Role of the ENSO–Indian Ocean coupling on ENSO variability in a coupled GCM

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Received 25 October 2005; revised 7 March 2006; accepted 10 March 2006; published 13 May 2006.

[1] The effect of the Indian Ocean on El Niño/La Niña life cycles has been studied using 200-yrs simulation data of a coupled GCM. The results show that the interactive feedback between the ENSO and the Indian Ocean holds the key to the rapid transition to an opposite phase. This remote impact of the Indian Ocean SST anomaly is linked to the change of zonal wind stress in the western Pacific, which leads to a rapid demise of El Nino/La Nina. Without the involvement of the Indian Ocean, the phase transition is much slower. This role of the ENSO–Indian Ocean coupling on ENSO transition is consistent with that derived from the observational analysis.

Citation: Kug, J.-S., T. Li, S.-I. An, I.-S. Kang, J.-J. Luo, S. Masson, and T. Yamagata (2006), Role of the ENSO–Indian Ocean coupling on ENSO variability in a coupled GCM, *Geophys. Res. Lett.*, *33*, L09710, doi:10.1029/2005GL024916.

1. Introduction

[2] A number of studies have focused on the impact of ENSO on the Indian Ocean [e.g., *Klein et al.*, 1999; *Reason et al.*, 2000; *Venzke et al.*, 2000; *Xie et al.*, 2002; *Lau and Nath*, 2003; *Li et al.*, 2003]. However, relatively few studies have been devoted to the impact of the Indian Ocean (IO) SST on the ENSO. Recently, though, several investigators have paid special attention to a possible role of Indian Ocean variability on ENSO variability [e.g., *Yu et al.*, 2002; *Wu and Kirtman*, 2004; *Annamalai et al.*, 2005; *Kug et al.*, 2005; *Kug and Kang*, 2006].

[3] In particular, *Kug and Kang* [2006, hereinafter referred to as KK06] emphasized an interactive feedback between ENSO and the Indian Ocean. Their interactive process can be described as follows. During an El Niño-developing summer, El Niño -induced anomalous Walker circulation brings initial SST warming over the western IO. The anomalous warming enhances anomalous easterlies in the equatorial IO, which are then able to generate additional warming in the western IO through various positive air-sea feedback processes [*Webster et al.*, 1999; *Saji et al.*, 1999; *Li et al.*, 2003]. As a result, the Indian Ocean SST further develops during the El Niño-developing autumn. At that time, however, the anomalous easterlies associated with the warming are only confined to the IO, and it has little impact on the tropical Pacific. During the boreal winter when the El Niño is in its mature phase, the anomalous warming extends eastward to cover the entire tropical IO, and the anomalous easterlies extend into the Western Pacific (WP). The anomalous easterlies in the WP generate oceanic upwelling Kelvin waves, which propagate eastward and accelerate the decay of the warm SST in the eastern Pacific. As a result, the El Niño is rapidly terminated, and a La Niña develops within one year from the El Niño mature phase. They concluded that the interaction between ENSO and the IO may generate a biennial tendency for ENSO.

[4] The samples used for the composite analysis by KK06 are rather limited, due to the relatively short length of the observational data. In this study, we intended to analyze a longer (200-yr) data set obtained from the simulation of a SINTEX-F (Scale INTeraction EXperiment-FRCGC) coupled GCM in order to verify the ENSO-IO feedback hypothesis. It turns out that the feedback process between ENSO and the IO is quite plausible not only from observations but also from the state-of-the-art coupled GCM.

2. Model

[5] The model used in this study is the SINTEX-F1. For detailed descriptions of the coupled GCM, readers are referred to *Luo et al.* [2003, 2005]. The ocean component of the coupled GCM is the reference version 8.2 of OPA with the ORCA2 configuration. The model longitude-latitude resolution is $2^\circ \times 2^\circ$ cos (latitude) with meridional resolution increased to 0.5° near the equator. There are 31 vertical levels with 19 of which lie in the top 400 meters. The atmospheric component is the latest version of ECHAM4 with a high horizontal resolution (T106) of about $1.1^\circ \times 1.1^\circ$. The coupling information without flux correction is exchanged every two hours between the OPA and ECHAM4 models by means of an OASIS 2.4 coupler. The CGCM was run for 220 years. In this study, we use the last 200 years' outputs as a control run.

[6] In order to isolate a role of the Indian Ocean on the Pacific variability, we used the "Decoupled Indian Ocean Run". In this run, air-sea coupled process is decoupled over the Indian Ocean, and the atmosphere feels climatological SST from the control run. The "Decoupled Indian Ocean Run" was integrated for 70 years. Details are referred to S. K. Behera et al. (A CGCM study on the interaction between IOD and ENSO, submitted to *Journal of Climate*, 2006).

3. Results

[7] Firstly, we defined El Niño and La Niña events from the 200-yrs model simulation. The El Niño (La Niña) events

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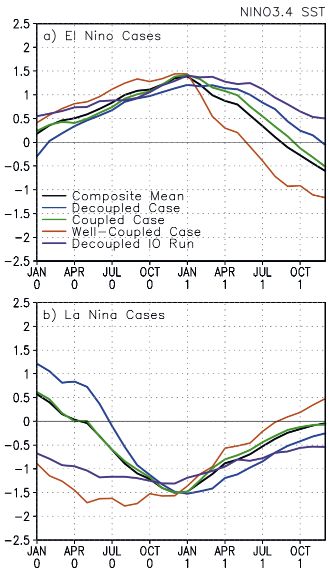

Figure 1. NINO3.4 SST evolution of (a) El Niño, (b) and La Niña events during its developing year, Y(0) and decaying year Y(1). Black, red, green, blue, and violet lines indicate an all case composite, well-coupled case, coupled case, decoupled case, and decoupled Indian Ocean run, respectively.

are defined when the NINO3.4 SST (120–170°W, 5°S–5°N) exceeds its standard deviation during November to the following January (NDJ). Based on this definition, we select 25 El Niño events and 20 La Niña events. Figure 1 illustrates the evolution of the NINO3.4 SST. The composite mean evolution (black line) indicates that the El Niño starts its development in the spring of Year (0), reaches its peak phase in the following winter, and decays and undertakes the transition into a weak La Niña one year after that.

[8] To investigate the impact of the Indian Ocean, we defined a Western Indian Ocean SST index (WISST) by averaging the SSTA over 40–60°E and 10°S–10°N, similar to KK05. Based on the value of the WISST during Nov.–Dec., we divided the 25 El Niño events into 3 groups as shown in Table 1. The first one is a "well-coupled" case. The second is a "coupled" case. The third is a "decoupled" case. Here "well-coupled" means that there is a significantly large SSTA in the IO during developing phases of El Niño or La Niña, while "decoupled" means that there is not, and the "coupled" scenario is somewhere between the two. Thus, the "well-coupled" denotes a strong interactive feedback between ENSO and the IO.

[9] A striking difference between the three groups appears in the El Niño-decaying phase, as seen in the composite evolutions at Year (1). For the "decoupled" composite, the NINO3.4 SST decays slowly so that a normal condition appears at the end of Year (1). By contrast, the termination of the "well-coupled" El Niño progresses rapidly, and the transition to a negative SSTA occurs in late spring or early summer of Year (1) and eventually a strong La Niña develops. This composite evolution of the "well-coupled" El Niño is similar to that of the actual 1997/98 El Niño event. For the "coupled" composite, a transition from an El Niño to a weak La Niña appears during the late summer of Year (1). Noted that the composite mean for the "well-coupled" case is significantly different from the mean composite at 99% confidence level during the El Nino-decaying phase. On the other hand, during the El Nino-developing and mature phases, the differences are not significant at even 90% confidence level. This may indicate the differences during El Nino-decaying phase are caused by not ENSO itself but other factors such as the Indian Ocean SST.

[10] In addition, we have analyzed the "Decoupled Indian Ocean Run", in which the IO is decoupled to atmosphere. This simulation will give a chance to examine whether the IO coupling can result in the fast transition of ENSO or not. Compared to the composite mean, the NINO3.4 evolution of the "Decoupled Indian Ocean Run" shows a much slower transition from El Nino to La Nina. Furthermore, the evolution is even slower than that of "Decoupled" case. This result supports that the IO itself plays an active role on the ENSO transition.

[11] Figure 1b shows NINO3.4 SST evolutions for the La Niña cases. When the La Niña events are divided into 3 groups as listed in Table 2. To avoid too small a sampling, we used slightly different criteria for the WISST. As shown is Figure 1b, the same conclusion is derived. This is, the "well-coupled" La Niña is rapidly terminated and developed into an El Niño state at Year (1), whereas the "decoupled" La Niña slowly decays so that a normal condition appears one year after. Also, the La Nina events in the "Decoupled Indian Ocean Run" slowly decays compare to those of the control run.

[12] The results above suggest that the Indian Ocean warming (cooling) is linked to the fast transition from El Niño (La Niña) to La Niña (El Niño). Through what processes does the IO warming effect the ENSO evolution? KK06 hypothesized that it was through the changes of WP zonal winds induced by the IO warming (cooling). In order to examine the processes in the coupled GCM simulation, we carried out a composite analysis by comparing the "decoupled" and "well-coupled" El Niño cases.

Table 1. Category of Well-Coupled El Niño, Coupled El Niño and Decoupled El Niño and the Number of El Niño Events Among 25 Cases[a]

	WISST	Number of Events
Well-Coupled El Niño	WISST > 1.5 STD	7
Coupled El Niño	0.5 STD < WISST < 1.5 STD	13
Decoupled El Niño	WISST < 0.5 STD	5
El Nino in the Decoupled IO Run	-	8

[a]STD denotes standard deviation of WISST.

Table 2. The Same as Table 1 Except for La Niña Case

	WISST	Number of Events
Well-Coupled La Niña	WISST < −1 STD	6
Coupled La Niña	−1 STD < WISST < 0	11
Decoupled La Niña	WISST > 0	3
La Nina in the Decoupled IO Run	-	10

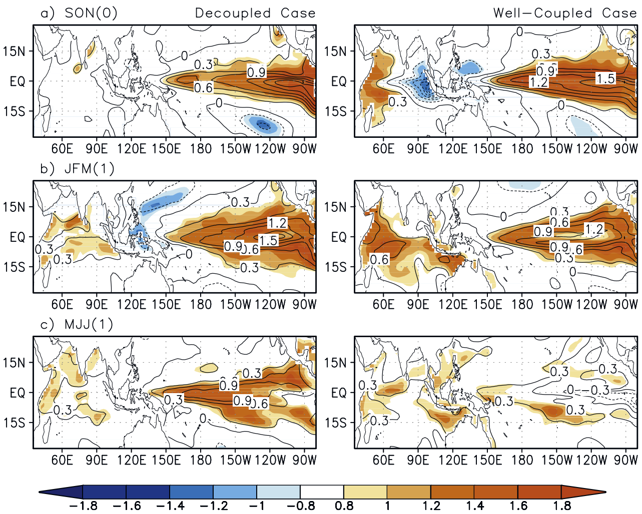

Figure 2. Composite of SST anomaly for a (right) well-coupled case and (left) decoupled case. Shading indicates standardized values of the SST anomaly.

[13] Figure 2 shows anomalous SST composites for the "decoupled" case and the "well-coupled" case, respectively. During SON, strong warm SST anomalies appear over the central and eastern Pacific for both "well-coupled" and "decoupled" cases. In particular, the magnitude of the eastern Pacific SSTA is comparable for both cases, though the central Pacific SST is slightly larger in the "well-coupled" case. However, a distinctive difference is found over the Indian Ocean. As we expected, there is no significant SSTA over the IO in the "decoupled" case, while a strong IO dipole-like pattern appears in the "well-coupled" case. That is, a strong warm SSTA exists in the western IO. During JFM at Year (1), a warm western IO SSTA further develops and is expanded into the eastern IO. *Annamalai et al.* [2005] suggested, based on atmospheric GCM experiments, that an east-west contrast in the IO SST does not generate a significant atmospheric Kelvin-wave response and thus has little impact on the tropical Pacific wind, whereas basin-wide SST anomalies can affect WP wind variability. Thus, the basin-wide IO SST warming in the "well-coupled" case, shown in Figure 2b, may generate anomalous easterly winds over the WP. In the "decoupled" case, however, this effect is modest due to a much weaker SSTA. Therefore, the eastern Pacific SSTA rapidly decays in the "well-coupled" cases, while in the "decoupled" case it decays at a much slower rate as shown in Figure 2c.

[14] Figure 3 shows composite differences between the "well-coupled" and "decoupled" cases. The composite difference is calculated from the "well-coupled" composite by subtracting the "decouple" composite. During SON, there is weak positive precipitation and a westerly wind difference over the tropical Pacific. These differences are related to the different El Nino magnitudes between the two cases. However, a distinctive difference is found over the IO. There is a strong dipole pattern of precipitation and its relevant wind differences. This is linked to the dipole-like SST pattern in the "well-coupled" El Nino case (Figure 2b). As the dipole pattern disappears and basin-wide warming appears over the IO during JFM(1), two significant precipitation differences are found over the western IO and western Pacific. Recently, *Watanabe and Jin* [2002] showed that the IO SST can contribute to the development of the western Pacific anticyclone by modulating the Walker circulation. Therefore, the western Pacific precipitation difference seems to originate from the Indian Ocean precipitation. Associated with these precipitation differences, there is an easterly difference over the western Pacific. Figure 3c shows the equatorial zonal wind differences over the WP. The easterly wind first appears at Dec. (0) and further strengthens and expands to the east during JFM(1).Therefore, we can deduce that the Indian Ocean SST difference causes the western Pacific wind difference between the "well-coupled" and "decoupled" composites. This conclusion is also supported from the AGCM experiments of KK06. KK06 showed in their Figure 11 that the western Pacific anticyclone and equatorial easterlies are produced when only the Indian Ocean SST anomalies are prescribed without any tropical Pacific SST anomaly to their AGCM experiments. In addition, they showed that the Indian Ocean SST is more effective in producing the equatorial WP wind variation than the tropical Pacific SST.

[15] Because the equatorial zonal winds are quasi-balanced with the zonal gradient of the thermocline which is directly related to the eastern Pacific SST anomaly, we have to consider the time tendency of zonal wind stress and thermocline depth in order to examine the role of wind changes on the SST cooling tendency. To do this, we calculated the changes of zonal wind and thermocline depth before and after the El Niño peak phase, i.e., Dec. at Year (0). This analysis explains how the WP wind changes can have an effect on the ENSO transition. For both the "decoupled" and "well-coupled" cases, an easterly tendency is observed to the west of the dateline (Figure 4). However, the magnitude of the wind tendency is much greater in the "well-coupled" case than that in the "decoupled" case. As mentioned, this difference of the wind tendency can be primarily attributed to the effect of the IO SSTA. The difference in the zonal wind can bring about different equatorial thermocline changes. As shown in Figure 4, the shoaling of the thermocline indeed progresses more rapidly in the "well-coupled" case. This leads to an

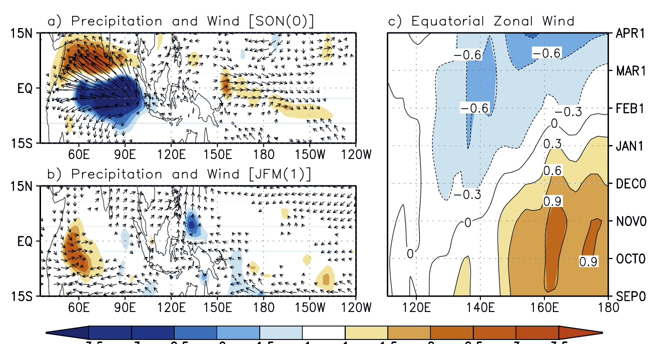

Figure 3. Composite differences of precipitation (shading) and surface wind (vector) between the "well-coupled" and "decoupled" cases during (a) SON(1) and (b) JFM(1). (c) The differences in the zonal wind along the equator. The differences are calculated from a "well-coupled" composite by subtracting "decoupled" cases.

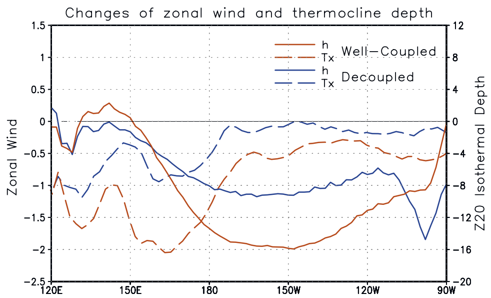

Figure 4. Differences in surface zonal wind (dashed line) and 20°C Isothermal depth (solid line) between Jan.-Feb.(1) and Sep.-Oct. (0) means of a well-coupled El Niño (red) and decoupled El Niño (blue) composites, respectively. The variables are averaged over 2°S–2°N. Positive (negative) value indicates positive (negative) time tendency at Dec. (0).

abrupt termination of the El Niño and the subsequent development of a La Niña in the "well-coupled" scenario.

4. Summary and Discussion

[16] In this study, the ENSO–Indian Ocean feedback hypothesis proposed by KK05 is further verified by analyzing the 200-yr simulation of the SINTEX-F coupled GCM. The model results show that an El Niño (La Niña) is abruptly terminated and a La Niña (El Niño) develops subsequently when the IO warming (cooling) is accompanied with the El Niño (La Niña). The anomalous convection due to the IO warming modulates anomalous Walker circulation associated with the El Niño, and induces an easterly tendency of zonal wind stress in the WP. The wind stress change leads to a fast transition from El Niño to La Niña. These results are consistent with those derived from the observational analyses (e.g., KK06), suggesting that the coupled feedback between ENSO and the Indian Ocean is plausible in the real climate system.

[17] The Indian Ocean–ENSO coupling seems to appear in both the El Niño and La Niña phases, as shown in Figure 1, but the strength of the coupling between ENSO and the Indian Ocean is relatively weaker in La Niña. That is, the El Niño events were more strongly correlated to IO warming, while the La Niña events were less significantly related to IO SST cooling. This feature is also found in KK05's observational analysis. The asymmetry of the coupling with the Indian Ocean may partially explain why the El Niño and La Niña life cycles are different – it is frequently observed that La Niña events (such as the 1970/71, 1973/1974, 1983/1984, and 1998/1999 La Niñas) are prolonged for 2–3 years whereas most El Niño events last for a much shorter period. It is possible that the cause of this difference can be attributed to the asymmetry of El Niño and La Niña coupling with the Indian Ocean. The question of why this asymmetric coupling appears calls for further theoretical and modeling investigation.

[18] **Acknowledgments.** This research was partly supported by the SRC program of the Korean Science and Engineering Foundation. This research was conducted when J.-S. Kug visited IPRC, University of Hawai'i. T. Li was supported by NSF grant ATM01-19490 and ONR grant N000140310739. I.-S. Kang was supported by the Ministry of the Environment as "The Eco-technopia 21 project". S.-I. An was supported in part by NOAA/OGP through the Pacific Program, and in part by Yonsei University Research Fund of 2005. The International Pacific Research Center is partially sponsored by the Japan Agency for Marine-Earth Science and Technology (JAMSTEC). This is SOEST contribution number 6748 and IPRC contribution number 378.

References

Annamalai, H., S.-P. Xie, J. P. McCreary, and R. Murtugudde (2005), Impact of Indian Ocean sea surface temperature on developing El Niño, *J. Clim.*, *18*, 302–319.
Klein, S. A., B. J. Soden, and N. G. Lau (1999), Remote sea surface temperature variation during ENSO: Evidence for a tropical atmosphere bridge, *J. Clim.*, *12*, 917–932.
Kug, J.-S., and I.-S. Kang (2006), Interactive feedback between the Indian Ocean and ENSO, *J. Clim.*, *19*, 1784–1801.
Kug, J.-S., S.-I. An, F.-F. Jin, and I.-S. Kang (2005), Preconditions for El Niño and La Niña onsets and their relation to the Indian Ocean, *Geophys. Res. Lett.*, *32*, L05706, doi:10.1029/2004GL021674.
Lau, N.-C., and M. J. Nath (2003), Atmosphere-ocean variations in the Indo-Pacific sector during ENSO episodes, *J. Clim.*, *16*, 3–20.
Li, T., B. Wang, C.-P. Chang, and Y. Zhang (2003), A theory for the Indian Ocean dipole-zonal mode, *J. Atmos. Sci.*, *60*, 2119–2135.
Luo, J.-J., S. Masson, S. Behera, P. Delecluse, S. Gualdi, A. Navarra, and T. Yamagata (2003), South Pacific origin of the decadal ENSO-like variation as simulated by a coupled GCM, *Geophys. Res. Lett.*, *30*(24), 2250, doi:10.1029/2003GL018649.
Luo, J.-J., S. Masson, E. Roeckner, G. Madec, and T. Yamagata (2005), Reducing climatology bias in Ocean-Atmosphere CGCM with improved coupled physics, *J. Clim.*, *18*, 2344–2360.
Reason, C. J. C., R. J. Allan, J. A. Lindesay, and T. J. Ansell (2000), ENSO and climate signals across the Indian Ocean basin in the global contest: part I, Interannual composite patterns, *Int. J. Climatol.*, *20*, 1285–1327.
Saji, N. H., B. N. Goswami, P. N. Vinayachandran, and T. Yamagata (1999), A dipole mode in the tropical Indian Ocean, *Nature*, *401*, 360–363.
Venzke, S., M. Latif, and A. Villwock (2000), The coupled GCM ECHO-2. part II: Indian Ocean response to ENSO, *J. Clim.*, *13*, 1371–1383.
Watanabe, M., and F. Jin (2002), Role of Indian Ocean warming in the development of Philippine Sea anticyclone during ENSO, *Geophys. Res. Lett.*, *29*(10), 1478, doi:10.1029/2001GL014318.
Webster, P. J., A. M. Moore, J. P. Loschnigg, and R. R. Leben (1999), Coupled ocean-atmosphere dynamics in the Indian Ocean during 1997–98, *Nature*, *401*, 356–360.
Wu, R., and R. Kirtman (2004), Understanding the impacts of the Indian Ocean on ENSO variability in a coupled GCM, *J. Clim.*, *17*, 4019–4031.
Xie, S.-P., H. Annamalai, F. A. Schott, and J. P. McCreary Jr. (2002), Structure and mechanisms of south Indian Ocean climate variability, *J. Clim.*, *15*, 864–878.
Yu, J.-Y., C. R. Mechoso, J. C. McWilliams, and A. Arakawa (2002), Impacts of the Indian Ocean on the ENSO cycle, *Geophys. Res. Lett.*, *29*(8), 1204, doi:10.1029/2001GL014098.

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