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Further evidences for the weakening relationship of Indian rainfall and ENSO over India

Sudipta Sarkar
Center for Earth Observing and Space Research (CEOSR), George Mason University, Fairfax, Virginia, USA

Ramesh P. Singh[1]
Department of Civil Engineering, Indian Institute of Technology, Kanpur, India

Menas Kafatos
Center for Earth Observing and Space Research (CEOSR), George Mason University, Fairfax, Virginia, USA

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[1] Numerous efforts have been made in the past to understand the effect of Indian monsoon and El Niño/Southern Oscillation (ENSO) over the Indian continent. Various approaches and analysis of datasets covering the last 140 years have shown a dominantly inverse relationship between the ENSO and Indian rainfall. But this dominant coupling between the ENSO and Indian rainfall has been observed to weaken in recent decades. In the present paper, we have analyzed rainfall trend over the Indian subcontinent and its relation with ENSO. Our results indicate a stronger circulation pattern over the Indian region in last two decades. We have also found that the effect of ENSO has increased in recent years but has failed to influence the Indian rainfall because of the stronger circulation pattern prevailing over India during this time. *INDEX TERMS:* 1630 Global Change: Impact phenomena; 1854 Hydrology: Precipitation (3354); 4522 Oceanography: Physical: El Niño; 9325 Information Related to Geographic Region: Atlantic Ocean.
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1. Introduction

[2] The South Asian monsoon in general and Indian monsoon in particular is one of the most important and influential phenomena of Earth's climate system [*Garnett and Khandekar*, 1992]. Numerous studies have been carried out in the last two decades to observe the long-term trend of the Indian rainfall and the South Asian rainfall. Earlier studies found a close relation between the Indian rainfall and the ENSO [*Walker and Bliss*, 1937; *Shukla and Paolino*, 1983; *Joseph et al.*, 1994]. Analyses using Global Circulation Models (GCM) have shown the possible influence of ENSO on interannual variability of the Indian Ocean climate through changes in the anomalies of the Walker circulation [*Latif et al.*, 1994; *Arpe et al.*, 1998; *Murtugudde and Busalacchi*, 1999]. The coupled ocean-atmosphere models have also found a close relation of South Asian precipitation and ENSO [*Ju and Slingo*, 1995; *Wainer and Webster*, 1996; *Meehl*, 1997]. Recently, *Krishnamurthy and Goswami* [2000] have carried out analysis of long observed precipitation records and have shown that the Indian monsoon rainfall and ENSO are strongly correlated on interdecadal time scale.

[3] In the last two decades the usual coupling between the Indian rainfall and ENSO defined as lower (higher) rainfall during warm (cold) events in the equatorial Pacific has been seen to change [*Kumar et al.*, 1999] as monsoon rainfall over India is found to be normal or above average during the last few ENSO events. The quantitative evaluation of the relationship between Indian rainfall and ENSO is still not clear. We have examined the precipitation patterns over India for the last 50 years. The present analysis shows variable interaction between ENSO and rainfall and also shows the effect of local climate anomaly in normal rainfall forcing over India during recent ENSO events.

2. Data

[4] We have considered two rainfall datasets. The first dataset, WMR (Willmott and Matsuura Rainfall), is a long-term precipitation record from January 1950 to December, 1999. This record has been produced from the Global Historical Climatology Network (GHCN version 2) and station records of monthly total precipitation [*Legates and Willmott*, 1990a, 1990b]. The station data have been interpolated to a 0.5 degree by 0.5 degree of latitude/longitude grid, where the grid nodes are centered on 0.25 degree. These data are taken from Goddard DAAC (http://lake.nascom.nasa.gov/tovas/cort/).

[5] The second dataset, CPR (Climatology Precipitation Record), is of more recent period, from January 1979 to October 2002, available from the Global Precipitation Climatology Project (GPCP) (http://precip.gsfc.nasa.gov). In present analysis, the 2002 data have not been included because of a data gap during November and December of 2002. The CPR dataset is based on integration of infrared (GOES) and microwave satellite estimates (SSM/I) of precipitation with rain gauge data from more than 30,000 stations over the globe.

[6] Both rainfall datasets are corrected for seasonality by calculating the deviations from the climatological mean annual cycle. The climatological annual cycle is con-

[1]Temporarily at Center for Earth Observing and Space Research (CEOSR), George Mason University, Fairfax, Virginia, USA.

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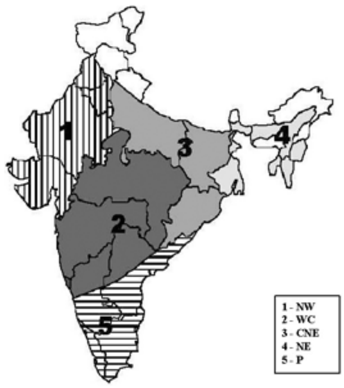

Figure 1. The five different meteorological zones.

structed, based on the duration of each dataset, 50 (WMR) and 23 (CPR) years, respectively. Detrending of the rainfall datasets have not been carried out in the absence of any significant trend. The most significant trend is found to be about 5–6% for the last 23 years over selected few areas which remains the same even over the last 50 years.

[7] The rainfall data for India are available (http://www.tropmet.res.in/) for five meteorological zones (Figure 1) namely North-West (NW), West-Central (WC), Central-North East (CNE), North-East (NE) and Peninsular (P) India. Details of these datasets are discussed by *Parthasarathy et al.* [1995].

[8] Southern Oscillation Index (SOI) measures the normalized sea level pressure fluctuations between Darwin, Australia (131°W, 12°S) and Papeete, Tahiti (149°W, 17°S) [*Ropelewski and Halpert*, 1987; *Allan et al.*, 1991]. This data set is obtained from the Climate Research Unit of the University of East Anglia (http://www.cru.uea.ac.uk/cru/data/soi.htm), covering the period from 1866–2001.

[9] The Dipole Mode Index (DMI) and the Meridional Hadley Circulation Index (MHI) are estimated from the data available from NCEP/NCAR reanalysis project (http://iridl.ldeo.columbia.edu/SOURCES/.NOAA/.NCEP-NCAR/) for January 1982 to December 2001. DMI shows the dipole nature of the SST anomaly over the western and eastern half of the Indian Ocean [*Saji et al.*, 1999]. The DMI is based on the difference in SST anomaly between the tropical western Indian Ocean (50°E–70°E, 10°S–10°N) and the tropical south-eastern Indian Ocean (90°E–110°E, 10°S–Equator). MHI is defined by the meridional wind (V) shear between 850 and 200 hPa (V850–V200) averaged over 10°–30°N and 70°–110°E [*Goswami et al.*, 1999]. The MHI provides information about the strength of the circulation pattern over India during the greater part of the last 24 years.

3. Results

[10] Figures 2a and 2b show the EOF analysis results for WMR and CPR, in both cases, the first two EOFs explain about 42–51% of the total variance. The percent variance explained by the first two modes using WMR and CPR datasets is shown in Table 1.

[11] The EOF1 for CPR (Figure 2b) shows a strong dipole behavior over the Indian Ocean region, similar behavior is also seen in the EOF2 of Sea Surface Temperature anomalies over the Indian Ocean [*Saji et al.*, 1999].

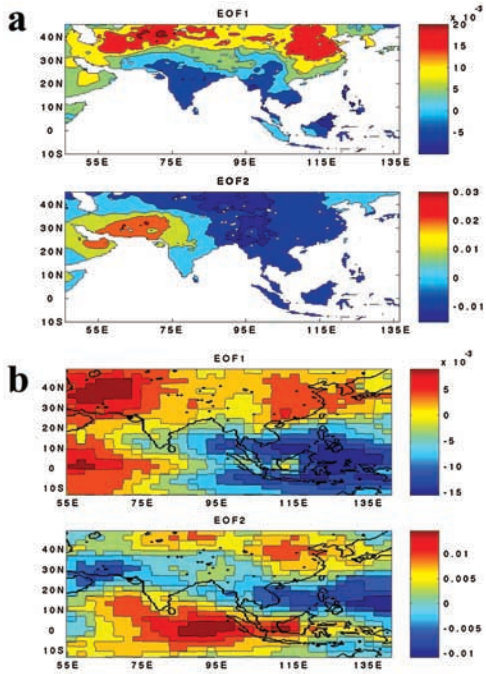

Figure 2. The first two principle modes, EOF1 and EOF2 for (a) WMR and (b) CPR.

EOF1 shows ENSO effect for both WMR and CPR rainfall. The cross correlation between the PC1 from WMR data and SOI is found to be 0.32 with 3 months lag whereas cross correlation of 0.85 is found between PC1 of CPR and SOI with a 4 month lag. These correlation values are significant at 99% level.

[12] Table 2 shows the regression of PC1 values with each of the five zonal rainfalls over India. The cumulative summer rainfall (JJAS) computed from the PC1 of WMR and CPR is regressed with the JJAS estimates of each of the zonal rainfalls and the cross correlation values are given in Table 2 for WMR and CPR, respectively. All values failing the test for significance at 99% are changed to zeros. The third column in Table 2 presents the correlation values between the JJAS estimates of PC1 from WMR, calculated for a limited period, 1979–99 (WMR79-99) with the JJAS estimates of the zonal rainfalls. PC1 values of WMR79-99 and CPR are found to be significantly correlated at 99% ($r = 0.60$, p value = 0.0) (Figure 3) thus implying compatibility between the two datasets. The PC1 values of both, the WMR79-99 and CPR show significant correlations with an increased number of meteorological zones (CNE, NE, NW, and WC) compared to the PC1 of WMR which shows significant correlation only for two zones (NE and NW) in the last 50 years. The CNE and WC zones are found to be significantly affected by the ENSO of the last two decades compared to the entire 50 years. The PC1 values of CPR do not show significant correlation with NE (Table 2). The

Table 1. The Variance Explained by Each Mode for WMR and CPR Years

	WMR (%)	CPR (%)
EOF1	30	36
EOF2	12	15

Table 2. Regression Between JJAS Estimates of PC1 and Zonal Rainfall

Zones	PC1 (WMR − 50 Yrs.)	PC1 (WMR79-99)	PC1 (CPR)
CNE	0	−0.52	−0.62
NE	−0.57	0.31	0
NW	−0.37	0.33	0.49
P	0	0	0
WC	0	0.33	0.45

Table 3. Regression Between JJAS Estimates of SOI and Zonal Rainfall

Zones	SOI (50 Yrs.)	SOI (23 Yrs.)
CNE	0	0.58
NE	0.67	0.41
NW	0.38	0.29
P	0	0
WC	0	−0.28

behavior of rainfall over peninsular India (P) is found to be consistent compared to other zones as no influence of ENSO has been observed with WMR and CPR datasets.

[13] The PC1 which is representative of ENSO shows greater influence over the zonal rainfalls in the last 24 years, showing significant correlations with a large number of meteorological zones compared to the entire period since 1950. This observation is supported from both the WMR79-99 and CPR JJAS estimates. It is difficult to comment on the extent of ENSO influence over the NE zone in last 24 years, based on the inconsistency in the correlation values with PC1 of WMR79-99 and CPR.

[14] Table 3 shows the correlation values between the JJAS estimates of SOI and zonal rainfalls, significant at 99% level. The correlation values are similar to the pattern noticed based on PC1 and zonal rainfalls (Table 2). The NE and NW show significant correlations with the SOI during 1950–1999 while the JJAS values of SOI during the last 23 years show significant correlations for a larger number of meteorological zones compared to 50 year period. The NE zone shows significant correlation during the CPR period and confirms the observation from WMR79-99 (Table 2).

[15] The variations of (a) DMI and SOI (b) DMI and MHI are shown in Figures 4a and 4b. The DMI and MHI anomalies are shown after being smoothed by a seven month moving average and the MHI has been adjusted for a 3 month lag with respect to DMI (r = 0.41). The DMI is found to be at a low from May 1983 till June 1990 and becomes stronger thereafter. The MHI or the overall strength of circulation over the Indian subcontinent is seen to follow DMI more closely and thus is more responsive to changes in DMI compared to that of SOI or the strength of ENSO. During the last 24 years the DMI is found to be strong for the greater part of the period thus forcing more enhanced circulation pattern over the Indian sub-continent. Thus, even though ENSO continued to have the same if not greater impact over the rainfall pattern, the rainfall remained normal or beyond average because of the greater intensity of the DMI, an exception being the 1986–87 ENSO. The record increase of DMI during 1997–98 coincided with heavy rainfall for this period despite the strong El Niño of the decade occurring at the same time. The correlation of PC1 of CPR is found to be significant (r = 0.60) with DMI and with the MHI (r = 0.58) with p-values of 0.019 and 0.023, respectively (for alpha value of 0.05), and thus we can say that these two indices play a very important role in controlling the Indian summer rainfall.

[16] Recent studies by *Ashok et al.* [2001] and *Guan et al.* [2003] have shown the importance of DMI in dictating surplus rainfall over the Indian region. A stronger dipole mode in the Indian Ocean leads to enhanced monsoon circulation over the Indian region that is reflected in the MHI. The MHI is found to show good correlation with extended monsoonal rainfall over Indian sub-continent and southern China and also shows a better correlation with the all India rainfall index [*Goswami et al.*, 1999]. *Wang and Fan* [1999] have also discussed in detail about the relevance of MHI in defining the monsoon circulation pattern in terms

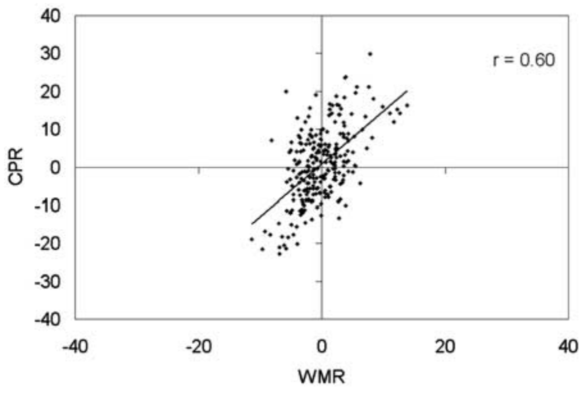

Figure 3. Scatterplot of CPR and WMR79-99.

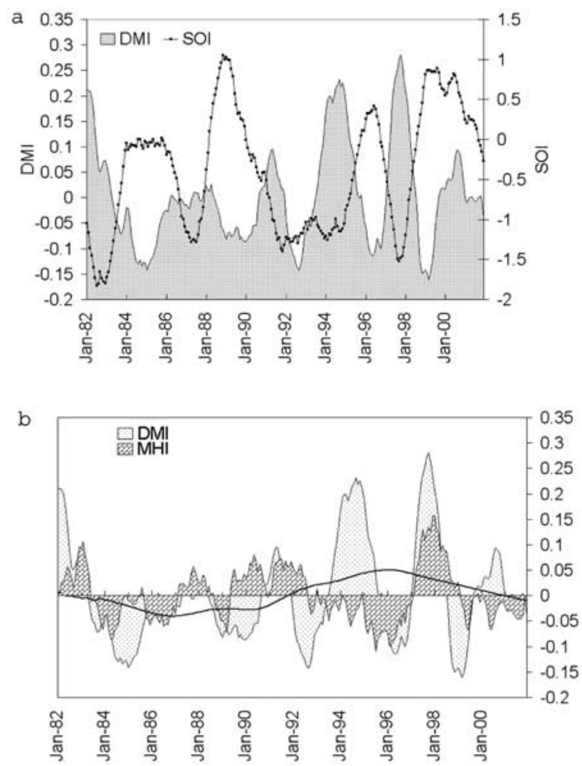

Figure 4. Variation of (a) DMI and SOI and (b) DMI with lag adjusted MHI for the period January 1982–December 2001. The solid black line shows the trend in DMI as estimated by a linear local regression model.

of intense westerly and southerly shear noticed in upper level wind and the better correlation of MHI with the convection over India during summer rainfall.

[17] The present analysis shows stronger Indian Ocean dipole activity and concurrent buildup of intense circulation pattern over India in recent years. The cyclicity observed in the DMI variation (Figure 4b) is interesting and suggests that Indian rainfall experiences highs during the periodic high phases of DMI.

4. Conclusion

[18] Our study suggests that the effect of ENSO on Indian precipitation has not decreased but on the contrary it has increased in recent times, and is secondary to the local dynamics in the area. The strength of ENSO is realized only at times of low bipolarity over the Indian Ocean. It is when the local dynamics weakens and the Walker circulation over this area becomes weak, a stronger ENSO further weakens this circulation with the shifting of the circulation cell towards the central Pacific and an overall low rainfall year ensues. The last two decade has seen mostly strong and persistent development of bipolarity in the Indian Ocean and hence a strong local dynamics and circulation pattern has offset any impact of ENSO. It may be possible that the increase in land-sea thermal contrast in recent years [*Kumar et al.*, 1999] and a stronger dipole mode activity in the Indian Ocean, as seen from our work may have worked in tandem and ensured a good rainfall during the last few ENSO events.

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M. Kafatos and S. Sarkar, SCS, George Mason University, 4400 University Drive, Fairfax, VA 22030, USA. (ssarkar@gmu.edu)

R. P. Singh, Department of Civil Engineering, IIT Kanpur, Kanpur 208016, India. (ramesh@iitk.ac.in)