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Impact of the Indian Ocean Dipole on the Relationship between the Indian Monsoon Rainfall and ENSO

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Abstract. The influence of the recently discovered Indian Ocean Dipole (IOD) on the interannual variability of the Indian summer monsoon rainfall (ISMR) has been investigated for the period 1958-1997. The IOD and the El Niño/Southern Oscillation (ENSO) have complementarily affected the ISMR during the last four decades. Whenever the ENSO-ISMR correlation is low (high), the IOD-ISMR correlation is high (low). The IOD plays an important role as a modulator of the Indian monsoon rainfall, and influences the correlation between the ISMR and ENSO. We have discovered that the ENSO-induced anomalous circulation over the Indian region is either countered or supported by the IOD-induced anomalous meridional circulation cell, depending upon the phase and amplitude of the two major tropical phenomena in the Indo-Pacific sector.

1. Introduction

The Indian summer monsoon rainfall (ISMR) occurring during June-September plays a crucial role on both the agriculture and economy of the Indian subcontinent. Of the many phenomena that excite the ISMR variability [*Krishna Kumar et al.*, 1995, *Slingo*, 1999], the most important large-scale forcing was the El Niño/Southern Oscillation (ENSO) till two decades back. The interannual variations of ISMR have motivated studies of the ENSO since the turn of the twentieth century [*Walker*, 1923, *Barnett*, 1984]. It is widely known that there was a negative correlation between the anomalies of the ISMR and NINO3 SST (area-averaged sea surface temperatures over 5^oN-5^oS, 150^oW-90^oW) anomalies. However, the relationship between the ISMR and ENSO is susceptible to decadal changes; it is now weakening [*Krishna Kumar et al.*, 1999]. We witnessed two major ENSO events in the last decade of twentieth century. But the ISMR was always normal or above normal during this period (as per the definition of the India Meteorological Department the ISMR is normal when the monsoon rainfall is between +110% to 90% of its seasonal mean). Since the Indian Ocean Dipole (IOD) has been catalogued recently as one of the major ocean-atmosphere coupled phenomena in the tropical Indo-Pacific sector [*Saji et al.*, 1999, *Webster et al.*, 1999], it is now natural to explore possible influences of the IOD on the ISMR.

An index to quantify the IOD has been defined [*Saji et al.*, 1999] as the SST difference between the tropical western Indian Ocean (50^oE-70^oE, 10^oS-10^oN) and the tropical southeastern Indian Ocean (90^oE-110^oE, 10^oS-equator). When the Indian Ocean Dipole Mode Index (IODMI) is positive, it leads to droughts (locally known as Tuarang) over the Indonesian region and heavy rains and floods over the East Africa. When the sign of the IODMI reverses, these anomalous fluctuations also swing to the opposite phase.

Saji et al. [1999] found the correlation between the IOD and ISMR as 0.32, and claimed that the relationship between the IOD and Indian Monsoon is not clear. However, of the 11 intense (anomalies more than one standard deviation) positive IOD events that occurred during 1958-1997, eight events (1961, 1963, 1967, 1977, 1983, 1994, 1993 and 1997; 73% of the positive IOD events during this period) correspond with the positive anomalies of the concurrent ISMR. Similarly, of the three negative IOD events during this 1958-1997, two events (1960 and 1992; 67% of the negative IOD events) correspond with negative anomalies of the ISMR. This observation, and the frequent occurrence of intense IOD events in the last decade, has prompted us to investigate whether the moving correlation between the IOD-ISMR changes from decade to decade and, in particular, its role in the weakening of the monsoon-ENSO correlation.

2. Observational Analysis

Using the ISMR data derived from the rain gauge *in situ* observations [*Parthasarathy et al.,* 1995] and the GISST 2.3b dataset [*Rayner et al.,* 1996], we have examined the relation between the ISMR and IODMI for the period from 1958 to 1997. Both the rainfall and SST have been subjected to 13-90 months band-pass filtering [*Murakami,* 1979]. The ENSO signal has been removed from the SST of the Indian Ocean using the regression technique [*Clark et al.,* 2000]. This is necessary because of the co-occurrence of the positive/negative IOD and El Nino/La Nina events during some years.

The 41-month sliding correlation coefficients between the ISMR and the IODMI are presented in Fig. 1, along with those between the ISMR and NINO3 SST. The figure reveals the amazing relationship among the ISMR, ENSO and IOD. The correlation coefficient between the IODMI and the ISMR is above 0.6 till about 1967, after which the correlation drops abruptly. In contrast, the negative correlation between the NINO3 SST and the ISMR is strengthened simultaneously from -0.45 to -0.85. Until around 1977 the IODMI has almost no correlation with the ISMR, whereas the ENSO strongly influences the ISMR during this period from 1967 through 1977. After this period, the ENSO-ISMR relation weakens, in agreement with *Krishna Kumar et al.* [1999]. By the late 1980s the correlation coefficient between the NINO3 and the ISMR drops a lot. This is in agreement with recent research indicating a very small correlation between the Indian rainfall and the Southern Oscillation Index during 1979-1998 [Fig.6 of *Trenberth and Caron,* 2000]. Meanwhile, the correlation between the IODMI and ISMR increases rapidly within a short period of about one year. The temporal evolutions of the correlations clearly complement each other through the study period. It is also seen that the IOD-ISMR correlation is currently on the rise. The high correlation observed in the early sixties can be attributed to intense IOD events during 1961, 1963, and 1967, which influenced the concurrent ISMR strongly. After that period, since there were not many strong IOD events till 1980s, the moving correlation values were very weak during this period. But the occurrence of intense IOD events in the 1980s and 1990s helped the correlation with the ISMR to rise.

When the ENSO occurs during the summer monsoon season, the correlation between the NINO3 SST and the ISMR is influenced by the IOD, depending on the phase and amplitude of the IODMI and NINO3 SSTA. This is because the IOD event is locked to the summer monsoon season [*Saji et al.*, 1999]. When the IOD event occurs in the absence of an intense El Niño/La Niña, it can strongly influence the season's rainfall, as in 1961 [*Saji et al.,* 1999], and 1994. This

GRL MS#13294: Ashok
Figure 1

is the reason why the ENSO-ISMR relation changes and shows a complementary decadal variation with the ISMR-IOD relation, as shown in Fig. 1.

The presence of a positive IOD has facilitated normal or excess rainfall over the Indian region during the summers such as 1983, 1994, and 1997 despite the simultaneous occurrence of the negative phase of the Southern Oscillation [*Behera et al.*, 1999, *Webster et al.*, 1999]. As typified during JJAS in 1997, the anomalous convergent flow in the lower troposphere is observed over the Bay of Bengal and the Indian subcontinent (Fig. 2a). The anomalous ENSO-induced subsidence over the Indian region that normally occurs during the 'ENSO only' years such as 1987 (Fig. 2b) is replaced by the IOD-induced convergence; this leads to the normal JJAS monsoon rainfall even during such strong El Niño years. On the other hand, during the years such as 1992, the prevailing negative IOD and El Niño have co-operatively caused an anomalously deficit rainfall during the monsoon season. The ISMR anomalies also depend on the relative intensities of the IOD and the El Niño/La Niña events. A relatively stronger NINO3 SSTA, with a normalized value of 1.7, as compared to the concurrent positive IODMI with a normalized value of 1.4, during the JJAS of 1982 may have caused a deficit in the ISMR. On the other hand, a stronger positive IOD in 1983 (as compared to the concurrent El Niño) may have caused a surplus in the monsoon rainfall. In further retrospect, 1914 and 1944 monsoon seasons witnessed strong rainfall when the positive IOD was accompanied by El Niño (figure not shown); while during years such as 1899, the strong negative IOD may have caused the observed deficit in the monsoon rainfall despite the simultaneous occurrence of La Niña.

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Figure 2

3. AGCM experiments and the proposed mechanism

To understand how the IOD influences the ISMR, we have conducted three sensitivity experiments using an atmospheric general circulation model (AGCM) with full physics [*Guan et al.*, 2000]. The model is a spectral model with T42 resolution in the horizontal, with 28 levels in the vertical. In all the experiments the model has been integrated for a full calendar year. Each experiment is an ensemble-average of three realizations, which differ from one another in the initial conditions. In the first experiment (the control experiment, referred to as Cntrl) we have adopted the seasonally varying climatological SST as the lower boundary condition. In the second experiment (referred to as pDM), we have imposed a positive IOD SST anomaly, obtained by the correlation analysis, on the lower boundary condition used in the first experiment. The third experiment (referred to as nDM) is similar to the second, except that we have imposed the negative IOD anomaly. The SST anomaly in the last two experiments is imposed from the month of April and is increased as observed [*Saji et al.*, 1999]. As an example, the SST anomaly imposed during the month of September in the pDM experiment is presented in Fig. 3. The anomaly in the nDM experiment is the same as that imposed in the pDM experiment except for the reversed sign.

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Figure 3

The rainfall difference between the pDM and Cntrl experiments (pDM-Cntrl) is presented in Fig. 4a along with the corresponding difference in simulated winds at 850 hPa. Over the Indian peninsula and the northern Bay of Bengal, heavy rainfall has been simulated in the pDM experiment. The cross-equatorial winds from the southeastern tropical Indian Ocean intensify the summer monsoon circulation in the pDM experiment. The intensified convergence of winds

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Figure 4

coming from southeast causes anomalously surplus rainfall over the monsoon trough area. The conventional monsoon flow over the western Arabian Sea is anomalously weak, because of the anomalous circulation around the anomalously warm SSTA off the coast of East Africa. Near the west coast of Indian peninsula, however, this is compensated by the cross-equatorial wind from the anomalously cold SSTA prevailing to the west of Indonesia. The AGCM simulates the rainfall and wind characteristics of the positive IOD realistically over the tropical western Indian Ocean and southeastern Indian Ocean. The simulated area-averaged ISMR anomaly (pDM-Cntrl) for summer monsoon period (from June to September) is calculated over the Indian region (5°N-30°N and 65°E-95°E) [*Ashok et al.*, 1995, *Mandke et al.*, 1999]. This value is found to be 1.02 mm/day (the individual experiment values are 1.57 mm/day, 0.75 mm/day, and 0.74 mm/day). The complementary results for the negative DM forcing over the tropical Indian Ocean clearly show the negative dipole characteristics (Fig. 4b). The rainfall simulated in the nDM experiment is much less over the Indian peninsula and the Bay of Bengal as compared to that simulated in the control experiment. The area-averaged rainfall anomaly during the summer monsoon season over the Indian region in this experiment is –0.64 mm/day (average of -0.26 mm/day, -1.3 mm/day, and –0.27 mm/day). The simulated monsoon circulation over the Indian peninsular region in the nDM is weaker than that in the control experiment. The analysis of Figs. 4a and 4b confirms that a positive (negative) IOD intensifies (weakens) the rainfall over the Indian region, while affecting the monsoon circulation. These results agree with the observations for the periods when ENSO-ISMR relation is weak.

To understand the mechanism behind the interesting IODMI-ISMR relation, we have calculated the difference of the velocity potential field (pDM - nDM) during June-September (Fig. 5). The colder SST anomaly in the eastern tropical Indian Ocean causes reduction in convection during the positive DM event and hence the anomalous subsidence and divergence at the 850 hPa (Fig. 5a). Over the Bay of Bengal, on the other hand, convergence is simulated in the lower troposphere; this indicates the enhanced meridional monsoon circulation at lower levels. Fig. 5b shows the divergence over the Bay of Bengal and convergence over the eastern tropical Indian Ocean at 200 hPa, suggesting anomalous intensification of the monsoon meridional circulation in the troposphere during the positive IOD event, as compared to the negative IOD event. The anomalous convergence-divergence patterns explain the anomalous rainfall distribution simulated over the Indian region. These results also agree with the earlier observational studies, which highlighted the importance of the cross-equatorial moisture transport from the southeastern tropical Indian Ocean [*Behera et al.*, 1999]. The present simulation confirms that the tropical Indian Ocean SST anomaly related to the IOD modulates the meridional monsoon circulation as well as the zonal circulation in the troposphere [*Saji et al.*, 1999; *Webster et al.*, 1999].

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Figure 5

4. Concluding Remarks

The above discussion has demonstrated that the IOD events affect the Indian summer monsoon on their own and thus apparently weaken or strengthen the influence of the ENSO on the ISMR. Because of existence of positive and negative events in the two major tropical climate phenomena, the influence on ISMR depends on the phase and amplitude of the IOD and ENSO. Despite the possibility that some IOD events could be linked to some ENSO events, the current approach to consider the IOD as one of the major coupled modes in the tropics seems to be successful, at least, in evaluating the IOD's influence on ISMR.

In view of the recent increasing correlation between IODMI-ISMR (Fig.1), it may be worthwhile to examine the possibility of using the IODMI for the climate prediction of the monsoon rainfall over India. The present finding has another implication for the modeling community for climate prediction. To obtain a realistic simulation of the ISMR in a coupled model, it is essential to have the capability of simulating the Indian Ocean Dipole events with the right phase and amplitude.

The present finding, as stated by a well-known physicist in another context, raises a new question, and a new possibility- to regard the old problem of the ISMR from a new angle, and to make a real advance in the predictability study.

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Figure 1. The 41-month sliding correlation coefficients between ISMR and IODMI (solid), and those between monthly ISMR and NINO3 SST (dashed; to be multiplied by –1) during 1958-1997. The significant correlation value at 90% confidence level is 0.38 (verified by 1,000 randomized time series, using the Monte-Carlo simulations)

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Figure 5. Simulated difference (pDM-nDM) of velocity potential (x 10^{-6} ; in $m^2 \cdot s^{-1}$) at (a) 850 hPa (b) 200 hPa.

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