A Triggering Process of Indian Ocean Basin-wide Warming in Relation to ENSO forcing.

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Abstract

The physical process of the Indian Ocean (IO) basin-wide warming is investigated using NCEP/NCAR reanalysis data and 1.5 layer ocean model experiments. Composite analysis of six warm episodes of the El Niño illustrates that the reversed Walker circulation (RWC) associated with El Niño-Southern Oscillation (ENSO) modulate the surface atmospheric circulation over the IO. During the autumn, the enhanced easterly wind anomalies and reduction of wind velocity are remarkable over the equatorial IO. This modulation of atmospheric circulation can be explained by the RWC, which effectively weaken the climatological westerly wind. To elucidate how remote El Niño forcing influences the underlying SST, we conduct sensitivity experiment. The anomalous zonal wind, assuming the general remote forcing from the El Niño, is imposed during the boreal autumn, while climatological wind are used during the other season of year in the experiment. As a result of this experiment, the basin-wide warming in the equatorial IO is reproduced in the succeeding winter through the reduction of evaporative cooling. Thus, a coupling process between the RWC associated with the El Niño events and the monsoon circulation during the boreal autumn has a sufficient potential to trigger the IO basin-wide warming.

Keywords: Indian Ocean, basin-wide warming, ENSO, Walker circulation.

1. Introduction

The impacts of atmosphere-ocean variability in the Indian Ocean (IO) are closely related to anomalous weather and climate condition in the surrounding regions. The interannual variation of sea surface temperature (SST) over the IO, including the modulation of monsoon circulation, has been documented in numerous investigations (e.g., Nicholls 1995; Hastenrath et al 2002). It is widely recognized that the dominant interannual variation of SST in the IO is basin-wide warming (cooling) which is lagged behinds to a mature phase of the El Niño (La-Nina) a few months (Nigam and Shen 1993 Tourre and White 1995; Chambers et al. 1999; Klein et al. 1999; Yu and Rienecker 1999; Lau and Nath 2003). The result in Venzke et al. (2000) suggests that the anomalous surface heat fluxes due to the weakened wind speed and the suppressed convective activity play an important role in warming SST in the IO.

Very recently, several studies have suggested that the coupled atmosphere-ocean dynamics plays a significant role in the formation and maintenance of these zonal SST contrast in the IO (e.g. Saji et al. 1999; Webster et al. 1999). Xie et al. (2002) have revealed the important role of the ocean dynamics, especially subsurface thermocline variability associated with the ocean Rossby wave, in modulation of SST over the south IO. Moreover, the cross-equatorial oceanic heat transports forced by the monsoon circulation are essential to keeping the upper ocean heat balance within bounds (Loschnigg and Webster 2000). Thus, the ocean dynamics and monsoon circulation over the IO is an important factor that regulates both the seasonal and interannual variation of SST.

While, there have been a small number of studies that focus on precise seasonal coupling processes between the monsoon circulation and the external forcing in view the basin-wide warming. Thus, the primary goal of this paper is to investigate the characteristics of the physical process involved in the basin-wide warming in the IO. For this purpose, we conduct the sensitivity experiments on SST by use of 1.5 layer ocean model. Data and model description are described in Section 2. The ENSO-monsoon coupling with regard to the model experiments are presented in Section 3. A summary of the major findings of this study are presented in the last section.

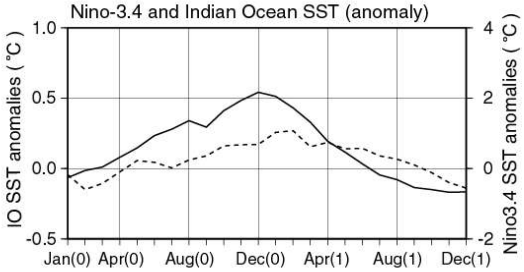


Fig. 1: Evolution of composite monthly mean Niño-3.4 SST (solid: 5ºS-5ºN, 120º-170ºW) anomalies and Indian Ocean SST (dashed: 20ºS-20ºN, 50º-100ºE) anomalies during the mature phase of the six warmest episodes.

2. Datasets and ocean model

We analyzed monthly atmospheric data derived from the National Centers for Environmental Prediction (NCEP)/ National Center for Atmospheric Research (NCAR) reanalysis (Kalnay et al. 1996) on Gaussian grids of T62. As a complementary dataset for comparing with the model data, reconstructed monthly SST datasets of 2-degree grid are also utlized (Smith et al. 1996). These data are prepared for the period from 1955 to 1999. To make reasonable composite, we pick out the most prominent warm El Niño episodes, using a similar method in Wang et al. (2000). Fig. 1 displays the time series of composites Niño3.4 (5ºS-5ºN, 120º-170ºW) and IO (20ºS-20ºN, 50º-100ºE) SST anomalies around the warm peaks of the major ENSO events. It is clear that the peak of composite SST anomalies in the IO lags behind those in Pacific by about 3 months.

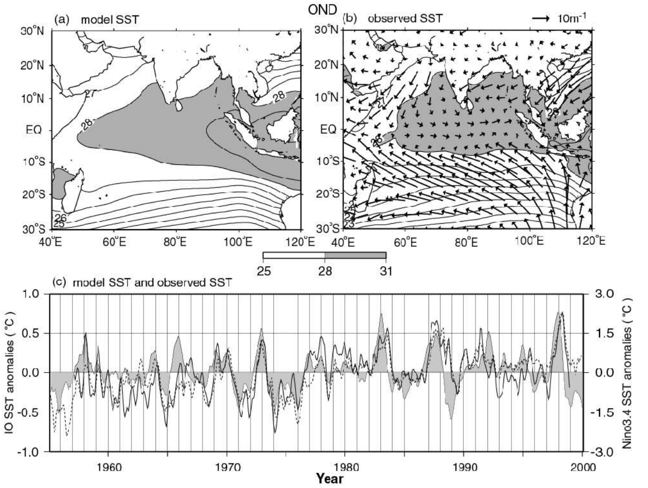


Fig. 2: Climatological (a)simulated SST, (b)observed SST and surface wind averaged between October and December. (c)The 3-month running mean of simulated SST (solid), observed SST (dash) over the IO and Niño 3.4 SST (light shading).

To estimate the variation of SST in the IO due to anomalous external forcing, associated with the ENSO signal, 1.5-layer reduced gravity ocean model (Zebiak and Cane 1987) is used. The physical grid has a horizontal resolution of 1º latitude × 0.5º longitude. The SST is determined by a balance between surface fluxes, horizontal advection by imposed winds, radiative cooling, horizontal diffusion, and entrainment from below the mixed layer. To compute the surface sensible and latent heat fluxes, we use a standard bulk formula. The radiative forcing including short wave radiation and long wave radiation are taken from the NCEP/NCAR reanalysis data. The distribution of simulated SST, observed SST, and flow field averaged between October and December are shown in Figs. 2a, b. Overall, observed SST field is well reproduced, with the meridional temperature gradients in both the Arabian Sea and southern Indian Ocean being captured. During the boreal fall, the equatorial westerly jet, shifted slightly northward from the equator, develops in response to the summer monsoon (Wyrtki 1973). Time series of simulated SST, observed SST anomalies averaged in the IO and Niño-3.4 SST are displayed in Fig. 2c. The correlation coefficient between the IO SST anomalies and Niño-3.4 exhibits 0.58 by 4 months lag that is consistent with previous studies (e.g., Klein et al. 1999). The time series between the simulated SST and observed SST are nearly similar to each other. Thus, the 1.5-layer ocean model sufficiently simulate spatial-temporal variability over the IO, which enable us to conduct idealized experiment in view of atmosphere-ocean coupled system.

3. Monsoon-ENSO coupling

We examine the remote impact of El Niño on the low-level monsoon flows over the tropical IO. To describe the evolution of anomalous circulation during the El Niño, composite analyses are performed based on those of major six warm episodes (1957, 1965, 1972, 1982, 1991 and 1997). We define months in the El Niño onset year as (0), those in the following year as (1).

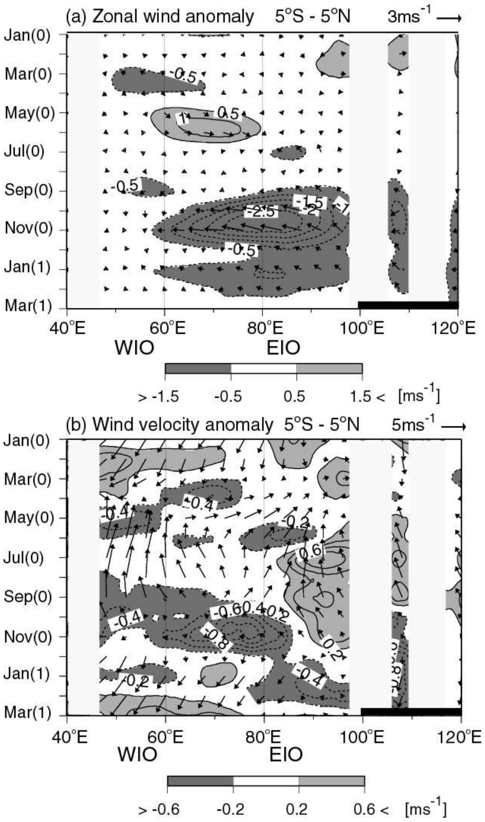


Fig. 3: Longitude-time section of composite anomalies of (a) surface zonal wind and wind vector from January (0) to March (1) for major warm episode of the El Niño year along latitudinal band between 5ºS and 5ºN. (b) Same as (a) except for wind velocity and law wind vector.

Figure 3 shows the longitude-time sections of composite anomalies of the surface zonal wind and wind velocity over the equatorial IO and maritime continent. The vectors represent the composited wind anomalies and raw wind, respectively. The easterly anomalies over the eastern and central IO are recognizable during the boreal autumn in conjunction with a mature phase of the El Niño (Fig. 3a). The most enhanced easterly anomalies are found to occur about 2 months prior to the warm peak of Niño3.4 SST (Fig. 1). The scalar wind velocity in the central IO, centered around 80ºE, is considerably reduced in the boreal autumn (Fig. 3b). It should be emphasized here that the climatological westerly wind is prominent around November in the equatorial IO (Wyrtki 1973). Thus, the climatological westerly wind in the central IO can be remarkably weakened, especially in the boreal autumn, in response to the ENSO-related divergent easterly wind.

To seek physical interpretations that explain the influence of El Niño, we present Fig. 4, the composite anomalies of Walker circulation between October (0) and December (0), corresponded to the mature phase of El

Niño. The convective activity in the western equatorial Pacific shifts eastward to the central and eastern Pacific. This shift in convection leads to a modulation of the Walker circulation, with anomalous rising over the central-eastern Pacific and sinking over the maritime continent. As for the tropical IO, in relation to the downward motion, the divergent easterly anomalies are prominent in the lower troposphere. These results indicate the presence of the reversed Walker circulation (hereafter RWC) extending from the tropical IO through Pacific Ocean.

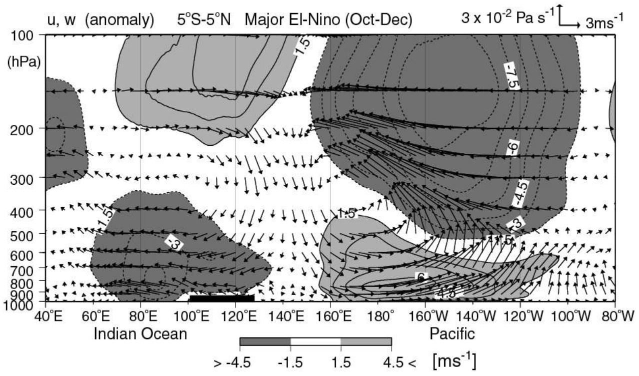
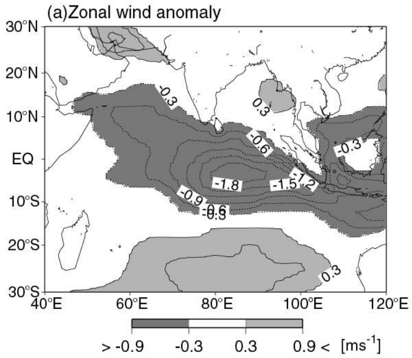


Fig. 4: Longitude-height section of composite anomalies of zonal and vertical wind averaged over the latitudinal band 5ºS-5ºN between October (0) and December (0) for major warm episode of the El Niño. Dark (light) shading denotes u-component wind less (greater) than -1.5 (+1.5) ms^{-1}.

The question we will now address is how the atmospheric change contributes to the interannual variation of SST in the IO. Ueda (2001) suggests that the influence of RWC to the underlying SST can be regulated by the strong monsoon seasonality. The divergent easterly anomalies during the boreal autumn weaken the climatological westerly wind. The reduction in wind speed is expected to induce reduced vertical mixing in the surface layer of the ocean and reduced evaporation from the ocean surface. Thus, in the succeeding winter, positive SST anomalies expand over the tropical IO.

To understand whether the basin-wide warming in the IO is actually due to the remote impact of El Niño in the boreal autumn, an idealized experiment is conducted that is designed to yield a straightforward answer to this question. We impose the divergent easterly anomalies onto the atmospheric circulation in the tropical IO, and ascertain its response to the underlying SST. In this experiment, we use monthly varying climatological surface heat flux. The composited zonal wind anomalies between September (0) and January (1) is used as a remote impact of the RWC (Fig. 5a). This wind anomaly is imposed for three months from October (0) through December (0). As stated above, the climatological westerly wind is prominent in these months, which is transition period of the monsoon. Monthly varying climatological wind is imposed during other months.

Figure 5b shows the model response to the easterly wind anomaly in January (1). In the tropical IO, warm SST anomaly emerges in the subsequent boreal winter. Although excessively warm SST is seen in the central IO, basin-wide warming is clearly simulated. Therefore, we conclude that the remote El Niño forcing in the autumn is the fundamental factor for triggering process of the basin-wide warming.


(a)Zonal wind anomaly

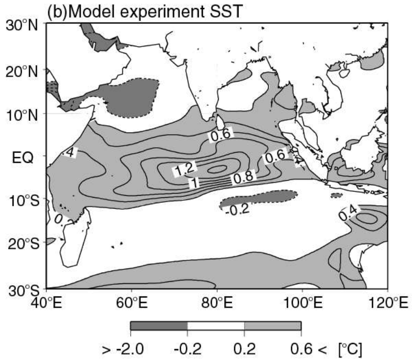

(b)Model experiment SST

Fig. 5: (a) Composite anomalies of surface zonal wind between September (0) and January (1) for the major warm episodes of the El Niño year. (b) SST anomalies in the sensitivity experiment.

4. Concluding remarks

In this study, we examined the basin-wide warming in the IO during the warm episode of El Niño, including the possible mechanisms that regulate the SST and its seasonal dependability. We have paid great attention to the changes in atmospheric circulation and its influence on the underlying SST. The result of the idealized experiment indicates that the seasonal coupling process between the seasonality of the monsoon circulation and remote El Niño forcing plays a crucial role in the trigger process of the basin-wide warming in the IO.

This conclusion is based on following findings. From the analysis of the atmospheric datasets derived from the NCEP/NCAR reanalysis, it is demonstrated that Walker circulation over the Pacific and IO is weakened by the ENSO forcing. During the boreal autumn, the RWC act to weaken the climatological westerly jet and thus reduce the evaporative cooling around the central IO. The 1.5 layer ocean model confirms that these atmospheric changes significantly contribute to the basin-wide warming in the IO. Consequently, it is conceivable that seasonal march of the climatological wind is the important factor to understand the physical process of basin-wide SST warming in the IO. This is consistent with the inferable opposite mechanism during a cold episode of El Niño that causes the basin-wide cooling in response to increased evaporative cooling through the reinforced Walker circulation.

Based on this study and those of previous investigators (Klein et al. 1999; Ventzke et al. 2000), it has become clear that atmospheric change accompanying El Niño induce surface warming of the IO. The previous investigators also indicate the significant effect of the change in cloud cover that contributes to the SST warming. More detailed analysis is needed to reveal the development process of the IO basin-wide warming.

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