Unusual Central Indian Drought of Summer Monsoon 2008: Role of Southern Tropical Indian Ocean Warming

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ABSTRACT

While many of the previous positive Indian Ocean dipole (IOD) years were associated with above (below)-normal monsoon rainfall over central (southern) India during summer monsoon months [June–September (JJAS)], the IOD event in 2008 is associated with below (above)-normal rainfall in many parts of central (southern peninsular) India. Because understanding such regional organization is a key for success in regional prediction, using different datasets and atmospheric model simulations, the reasons for this abnormal behavior of the monsoon in 2008 are explored. Compared to normal positive IOD events, sea surface temperature (SST) and rainfall in the southern tropical Indian Ocean (STIO) in JJAS 2008 were abnormally high. Downwelling Rossby waves and oceanic heat advection played an important role in warming SST abnormally in the STIO. It was also found that the combined influence of a linear warming trend in the tropical Indian Ocean and warming associated with the IOD have resulted in abnormal warming of the STIO. This abnormal SST warming resulted in enhancement of convection in the southwest tropical Indian Ocean and forced anticyclonic circulation anomalies over the Bay of Bengal and central India, leading to suppressed rainfall over this region in JJAS 2008.

The above mechanism is tested by conducting several model sensitivity experiments with an atmospheric general circulation model (AGCM). These experiments confirmed that the subsidence over central India and the Bay of Bengal was forced mainly by the anomalous warming in the STIO region driven by coupled ocean–atmosphere processes. This study provides the first evidence of combined Indian Ocean warming, associated with global warming, and IOD-related warming influence on Indian summer monsoon rainfall. The combined influence may force below-normal rainfall over central India by inducing strong convection in the STIO region. The conventional seesaw in convection between the Indian subcontinent and the eastern equatorial Indian Ocean may shift to the central equatorial Indian Ocean and the Bay of Bengal if the central Indian Ocean consistently warms in the global warming scenario.

1. Introduction

Each Indian summer monsoon exhibits different characteristics and poses several challenges to scientists to unravel the mechanisms of its variability. Of particular interest is the regional distribution of rainfall anomalies during “normal” monsoon years. During years of extreme droughts or floods, the rainfall anomaly tends to be homogeneous over the whole country (Shukla 1987; Mooley and Shukla 1987). While during normal monsoon years, the rainfall anomaly tends to be inhomogeneous over the country (Fig. 1a; Xavier and Goswami 2007) with a reasonably large region of flood or drought appearing during such years. The Indian summer monsoon 2008 was such a typical example. While the monsoon was normal with the seasonal mean rainfall being 98% of the long-term average, a large pocket of significant drought prevailed over central India (Fig. 1b, discussed later). Prediction of these rainfall anomalies is crucial for agricultural planning and water resource management. Understanding factors responsible for such regional organization of rainfall anomalies would be helpful for improving regional forecasts. In the present study, we make an attempt to understand the regional organization of precipitation during 2008. The coupled ocean–atmosphere phenomenon in the tropical Indian Ocean, popularly known as a positive (negative) Indian Ocean dipole, is associated with cooler (warmer)-than-normal sea surface temperature in the eastern equatorial Indian
Ocean and warmer (cooler)-than-normal SST in the western tropical Indian Ocean (Saji et al. 1999). Several studies attributed the variations in Indian summer monsoon rainfall from June to September (JJAS) to this coupled phenomenon (e.g., Behera et al. 2006; Ashok et al. 2001, 2004; Krishnan et al. 2006). There is a clear consensus among all of these studies that a positive (negative) dipole mode has a tendency toward above (below)-normal rains over central India (Fig. 2). Both SST and sea surface height (SSH) anomalies in the eastern equatorial Indian Ocean are significantly correlated with the rainfall over central India (Figs. 2b,c). This association confirms the results of previous studies, that the Indian Ocean dipole (IOD) in the tropical Indian Ocean influences the monsoon rainfall over central India. The mechanism proposed to explain this relation, so far, is as follows: the suppressed convective activity over the eastern equatorial Indian Ocean leads to suppressed subsidence over the Indian subcontinent by counteracting El Niño–forced subsidence over India (Ashok et al. 2001; Krishnan et al. 2006) through modulation of the local Hadley circulation. In 2008, a moderate IOD event with cooling in the eastern equatorial Indian Ocean below two standard deviations is observed in the tropical Indian Ocean (Fig. 2a) and hence, it was expected that central India will receive normal or above-normal rainfall in 2008. However, the monsoon in 2008 witnessed drought conditions over central India (Fig. 1b) irrespective of the positive IOD event (Fig. 2a). A relatively weaker IOD event in 2003 also resulted in above-normal rainfall over central India (figure not shown). However, the rainfall over many parts of central India is about 20%–30% below the long-term average during the 2008 monsoon. In recent years, the rainfall patterns associated with positive dipole years are undergoing a transition to the opposite phase. Above-normal rainfall is dominant over central India (18°–26°N) in 1994, 1997, and 2003 IOD events, while below-normal rainfall is dominant in regions south of it. The same is reflected in Figs. 2b,c. In 2008, the pattern is completely opposite and, therefore, we wish to investigate the reasons behind
this transition. Since the 2006 IOD event, parts of central India started receiving below-normal rainfall consistently; in 2008 major parts of central India received below-normal rainfall. The Indian Ocean has been continuously warming during the last 30 years and the impact of this warming on the Indian summer monsoon is not yet understood. Ajayamohan and Rao (2008) showed that the linear warming trend in SST in the tropical Indian Ocean may increase the frequency of occurrence of positive IOD events, and thereby enhance the number of heavy rainfall events over central India. However, the role of the Indian Ocean warming and increased frequency of IOD events on seasonal monsoon rainfall over India is yet to be investigated. Here we show that the warming of the Indian Ocean played a crucial role in producing the air–sea interaction that eventually led to the regional organization of precipitation over the Indian continent. Using different datasets and by conducting several model sensitivity experiments, reasons for this abnormal behavior and the role of linear warming trend in the tropical Indian Ocean are investigated. Section 2 presents details on data. Model setup is described in section 3, and results are presented in section 4.

2. Data and model

To understand the abnormal behavior of the monsoon in 2008, optimally interpolated (1° × 1°) Reynolds version-2 SST monthly data (1982–2007; Reynolds et al. 2002), monthly winds, specific humidity from the National Centers for Environmental Prediction reanalysis version-2 (1979–2007; Kanamitsu et al. 2002) and rainfall from the Climate Prediction Center Merged Analysis of Precipitation (CMAP; Xie and Arkin 1997); sea level derived from simultaneous measurements of Envisat, Geosat Follow-On (GFO), Jason-1, and Ocean Topography Experiment (TOPEX)/Poseidon (T/P) for 1993–2007; and India Meteorological Department (IMD) gridded daily rainfall (version-2) dataset (Rajeevan et al. 2006) were used in this study. Anomalies of each field are computed by removing the mean seasonal cycle from each time series. Since anomalous cooling of SST first develops and then terminates at the eastern pole of the
IOD (10°S–equator, 90°–110°E), we use the SST anomaly (SSTA) at the eastern pole of the IOD to represent the IOD phenomenon. Simple correlation analysis is performed to understand the relation between the IOD phenomenon and rainfall over India from June to September. IOD composite precipitation anomalies are computed based on five recent IOD events (1994, 1997, 2003, 2006, and 2007). Since the IOD event of 1999 was associated with a basinwide cooling event (Harrison and Vecchi 2001), it is not included in the IOD composite. To gain further dynamical insight into the mechanism of abnormal behavior of the monsoon in 2008, we calculated anomalous moisture transport in the Indian Ocean. The vertically integrated water vapor transport \( Q \) is defined as

\[
Q = \frac{1}{g} \int_{P_{300}}^{P} q \mathbf{V} dP,
\]

where \( g \) is the acceleration due to gravity, \( q \) is the specific humidity, \( P_3 \) is surface pressure, \( P_{300} \) is pressure at the top of the atmosphere, and \( \mathbf{V} \) is the wind vector (Chen 1985; Behera et al. 1999). Use of the Helmholtz theorem allows us to separate the moisture transport into rotational and irrotational (flux divergence) components. To understand the relative influence of oceanic advection processes and ocean–atmosphere heat fluxes on abnormal warming in the south tropical Indian Ocean (STIO), the oceanic heat budget in the upper 50 m of the southwestern Indian Ocean is analyzed. For this purpose, we used the reanalysis product, which is available at 5-day intervals from the NCEP Global Ocean Data Assimilation System (GODAS). GODAS is forced by the momentum flux, heat flux, and freshwater flux from the NCEP Atmospheric Reanalysis-2 (NCEP R-2). In addition, the temperature in the top model level is relaxed to weekly analyses of SST, while the surface salinity is relaxed to annual salinity climatology. GODAS assimilates temperature profiles and synthetic salinity profiles as well. The assimilation method used is the three-dimensional variational data assimilation (3DVAR) scheme (further details of this dataset and model configuration can be found at http://www.cdc.noaa.gov/cdc/data.godas.html).

3. Design of numerical experiments

The most recent version of the Max Planck Institute for Meteorology atmospheric general circulation model, ECHAM5, is used to understand the response of the IOD and linear warming trend in Indian Ocean on Indian summer monsoon rainfall. The model is a spectral model, which we ran at T106 resolution with 19 levels in the vertical. A comprehensive model description of ECHAM5 is given in Roeckner et al. (2003, 2006). Model-simulated JJAS rainfall climatology is in good agreement with observations, particularly over central India (cf. Figs. 1a and 1c). The model underestimates rainfall over the Western Ghats (topography is probably not well represented in the model), while the model overestimates over northeast India (maybe due to the model climatology). The ECHAM5-simulated rainfall percentage departures during JJAS 2008 are similar to the observed rainfall percentage departures obtained from the IMD gridded dataset, particularly over central India (cf. Figs. 1b and 1d). The patterns have similarities with observed anomalies; however, the magnitudes are a little underestimated in the model. Nevertheless, the model is able to capture the large-scale circulation patterns reasonably well and, therefore, can be used to study the abnormal behavior of the Indian summer monsoon. Four sets of model experiments are performed in this study:

1) Control (CTL) run: Forced with climatological SSTs for 20 years;
2) IOD run: Forced with climatological SSTs combined with SST anomalies associated with positive IOD in the tropical Indian Ocean (Fig. 9a, discussed later);
3) IOD + STIO anomaly run: Combined forcing of IOD run with warming in the STIO region (Figs. 9b,c, discussed later); and
4) Atmospheric Model Intercomparison Project (AMIP)-type run: Forced with observed SST and sea ice from 1979 to 2008.

In the first experiment the model has been integrated for 20 years and in the IOD and STIO anomaly runs the model is integrated for a full calendar year. Each experiment is an ensemble-average of nine realizations, which differ from one another in the initial conditions. Model integration is performed with full physics. In the first experiment (CTL run) we have adopted the monthly varying climatological SST and sea ice as the lower boundary condition. In the second experiment, we have imposed a positive IOD SST anomaly, obtained from a composite of five recent IOD events (1994, 1997, 2003, 2006, 2007), on the lower boundary condition used in the first experiment. The third experiment is similar to the second except that we have imposed the STIO SST anomaly in JJAS, obtained by taking the difference between SST anomalies of the IOD event in 2008 and the IOD composite based on five recent IOD events.

4. Results and discussion

a. Observed anomalies

The observed composite SST anomalies during positive IOD events, SST anomalies in 2008, and the SST
differences between the 2008 IOD event and composite IOD event are shown in Fig. 3 together with its climatological SST distribution in JJAS. It is known that to maintain strong convection, SST has to exceed a threshold value of about 27°C (Gadgil et al. 1984; Graham and Barnett 1987). The SST in normal years in the northern tropical Indian Ocean and in near-equatorial regions remains above 27°C throughout the monsoon season, with an exception of the west Arabian Sea (Fig. 3a). Therefore, small changes in this warm pool temperature will have significant influence on the atmospheric circulations and monsoon rainfall in the tropical Indian Ocean. During a normal positive IOD event, the peak cooling (warming) in the eastern (western and central) equatorial Indian Ocean warm pool can reach above 1°C (0.5°C, Fig. 3b). In JJAS 2008 the warming in the central equatorial Indian Ocean is warmer-than-normal IOD events by 0.6°C, and everywhere else the SSTs are cooler than for normal IOD events (Figs. 3c,d).

Associated with the above changes in SST, the corresponding changes in rainfall are also noticed (Fig. 4). In normal monsoon years, three strong convection centers are noticed: the Bay of Bengal, equatorial Indian Ocean, and west coast of India (Fig. 4a). In normal positive IOD years, rainfall in the eastern (central) equatorial Indian Ocean is suppressed by more than 5 (1) mm day⁻¹. The strong convection center over the Bay of Bengal and western India also strengthens. One important aspect of the positive IOD is that it enhances rainfall over central India in JJAS (Fig. 4b). Interestingly, in JJAS 2008, the rainfall is below (above)-normal from west central India to the central east coast of India (near foothills of the Himalayas and adjacent regions, southwestern equatorial Indian Ocean; Fig. 4d). Anomalous circulation

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Fig. 3. (a) JJAS mean SST in the tropical Indian Ocean (SSTs above 27°C only are shown), (b) composite JJAS SST anomalies during positive dipole years (1994, 1997, 2003, 2006, 2007), (c) SST anomalies in JJAS 2008, and (d) difference between JJAS 2008 SST anomalies and composite SST anomalies. Positive (Negative) SST anomalies are represented by solid (dotted) contours (Figs. 3b–d).
patterns associated with these changes in rainfall are strong cyclonic (anticyclonic) circulation in the southwestern tropical Indian Ocean (extending from the Bay of Bengal to west-central India). During normal monsoon years, the strong south westerlies are seen south of 20°N over the Indian subcontinent, while in positive IOD years these westerlies are shifted to central India. On the other hand, in JJAS 2008 the strong westerlies from the Arabian Sea are shifted north of 20°N (Fig. 4).

The divergent component of moisture transport and associated divergent wind vectors are presented in Fig. 5. During a normal monsoon year strong moisture divergence takes place from the Mascarene high and moisture convergence takes place over India and at the head of the Bay of Bengal (Fig. 5a). In a normal IOD event, anomalous moisture divergence takes place from the eastern equatorial Indian Ocean. As a result, the moisture convergence takes place over India and at the head of the Bay of Bengal (Behera et al. 1999; Ajayamohan and Rao 2008) and the western equatorial Indian Ocean. In 2008, the anomalous convergence of moisture in the western equatorial Indian Ocean is abnormally strong and resulted in moisture divergence over the Bay of Bengal and central India (Fig. 5c). In fact, the moisture convergence over the western and central equatorial Indian Ocean is stronger compared to the moisture divergence over the eastern equatorial Indian Ocean, which is quite contrary to the moisture transports in normal IOD years. The major difference in moisture transport from a normal IOD year and 2008 is the strong anomalous convergence in the western equatorial Indian Ocean and near the Himalayan regions. Moisture divergence is observed over the Bay of Bengal and the same is extended up to central India.
b. Abnormal warming in the STIO region

Conspicuous difference between JJAS 2008 and normal IOD SST anomalies is the abnormal SST warming in the STIO region. This warming resulted in enhanced convection over the STIO and forced anticyclonic anomalies over the Bay of Bengal and parts of India extending up to central India (Fig. 5). The reasons for this strong warming are analyzed in this section to find out the relative influence of atmospheric fluxes and oceanic advection processes. Oceanic heat budget analysis is carried out in the top 50-m water column in the STIO region (10°S–5°S, 60°–85°E). It is noticed that the horizontal advection plays a very important role in warming the STIO region during the JJAS season. During the same period ocean–atmosphere heat fluxes are favorable for a cooling tendency (Fig. 6). In a normal IOD event, the anomalous downwelling Rossby waves in the southern tropical Indian Ocean reach the central and western basin only after the JJAS season (Fig. 7). However, in 2008 the downwelling Rossby wave reached the central basin by June itself. This abnormal downwelling Rossby wave is also responsible for the abnormal warming in the STIO region. The downwelling Rossby wave helped in warming the STIO by deepening the thermocline in this region. Rao and Behera (2005) showed that the Rossby waves during IOD years are forced mainly by the wind stress curl in the southeastern equatorial Indian Ocean and eastern boundary variations play a minor role. Confirming their results, strong anomalous anticyclonic wind stress curl is apparent in the STIO in May (figure not shown), and we believe that this wind stress curl forced the downwelling Rossby waves in the STIO in JJAS 2008. Convection associated with the abnormal warming forced cyclonic wind
stress curl in the following months and resulted in weakening the downwelling Rossby wave signals by September, thereby highlighting that the warming in the STIO region involves both ocean and atmosphere coupled processes. It has been identified by Ajayamohan and Rao (2008) that the SST in the Indian Ocean in recent decades shows a strong linear trend, particularly in the central tropical Indian Ocean. Here, we investigated the role of

Fig. 6. Ocean heat budget terms (°C month⁻¹) in the upper 50 m in the STIO region (line with triangle: ocean heat content tendency, thin black line: heat fluxes term, thin dash line: horizontal advection term, and line with asterisk: vertical heat advection).

Fig. 7. Satellite-derived sea level anomalies (cm) in the STIO region (averaged between 5° and 10°S) during different IOD years. JJAS months are highlighted with black ellipse; positive anomalies are dark grayscale.
this linear warming trend in the formation of abnormal warming in the STIO in JJAS 2008. The linear trend of SST anomalies over the last 27 years (1982–2008) is shown in Fig. 8a. Both the linear warming trend and SST anomalies in JJAS 2008 (Fig. 3c) exhibited similar patterns in the tropical Indian Ocean. However, when we remove the linear trend from the JJAS 2008 SST anomalies, the SST anomalies are similar to the composite SST anomalies in Fig. 3b. Pattern correlation between Fig. 3b and Fig. 8b is about 0.5 and, if we restrict the domain to 10°S–10°N, the pattern correlation comes approaches about 0.73. This confirms that the observed SST anomalies in 2008 are due to the combined influence of the linear warming trend and IOD-related anomalies.

c. Model sensitivity experiments

To test the hypothesis that the central Indian drought in 2008 is forced by STIO SST anomalies, we have carried out a suite of sensitivity experiments with ECHAM5. Model-simulated seasonal rainfall anomalies in 2008 from the AMIP run are shown in Fig. 1d. The model underestimates the rainfall departures from model long-term mean in JJAS 2008; however, the patterns match well with observations. Pattern correlation between model-simulated rainfall and observed rainfall over the Indian region is about 0.6. The good similarity between observed rainfall departures and simulated rainfall departures proves that the model used in this study is capable of simulating the large-scale circulation patterns to a given SST forcing, particularly in the Indian Ocean region.

To understand the model response to IOD-related SST anomalies on the Indian summer monsoon, the model is forced with IOD-related SST anomalies (Fig. 9a) combined with climatological SSTs in the CTL run. The IOD run mimics the observed rainfall and circulation patterns (cf. Figs. 4b and 10a), suggesting that the model performance of simulating the IOD response is reasonable in the model. The model reproduces the above-normal rainfall over west central India to the central east coast of India. Compared to observed circulation patterns, a slight shift in the strong westerly flow over the Indian subcontinent is observed in the model.

The abnormal SST warming observed in the STIO from observations is superimposed on SSTs of the IOD run. Now, the model reproduces the observed rainfall anomalies and circulations patterns reasonably well. Suppressed rainfall over west-central India to the central east coast of India and related circulation anomalies are reasonably reproduced (Figs. 10b and 1d). Just by adding additional warming in the STIO region to the IOD-related SST anomalies (Fig. 9a), the model is able to reproduce the observed JJAS 2008 rainfall anomalies very well, thereby supporting our hypothesis that the abnormal warming in the STIO is responsible for the suppressed rainfall from west-central India to the central east coast of India.

As in observations, strong anticyclonic (cyclonic) circulation over the suppressed rainfall region over India and the Bay of Bengal (STIO) is noticed in the model. To test the response of STIO warming alone, differences between the IOD + STIO anomaly run and IOD run are shown in Fig. 10c. Interestingly, the simulated patterns in Fig. 10c are almost similar to the patterns observed in Fig. 10b except in the southeastern equatorial Indian Ocean. This suggests that the STIO abnormal warming has played a pivotal role in suppressing the rainfall from west-central India to the central east coast of India in 2008. The warming in the STIO is so strong that it nullified
the influence of the IOD on monsoon rainfall over the Indian subcontinent. It may be mentioned here that the suppressed convection over the southeastern equatorial Indian Ocean due to strong surface cooling played a very important role in normal IOD years because the suppressed convection anomalies are much stronger compared to the enhanced convection in the central equatorial Indian Ocean. However, in the 2008 IOD event, the enhanced convection anomalies, owing to abnormal warming in the STIO, are much stronger compared to suppressed convection anomalies in the southeastern equatorial Indian Ocean. Therefore, even though the IOD is active in the tropical Indian Ocean, the abnormal warming in the STIO region overwhelms the effects due to cool SST anomalies.

**Fig. 9.** SST anomalies (°C) superimposed on the CTL run for various sensitivity experiments: (a) IOD composite SST anomalies, (b) STIO warming, and (c) IOD + STIO anomaly run. Positive anomalies are shaded and negative anomalies are contoured by dotted lines.

**Fig. 10.** Simulated rainfall (mm day$^{-1}$) and wind anomalies (m s$^{-1}$) at 850 hPa in the (a) IOD run, (b) IOD + STIO anomaly run, and (c) differences between the IOD + STIO anomaly run and IOD run.
in the eastern equatorial Indian Ocean. The moisture transport in two different experiments (IOD and IOD + STIO anomaly) and their differences are shown in Fig. 11c. The results shown in this figure agree reasonably well with the observations; however, the magnitudes are stronger in the model and this difference may be due to the warming in the STIO region alone prescribed in the model runs.

Another major difference in SSTAs in 2008 is the strong cooling observed in the Arabian Sea. We have also tested the impact of this strong cooling on Indian monsoon rainfall; however, the central Indian drought conditions cannot be explained by this strong cooling in the Arabian sea. Therefore, we do not discuss the results here.

The mechanism responsible for the model response is that the enhanced convection over the STIO region, as a response to coupled ocean–atmosphere processes driven by SST warming in the STIO, suppresses convection over the Bay of Bengal and central India through a regional anomalous Hadley circulation. Similar anomalous patterns are also noticed in observations (Fig. 12). This confirms that the mechanism proposed here is responsible for the observed abnormal behavior of the 2008 monsoon.

5. Conclusions

Prediction of summer monsoon rainfall during JJAS averaged over all India is not useful as there is considerable inhomogeneity in anomalies of seasonal mean rainfall. The prediction of regional anomalies is crucial for agricultural planning during such years. Understanding the mechanisms for organization of rainfall anomalies on a regional scale is imperative for advancing the prediction of regional anomalies. The summer monsoon of 2008 provided a test bed for understanding a case of such regional organization of rainfall anomalies. It attracted our attention because there was a large central Indian drought (organized negative anomaly over central India), although the Indian monsoon was close to normal (98% of the long-term average). The 2008 monsoon was also intriguing as there was a moderate IOD event, but the rainfall anomalies over India were atypical of an IOD year.

During a normal IOD year, above-normal rainfall is noticed over the central Indian region and none of the recent five IOD years (1994, 1997, 2003, 2006, and 2007) are associated with below-normal rainfall over the Indian subcontinent. However, the IOD event in 2008 showed abnormal behavior of below-normal rainfall (−30%) for the first time over central India. Reasons for the abnormal behavior of the monsoon in 2008 are investigated using observations and model sensitivity experiments. It is found that the warming in the STIO region is abnormally strong owing to the combined influence of a positive IOD and linear warming trend in the tropical Indian Ocean. Coupled ocean–atmosphere processes are involved in abnormally warming the STIO region in 2008, downwelling Rossby wave forced by wind stress curl, and ocean advection played a dominant role in warming the STIO region. Model experiments suggest that, associated with this warming, stronger-than-normal convection anomalies are also observed in this region in JJAS.
2008. These convection anomalies forced anticyclonic circulation anomalies over the Indian subcontinent and Bay of Bengal region, resulting in below-normal rainfall from west central India to the central east coast of India. The results presented in this study suggest that, in the warming environment, increased frequency of IOD events may lead to considerable changes in the monsoon circulation in coming decades.

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