddy momentum transport. In addition, the ISO intensity over India increases (decreases) during the ENSO developing (decaying) summers.


1. Introduction

The India monsoon experiences strong intraseasonal and interannual variations. Circulation patterns associated with the intraseasonal and interannual variations of the Indian summer monsoon resemble each other [Goswami and Mohan, 2001; Ferranti et al., 1997]. Physically, it is not clear how the ISO over the Indian monsoon region links to the strength of the summer mean monsoon. There are controversy results regarding the relationship between them. By examining the long-term records of daily rainfall data over India, Singh et al. [1992] and Krishnamurthy and Shukla [2000] found that the ISO and the summer monsoon rainfall anomalies are unrelated. Lawrence and Webster [2001], on the other hand, showed that the summer ISO activity over India exhibits an out-of-phase relation with the Indian monsoon strength.

Different from the equatorial trapped eastward-moving Madden Julian Oscillation (MJO) that is pronounced in boreal winter, boreal summer ISO exhibits prominent northward propagation over the Indian monsoon sector [e.g., Yasunari, 1979; Krishnamurti and Subrahmanyan, 1982; Wang and Rui, 1990; Li and Wang, 1994; Annamalai and Slingo, 2001]. This northward propagating ISO is related to the active-break cycles of the monsoon rainfall over India [Yasunari, 1979; Sikka and Gadgil, 1980; Wang et al., 2005]. Hendon et al. [1999] and Slingo et al. [1999] examined the connection between the winter ISO activity and ENSO, but found no significant relationships between them. Lawrence and Webster [2001] noted that the summer ISO activity has a weak positive correlation with the tropical eastern Pacific SST at the beginning of the Indian monsoon season, but the relationship is unclear for a whole summer season.

In this study we intend to examine the interactive nature of the ISO-mean Indian monsoon relationship and to understand the physical mechanism behind the observed relationship. Given the distinctive background circulation patterns between the ENSO developing and decaying summers, we will also investigate ENSO-phase-dependent ISO activity characteristics over South Asia.

2. Data and Methods

The all-India rainfall index (AIRI), an average of the June–September (JJAS) rainfall based on rain gauges across India [Parthasarathy et al., 1995], is used to measure the Indian summer monsoon strength and to categorize wet and dry monsoon years. In addition, the NCEP/NCAR reanalysis, the Nino3.4 (5°S–5°N, 120°W–170°W) SST anomaly (SSTA) from reconstructed ERSST V2 with a 2° × 2° resolution and daily outgoing longwave radiation (OLR) [Liebmann and Smith, 1996] data with a 2.5° × 2.5° grid from National Oceanic and Atmospheric Administration (NOAA) are used.

All datasets including OLR are taken the same record length from 1975 to 2003 (29 years). We consider June–September (JJAS) as the Indian summer monsoon season. A band-pass filter is used to extract the intraseasonal (30–60 days) signal. The standard deviation of the filtered OLR field in JJAS is used to assess the ISO intensity. A student t-test is applied to test the significance of correlation and regression patterns.

3. Impact of the Seasonal Mean Monsoon on ISO

The simultaneous correlation between the summer ISO intensity and AIRI is shown in Figure 1a. A significant negative correlation appears over the Indian monsoon region from the central-eastern India to the western Bay of Bengal (BOB). The correlation coefficients exceed the 95% significant level. The result indicates that the interannual variation of the ISO intensity exhibits a strong out-of-phase relationship with the seasonal mean monsoon rainfall.
anomaly in JJAS, that is, a wet (dry) monsoon is associated with a weak (strong) ISO activity in situ.

[8] The out-of-phase ISO-mean monsoon relationship may be further revealed by the time series of the box-averaged ISO intensity and AIRI (Figure 1b). Here the ISO intensity is averaged over the box of (10°–20°N, 75°–90°E) shown in Figure 1a. By calculating the correlation with OLR, we note that AIRI represents rainfall anomalies over in a larger area including the India subcontinent and western BOB. Both the ISO intensity and the summer mean monsoon exhibit strong interannual variations. The correlation between the two time series in Figure 1b reaches −0.59.

[9] What causes the out-of-phase relation? Previous studies showed a seesaw relationship between convective branches over the monsoon trough (15°–20°N) and the equatorial eastern Indian Ocean (EEIO) [Goswami and Shukla, 1984; Annamalai and Slingo, 2001; Gadgil, 2003]. An examination of the regression pattern between the summer mean OLR and AIRI reveals that the largest negative correlation is located along the monsoon trough region, while a positive correlation is seen over the EEIO, especially over the region of (2.5°S–2.5°N, 90°–100°E).

Figure 2 shows the time series of AIRI and the seasonal mean (JJAS) OLR anomaly over EEIO for period of 1975–2003. The correlation between the two time series is −0.41, indicating that a strong Indian summer monsoon is associated with suppressed convection over the EEIO.

[10] How does the mean convection over EEIO impact the overall ISO activity over the Indian Ocean (IO)? As we know, the EEIO is a preferred region of ISO intensification. ISO convection is often initiated over the western IO and then moves eastward and reaches its peak over the EEIO [Jiang and Li, 2005; Wang et al., 2006]. It has been noted that the interannual variation of the ISO intensity over the IO is closely related to the change of the mean convection over EEIO [Teng and Wang, 2003]. Thus the seasonal mean convection over EEIO may exhibit a large-scale control on ISO activity. To demonstrate the dependence of ISO on the mean monsoon state, we perform a wavenumber-frequency analysis in a limited zonal and meridional domain following Teng and Wang [2003], composed based on the wet and dry monsoon years, respectively. Figure 3 shows that during the wet (dry) Indian monsoon, eastward-propagating ISO variance along the equatorial IO and northward–propagating ISO variance over the BOB/northern IO are significantly
reduced (enhanced), owing to the weakening (strengthening) of the convection over EEIO. The reduced (enhanced) northward propagation leads to the weakening (strengthening) of the intraseasonal variability over India. Thus, the change of the mean monsoon is crucial in determining the overall strength of ISO activity over IO and India.

4. Feedback of the ISO to the Mean Monsoon

In this section we investigate the possible ISO feedback to the seasonal monsoon anomaly from both linear and nonlinear dynamics perspectives. We calculate the sum of 30–60-day filtered OLR anomalies from 1 June to 30 September over the box shown in Figure 1a to examine whether this accumulated quantity associated with the ISO perturbation linearly contributes to the summer mean OLR anomaly. Our analysis shows that the correlation between the time series of the accumulated ISO contribution and the seasonal mean OLR anomaly is \(0.04\) for the period of 1975–2003. The near zero correlation between the two time series indicates that ISO does not linearly contribute to the seasonal mean anomaly.

To depict the nonlinear effect of the ISO on the mean monsoon, we calculate the seasonal mean zonal wind tendency induced by eddy momentum transport. The ISO contribution on the mean westerly tendency may be expressed as:

\[
\frac{\partial \bar{u}}{\partial t} \propto -\frac{\partial \bar{u} \bar{v}}{\partial y} - \frac{\partial \bar{u} \bar{u}}{\partial x}
\]

where \(u\) and \(v\) denote zonal and meridional winds, respectively; a bar represents annual cycle (annual and semi-annual harmonics) fields, and a prime denotes the ISO perturbation fields. Daily 850-hPa zonal and meridional winds from the NCEP reanalysis are used for the wind tendency calculation.

Climatologically, a positive low-level westerly wind tendency occurs during the monsoon development stage (say, in June–July). In order to investigate the potential feedback of the ISO activity on the development of the monsoon westerly, the actual zonal wind tendency (left side of Equation 1) and the tendency due to the nonlinear eddy momentum transport (right side of Equation 1) in June–July are calculated over India for the strong and weak ISO years respectively. The weak minus strong ISO composite reveals that while the actual zonal wind anomaly tendency is positive (with a value of \(4.1 \text{ m/s}^2\), indicating a strengthened monsoon), the nonlinear ISO contribution is negative (\(-12.9 \text{ m/s}^2\)). This indicates that a weak ISO, while induced by a wet monsoon, tends to weaken the strength of the summer mean monsoon to a certain extent.

5. Contrast of ISO Activity During the ENSO Developing and Decaying Summers

By examining the relationship between the ISO activity and ENSO, we note that while the simultaneous correlation between the summer ISO intensity over India and Nino 3.4 SSTA is insignificant, their relationship experiences a remarkable interannual variation and depends on the phase of ENSO. Figures 4a and 4b illustrate the composite ISO intensity for the developing and decaying summers of ENSO (El Nino minus La Nina), respectively. Here the Nino3.4 SST anomalies are used to classify the El Nino or La Nina years for the period of 1975–2003, with the seasonal mean SSTA above \(1\) standard deviation as El Nino (La Nina) years. For the developing phase, there are four El Nino (1987, 1991, 1997, 2002) and four La Nina (1975, 1988, 1998, 1999) years; for the decaying phase, there are five El Nino (1983, 1987, 1992, 1995, 1998) and five La Nina (1976, 1985, 1989, 1999, 2000) years. It is noted that a strengthened (weakened) ISO activity appears over India in the composite of the El Nino developing (decaying) summers. The opposite is true for the La Nina episodes.

The cause of the dependence of the summer ISO intensity on the ENSO phase may be explained by remote and local SSTA impacts. During the developing summer of an El Nino, the western Pacific subtropical high is strengthened and westward shifted due to the Rossby wave response to the weakened convective heating over maritime continent.

Figure 2. Time series of the all-India monsoon rainfall anomaly (dashed curve) and the seasonal mean OLR anomaly averaged over the region of \((2.5°S–2.5°N, 90°–100°E)\) (solid curve) in JJAS for 1975–2003.
The strengthened western Pacific subtropical high accompanies a weakened Indian summer monsoon [Zhang, 2001]. As a result, the ISO intensity increases. During the mature and decaying phases of an El Nino, a warm SSTA persists over the IO from the northern winter to the subsequent summer. The positive SSTA over the tropical IO increases local moisture due to enhanced surface evaporation, and the enhanced moisture transport further leads to a strong Indian monsoon [Li et al., 2001; Li and Zhang, 2002]. As a result of the strong mean monsoon, the ISO intensity decreases.

A further examination of the individual warm and cold episodes indicates that there are some exceptions that deviate greatly from the composite mean state (see Figures 4c and 4d). For example, the cold episode in 1985 experiences a great reduction of the ISO variability while all other cold episodes are associated with enhanced ISO activity over India (Figure 4d).

6. Conclusion

The relationship between interannual variations of the summer mean monsoon and the ISO intensity over the Indian monsoon region is investigated using OLR and all-India rainfall data for the period of 1975–2003. It is found that there exists a strong out-of-phase relationship between the 30–60-day oscillation and the seasonal mean monsoon anomalies.

The out-of-phase relationship is primarily attributed to the impact of the mean monsoon on ISO. A strong Indian monsoon leads to suppressed seasonal mean convection over EEIO, which causes the decrease of eastward and northward propagating ISO variances. The weakening of the northward propagating ISO further leads to the suppressed intraseasonal variability over the Indian monsoon region.

The sum of 30–60-day filtered OLR anomalies from 1 June to 30 September does not contribute to the seasonal mean OLR anomaly. However, ISO does have a nonlinear impact on the mean monsoon in situ through the eddy momentum transport. A weak ISO over India, induced by a wet monsoon due to the remote ENSO impact for example, may further modulate the mean monsoon by significantly reducing its strength. The result implies that the overall negative correlation between the interannual variations of the ISO activity and the mean monsoon results from the impact of the mean state on ISO; the feedback of ISO to the mean monsoon is of secondary importance.

The simultaneous correlation between the summer ISO intensity over India and the Nino3.4 SSTA is weak. However, this relationship experiences a marked interannual...
variation and depends on the phase of ENSO. During the El Nino developing summers, the ISO intensity is strengthened, because the remote eastern Pacific SSTA forcing leads to a dry Indian monsoon. In a sharp contrast, the summer ISO activity weakens significantly over India during the decaying phase of an El Nino, possibly due to the effect of a basin-wide IO warming that tends to strengthen the Indian summer monsoon.

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References


Figure 4. (left) Composite difference of the summer ISO intensity between El Nino and La Nina during the ENSO (a) developing and (b) decaying phases. Values exceeding the 95% confidence level are shaded. (right) Summer ISO intensity (climatological ISO intensity has been subtracted) over India for individual El Nino (circles) and La Nina (triangles) events during their (c) developing and (d) decaying phases. The solid circle/triangle denotes the ensemble mean of the ISO intensity.


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