



## Atlantic forced component of the Indian monsoon interannual variability

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[1] The Indian monsoon interannual variability is modulated by the El Niño Southern Oscillation (ENSO), with a drier than normal monsoon season usually preceding peak El Niño conditions, and vice versa for La Niña phase. Pacific sea surface temperature (SST) anomalies, however, are not the only player. Building upon our recent discovery that atmospheric teleconnections between the tropical Atlantic and the Indian basin contributed to the weakening of the ENSO-monsoon anticorrelation during the '80s and '90s, we investigate the role of south equatorial Atlantic SSTs in forcing the Indian monsoon rainfall (IMR). Using two observational data sets and two ensembles of simulations we show that the residual in the IMR time series for observed and modeled data, obtained by subtracting the ENSO-forced component of the IMR that is linearly related to the NINO34 index, is significantly correlated with south equatorial Atlantic SSTs. Our results have important implications for seasonal forecast efforts.

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### 1. Introduction

[2] The Indian monsoon is strongly influenced by the El Niño Southern Oscillation (ENSO) on interannual scales [Walker, 1924; Rasmusson and Carpenter, 1983]. The strength of anticorrelation between ENSO indices and the Indian Monsoon Rainfall (IMR), however, varies at decadal times [e.g., Webster and Yang, 1992; Ju and Slingo, 1995] and it weakened substantially during the '80s and '90s [Krishna Kumar et al., 1999; Torrence and Webster, 1999].

[3] The cause of such a weakening has been attributed to a broad range of phenomena: From changes in the atmospheric fields due to global warming [Krishna Kumar et al., 1999], to natural low-frequency atmospheric variability [Krishnamurthy and Goswami, 2000; Gershunov et al., 2001]; From changes in the atmospheric circulation in the North Pacific [Kinter et al., 2002] and in the Eurasian snow cover [Chang et al., 2001], to variability of the Pacific Decadal Oscillation [Krishnan and Sugi, 2003]; From changes in the ENSO characteristics [Annamalai and Liu, 2005; Krishna Kumar et al., 2006] to the co-occurrence of ENSO and the Indian Ocean Zonal Mode (IOZM) [Saji et

al., 1999; Webster et al., 1999]. Finally, a recent study by Kucharski et al. [2007] (hereinafter referred to as K2007) found that tropical Atlantic SST modulate the ENSO-Indian monsoon relationship and reproduced observed trends in the IMR time series during the 1950–1999 period with a suite of ensemble experiments.

[4] The SST anomalies identified by K2007 extend in the southeastern Tropical Atlantic from the Angola coast to the Gulf of Guinea in boreal spring and summer and are usually referred as southern tropical Atlantic (STA) pattern [Huang et al., 2004] or Atlantic Niño [Chang et al., 2006]. Several studies investigated the ENSO influence on tropical Atlantic variability [e.g., Zebiak, 1993; Latif and Grötzner, 2004]. Recent works pointed out that STA anomalies may be independent on ENSO, which influences tropical Atlantic SSTs mainly north of the equator [Chang et al., 2006], but result from air-sea interactions along the coast of Africa with intensification by local physical processes, including slow Rossby wave propagation, Ekman pumping and Bjerknes feedbacks [Hu and Huang, 2007]. South equatorial tropical Atlantic SSTs may therefore influence the IMR independently on ENSO.

[5] Here we generalize the results of K2007 by exploring how important is the tropical Atlantic contribution to the interannual variability of the Indian monsoon. To this goal we further analyze the integrations described in K2007, performed for the CLIVAR International “Climate of the 20th Century” Project [Folland et al., 2002], and we extend our investigation to two observational data-sets, the precipitation data of the Climate Research Unit (CRU) [New et al., 1999] and the All Indian Rainfall Index (AIR) [Parthasarathy et al., 1995].

### 2. Model and Experimental Set-Up

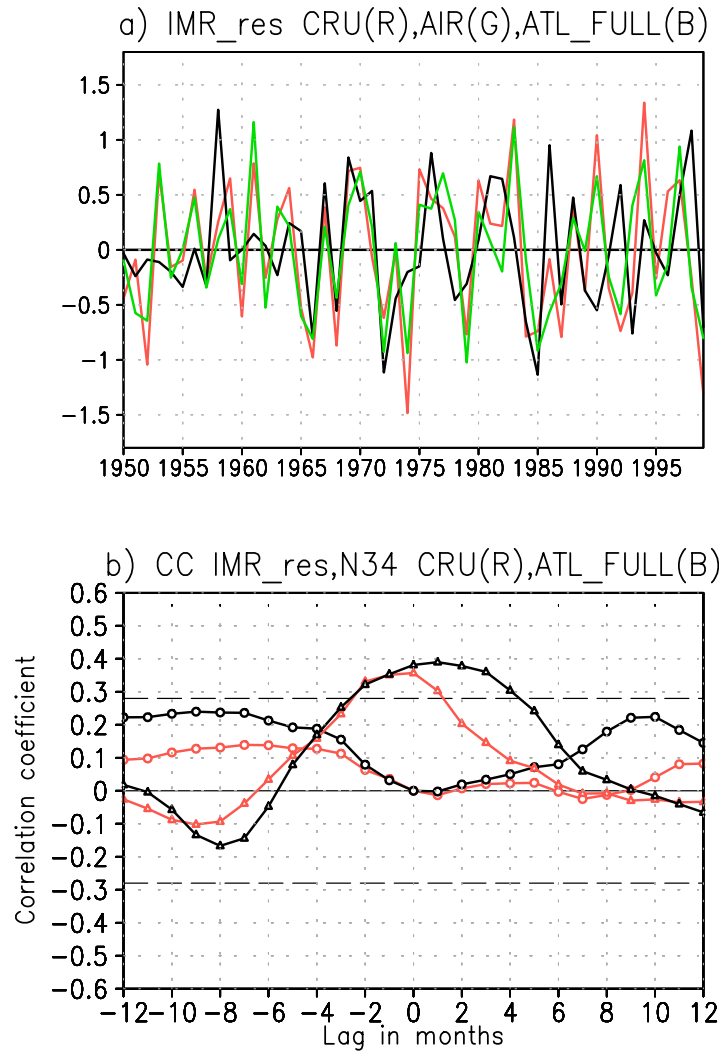
[6] We analyze two ensembles realized with the ICTP AGCM [Molteni, 2003; Bracco et al., 2004; Kucharski et al., 2006] in its 8-layer configuration and T30 horizontal resolution coupled in the Indian basin to MICOM version 2.9 [Bleck et al., 1992] in a regional domain with 20 vertical levels and  $1^\circ \times 1^\circ$  horizontal resolution. This model has been intensively tested and despite its coarse resolution reproduces the monsoon climatology and variability very well [Bracco et al., 2007], and the ENSO-IMR teleconnection, essential in this study, close to the theoretical potential predictability limit (see K2007 for a discussion). The coarse resolution, on the other hand, limits the representation of regionally important details, often linked to topographic features, as for example the local intensification of rainfall along the Western Ghats.

[7] MICOM domain extends from  $35^\circ\text{S}$  to  $30^\circ\text{N}$  and from the east coast of Africa to about  $140^\circ\text{E}$ . A  $3^\circ$ -wide zone south of  $32^\circ\text{S}$  and east of  $137^\circ\text{E}$  blends ocean model

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**Figure 1.** (a) Time series of the (detrended)  $IMR_{res}$  for CRU (red), AIR (green) and  $ATL_{FULL}$  (black). The units are mm/day. (b) CCs between  $IMR_{res}$  in JJAS and the lagged 4-month mean NINO34 (circles) and tropical Atlantic (triangles) indices, for CRU (red) and  $ATL_{FULL}$  (black), respectively. The horizontal dashed lines indicate the 95% confidence limits.

SSTs to observed values and subsurface quantities to Levitus monthly climatology. Outside the Indian Ocean the AGCM is forced with the Hadley Center SST data-set (HadISST) [Rayner *et al.*, 2003] from 1950 to 1999. The two sets of integrations differ only over the Atlantic Ocean, where observed SSTs in the first ensemble ( $ATL_{FULL}$ ) and climatological values in the second one ( $ATL_{CLIM}$ ) force the AGCM.

[8] Each ensemble consists of ten members created by randomly perturbing the initial conditions and by performing a 20-year spin-up integration. In the following, only ensemble means are considered.

### 3. Results

[9] We first define an IMR index in CRU and model data as the average June to September (JJAS) rain anomalies over land in the region  $70^{\circ}E$  to  $85^{\circ}E$  and  $10^{\circ}N$  to  $30^{\circ}N$ , covering most of the Indian Peninsula. The IMR index for CRU is highly correlated with the AIR (correlation coefficient

$CC = 0.88$ ) and is thus representative of the monsoon strength. Using the NINO34 index (i.e. the average JJAS SST anomalies in the region  $170^{\circ}W$  to  $120^{\circ}W$  and  $5^{\circ}S$  to  $5^{\circ}N$ ), we isolate the residual component of the IMR that is not remotely forced by ENSO in the model output, CRU and AIR as function of time  $t$  according to

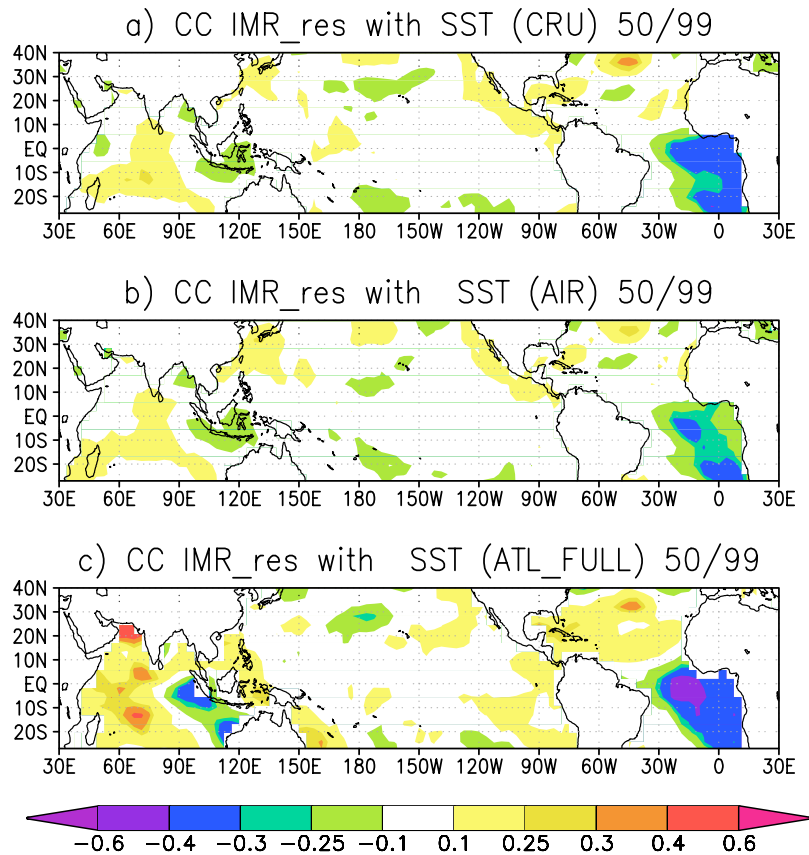
$$IMR_{res}(t) = IMR(t) - IMR_{ENSO}(t), \quad (1)$$

where

$$IMR_{ENSO}(t) = b \text{ NINO34}(t). \quad (2)$$

where  $b$  is a constant and is determined by least-square fits (linear regression) for each dataset, while the IMR and NINO34 indices are defined as anomalies.

[10] Figure 1a shows the time series of  $IMR_{res}$  for CRU (red), AIR (green) and  $ATL_{FULL}$  (black). The low-frequency component has been removed by subtracting an 11-year running mean to avoid contamination by interdecadal



**Figure 2.** Distribution of the Correlation Coefficients (CC) between the  $IMR_{res}$  time series and observed SSTs in (a) CRU, (b) AIR, and (c)  $ATL_{FULL}$ . Absolute CC larger than 0.25 are 90% statistical significant, larger than 0.3 95% statistical significant.

trends. Results, however, are very similar if unfiltered data are used instead. Not surprisingly, the  $IMR_{res}$  time series of CRU and AIR are also highly correlated ( $CC = 0.86$ ), while the CCs of the detrended  $IMR_{res}$  of  $ATL_{FULL}$  with CRU and AIR are 0.42 and 0.31, respectively, both being 95% statistically significant. These correlations suggest that there is a forced contribution in the residual component, although internal variability and possibly model biases are dominating.

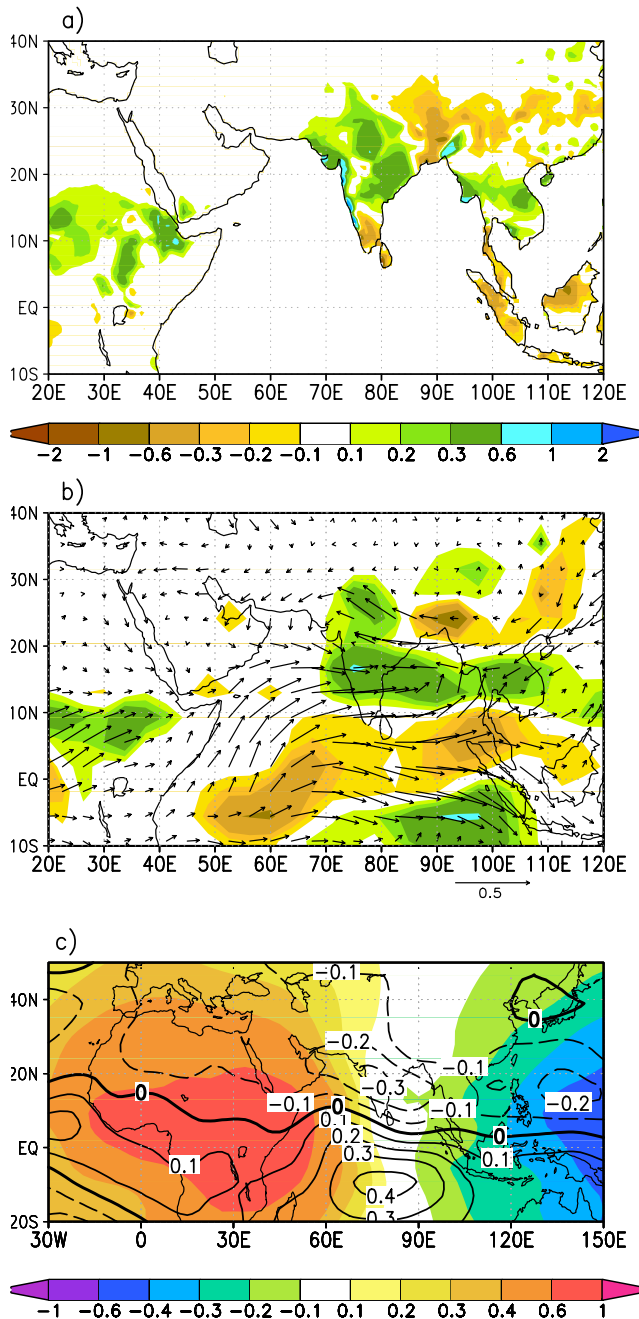
[11] The implicit assumption of a linear relationship between ENSO and the Indian monsoon in equation (2) is based on the simultaneous high correlation between the NINO34 and IMR indices ( $CC = -0.53$  for CRU,  $-0.53$  for AIR and  $-0.63$  in  $ATL_{FULL}$  ensemble mean). This instantaneous linear relationship has been removed from IMR to define  $IMR_{res}$ . However, we cannot exclude a priori a time-lagged impact of ENSO SSTs on the  $IMR_{res}$ . To assess this, in Figure 1b we calculated lagged CCs between JJAS  $IMR_{res}$  and the 4-month mean NINO34 index for CRU (red, circles) and  $ATL_{FULL}$  (black, circles). At negative lags NINO34 leads  $IMR_{res}$ , and vice versa. For CRU the lagged CCs is always smaller than 0.15 and statistically insignificant; for  $ATL_{FULL}$  the CCs reach slightly greater values (0.23), but still below the 95% significance level, for ENSO leading  $IMR_{res}$  by 8 months. Thus a statistically important time-lagged influence of ENSO on  $IMR_{res}$  can be ruled out.

[12] The ability of  $ATL_{FULL}$  to partially reproduce the  $IMR_{res}$  variability in CRU and AIR, suggests that part of the  $IMR_{res}$  signal is forced by SSTs. Given our  $IMR_{res}$  defini-

tion and the absence of a substantial time-lagged influence of ENSO on  $IMR_{res}$ , those SSTs are i) independent of ENSO or ii) nonlinearly teleconnected to ENSO. To locate the SSTs that force the  $IMR_{res}$  we calculate the distribution of CCs between the detrended  $IMR_{res}$  time series of Figure 1a and the SSTs from the HadISST dataset. Figures 2a–2c show the results for CRU, AIR and  $ATL_{FULL}$ , respectively. Absolute CCs greater than 0.25 are 90% statistical significant and greater than 0.3 are 95% significant. The south equatorial Atlantic Ocean plays the most important role for all datasets.

[13] Introducing the tropical Atlantic index, defined (similar to K2007) as the negative area averaged JJAS SST anomalies in the region  $30^{\circ}W - 10^{\circ}E$  and  $20^{\circ}S - 0^{\circ}S$ , we find that the correlation between such an index and the detrended  $IMR_{res}$  for CRU, AIR and  $ATL_{FULL}$  are, respectively, 0.35, 0.28 and 0.40, all 95% statistically significant. This suggests that cooling in the tropical Atlantic favors an increase of monsoon precipitation over India independently on ENSO. The relevance and independence of the south equatorial Atlantic anomalies is also confirmed by the lagged CCs between  $IMR_{res}$  and the tropical Atlantic index (Figure 1b; triangles), which are 95% statistically significant for lags between  $-2$  and 4 month for  $ATL_{FULL}$  and  $-2$  and 1 months for CRU.

[14] In Figure 2 the CC pattern over the Indian Ocean reminds of the IOZM in its positive phase. The coefficients, however, have small amplitude in both AIR and CRU. In



**Figure 3.** Regressions onto the tropical Atlantic Index of (a) CRU rain and (b) ATL<sub>FULL</sub> rain and 925 hPa winds, and (c) ATL<sub>FULL</sub> - ATL<sub>CLIM</sub> 925 hPa streamfunction ( $\psi$ ; contours) and 200 hPa velocity potential ( $\chi$ ; shaded). All units are per standard deviation of the regression index: mm/day in Figures 3a and 3b, m/s for wind in Figure 3b,  $10^6 \text{ m s}^{-2}$  for  $\chi$  and  $\psi$  in Figure 3c.

the observations, indeed, the IOZM and NINO34 indices are correlated (in JJAS CC is 0.57 in the HadISST dataset) and part of the IOZM influence is contained in the IMR component linearly forced by ENSO. In ATL<sub>FULL</sub> the SST anomalies in the Indian Ocean play a greater role in forcing the monsoon rainfall compared to observations due to the independence on ENSO of the IOZM-like variability produced by the regionally coupled model [see Bracco *et al.*, 2005, 2007].

[15] The analysis of the ATL<sub>CLIM</sub> ensemble, with the tropical Atlantic SSTs set to climatological values, confirms the importance of south equatorial SST anomalies in modulating the IMR. In those runs the correspondence between the IMR<sub>res</sub> time series and the corresponding CRU and AIR ones decreases drastically to non significant values (CC = -0.05 and 0.07, respectively).

[16] Figure 3a, finally, shows the regression of the tropical Atlantic index onto the JJAS mean CRU rain, and Figure 3b the corresponding regression for ATL<sub>FULL</sub>. The similarity of the two regression patterns is striking. In both CRU and model data, rainfall increases over the Indian subcontinent in combination with cold south equatorial Atlantic SST anomalies, particularly in the western regions. The area averages over the IMR region defined above in the regressions of Figures 3a and 3b are 0.24 mm/day for CRU and 0.26 mm/day for ATL<sub>FULL</sub>, whereas the corresponding ones for the NINO34 regression are -0.42 mm/day and -0.58 mm/day, respectively. In the model the increase in rainfall results from a moist south-westerly flow from the western equatorial Indian Ocean towards the Indian subcontinent.

[17] The physical mechanism behind the Atlantic influence on the Indian monsoon relies on a Rossby wave response induced by tropical Atlantic SSTs. Negative SST anomalies in the south equatorial Atlantic excite a wave projecting positively on the time-mean monsoon circulation, which is in turn intensified (K2007). This is further illustrated in Figure 3c by regressing the 925 hPa streamfunction  $\psi$  (contours) and 200 hPa velocity potential  $\chi$  (shaded) of the difference of ATL<sub>FULL</sub> and ATL<sub>CLIM</sub> onto the tropical Atlantic index. A cold anomaly in the south equatorial Atlantic Ocean forces upper-level convergence (positive  $\chi$ ) over tropical Africa and the Atlantic Ocean, compensated by divergent motion, mainly in the western Pacific. The Indian subcontinent lies on the gradient between these  $\chi$  centres and two surface cyclones - negative (positive)  $\psi$  in the northern (southern) hemisphere - develop over India and south of the Equator at the same longitude. The cyclone over India leads to the moist south-westerly flow seen in Figure 3b.

#### 4. Discussion and Conclusions

[18] We have shown that deviations in Indian Monsoon Rainfall from the linear ENSO response are not only due to internal variability of the climate system, but can be partially simulated by an AGCM regionally coupled to an ocean model in the Indian basin. A correlation analysis with observed SSTs identifies the south equatorial tropical Atlantic (STA) SSTs as the main driver for those deviations. Cold SSTs in the STA region in spring and summer increase the IMR.

[19] This results has important implications for seasonal forecasting efforts. The correlation between CRU and the modeled IMR time series drops from 0.62 when ATL<sub>FULL</sub> is considered to 0.42 for the ATL<sub>CLIM</sub> ensemble. This corresponds to a considerable change in explained variance, more than doubled in ATL<sub>FULL</sub> with respect to ATL<sub>CLIM</sub> ( $CC^2 = 0.38$  and 0.17, respectively). We can conclude that predicting correctly tropical Pacific SSTs is not enough to estimate the remotely forced component of the IMR: Trop-

ical Atlantic temperature anomalies are also necessary, the latter having been identified as a major source of errors in the DEMETER project [Stockdale et al., 2006].

[20] Nevertheless, a major part of the deviations in the IMR time series remain unexplained by SST anomalies in our analysis. Within this work, it cannot be assessed if the remaining is due to atmospheric internal variability, or is related to other forcing not included in our simulations.

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