Vol.16 No.3 JOURNAL OF TROPICAL METEOROLOGY September 2010

Article ID: 1006-8775(2010) 03-0271-09

IMPACTS OF THE TROPICAL PACIFIC COUPLED PROCESS ON THE INTERANNUAL VARIABILITY IN THE INDIAN OCEAN

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Abstract: The basic features of climatology and interannual variations of tropical Pacific and Indian Oceans were analyzed using a coupled general circulation model (CGCM), which was constituted with an intermediate 2.5-layer ocean model and atmosphere model ECHAM4. The CGCM well captures the spatial and temporal structure of the Pacific El Niño-Southern Oscillation (ENSO) and the variability features in the tropical Indian Ocean. The influence of Pacific air-sea coupled process on the Indian Ocean variability was investigated carefully by conducting numerical experiments. Results show that the occurrence frequency of positive/negative Indian Ocean Dipole (IOD) event will decrease/increase with the presence/absence of the coupled process in the Pacific Ocean. Further analysis demonstrated that the air-sea coupled process in the Pacific Ocean affects the IOD variability mainly by influencing the zonal gradient of thermocline via modulating the background sea surface wind.

Key words: coupled GCM; IOD; tropical Pacific Ocean; ENSO

CLC number: P732.6 **Document code:** A **doi:** 10.3969/j.issn.1006-8775.2010.03.009

1 INTRODUCTION

The air-sea coupled system in the Indian Ocean has long been considered a response to that of the Pacific Ocean. Research on it is rare due to the lack of observations. However, air-sea interactions in the Indian Ocean have attracted unprecedented interest since the discovery of IOD phenomenon[1], which is characterized by opposite signs of sea surface temperature anomaly (SSTA) in the western and eastern tropical Indian Ocean. Then, the debate has shifted the focus on the relationship between the Pacific and Indian Ocean variability[2-4]. Many scientists believe that they are related to each other[5-7], i.e., the ENSO variability can be affected by variations in the Indian Ocean[8-13], and vice versa.

Previous research studied the influence of ENSO on the Indian Ocean by either analyzing observations or performing numerical experiments. So far, most scientists believe that the ENSO event can significantly affect the Indian Ocean SST variability through both atmospheric and oceanic processes[14, 15]. During the mature phase of El Niño, the suppressing of the ascending branch of the Walker circulation leads to reduced cloud cover and increased solar radiation over the eastern Indian Ocean. Therefore, the increase of net heat flux results in warm SSTA in all regions but the southwest tropical Indian Ocean. Albeit with the instantaneous atmospheric response, the SST variability of the eastern Indian Ocean usually lags behind the ENSO variability[16]. Xie et al.[15] also pointed out that the two anticyclonic circulations on both sides of the equator, produced by the equatorial anomalous easterly associated with ENSO, can emanate westward propagating Rossby wave, which will lead to warm SSTA in the western Indian Ocean. Since it usually takes a few months for the downwelling Rossby wave to propagate to the west, warm SSTAs in the western and eastern Indian Ocean are not synchronous. Using a full CGCM of SINTEX-F1 (Scale Interaction Experiment Frontier version 1), Behera et al.[17] studied the IOD event and its relationship with ENSO. Their results suggested that the prominent period of Dipole Mode Index (DMI) is about 3.5–4 years in the control run with a global air-sea coupling. However, the main period of DMI is about 2-year in the numerical experiment without the ENSO process, and the IOD mode turns into the first

Received date: 2009-11-23; **revised date:** 2010-05-28
Foundation item: National Natural Science Foundation of China (40776013, 40306006); State Key Basic Research Development Project (2006CB403603)
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mode, rather than the second mode as in the control run.

The ocean-atmosphere system in the Indo-Pacific region has a significant influence on the ambient, or even global, weather and climate. So it is not only of social benefits but also very important in practice to study the air-sea interaction and its mechanism in this region. Although a number of works regarding the effect of ENSO on the Indian Ocean have been published, there is not yet specific agreement on this issue because of its complexity, and most of the results are based on the full CGCM. Here, in the present study, we will further investigate the above scientific problem in the Indo-Pacific region by utilizing an intermediate CGCM, which has lower computational costs and much clearer physical processes in contrast to the fully coupled model.

The organization of this paper is as follows. In section 2, the air-sea coupled model used in the study will be briefly described. The model outputs are analyzed and the results will be shown in section 3. Finally, section 4 comprises an overall summary and conclusions.

2 MODEL DESCRIPTION AND EXPERIMENTS DESIGN

The intermediate coupled model, used in the present paper, was developed by University of Hawaii. Details of it are described in Wang et al.[18] and Fu et al.[19]. Only a brief description is given here. The atmospheric component is ECHAM4 from Max Planck Institute for Meteorology (MPI-M), with a horizontal resolution of T42 (a triangular truncation at wave number 42), about 2.8º×2.8º, and 19 levels in the vertical. A 2.5-layer ocean model (as shown in Fig. 1), including a variable mixed layer, a variable thermocline layer and a deep resting layer, was used as the oceanic component in the CGCM. Its horizontal resolution is 0.5º×0.5º. The ocean simulation region is (30ºS–30ºN, 0º–360ºE). The atmosphere model exchanges information with the ocean model once a day. The former provides the latter with daily mean surface winds and heat fluxes, and the latter sends daily mean SST back to the former. The initial atmospheric field is from the European Centre for Medium-Range Weather Forecasts (ECMWF) analysis on January 1, 1988. The initial ocean field is a steady state for January of 10-yr integrations of the ocean model forced by observed climatological surface wind and heat flux. Two numerical experiments were conducted. In the first experiment the global tropical ocean was fully coupled with the atmosphere, while the Pacific Ocean was decoupled in the second one. The two experiments will be refered to as CTRL and Pacific_Decouple respectively hereafter. Both experiments were integrated for 40 years. The climatological fields were obtained by averaging the 34-year output over simulation year 7 to 40. The outputs from year 11 to 40 were selected to analyze the interannual variability.

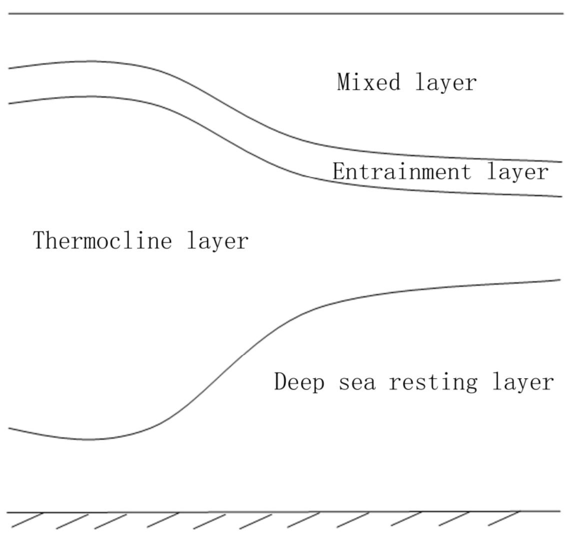

Fig. 1. Schematic diagram of the 2.5-layer ocean model structure

3 RESULTS

3.1 *Experiment design*

3.1.1 HORIZONTAL FLOW FIELDS

The CTRL-simulated annual mean SST, together with its difference from the observation, is shown in Fig. 2. It can be seen that the main SST features in the Indo-Pacific region are well captured by the intermediate CGCM, which indicates the skills of the model in reproducing the basic status of climate variability. The difference between observed SST and that from CTRL is large in some regions, like, along the coast of the eastern Pacific where it is 1.5–2°C. However, the difference is lower than 0.5°C in the regions of the western Pacific warm pool and the Indian Ocean, where the air-sea interaction is active.

Figure 3 shows the distribution of thermocline depth and surface wind stress in the Indo-Pacific region. It is illustrated in the Fig. 3a that the deep/shallow thermocline in the western/eastern Pacific Ocean, associated with the tropical trade wind, corresponds to the Pacific warm pool/cold tongue (Fig. 2a), which further indicates that the air-sea backgroud is simulated successfully by the model. During the Indian summer monsoon, the southeasterly (Fig. 3c) becomes strong in the southeast Indian Ocean. Consequently, sea water in the eastern Indian Ocean accumulates to the west and deepens the thermocline there. Meanwhile, the Somali current is intensified because of the enhanced wind forcing. As a result, the upwelling enhances, partly contributing to the western Indian Ocean SST cooling. The results during the northeast monsoon season are generally opposite (Fig. 3b).

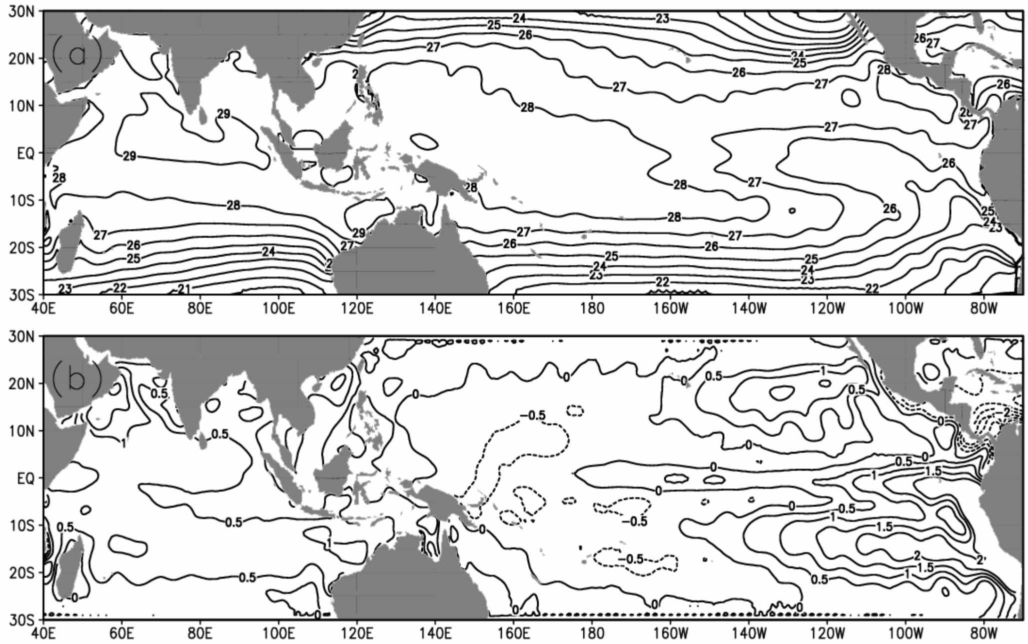

Fig. 2. Simulated SST in CTRL experiment (a) and its difference from the observations (b) Unit: °C

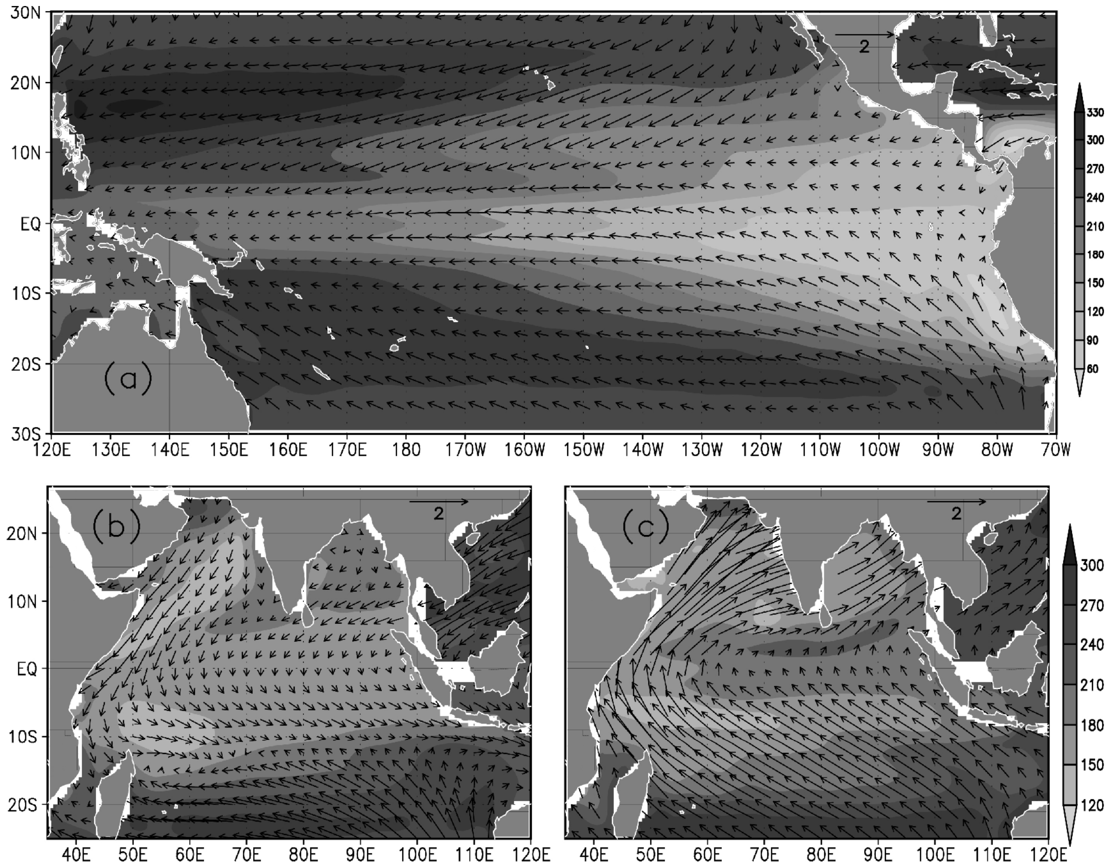

Fig. 3. Thermocline depth (shaded, unit: m) and sea surface wind stress (vector, unit: Pa) distribution of (a) annual mean in Pacific Ocean, (b) Indian Ocean in February, and (c) Indian Ocean in August

3.1.2 INTERANNUAL VARIABILITY

Time series of Niño3 index and its wavelet analysis are depicted in Fig. 4. We can see clearly that the prominent period of ENSO simulated in CTRL is 4–7 years, closing to the observation.

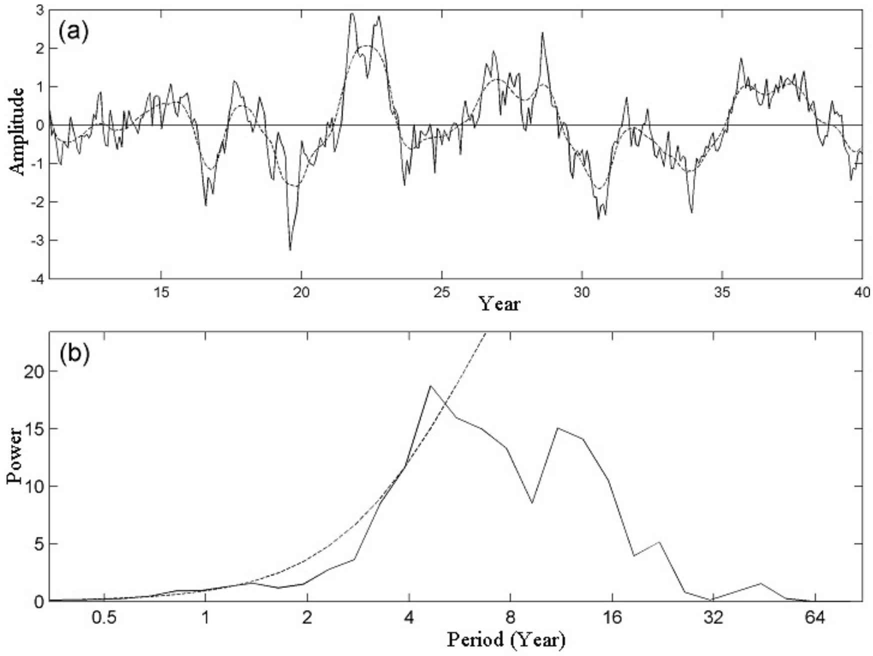

Fig. 4. (a) Niño3 index time series with 5-month running mean series in dashed line (unit: ºC), and (b) its dominant period from wavelet analysis with dashed line denoting 95% significant level

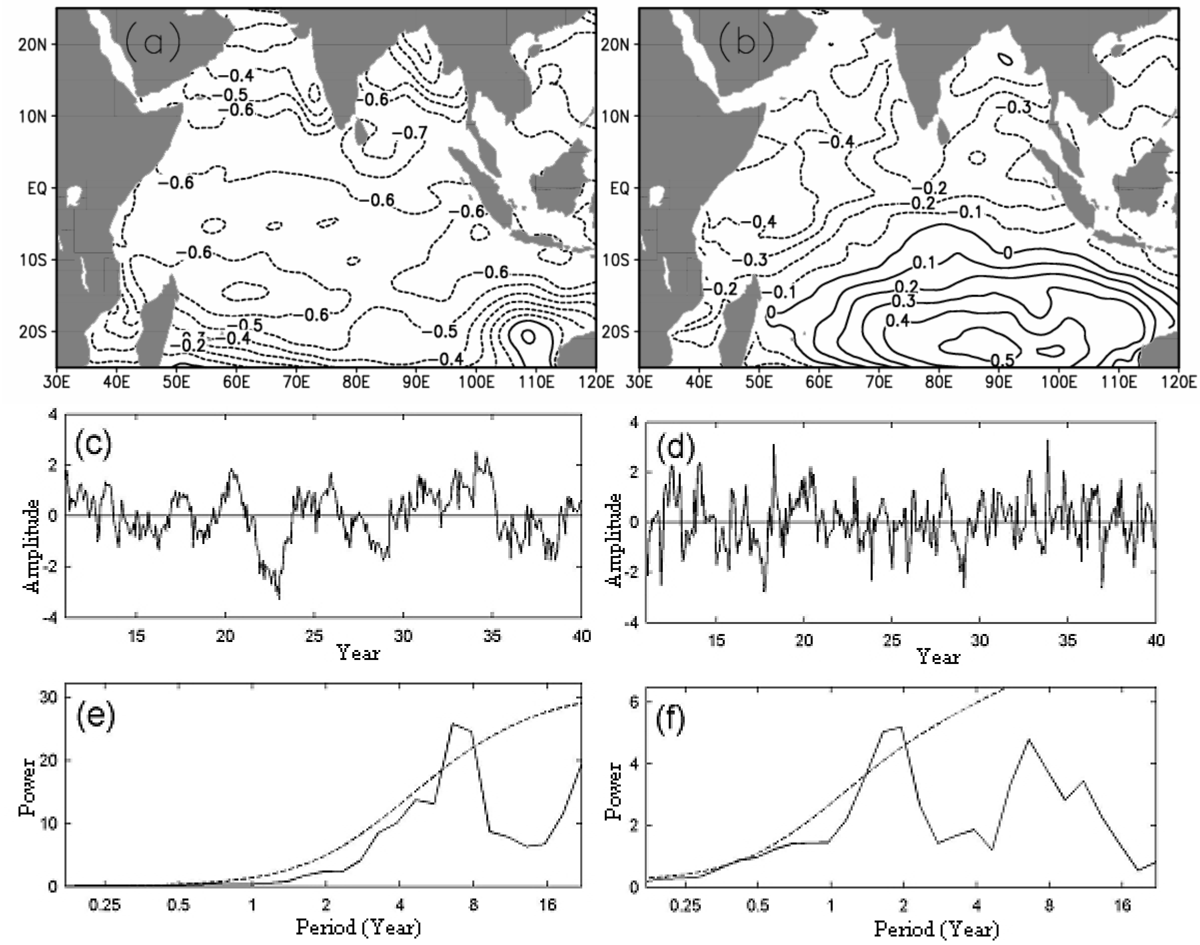

Fig. 5. First EOF mode associated with SSTA in CTRL: (a) space distribution, (c) time series, (e) wavelet analysis of time series (with dashed line denoting 95% significance level). (b), (d), (f) are the same as (a), (c), (e), respectively, but for the second EOF mode.

In order to investigate the interannual variability in the Indian Ocean, EOF (Empirical Orthogonal

Function) analysis was carried out on the SSTA field. Results are presented in Fig. 5. The spatial pattern associated with the first mode, which accounts for 31% of the total variance, exhibits a basin-wide union mode. For its corresponding time series, a main period is about 5–8 years (Fig. 5e), consistent with that of ENSO, which suggests that the first mode is related to ENSO. The second substantial EOF mode, representing 7% of the variance for the SSTA, is the dipole mode which is characterized by opposite signs in the western and eastern Indian Ocean. Correspondingly, the time series derived from the wavelet analysis show an interannual signal with a 2-year period.

To compare the above results with the observation, EOF analysis for Hadley SST over 1971–2000 was conducted. Results are shown in Fig. 6. The first and the second EOF modes represent 30% and 13% of the total variance, respectively. The primary periods of corresponding time series are 3–6 and 2 years with confidence level exceeding 95%. By comparing Fig. 5 with Fig. 6, we can conclude that the CTRL experiment basically reproduces the interannual variability of the Indian Ocean, albeit with some differences both in ENSO period and IOD pattern, which may have something to do with the resolution of the model. Additionally, the air-sea flux with monthly mean solar radiation may also contribute to the error in the model integration.

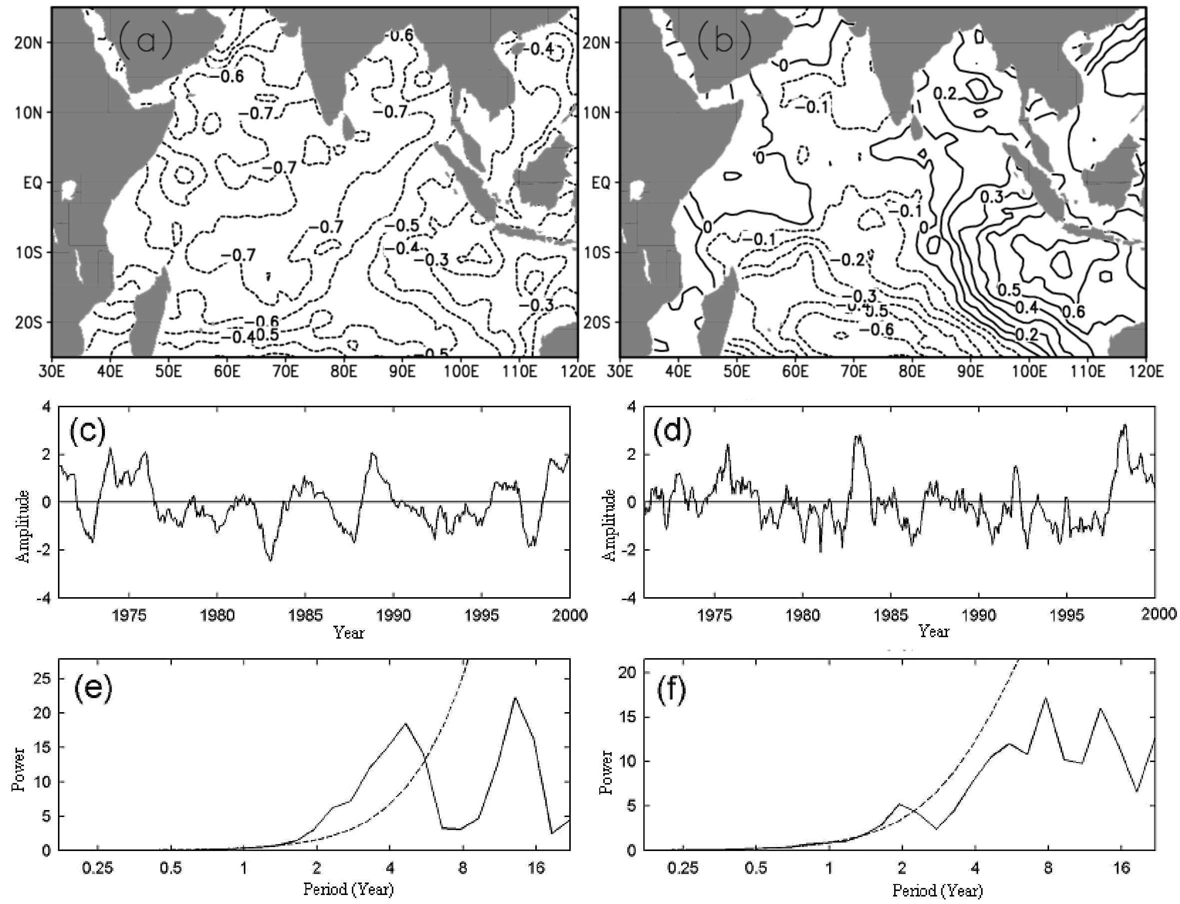

Fig. 6. Same as Fig. 5, but for Hadley SST

In a word, this intermediate coupled model can well simulate the seasonal and interannual variability in the Indo-Pacific region.

3.2 *Effects of Pacific coupled process on the Indian Ocean*

In order to assess the influence of Pacific coupled process on the Indian Ocean variability, we designed a Pacific_Decouple experiment, in which the ocean model in Pacific was decoupled from the atmosphere model. This section will compare its outputs with those from CTRL.

3.2.1 Indian Ocean variability in the Pacific_decouple

SSTA variability was also investigated by carrying out EOF analysis. The first and the second EOF modes represent 16% and 10% of the total variance, respectively. As shown in Fig. 7, the spatial pattern of the primary mode still exhibits a basin-wide mode. However, the wavelet analysis result of temporal coefficients shows a dominant period of about 0.5–1 year, suggesting that the prominent variation is not an interannual signal. The second EOF mode is characteristic of IOD, with the associated time series showing about a 2-year period. Both the temporal and spatial variability of IOD are close to those simulated in CTRL, indicating the occurrence of IOD events without the Pacific coupled process.

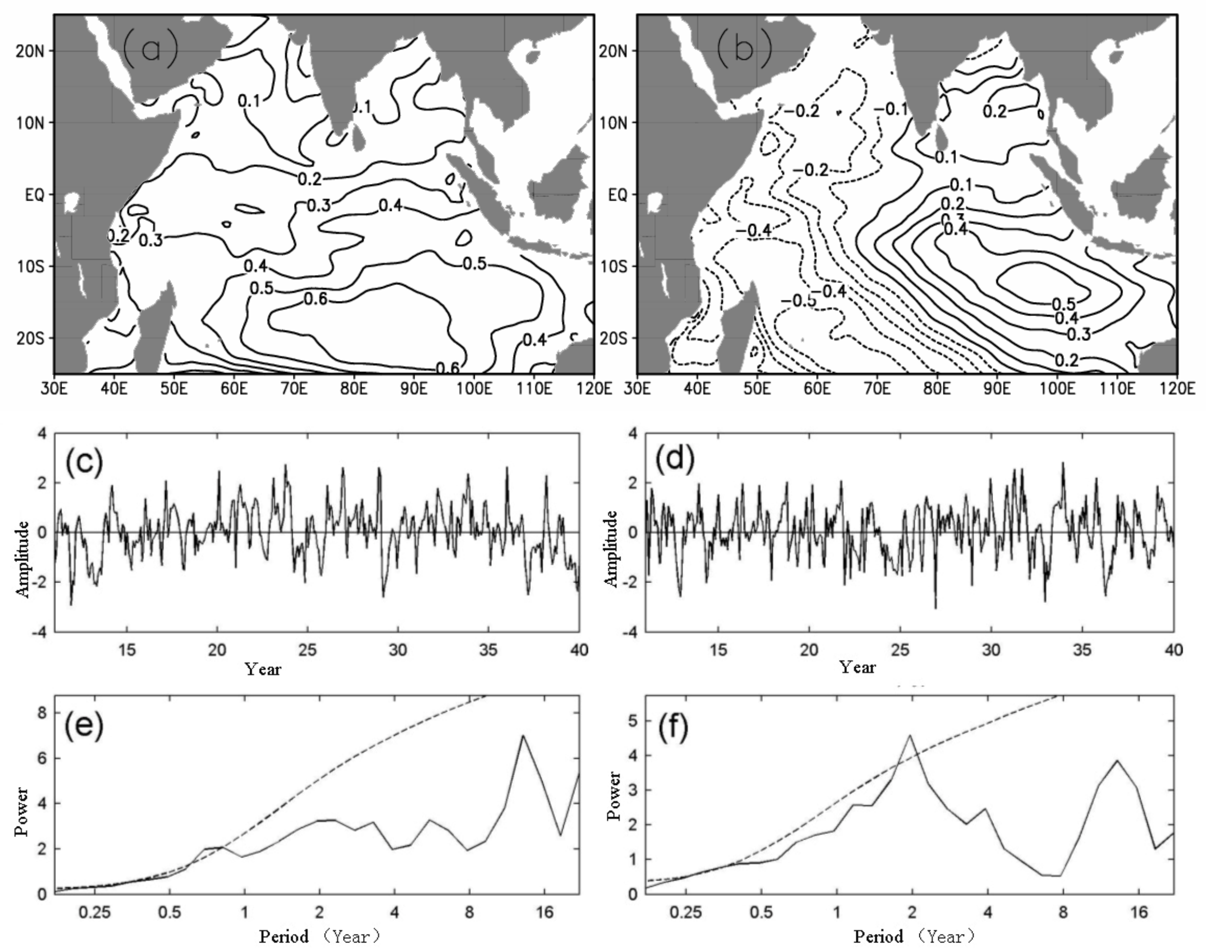

Fig. 7. Same as Fig. 5 but for SSTA in Pacific_Decouple experiment

3.2.2 INFLUENCE ON THE IOD PATTERN

Based on the previous studies, we also selected the difference of SSTA between western and eastern Indian Ocean to characterize the strength of IOD. The SSTA was preprocessed as follows. The zonal mean of SSTA was firstly extracted from the original SSTA series at each grid point so as to get rid of the seasonal influence of solar radiation on the whole basin. Then the Western Indian Ocean Index (WII) and Eastern Indian Ocean Index (EII) were calculated by the average of SSTA in the regions (5ºS–5ºN, 60ºE–75ºE) and (10ºS–0º, 90ºE–110ºE), respectively. By carrying out the bandpass filter between 3 months and 8 years, we can obtain the interannual time series of WII and EII. The DMI, which evaluates the IOD strength, is defined as the difference between WII and EII. We adopted the occurrence criteria of IOD introduced by Saji[8], i.e., signs of WII and EII should be opposite which sustain for at least 3 months, and DMI is required to exceed 0.5 standard deviation (STD) for at least 3 months. A positive/negative IOD event is defined by a positive/negative value of DMI.

Figures 8a & 8c show the DMI time series simulated in CTRL and Pacific_Decouple experiments, respectively. Wavelet analysis results are shown in Figs. 8b & 8d, with the dashed line denoting a confidence level of 95%. According to the identifying criteria given above, the numbers of positive/negative IOD events in CTRL and Pacific_Decouple experiments are 5/7 and 8/6, respectively, over 30 years of the model outputs. Composite patterns of positive events from the two experiments are shown in Fig. 9. It can be demonstrated from Fig. 8 and Fig. 9 that the IOD phenomenon with mainly 2-year period can be simulated in both the experiments. However, the amplitude of DMI during most of the IOD events simulated in CTRL is larger than that in Pacific_Decouple, as suggested in Figs. 8a & 8b. In other words, when there are air-sea coupled processes in the Pacific Ocean, the strength of IOD can be enhanced, and the number of positive/negative IOD events decreases/increases as suggested by the statistical analysis. In addition, the occurrence probability of IOD, independent of the ENSO events simulated in CTRL, is 59%.

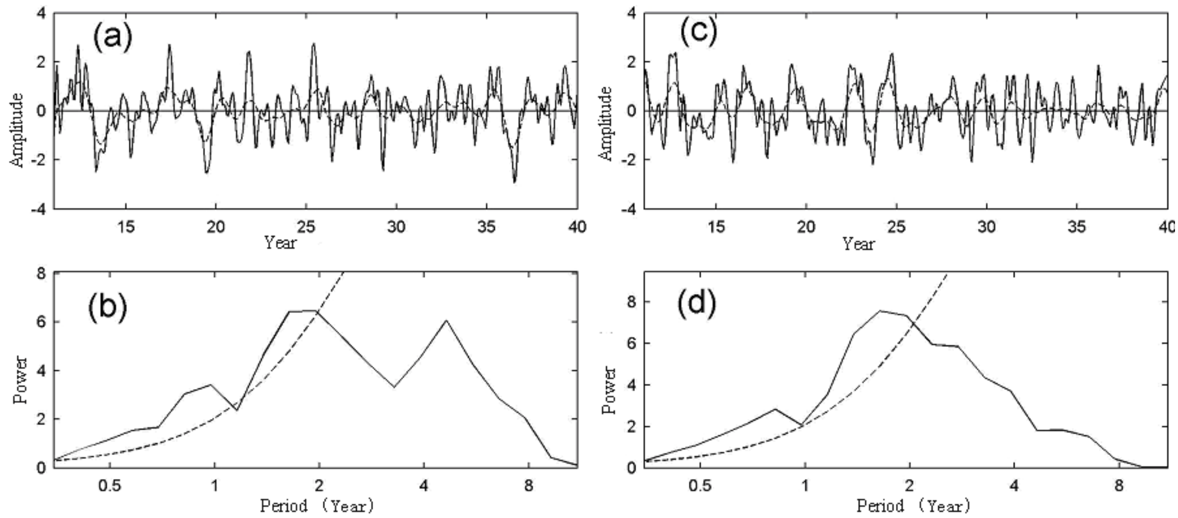

Fig. 8. Time series of DMI simulated in (a) CTRL and (b) Pacific_Decouple, with the dashed line denoting a 5-month running mean (unit: ºC). Prominent period of DMI using Wavelet analysis for (c) CTRL, (d) Pacific_Decouple, with dashed line denoting 95% significance level

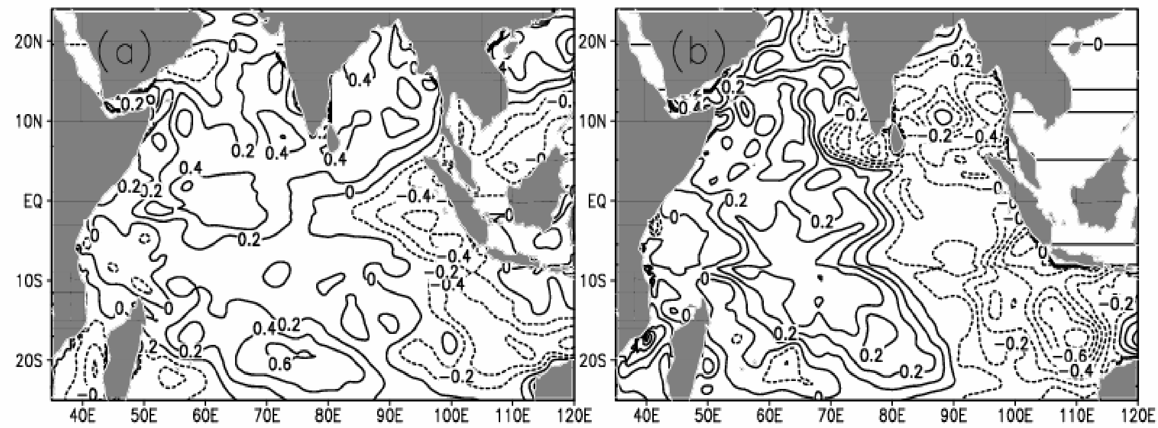

Fig. 9. Composite SSTA pattern in the mature phase during a positive IOD event simulated in (a) CTRL and (b) Pacific_Decouple (Unit: ºC)

In order to further understand how the coupled process in the Pacific influences the IOD, the seasonal cycle of sea surface wind difference, thermocline depth difference and SST difference between CTRL and Pacific_Decouple in the equatorial Indian Ocean were analyzed. Results are displayed in Fig. 10. From a climatological point of view, when the coupled process occurs in the Pacific Ocean, the anomalous easterly and westerly are popular during winter and summer monsoon (Fig. 10a), respectively. In other words, the coupled process in the Pacific can lead to strong summer and winter monsoons in the Indian Ocean. As a result, during summer and autumn, the thermocline is shallower in the west than in the east (Fig. 10b), and SSTA is colder in the west than in the east (figures not shown). However, the anomalous easterly appearing during winter monsoons is too weak to induce a significant thermocline difference between the west and the east (Fig. 10a). Therefore, the spatial pattern of annual mean is similar to that during the summer time. This background condition is in favor of the occurrence of negative IOD events and disadvantageous to that of positive IOD events. Furthermore, the meridional wind change in some distinct regions also has some contribution. For instance, the anomalous southward wind along the Sumatra-Java coast can somewhat favor the development of negative IOD events.

3.2.3 INFLUENCE ON THE SPATIAL PATTERN

The STD of SSTA simulated in CTRL and Pacific_Decouple experiments are displayed in the upper and lower panels of Fig. 11, respectively, with the shades denoting values exceeding 0.4. It is clearly seen from the figures that the SSTA variability is significantly influenced by the Pacific air-sea coupled process during most seasons, especially in the region north of 10°S. Generally, from October to next May, a time that covers the life-cycle of ENSO, the STD of SSTA north of 10°S is relatively larger in CTRL. The activity in south tropical Indian Ocean 15°S–0º over December–March is also remarkable. These facts further confirm that the IOD is stronger in CTRL, a conclusion we have come to in previous sections.

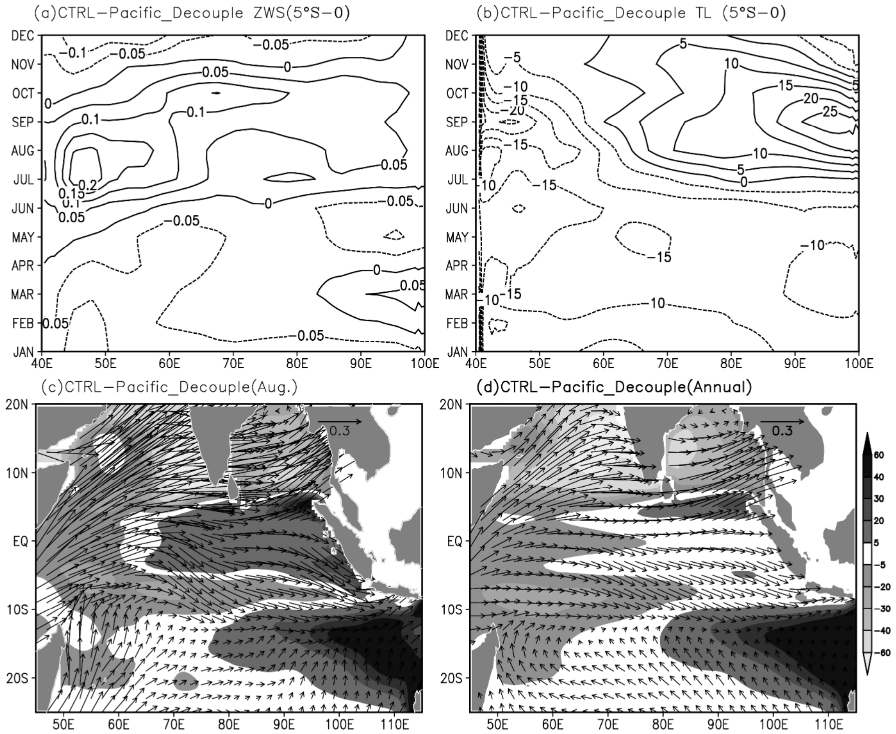

Fig. 10. Seasonal cycle of difference between CTRL and Pacific_Decouple in the equatorial region (5ºS–0º) of the tropical Indian Ocean for (a) zonal wind stress (ZWS) (unit: Pa) and (b) thermocline layer depth (TL) (unit: m). The wind stress and thermocline depth difference between CTRL and Pacific_Decouple of the tropical Indian Ocean in (c) summer and (d) annual mean (The vecor is wind stress, unit: Pa; the shades are thermocline depths, unit: m)

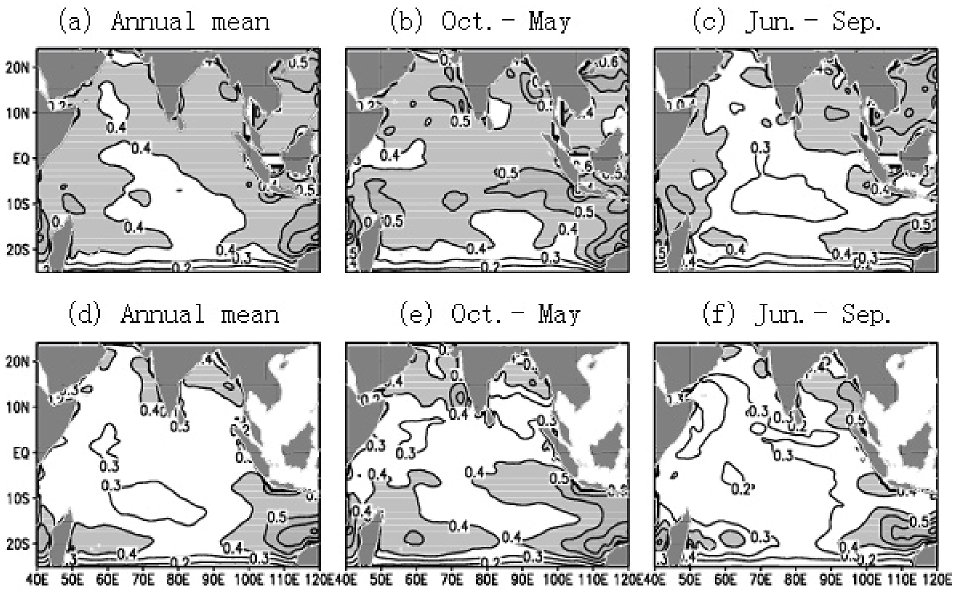

Fig. 11. Standard deviation of SSTA in CTRL for (a) annual mean, (b) October–next May, (c) June–September, and that in Pacific_Decouple for (d) annual mean, (e) October–next May, (f) June–September, with the shades denoting values that exceed 0.4 (unit: ºC)

4 SUMMARY AND CONCLUSIONS

This present work studied the variability in the tropical Indian and Pacific Oceans by employing an intermediate CGCM. The CGCM is capable of reproducing the seasonal and interannual signals in the Indian and Pacific Oceans. It well captures the spatial pattern of ENSO and its irregular period feature. The IOD phenomenon is also simulated successfully. By carrying out numerical experiments, the influence of the coupled process in the Pacific on the Indian Ocean was investigated. It was found that, if the atmosphere and ocean couple together in the Pacific Ocean, the occurrence of a positive/negative IOD event will be more/less frequent. Further analysis suggested that the coupled process in the Pacific Ocean can affect the zonal gradient of the tropical Indian Ocean thermocline depth through modulating sea surface wind, and hence the IOD. Moreover, results also show that the Pacific air-sea coupled process affects the variability north of 10°S in the Indian Ocean significantly during the life cycle of ENSO over October–May, but insignificantly during June–September.

REFERENCES:

[1] SAJI N H, GOSWAMI B N, VINAYACHANDRAN P N, et al. A dipole mode in the tropical Indian Ocean [J]. Nature, 1999, 401: 360-363.
[2] LI Chong-yin, MU Ming-quan. The dipole in the equatorial Indian Ocean and its impacts on climate [J]. Atmos. Sci., 2001, 25 (4): 433-442.
[3] CHAO Ji-ping, YUAN Shao-yu, CAI Yi. Large-scale air-sea interaction events in the tropical Indian Ocean [J]. J. Meteor., 2003, 61(2): 508-512.
[4] FENG M, MEYERS G. Interannual variability in the tropical Indian Ocean: A two-year time scale of IOD [J]. Deep-Sea Res., 2003, 50: 2 263-2 284.
[5] LIU Lin, YU Wei-dong, LIU Yu-guo. Interannual variability of Indian Ocean dipole event and its connection with ENSO [J]. J. Zhanjiang Ocean Univ., 2006, 26(3): 50-55.
[6] KARUMURI A, GUAN Z Y, YAMAGATA T. A look at the relationship between the ENSO and the Indian Ocean dipole [J]. J. Meteor. Soc. Japan, 2003, 81(1): 41-56.
[7] WU R G, KIRTMAN B. Understanding the impacts of the Indian Ocean on ENSO variability in a coupled GCM [J]. J. Climate, 2004, 17: 4 019-4 031.
[8] SAJI N H, YAMAGATA1 T. Possible impacts of Indian Ocean dipole mode events on global climate [J]. Climate Res., 2003, 25: 151-169.
[9] KUG J S, KANG I S. Interactive feedback between the Indian Ocean and ENSO [J]. J. Climate, 2006, 19: 1 784-1 801.
[10] WU R G, KIRTMAN B. Understanding the impacts of the Indian Ocean on ENSO variability in a coupled GCM [J]. J. Climate, 2004, 17: 4 019-4 031.
[11] ANNAMALAI H, XIE S P, MCCREARY J P, et al. Impact of Indian Ocean sea surface temperature on developing El Niño [J]. J. Climate, 2005, 18: 302-319.
[12] YU J Y, MECHOSO C R, MCWILLIAMS J C, et al. Impacts of the Indian Ocean on the ENSO cycle [J]. Geophys. Res. Lett., 2002, 29(8): 461-464.
[13] KUG J S, KIRTMAN B P, KANG I S. Interactive feedback between ENSO and the Indian Ocean in an interactive ensemble coupled model [J]. J. Climate, 2006, 19: 6 371-6 381.
[14] LAU N C, NATH M J. Impact of ENSO on the variability of the Asian–Australian monsoons as simulated in GCM experiments [J]. J. Climate, 2000, 13: 4 287-4 309.
[15] XIE S P, ANNAMALAI H, SCHOTT F A, et al. Structure and mechanisms of south Indian Ocean climate variability [J]. J. Climate, 2002, 15: 864-878.
[16] KLEIN S A, SODEN B J, LAU N G. Remote sea surface temperature variation during ENSO: Evidence for a tropical atmosphere bridge [J]. J. Climate, 1999, 12: 917-932.
[17] BEHEAR S, LUO J J, SEBAASTIEN M, et al. A CGCM study on the interaction between IOD and ENSO [J]. J. Climate, 2006, 19: 1 688-1 705.
[18] WANG B, LI T M, CHANG P. An intermediate model of the tropical Pacific Ocean [J]. J. Phys. Oceanogr., 1995, 25: 1 599-1 616.
[19] FU X H, WANG B. A Coupled modeling study of the seasonal cycle of the Pacific cold tongue, Part I: simulation and sensitivity experiments [J]. J. Climate, 2001, 14: 756-779.

Citation: FENG Jun-qiao and BAI Xue-zhi. Impacts of the tropical Pacific coupled process on the interannual variability in the Indian Ocean. *J. Trop. Meteor.*, 2010, 16(3): 271-279.