GEOPHYSICAL RESEARCH LETTERS, VOL. 33, L11701, doi:10.1029/2006GL025871, 2006

Impacts of the tropical Indian and Atlantic Oceans on ENSO

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Received 18 January 2006; revised 10 April 2006; accepted 20 April 2006; published 2 June 2006.

[1] The impacts of the tropical Indian and Atlantic Oceans on ENSO are studied using a series of 500 years long GCM simulations, in which the tropical Indian and/or Atlantic Ocean SSTs are fixed. The results indicate that the tropical Indian and/or Atlantic Oceans SST anomalies substantially influence the coupling over the equatorial Pacific. In the absence of SST variability in the tropical Indian and/or Atlantic Ocean, the main ENSO period is shifted by almost one year. The total SST variance in the equatorial Pacific region is reduced if either Indian or Atlantic Ocean variability is present. At the same time the atmospheric ENSO teleconnections are damped more strongly than the SST. The results can be understood in the context of the recharge oscillator model. However, it is difficult to verify the feedback of the Indian and/or Atlantic Oceans onto ENSO only with statistical analyses of the coupled model control integration or observations. **Citation:** Dommenget, D., V. Semenov, and M. Latif (2006), Impacts of the tropical Indian and Atlantic Oceans on ENSO, *Geophys. Res. Lett.*, *33*, L11701, doi:10.1029/2006GL025871.

1. Introduction

[2] The global climate impact of the El Niño Southern Oscillation (ENSO) phenomenon is well documented in the literature. It has been shown that both the tropical Indian [*Latif and Barnett*, 1995; *Venzke et al.*, 2000] and Atlantic Oceans [*Hastenrath et al.*, 1987; *Enfield and Mayer*, 1997; *Mo and Häkkinen*, 2001; *Huang*, 2004] are strongly influenced by ENSO.

[3] However, very recently several studies have suggested an influence of the Indian Ocean sea surface temperatures (SST) on ENSO [*Yu et al.*, 2002; *Liu*, 2002; *Wu and Kirtman*, 2004; *Annamalai et al.*, 2005; *Kug and Kang*, 2006]. *Liu* [2002] illustrated in a simple model that ENSO can be suppressed when forced by external periodic forcing from the Indian Ocean. *Yu et al.*'s [2002] and *Wu and Kirtman*'s [2004] general circulation model (GCM) results agree in that the interannual Indian Ocean SST variability increases the ENSO variability, while both find contradicting effects on the ENSO period. *Kug and Kang* [2006] found indications in observations that Indian Ocean SST anomalies shorten the duration of warm ENSO extremes. They found that warming in the Indian Ocean produces easterly wind stress anomalies in the western Pacific, which subsequently initiates a more rapid termination of El Niño and a faster transition to La Niña conditions. The simulations of *Yu et al.* [2002] and *Wu and Kirtman* [2004] are, however, based on only 40 years and the observational period analyzed by *Kug and Kang* [2006] is also relatively short, with only 5 events in each of their composites, which limits the significance of their findings. Furthermore, *Wu and Kirtman* [2004] and *Kug and Kang* [2006] discuss observed statistical relations between ENSO and the Indian Ocean SST, which they interpret as evidence for an influence of the Indian Ocean SST onto ENSO. However, the interpretation of the presented statistics is difficult, since ENSO and the Indian Ocean SST are related to each other, due to the primary forcing of ENSO on the Indian Ocean SST.

[4] Assuming the Indian Ocean has an influence on ENSO, one may also wonder, if the tropical Atlantic Ocean could have a similar impact on ENSO, via atmospheric teleconnections. However, there exists not much discussion about the tropical Atlantic SST influence on ENSO in the recent literature. Some indications of an Atlantic influence on ENSO was given, however, in the early work of *Wright* [1986].

[5] In this study, we examine the influence of the interannual Indian and Atlantic Oceans SST variability on ENSO by analyzing a set of 500 years long sensitivity experiments, in which the tropical Indian and/or Atlantic Oceans were decoupled from the atmosphere. The impact of the two tropical oceans on ENSO will be discussed in the context of the simple recharge oscillator model of *Burgers et al.* [2005]. It will be discussed further, if the potential influence of the two tropical oceans can be verified from the statistics derived from observations.

2. Model Simulations

[6] We use the ECHAM5/MPI-OM coupled ocean-atmosphere general circulation model (GCM) developed at the Max Planck Institute for Meteorology (MPI). The atmospheric component is ECHAM5 [*Roeckner et al.*, 2003] with 19 vertical levels and a horizontal spectral resolution of T31, corresponding to approximately 3.75 degrees. The ocean model is MPI-OM [*Marsland et al.*, 2003] with 40 vertical levels and variable horizontal resolution (≈350 km in the Tropics). The coupled model does not employ flux adjustment or any other corrections. Like many non-flux corrected models, the model suffers from a cold bias in the Tropics, and the equatorial cold tongue extends across the equatorial Pacific. The 500 year long control integration [*Gregory et al.*, 2005] of the coupled model exhibits a realistic ENSO period with maximum variance at a period of about 3 years. The ENSO dynamics appear to be similar to the observed, with slow eastward propagating heat content anomalies in the subsurface ocean and a standing SST mode. The ENSO variability, however, is stronger and more regular in comparison to observations.

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[7] To analyze the role of the tropical Indian and Atlantic Oceans for the ENSO variability, three additional 500 years long partially coupled simulations were performed. In these simulations, the upper layer oceanic temperatures in the tropical (20S–20N) Indian, tropical Atlantic, and both the tropical Indian and Atlantic Oceans were prescribed by monthly varying climatologies obtained from the control integration, thus removing interannual SST variability in those regions. The mean state of the tropical regions in the sensitivity simulations has not changed significantly (the mean RMS-error of monthly mean SST in the tropics is less than 0.07 K) and the seasonal mean difference is nowhere larger than 0.4 K.

3. Analysis of Decoupled GCM Simulations

[8] The spectrum of unfiltered monthly mean SST anomalies in the NINO3 region (5°S–5°N/150°W–90°W), T_p, in the control run shows a peak at a period of 3 years and additional subharmonics at 1.5 and 0.75 years (Figure 1). In all three decoupled runs we find a shift in the spectral variance toward longer periods. The variance for periods longer than the control run's ENSO peak increases by 2.0/1.5/2.5 (Indian/Atlantic/both Oceans decoupled) times the control run variance. The variance decreases in the frequency range between the control run ENSO peak and the first subharmonic by $\frac{1}{2}/\frac{1}{2}/\frac{1}{2.5}$. The total variance changes by 1.2/1.0/1.3 times the control run variance. The peak frequency shifts from about 2.8yrs (34mon) toward about 3.8yrs (45mon). Interestingly, the subharmonics at 1.5 years and 0.75 years period have not shifted toward longer periods in the decoupled runs, indicating that these subharmonics may be intrinsic to the tropical Pacific atmosphere-ocean system.

[9] Each ENSO extreme has, in addition to the SST evolution, a characteristic evolution of the zonal winds in the equatorial Pacific. In the model simulation, the strongest zonal wind response is found in a region around the western equatorial Pacific. Figure 2 illustrates that westerly 10m wind anomalies in the western equatorial Pacific are much stronger in the decoupled simulations compared to those in the control simulation. They also persist longer (not shown), which is consistent with the increased ENSO period. The variance increase in the western equatorial Pacific zonal winds amounts to 1.4/1.5/1.2 times the control run variance, which is larger than the increase in SST variance. Even stronger changes are found for the sea level pressure (SLP) variance over the Pacific region and especially in the regions of the fixed tropical Indian and/or Atlantic Oceans, where the total variance of SLP has increased up to twice the control run variance (not shown). Thus the tropical Indian and Atlantic SST variability have a strong damping affect on ENSO.

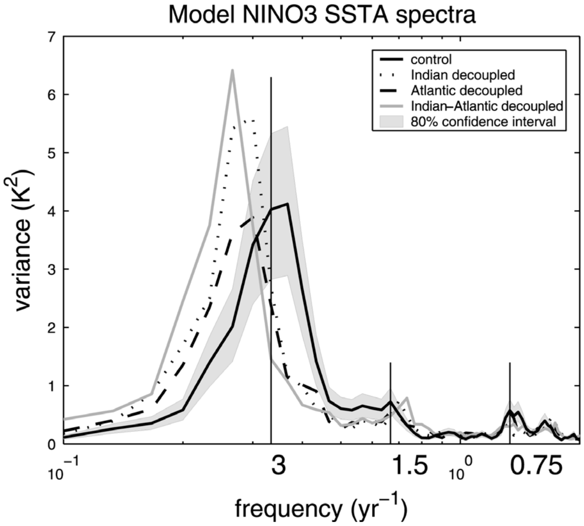
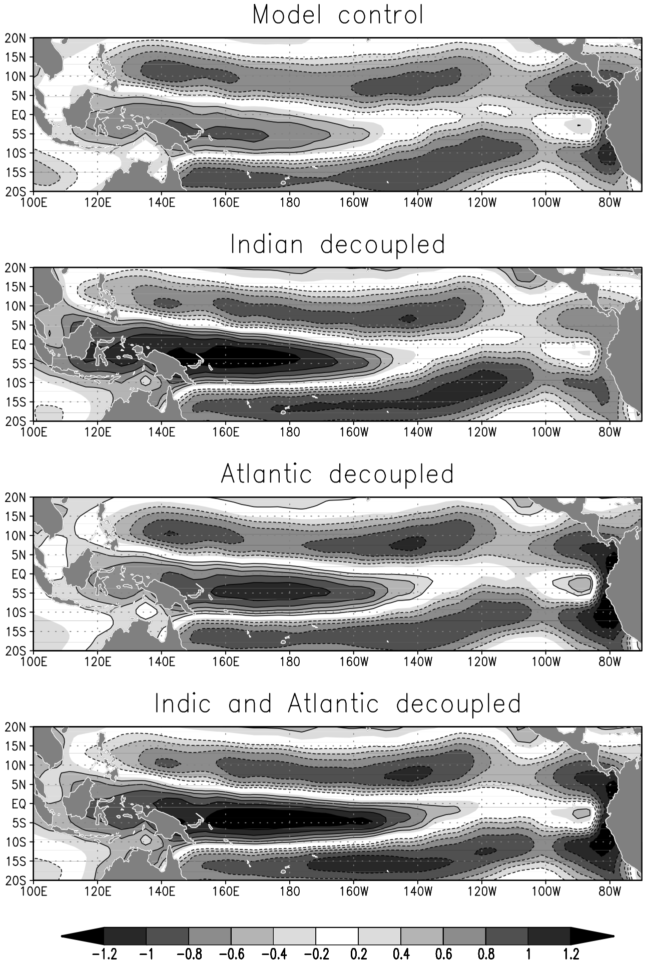

Model NINO3 SSTA spectra

Figure 1. Spectra, Ψ, of monthly mean NINO3 SST anomalies (SSTA) for the GCM simulations. Plotted is the log-scale of the frequency, log(f), versus $\Psi \cdot f$. Subsequently is the area underneath the curves proportional to the total variance of the SSTA.


Model control

Indian decoupled

Atlantic decoupled

Indic and Atlantic decoupled

Figure 2. Model composite mean values of zonal 10m wind anomalies for all ENSO extreme years ($|T_p(december)| > \sigma(T_p)$) averaged from December to May of the following year. For La Niña events the zonal 10m wind is considered with reversed sign in the composites mean. Amplitudes are in fractions of the standard deviation of the zonal wind.

4. Discussion

[10] The aim of this study was to investigate the influence of the tropical Indian and Atlantic Oceans on ENSO. The

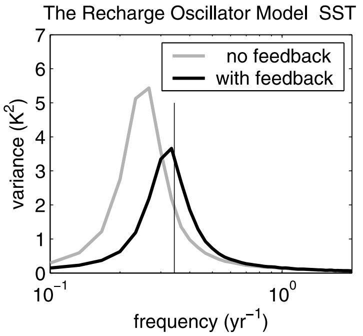


Figure 3. Spectra of T_p in the recharge oscillator model with interactions to T_{ia}.

results of a number of 500 years long GCM model runs showed that both the tropical Indian and Atlantic Ocean SSTs feed back on the periodicity and amplitude of ENSO. The findings with respect to the change in periodicity due to the tropical Indian Ocean SST are in agreement with the model results of *Wu and Kirtman* [2004]. However, the increase in variance when the tropical Indian Ocean is suppressed is in disagreement with the findings of *Yu et al.* [2002] and *Wu and Kirtman* [2004].

[11] It is instructive to discuss the influence of the tropical Indian and Atlantic Oceans on ENSO with a simple toy model. For this purpose, we use the recharge oscillator model of *Burgers et al.* [2005]. We ask also whether or not the feedback of the tropical Indian and Atlantic Oceans on ENSO can be verified by the statistics of the coupled model simulations and ultimately by observations, as discussed by *Wu and Kirtman* [2004] or *Kug and Kang* [2006].

[12] The recharge oscillator model is given by a differential equation for T_p and for the mean thermocline depth anomalies, h, along the equatorial Pacific:

$$\frac{\partial T_P}{\partial t} = -2\gamma T_p + \omega_0 h + \xi_{T_p} \tag{1}$$

$$\frac{\partial h}{\partial t} = -\omega_0 T_p + \xi_h \tag{2}$$

[13] The two quantities are forced by the white noise forcings ξ_{Tp} and ξ_h. *Burgers et al.* [2005] estimated from observations that the damping $\gamma^{-1} = 24^{+22}_{-11}$ months and the oscillation period $2\pi\omega_0^{-1} = 36^{+8}_{-4}$ months. From the statistics of the control GCM simulation we estimated the parameters to $\gamma^{-1} = 22$ months and $2\pi\omega_0^{-1} = 44$ months, which agrees with the observations relatively well.

[14] The T_p anomalies during an ENSO extreme force changes in the Walker circulation which lead to changes in the heat flux and wind stress over the tropical Indian [*Venzke et al.*, 2000] and Atlantic Ocean [*Hastenrath et al.*, 1987]. These changes lead to warming in both tropical oceans. Hence we can simply couple the Indian or Atlantic SST, T_{ia}, to the model by assuming that T_{ia} is driven by T_p and white noise ξ_{Ti}:

$$\frac{\partial T_{ia}}{\partial t} = -\gamma_i T_{ia} + c_{ip} T_p + \xi_{T_{ia}} \tag{3}$$

[15] The values of the damping γ_i, the coupling parameter c_{ip} and the strength of the white noise forcing ξ_{Tia} can be estimated from the statistics of the coupled GCM simulations or observations.

[16] The GCM model results indicated that the original equations (1) and (2) of *Burgers et al.* [2005] must be extended to include a feedback from T_{ia}. In the GCM simulations, a T_{ia} forcing onto T_p (present in the control run) leads to a weaker response of the Walker circulation and associated changes in zonal wind and SLP, and subsequently to reduced T_p variability, if compared to the decoupled runs (without a T_{ia} forcing). This indicates that T_{ia} anomalies damp the Walker circulation response, which acts on T_p as a negative feedback. If we assume that the forcing is proportional to T_{ia}, then the feedback introduced in equation (2) has essentially no effect onto the periodicity of T_p, while introduced in equation (1) it has a significant influence on the periodicity of T_p (an inclusion in both equations does not modify the following discussion):

$$\frac{\partial T_P}{\partial t} = -2\gamma T_p + \omega_0 h - c_{pi} T_{ia} + \xi_{T_p} \tag{4}$$

The coupling parameter c_{pi} can again be estimated from the statistics of the coupled GCM simulation. The model based on (1), (2) and (3) assumes that T_{ia} is slaved to T_p and that T_p is not influenced by T_{ia}, representing the decoupled cases of the GCM simulations. The model based on (2), (3) and (4) have the T_p and T_{ia} interacting with each other in both directions and is taken to represent the situation of the control GCM simulation.

[17] Figure 3 shows the spectra of T_p for the two different toy-models with the parameters fitted to mimic the statistics of the GCM control simulation: $\gamma^{-1} = 22$ months; $2\pi\omega_0^{-1} = 48$ months; $\gamma_i = c_{ip} = \gamma$; $c_{pi} = 4\gamma$; $\sigma(\xi_{Tia}) = 0.2\sigma(\xi_{Tp})$ The forcings ξ_{Tp} and ξ_h have been chosen with identical amplitudes. The shift in variance toward shorter periods, when a feedback from T_{ia} onto T_p exists, is similar to the shift in the GCM simulation as shown in Figure 3.

[18] This simple toy-model suggests that the influence of the tropical Indian and/or Atlantic Ocean onto ENSO can be understood as a linear forcing onto T_p which is proportional to the SST anomalies in the tropical Indian and/or Atlantic Ocean. Furthermore, we find that the oscillation period of the tropical Pacific alone, ω_0, is longer than that is observed in the fully coupled system.

[19] *Wu and Kirtman* [2004] and *Kug and Kang* [2006] argued that the tropical Indian Ocean drives zonal wind changes in the tropical Pacific, thereby affecting ENSO. Zonal wind changes act on both the tendencies of h in (2) and on the tendencies of T_p in (1), where the tendencies of T_p are also influenced by other factors [*Jin*, 1997; *Burgers et al.*, 2005]. Since the feedback of T_{ia} is in (4), this toy model may suggest that this feedback is not associated with zonal wind anomalies only, but that other factors such as latent heat flux or short wave radiation may play a role too.

[20] The cross correlation between T_p and T_{ia} shows that T_{ia} has an out-of-phase relation with both T_p and h, indicating that the T_{ia} feedback term in (4) is substantially different from the pure damping and the pure oscillation

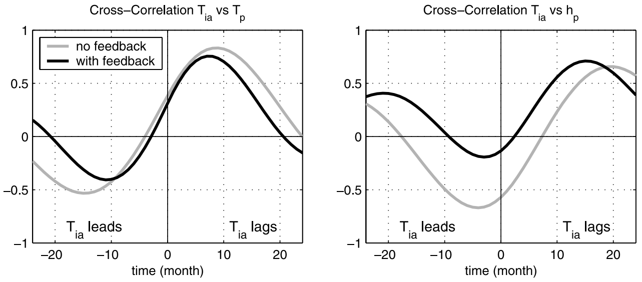


Figure 4. Cross correlations between T_{ia} and T_p(left) and T_{ia} and h_p(right) in the recharge oscillator model with interactions to T_{ia}.

terms (Figure 4). Thus the T_{ia} feedback in (1) is a mixture of a damping and an oscillation term leading to the change of the total variance and a shift of the period as shown in Figure 3. This out-of-phase relation of T_{ia} with both T_p and h may explain why introducing a feedback in the tendency equation of h may have no effect on the peak period of ENSO.

[21] It is interesting to note that the lead-lag correlation between T_p and T_{ia} is more pronounced in the absence of a feedback from T_{ia} onto T_p (Figure 4). Conditional composites, as discussed by *Wu and Kirtman* [2004] and *Kug and Kang* [2006], show similar deviations from the unconditional composite independent of whether the feedback from T_{ia} onto T_p exists or not (not shown). The fact that T_{ia} has a tight relationship to ENSO even in the absence of any feedback from T_{ia} on ENSO, makes it complicated to verify any such feedback from statistical analysis of the coupled model simulations or observations alone. Such analysis will depend on some model assumptions.

[22] The model results of this study are relevant to the predictability of ENSO. We show that ENSO is not just a coupled mode in the tropical Pacific influencing other parts of the world, but that the other two tropical oceans have a significant feedback on ENSO. However, it should be mentioned that the origin of ENSO is in the equatorial Pacific. Predictions of ENSO are likely to be improved if the states of the tropical Indian and Atlantic Oceans are considered to initialize ENSO forecasts.

[23] **Acknowledgments.** We like to thank Gerrit Burgers, Noel Keenlyside, and an anonymous reviewer for discussions and fruitful comments.

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