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Influences of the tropical Indian and Atlantic Oceans on the predictability of ENSO

Claudia Frauen[1,2] and Dietmar Dommenget[2]

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[1] The El Niño Southern Oscillation (ENSO) is the leading mode of climate variability and predictable on interannual time scales. Recent studies suggest that the tropical Indian and Atlantic Oceans influence the dynamics and predictability of ENSO. Here we investigate these effects in a hybrid coupled model consisting of a full complexity atmospheric general circulation model (GCM) coupled to a strongly simplified linear 2-dimensional ENSO recharge oscillator ocean model. We find that the tropical Indian and Atlantic Oceans have distinct effects on the dynamics and predictability. The decoupling of the tropical Indian Ocean has a strong impact onto ENSO dynamics, but the initial conditions of it have only a small impact on the ENSO predictability. In contrast, initial conditions of the tropical Atlantic have a stronger impact on the predictability of ENSO, but the decoupling of the tropical Atlantic has almost no effect on the ENSO dynamics. **Citation:** Frauen, C., and D. Dommenget (2012), Influences of the tropical Indian and Atlantic Oceans on the predictability of ENSO, *Geophys. Res. Lett.*, *39*, L02706, doi:10.1029/2011GL050520.

1. Introduction

[2] For global seasonal and long-term climate predictions the predictability of ENSO is of particular importance. The origin of the ENSO mode lies in the interactions of the tropical atmosphere and the tropical Pacific Ocean, but the teleconnections of ENSO reach far beyond the tropical Pacific region. Areas influenced by ENSO are especially the tropical Indian and Atlantic Oceans and the adjacent continents [see, e.g., *Latif and Barnett*, 1995; *Enfield and Mayer*, 1997].

[3] Recently, different studies suggest the tropical Indian and Atlantic Oceans may not only react to ENSO, but also have an influence on ENSO themselves [*Liu*, 2002; *Yu et al.*, 2002; *Wu and Kirtman*, 2004; *Annamalai et al.*, 2005; *Kug and Kang*, 2006; *Dommenget et al.*, 2006; *Jansen et al.*, 2009]. However, they find somewhat contradictory results regarding the Indian Oceans influence on ENSO amplitude or period.

[4] Regarding the Atlantic Ocean *Dommenget et al.* [2006] found in their coupled GCM study a shift in ENSO period towards longer periods and an increase in ENSO variability if the SST variability in the tropical Atlantic Ocean is suppressed. *Jansen et al.* [2009] found in their conceptual model study only very little changes in the frequency and variability of ENSO by including a feedback from the Atlantic Ocean. However, an inclusion of the Atlantic Ocean can improve the ENSO forecast skill of their simple conceptual model based on parameters from observations. Recently, *Rodriguez-Fonseca et al.* [2009] and *Ding et al.* [2011] suggested an influence of the Atlantic zonal mode on ENSO. Most of these analyses are either based on short time series or are based on model studies with decoupled ocean basins.

[5] Thus, many studies indicate possible influences of the tropical Indian and Atlantic Oceans on ENSO, but the exact characteristics are not fully known yet, and the mechanisms of these teleconnections are not yet understood. In this study we use a hybrid coupled model consisting of a full complexity atmospheric GCM coupled to the minimum complex ENSO recharge oscillator ocean model in the tropical Pacific to analyze the influences of the tropical Indian and Atlantic Oceans on ENSO and ENSO predictability. We want to address the questions what the interactions between the ocean basins are in such a minimalistic model and how the interactions between the ocean basins can improve real perfect model forecast ensembles prediction skills.

2. The Model Simulations

[6] The model used for this study is the hybrid coupled model RECHOZ as described by *Frauen and Dommenget* [2010]. The model consists of the atmospheric GCM ECHAM5 [*Roeckner et al.*, 2003] coupled to the ENSO recharge oscillator ocean model based on *Burgers et al.* [2005] in the tropical Pacific and a simple single column mixed layer ocean model elsewhere [*Dommenget and Latif*, 2008].

[7] Despite the simplistic and, by construction, linear representation of the ENSO ocean dynamics in the RECHOZ model, it is able to correctly simulate the main statistical features of ENSO, such as the power spectrum, skewness, and seasonal phase locking. The advantage of this kind of model is that the SST in various regions can easily be controlled and influences of different feedbacks on ENSO can be quantified in terms of changes in the recharge oscillator parameters. In particular, we can alter or eliminate initial SST or thermocline depth anomalies without causing dynamical shocks to the ocean locally or at remote regions.

[8] The recharge oscillator model is the dynamical core of the RECHOZ model in the tropical Pacific, but it can also be used as a diagnostic tool to estimate the parameters of it from the RECHOZ model output statistics, as done by *Burgers et al.* [2005] for observations. The statistically derived parameters are not the same as those prescribed to the RECHOZ model, as the atmospheric GCM ECHAM5

[1]Leibniz Institute of Marine Sciences at University of Kiel (IFM-GEOMAR), Kiel, Germany.
[2]School of Mathematical Sciences, Monash University, Clayton, Victoria, Australia.

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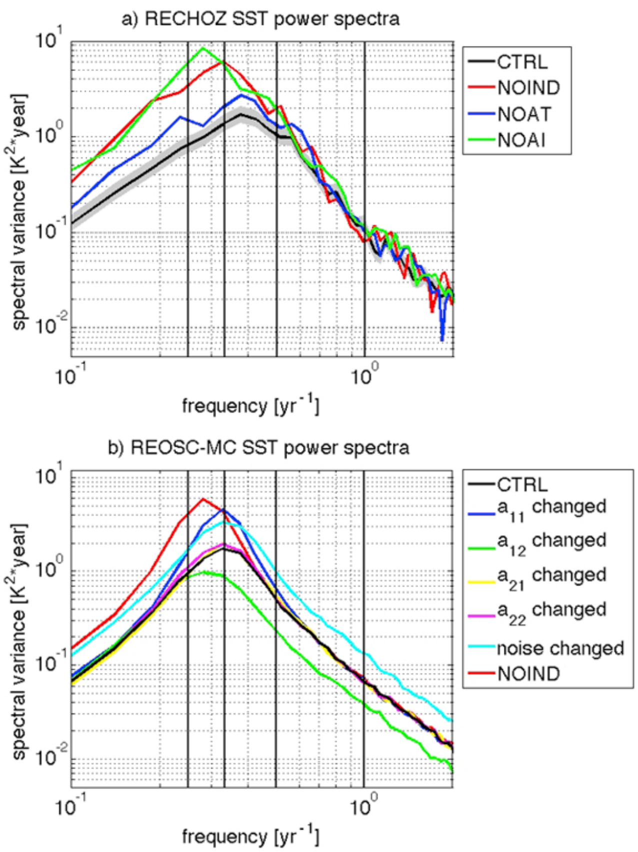

Figure 1. (a) Spectra of monthly mean NINO3 SST anomalies for the CTRL run (black), the NOIND experiment (red), the NOAT experiment (blue), and the NOAI experiment (green). The grey shading indicates the 90% confidence interval of the CTRL run spectrum. The black vertical lines indicate periods of 1, 2, 3, and 4 years. (b) Spectra of monthly mean NINO3 SST anomalies for the REOSC-MC experiments with the parameters obtained from the CTRL run (black), the NOIND run (red), and all parameters from the CTRL run despite a_{11} from the NOIND run (blue), a_{12} from the NOIND run (green), a_{21} from the NOIND run (yellow), a_{22} from the NOIND run (magenta), and the standard deviations of the noise terms from the NOIND run (cyan). The black vertical lines indicate periods of 1, 2, 3, and 4 years.

produces heat flux and wind stress forcings that are not just random white noise, and changes in the atmospheric forcings will lead to changes in the diagnosed parameters. We can therefore use the diagnosed parameters of the recharge oscillator model to quantify the impact of decoupling the tropical Indian and/or Atlantic Oceans on ENSO.

[9] For comparison, these diagnosed parameters are also used to drive a simple Monte Carlo reference model (REOSC-MC), in which the recharge oscillator equations are integrated in time with white noise forcing instead of the ECHAM5 forcing.

3. The Effects of Decoupling the Tropical Indian and Atlantic Oceans

[10] To study the interactions of the tropical Indian and Atlantic Oceans with ENSO three 500 years long sensitivity experiments were performed with the RECHOZ model in addition to a 500 years long control run (CTRL). In each of the sensitivity experiments the SST in a specific region is prescribed by monthly varying climatologies obtained from the control run. First the SST in the tropical Atlantic (30°S – 30°N) (NOAT), then the SST in the tropical Indian Ocean (30°S – northern boundary) (NOIND), and finally the SST in both tropical oceans is prescribed (NOAI).

[11] The resulting power spectra of monthly mean NINO3 SST anomalies for the different experiments illustrate that decoupling the tropical Indian and/or Atlantic Oceans has a significant impact on the ENSO statistics (Figure 1a). Decoupling the tropical Atlantic Ocean leads to a 25% increase in NINO3 standard deviation while decoupling the tropical Indian Ocean not only leads to a 63% increase in NINO3 standard deviation but also shifts the period of ENSO towards longer periods. When both tropical oceans are decoupled the increase in NINO3 standard deviation is of same magnitude but the shift in the period is even stronger. The results concerning the Indian Ocean are in agreement with *Kug and Kang* [2006], *Dommenget et al.* [2006], and *Jansen et al.* [2009]. Only the increase in NINO3 SST variability is stronger than in previous studies. For the Atlantic Ocean the results are also in agreement with *Jansen et al.* [2009] while *Dommenget et al.* [2006] also find a shift in ENSO period by decoupling the tropical Atlantic.

[12] No significant differences in the diagnosed parameters are found between the NOAT and the CTRL experiments apart from a 10% increase in the standard deviations of the residuals, which correspond to the noise forcing terms ξ_1 and ξ_2 in the NOAT run (see Table 1). For the NOIND and the NOAI experiments the differences in the parameters compared to the CTRL run are of similar magnitude. Thus, in the following only the differences between the NOIND and the CTRL experiments will be analyzed. The strongest differences are found in the damping of SST (a_{11}) and the coupling of SST to the thermocline (a_{12}). Further, the standard deviations of the noise forcing terms ξ_1 and ξ_2 are increased by 13% each in the NOIND run. Runs of the diagnostic REOSC-MC model can illustrate the implications of these differences in the parameters. Different 10000 years long experiments with the REOSC-MC model were performed in which the parameters resulting from the CTRL and NOIND experiments and combinations of these were used. First of all we note that the shift in the power spectrum from CTRL to NOIND is about the

Table 1. Resulting Model Parameters From the NOIND, NOAT, and NOAI Experiments Compared to the CTRL Run With 95% Confident Intervals

	a_{11} $\left[\frac{1}{\text{month}}\right]$	a_{12} $\left[\frac{\text{K}}{\text{month m}}\right]$	a_{21} $\left[\frac{\text{m}}{\text{K month}}\right]$	a_{22} $\left[\frac{1}{\text{month}}\right]$	$\sigma(\xi_1)$ $\left[\frac{\text{K}}{\text{month}}\right]$	$\sigma(\xi_2)$ $\left[\frac{\text{K}}{\text{month}}\right]$
CTRL	-0.065 ± 0.009	0.025 ± 0.001	-1.126 ± 0.006	-0.023 ± 0.001	0.272	0.207
NOIND	-0.031 ± 0.006	0.019 ± 0.001	-1.145 ± 0.005	-0.018 ± 0.001	0.308	0.234
NOAT	-0.059 ± 0.008	0.024 ± 0.001	-1.132 ± 0.006	-0.022 ± 0.001	0.297	0.227
NOAI	-0.035 ± 0.006	0.018 ± 0.001	-1.139 ± 0.005	-0.018 ± 0.001	0.330	0.256

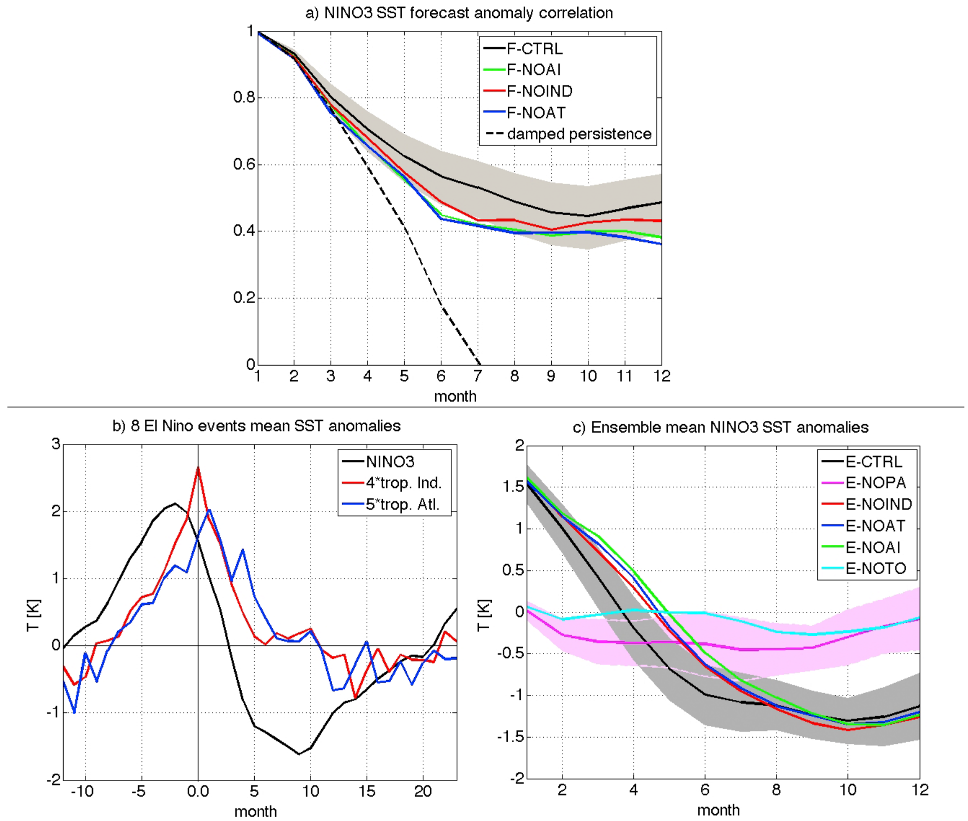

Figure 2. (a) Correlation of monthly mean NINO3 SST anomalies from the CTRL time series with monthly mean NINO3 SST anomalies from the F-NOAT experiment (blue), the F-NOIND experiment (red), the F-NOAI experiment (green), the F-CTRL experiment (black), and the persistence of the CTRL time series (dashed line). The grey shading indicates the 90% confidence interval of the F-CTRL experiment according to a Fisher z transform. (b) Mean evolution of the NINO3 SST anomalies (black), tropical Indian Ocean SST anomalies (red), and tropical Atlantic Ocean SST anomalies (blue) for the 8 events from the CTRL run chosen for the forecast experiments. (c) Ensemble mean NINO3 SST anomalies for the E-CTRL experiment (black), the E-NOIND experiment (red), the E-NOAT experiment (blue), the E-NOAI experiment (green), the E-NOPA experiment (magenta), and the E-NOTO experiment (cyan). The grey shading indicates the 90% confidence interval of the E-CTRL experiment according to a t-test with 8 degrees of freedom and the magenta shading the equivalent for the E-NOPA experiment.

same as in the RECHOZ model, indicating that the REOSC-MC model dynamically behaves in a similar way (see Figure 1b). Further, we find that the changes in the coupling of the thermocline to SST (a_{21}) and the damping of the thermocline (a_{22}) have no influence on frequency and amplitude of ENSO. The changes in the standard deviations of the noise forcing terms ξ_1 and ξ_2, where ξ_2 represents the zonal wind stress forcing and ξ_1 a combination of the zonal wind stress and the net heat flux forcing, lead to increased variability on all time scales. The decrease of the damping of SST (a_{11}) leads to increased variability on ENSO time scales. Only the change in the coupling of SST to the thermocline depth (a_{12}) leads to decrease of variability on time scales up to four years and shifts the peak of the spectrum towards longer periods.

4. The Effects of the Initial SST of the Tropical Indian and Atlantic Oceans in ENSO Forecast Experiments

[13] To study the influences of the tropical Indian and Atlantic Oceans on ENSO predictability two sets of perfect model forecast experiments were performed. First, based on the CTRL run, every 5 years 12 months long forecast experiments were started on January 1st and July 1st. For each of the 200 forecast start dates four ensemble members with slightly perturbed initial SST conditions were calculated. In addition to the control experiments (F-CTRL) again three sensitivity experiments were performed in which the initial conditions in the tropical Indian Ocean (F-NOIND), the tropical Atlantic Ocean (F-NOAT), and both tropical oceans (F-NOAI) were set to climatological values. The anomaly correlation skill of the forecasts decreases significantly for all three sensitivity experiments compared to the F-CTRL experiment (see Figure 2a). The strongest reduction in the forecast skill is found for the F-NOAT experiment, which is outside the 90% confidence interval of the F-CTRL experiment for months 6 and 7 after the restart, while the reduction of the forecast skill is smaller for the F-NOIND experiment. These results are in good agreement with *Jansen et al.* [2009], although in our experiments the effects are much stronger.

[14] To study possible mechanisms leading to enhanced forecast skill if the Indian and/or Atlantic Oceans initial states are included another set of experiments was performed.

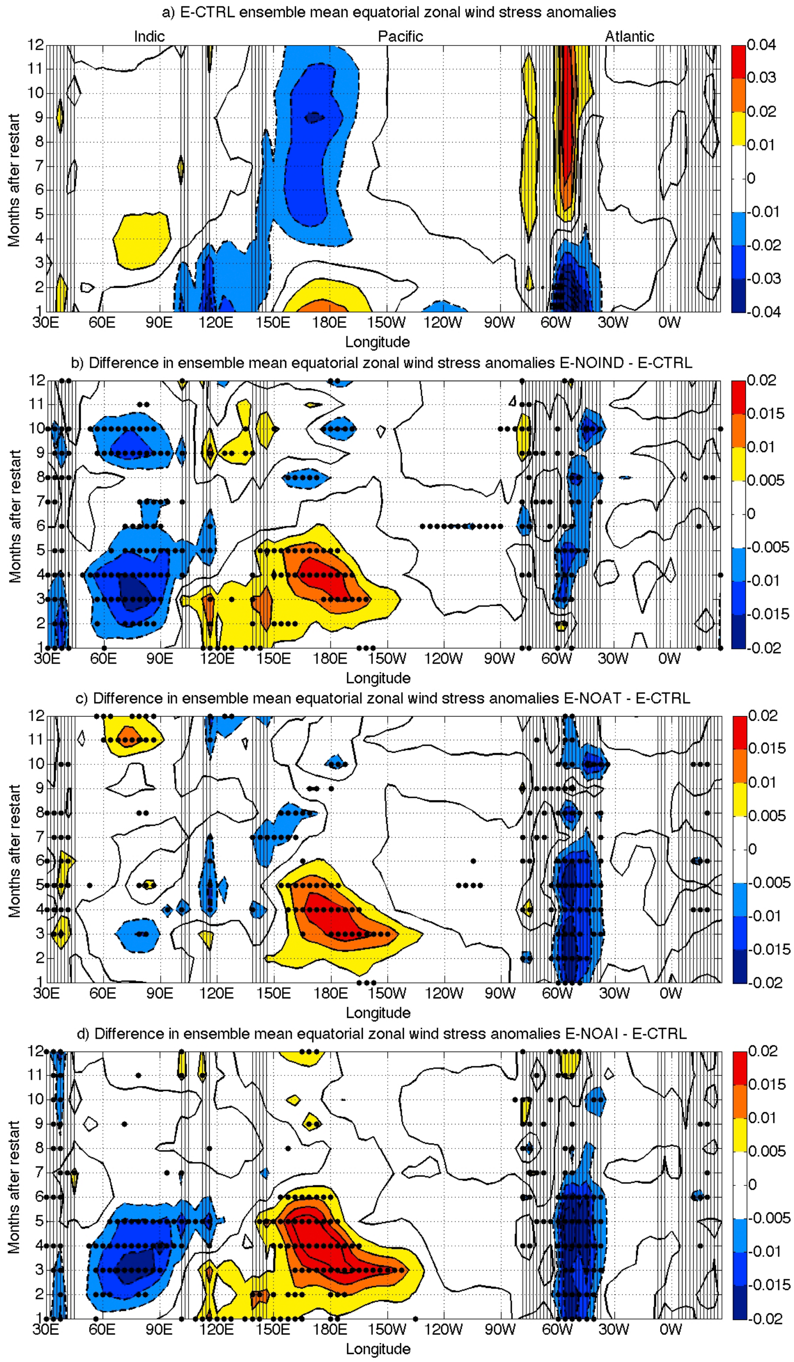

Figure 3. (a) Hovmöller diagram of monthly mean zonal wind stress anomalies averaged from 6S – 6N for the E-CTRL experiment. (b) Difference in monthly mean zonal wind stress anomalies between the E-NOIND and the E-CTRL experiments. (c) Difference in monthly mean zonal wind stress anomalies between the E-NOAT and the E-CTRL experiments. (d) Difference in monthly mean zonal wind stress anomalies between the E-NOAI and the E-CTRL experiments. The vertical lines indicate areas where at least one grid point included in the average is a land point. The dotted areas indicate a statistically significant difference at the 90% level estimated by a t-test where we assume 8 degrees of freedom for months 1 to 3 and 32 degrees of freedom for all other months. Note the different scales between Figure 3a and Figures 3b–3d.

Therefore, 8 events were selected from the CTRL time series in which a strong positive SST anomaly in the tropical Pacific was followed by relatively strong positive anomalies in both the tropical Indian and Atlantic Oceans. Mean SST anomalies for these 8 events can be seen in Figure 2b. For each of the 8 events 6 different forecast experiments were performed with four ensemble members each. In addition to a control experiment (E-CTRL) and experiments with the initial conditions in the tropical Indian Ocean (E-NOIND), the tropical Atlantic Ocean (E-NOAT), and both tropical oceans (E-NOAI) set to climatological values two experiments were performed in which the initial conditions in the tropical Pacific (E-NOPA) and all tropical oceans (E-NOTO) were set to climatology. First of all, we find that in all forecasts that exclude the initial SST anomalies of the Indian and/or Atlantic Oceans the positive NINO3 SST anomaly persists longer than in the control simulation, which is consistent with the findings of *Kug and Kang* [2006], *Dommenget et al.* [2006], and *Jansen et al.* [2009], that positive (negative) SST anomalies in both tropical oceans force a negative (positive) SST trend in the tropical Pacific (see Figure 2c). This is also supported by the E-NOPA experiment, where the forcing from the tropical Indian and/or Atlantic Oceans leads to negative NINO3 SST anomalies. The E-NOTO experiment further illustrates that none of the initial conditions outside the tropical oceans lead to any significant NINO3 SST anomalies.

[15] To understand the reduction of the forecast skill when the Indian and/or Atlantic Oceans are decoupled one can have a look at the evolution of the equatorial zonal wind stress anomalies in the different experiments (Figure 3). In the E-CTRL experiment one finds a positive zonal wind stress anomaly around the date line, which lasts until month 3. Over the eastern part of the Indian Ocean develops a negative zonal wind stress anomaly, which extends across the western Pacific in month 4. In the experiment without the Indian Ocean the negative anomaly over the eastern Indian Ocean is reduced and shifted further to the west, and the positive anomaly over the western Pacific lasts longer. This is in accordance with the changes of the equatorial Walker circulation during an El Niño event where the uprising branch of the Walker circulation is shifted to the central Pacific. For the experiment without the Atlantic no changes can be seen over the Atlantic. But the negative anomaly over South America gets stronger and lasts longer, and again the positive anomaly over the western Pacific lasts longer. This can again be explained by El Niño-like changes in the Walker circulation. Removing the initial conditions in both tropical Oceans leads to a sum of the changes of the previous two experiments.

5. Conclusion

[16] We used the hybrid coupled model RECHOZ to study the influences of the tropical Indian and Atlantic Oceans on ENSO and ENSO predictability. By analyzing different sets of sensitivity experiments it was shown that the main aspects of the tropical Indian and Atlantic Oceans influence on ENSO can be understood relatively well in the framework of the simple linear ocean dynamics of the RECHOZ model. First, a set of experiments was performed, in which SSTs in the tropical Indian and/or Atlantic Oceans were prescribed with monthly varying climatologic values. Second, a set of perfect model forecast experiments were performed, in which the initial conditions in the different basins were set to climatology.

[17] Decoupling the tropical Atlantic Ocean has only little influence on amplitude and frequency of ENSO. Without the Atlantic Ocean the NINO3 variance is slightly increased, but no significant changes in the parameters of the recharge oscillator are found. For the Indian Ocean, however, a strong influence on amplitude and frequency of ENSO is found. Decoupling the Indian Ocean leads to an increase in NINO3 variability and shifts the period of ENSO towards longer time scales. This can also be seen in the parameters of the recharge oscillator. The damping of SST is halved and the coupling between SST and thermocline is reduced. The results for the Indian Ocean are in good agreement with *Kug and Kang* [2006], *Dommenget et al.* [2006], and *Jansen et al.* [2009]. Earlier studies by *Yu et al.* [2002] and *Wu and Kirtman* [2004] found somewhat contradicting results but were only based on very short time series. For the Atlantic Ocean the results are in good agreement with *Jansen et al.* [2009] while *Dommenget et al.* [2006] find also a shift in ENSO period when decoupling the tropical Atlantic.

[18] An important finding of this study is that the tropical Indian and Atlantic Oceans have an influence on the predictability of ENSO. Removing the initial SST anomalies in these basins leads to a reduced forecast skill for NINO3 SST anomalies due to changes in the atmospheric circulation and thus changes in the central Pacific zonal wind stress anomalies. A warm (cold) SST anomaly in the Indian or Atlantic Ocean induces negative (positive) zonal wind stress anomalies over the central Pacific which then leads to cold (warm) SST anomalies in the Pacific. This mechanism is consistent with the results of *Kug and Kang* [2006] for the tropical Indian Ocean and *Rodriguez-Fonseca et al.* [2009] and *Ding et al.* [2011] for the tropical Atlantic Ocean. However, although the Atlantic Ocean has much weaker influence on amplitude and frequency of ENSO, its influence on ENSO predictability is larger than the influence of the Indian Ocean, suggesting that knowing the initial conditions and simulating the evolution of the tropical Atlantic is more important.

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D. Dommenget and C. Frauen, School of Mathematical Sciences, Monash University, Clayton, Vic 3800, Australia. (dietmar.dommenget@monash.edu; claudia.frauen@monash.edu)