AIR-SEA INTERACTIONS OVER THE INDO-PACIFIC REGION DURING ENSO

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ABSTRACT

Numerical experiments are performed with a coupled atmosphere-ocean GCM (CGCM) to study the interactions between climate variability over the Indian Ocean and Pacific ENSO. One CGCM experiment includes only the tropical Pacific in the coupled domain, and the other includes both the tropical Pacific and Indian Oceans. There are three principal new findings of this study. First, an active Indian Ocean can enhance ENSO magnitude and prolong ENSO period. A strong interdecadal modulation in ENSO activity is also produced when the Indian and Pacific Ocean are allowed to interlace with each other in the CGCM. Second, air-sea interactions in the Indian Ocean are very different from those in the Pacific Ocean. Surface heat flux is an active forcing to the interannual variability of the Indian Ocean, while it is a passive damping to ENSO in the Pacific. Third, the interannual variability in the Indian Ocean is characterized by two major features. One is an east-west contrast in sea surface temperature (SST) anomalies along the equator, which is similar to the major feature of Pacific ENSO. The other feature is a strong north-south shifting of sea surface temperature (SST) anomalies across the equator, which is not seen in the Pacific. This study identifies an Indo-Pacific SST anomaly pattern, which includes five major SST teleconnection features over the Indo-Pacific Oceans during ENSO events.

1. INTRODUCTION

The fundamental physical processes that give rise to the El Niño-Southern Oscillation (ENSO) phenomenon are believed to reside within the tropical Pacific. This belief is supported by the successful ENSO simulations of many coupled atmosphere-ocean models that include only the tropical Pacific Ocean (e.g., Cane and Zebiak 1985; Schopf and Suarez 1988; Battisti and Hirst 1989; Yu and Mechoso 2000). However, there is evidence that climate variability originated from the Indian Ocean can be intertwined with ENSO activity through atmospheric or oceanic connections (e.g., Meehl 1987; Barnett 1984; Webster and Yang 1992; Wyrtki 1987; Philander and Delecluse 1983). Major climate variations in the Indian Ocean include: weak and strong summer Asian Monsoons, interannual Indian Ocean warming, and volume fluctuations in the Indonesian throughflow. It has been suggested that those climate features can affect the magnitude and frequency of ENSO. The decade-to-decade changes of ENSO activity may be related to such inter-basin interactions. This study is aimed at obtaining a better understanding of the interactions between climate variability over the Indian Ocean and ENSO activity in the Pacific Ocean.

Since the climate system over the Indo-Pacific region is characterized by strong interactions between the atmosphere and ocean, we chose to use a coupled atmosphere-ocean general circulation model (CGCM) for this study. Two long-term CGCM simulations are performed with the UCLA CGCM. One of them includes only the tropical Pacific Ocean in the oceanic component (hereafter, the Tropical-Pacific Run), and the other includes both the tropical Pacific and Indian Oceans (the Indo-Pacific Run). By contrasting climate variability produced in these two CGCM runs, we examine (1) the impacts of an active Indian Ocean on Pacific ENSO, (2) the impacts of Pacific ENSO on the interannual variability of the Indian Ocean, and (3) the differences between air-sea interactions over the Indian Ocean and those over the Pacific on interannual timescales.

2. MODEL AND SIMULATIONS

The UCLA CGCM consists of the UCLA atmospheric GCM (AGCM) and the GFDL Modular Ocean Model (MOM) (see Yu and Mechoso 2000 for a description of the version of the UCLA CGCM used in this study). The AGCM is global with a horizontal resolution of 5-deg longitude by 4-deg latitude and 15 levels in the vertical. In the Tropical-Pacific Run, the OGCM covers the Pacific between 30°S and 50°N and

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between 130°E and 70°W. In the Indo-Pacific Run, the ocean model domain is extended to include the Indian Ocean. Outside the OGCM domain, SSTs are prescribed based on a monthly-varying SST climatology. In both runs, the OGCM has the same longitudinal resolution of 1°. Their latitudinal resolutions vary gradually from 1/3° between 10°S and 10°N to about 3° at both 30°S and 50°N. The OGCM has 27 layers in the vertical. Figure 1 shows the ocean model domain and sea/land masks used for these two runs. Both the Tropical-Pacific and Indo-Pacific Runs are integrated for 53 years. The long-term mean sea surface temperature (SST) simulated by these two runs are also displayed in Fig. 1. It shows that both runs produce realistic simulations of the mean climate states in the Indo-Pacific Oceans. Also the mean states produced by these two runs over the Pacific ocean are similar, which suggest that adding an active Indian Ocean into the CGCM does not affect the Pacific mean state.

3. IMPACTS OF AN ACTIVE INDIAN OCEAN ON PACIFIC ENSO

We first examine whether or not ENSO behavior is affected by an active Indian Ocean. We contrast in Fig. 2 the interannual variability of equatorial SST produced by the two CGCM runs. The variability is calculated by first removing the long-term monthly means (i.e., the annual cycle) from the simulated monthly-mean SSTs and then removing the variability with timescales shorter than one year using a low-pass filter. Figure 2a shows that the Tropical-Pacific run produces warm events approximately every 3-5 years in the Pacific Ocean. The largest warm ENSO event has a maximum SST anomaly close to 2°C. The spatial structures and temporal evolutions of these warm and cold events have been thoroughly examined in Yu and Mechoso (2000) and were shown to closely resemble observed ENSO events.

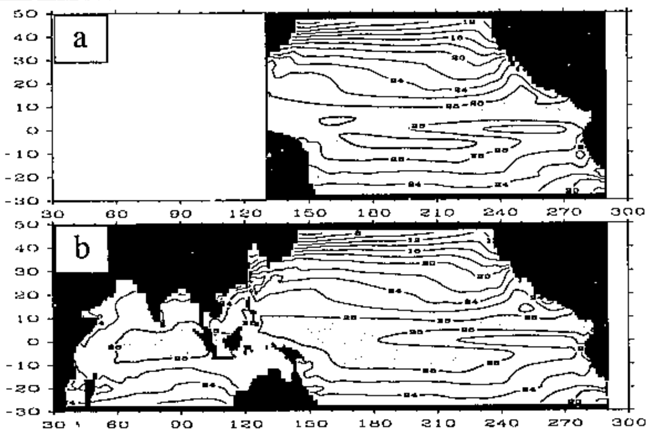

Figure 1. Ocean geometry used in the (a) Tropical-Pacific run and (b) Indo-Pacific run. Also shown are the long-term mean SSTs produced these two runs. Contour intervals are 2°C. Values greater than 28°C are shaded.

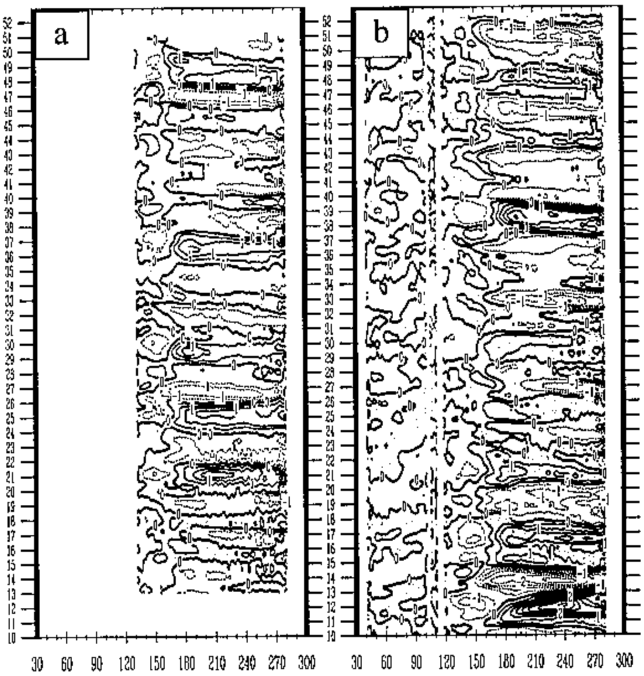

Figure 2. Interannual variability of SST along the equatorial Indo-Pacific Oceans produced from the (a) Tropical-Pacific run and (b) Indo-Pacific run. Annual cycles are removed, and a low-passed filter is applied to remove variability with timescales less than 12 months. Contour intervals are 0.5°C. Positive values are shaded.

Figure 2b shows that the Indo-Pacific Run produces stronger interannual variability in the equatorial Pacific than the Tropical-Pacific Run. The largest simulated warm event (at Year 12) has a maximum magnitude of 3°C. Apparently, an active Indian Ocean allows the CGCM to produce stronger ENSO events. This increase may be related to the fact that the tropical warm pool covers both the western equatorial Pacific and the eastern Indian Oceans. In the Tropical-Pacific Run, the Indian Ocean portion of the warm pool is prescribed and is fixed even when the warm pool in the western Pacific portion moves eastward during warm ENSO events. Therefore, the degree to which the zonal atmospheric circulation can be changed or reversed is limited. The positive feedback provided from Walker circulation to ENSO SST anomalies may be not as large as in the Indo-Pacific Run, in which the eastern Indian Ocean warm pool can respond interactively to Pacific ENSO events.

By contrasting Figs. 2a and b, it is also noticed that warm and cold events are produced more irregularly in the Indo-Pacific Run than in the Tropical-Pacific Run. There is almost no warm event produced during the

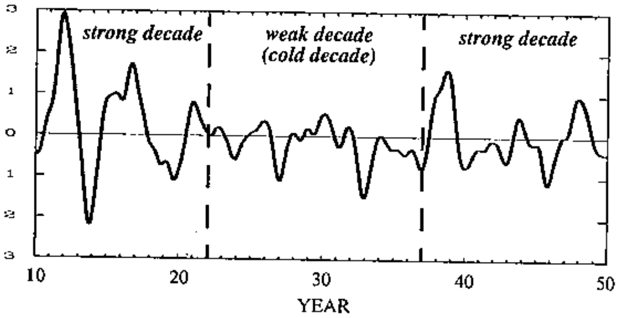

Figure 3. Time series of NINO3 SST anomalies produced by the Indo-Pacific Run.

period from Year 22 to Year 37. Strong warm events reappear in the simulation after this period. This interdecadal ENSO modulations does not appear in the Tropical-Pacific Run. To better show this interdecadal modulation, Fig. 3 displays the time series of NINO3 SST anomalies produced from the Indo-Pacific Run. It is apparent that its 53-year integration can be separated into two "strong decades" with large warm and cold events and a "weak decade" with persistent cold events and almost no warm event. No such clear decadal differences are seen in the Tropical-Pacific Run.

To examine the impact of an active Indian Ocean on the period of ENSO, we use the Multi-Channel Singular Spectrum Analysis (M-SSA) method to extract the simulated ENSO cycles from these two runs. The M-SSA technique is an extension of the principal component analysis of a time series of spatial vectors to include additionally an analysis of temporal structure (Keppenne and Ghil 1992). The technique has been shown to be capable of extracting near-periodicities, and their associated spatiotemporal structures, from short noisy time series. In order to examine air-sea interactions associated with the simulated ENSO, we apply the M-SSA to combined atmospheric and oceanic variables in the Indo-Pacific Ocean domain. The variables included are SST, surface wind stress, surface heat flux. All variables are low-pass filtered after their annual cycles are removed. The anomalies are then scaled by appropriate constants to obtain values with similar orders of magnitude. The first two leading modes of this combined M-SSA have similar eigenvalues and principal components (not shown), and represent the simulated ENSO cycles.

Figure 4a shows the eigenvector structures of SST along the equator obtained from the leading M-SSA mode (i.e., the ENSO mode). It shows that the dominant period of the ENSO cycle increase from 4 years in the Tropical-Pacific Run to about 4.5 years in the Indo-Pacific Run. The longer ENSO period is accompanied with very different zonal wind stress anomalies. Figure 4b shows that the wind stress anomalies in the Indo-Pacific run have stronger westward propagation originating from the Indian to the Pacific Oceans. There have been many studies suggesting that the east-west circulation in the atmosphere provides a mechanism for Indian Ocean climate variations to affect ENSO (e.g., Barnett 1984; Wainer and Webster 1996). They argued that variations in the strength of the Monsoon, for example, can affect Pacific trade winds, and, consequently, the period and magnitude of ENSO. Our CGCM results appear to be consistent with these hypotheses.

4. IMPACTS OF PACIFIC ENSO ON THE INDIAN OCEAN CLIMATE VARIABILITY

In this section, we examine how the Indian Ocean is affected by ENSO activity in the Pacific. Figure 5 displays the structures of SST anomalies during different stages of the warm phase of the leading M-SSA mode obtained from the Indo-Pacific Run. The structures corresponding to the cold phase are similar to

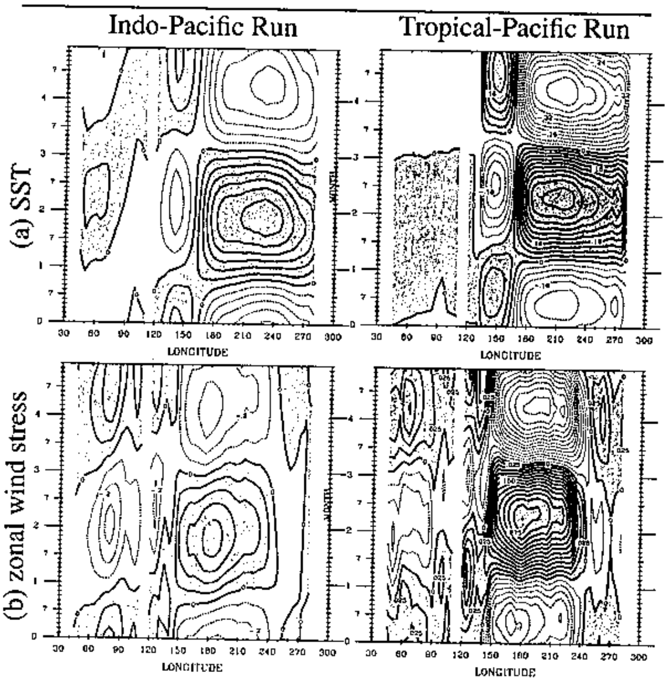

Figure 4. The eigenvector structure of (a) SST and (b) zonal surface wind stress anomalies along the equator for the leading M-SSA mode obtained from the combined 3-variable M-SSA. The coordinate is the 61-month lag used in M-SSA. Contour intervals for SST are 0.04°C and 0.02°C for the Tropical-Pacific and Indo-Pacific Runs, respectively. Contour intervals for zonal wind stress are 0.025 and 0.1 dyn/cm**2 for the Tropical-Pacific and Indo-Pacific Runs, respectively. Positive values are shaded.

these but with reversed signs. Figure 5 shows that there are significant variations produced in Indian Ocean SSTs during the development of a warm ENSO event in the Pacific. The major phenomenon is the warming of the entire Indian Ocean, which begins about 6 months after the onset of the warm ENSO. This simulated relationship between Pacific and Indian Ocean SST warming is consistent with the finding of Webster et al. (1998) from the observations. They showed that the mean tropical Indian Ocean SST is positively correlated with Pacific Ocean warm and cold events for the period 1951 through 1998.

The simulated Indian Ocean warming is characterized by two major features. The first feature is that the largest warming occurs in the western sector, which represents a westward displacement of the Indian Ocean warm pool. This feature is seen in the observations and has been used to suggest that the Indian Ocean warming resembles the Pacific ENSO warming (e.g., Webster et al. 1998). The second feature of the Indian Ocean warming is that the warming begins from the southern ocean. As the event develops in the western sector, the warming moves gradually to the northern ocean. Before the decay of the event, most warming is confined to the north of the equator. This north-south movement of SST anomalies is an unique feature of the Indian Ocean warming.

Kawamura and Iizuka (2000) identified a similar feature in the observations and referred it as an "equatorially asymmetric mode". They found that this mode is a dominant precursory signal of a strong/weak summer Asian monsoon. In the spring preceding a weak summer monsoon, for example, the Indian Ocean is characterized by negative SST anomalies in the northern and positive anomalies in the south. The positive anomalies later move northward and cover the entire region of the northern Indian Ocean by the time the monsoon season begins. The warmer ocean temperatures reduce the sea-land thermal contrast in the region and lead to a weak Asian monsoon. The north-south movement of Indian Ocean SST anomalies shown in Fig. 5 for our simulated warm ENSO cases is very consistent with the evolution described by Kawamura and Iizuka (2000) for weak summer monsoon cases. Since weak (strong) monsoons are often associated with warm (cold) ENSO events, this consistency further indicates the reality of climate features shown by the simulated ENSO mode of the Indo-Pacific Run.

To explore the generation mechanisms of the SST variations in the Indian Ocean, we contrast surface fluxes produced in the region by the Tropical-Pacific

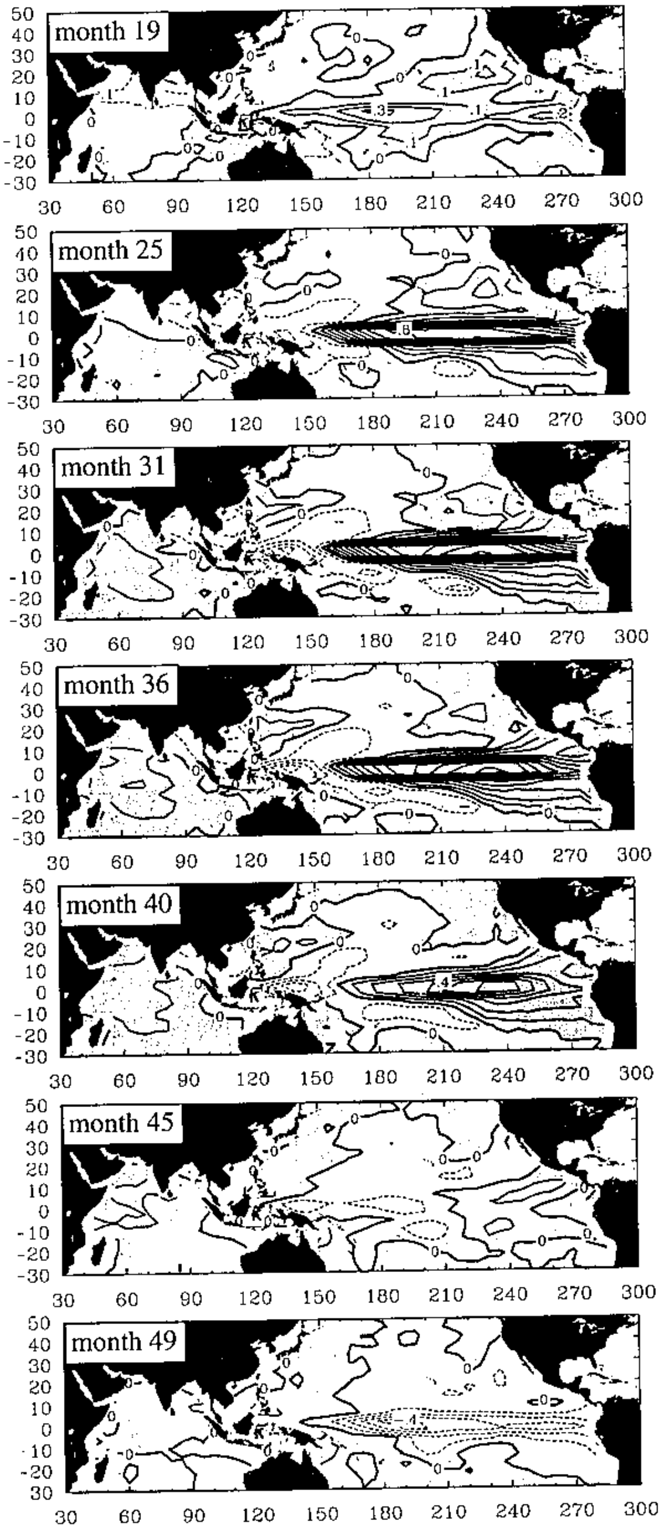

Figure 5. Evolutions of SST and surface wind stress anomalies of the leading M-SSA mode obtained from the 25-year Indo-Pacific run. Contours represent SST anomalies. Surface wind stress anomalies are indicated by vectors. Contour intervals are 0.1°C. The number of month indicated in the upper left corner of each panel corresponding to the window-lag shown in Fig. 4a.

and Indo-Pacific Runs. Figure 3a shows that the Tropical-Pacific Run produces easterly wind stress anomalies over the equatorial Indian Ocean during the warm phase of the simulated ENSO cycle. This direction of wind stress anomalies is opposite that of the climatological circulation over the region and can lead to warming in the western Indian Ocean, where the thermocline is shallow. This is consistent with the generation mechanism proposed by Webster et al. (1999) for the Indian Ocean warming/cooling. They argued that strong, anomalous surface easterly winds reverse the near-equatorial sea surface temperature gradient and drive prolonged periods of warmer temperatures in the west and cooler temperatures in the east. Figure 3b shows that when the Indian Ocean is allowed to respond to atmospheric forcing in the Indo-Pacific Run, much stronger wind stress anomalies are produced over the Indian Ocean. The ratio between wind stress anomalies over the equatorial Indian Ocean and those over the equatorial Pacific increases from about 16% in the Tropical-Pacific Run to about 75% in the Indo-Pacific Run. This five-fold enhancement indicates strong positive feedbacks between the atmosphere and ocean through momentum exchanges over the Indian Ocean.

Figure 6a shows that, during the warm phase of the ENSO cycle, surface heat flux to the ocean is reduced over the Pacific but increased over the Indian Ocean in the Tropical-Pacific Run. These anomalies over the Indian Ocean would produce a warming tendency to the ocean. The flux anomalies are largest over the western Indian Ocean, which is the region where the Indo-Pacific Run produces the largest warming. Apparently, the Indian Ocean warming/cooling is driven both by surface wind stress and surface heat flux forcing. Surface heat flux over the Indian Ocean plays an active, rather than passive, role in the warming/cooling events. This is very different from the Pacific ENSO, which is primarily driven by surface wind stress feedback and surface heat flux is a passive response. Figure 6b shows that the Indo-Pacific Run produces very small surface heat flux anomalies over the Indian Ocean. This is similar to the compensating relationship between SST and surface heat flux found by Yu and mechoso (1999) in many regions of the tropical Pacific. They showed that this kind of compensated relationship is most obvious over the regions where SST are not strongly controlled by ocean dynamics but by surface thermal forcing. Therefore, Fig. 6 implies that the interannual warming/cooling in the equatorial Indian Ocean may be driven more by surface heat flux forcing than by surface wind stress forcing.

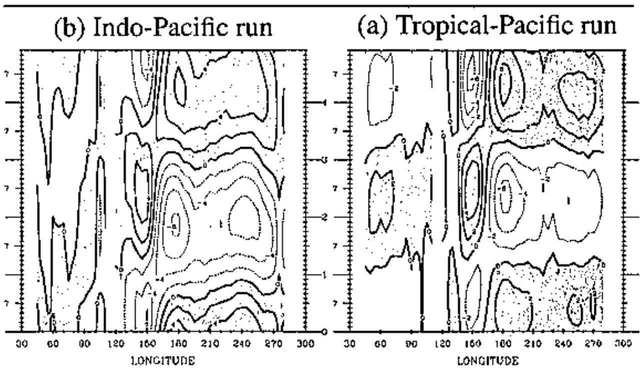

Figure 6. The same as Fig. 4, but for surface heat flux anomalies. Contour intervals are 2 W/m**2. Positive anomalies indicate larger than normal heat flux into the ocean surface, or less heat flux out of the ocean. Positive values are shaded.

5. THE INDO-PACIFIC SST PATTERN OF ENSO

In additional to the Indian Ocean warming/cooling, there are two other major climate features in Fig. 5 that are also in associated with Pacific ENSO. One is an SST anomaly dipole in the northeastern Pacific (10°N-30°N and 170°E-240°E), and the other is a dipole in the northwestern Pacific (10°N-30°N and 120°E-160°E). The northeastern Pacific SST dipole was observed to be accompanied with an anomalous cyclonic surface circulation during the 1997-98 ENSO event (Liu at el. 1998). Yu et al. (2000) has shown that this SST dipole is a typical subtropical teleconnection to tropical Pacific SST variations during ENSO events. The dipole tends to develop simultaneously with the ENSO cycle and is thermally forced by the anomalous atmospheric circulation in the Northern Pacific. The northwestern SST dipole was also observed during the 1997-98 ENSO event and was accompanied by an anomalous anticyclonic surface circulation. This dipole has been linked to the Yangtze River flooding in China and other climate variations in the East Asia. This dipole was suggested to be generated by a similar thermal forcing mechanisms as that of the northeastern SST dipole (Hsu and Chen 1999) and local air-sea interaction process (Wang et al. 1999).

In summary, there are five major climate features in Indo-Pacific SSTs that are closely related to the Pacific ENSO. They include: (1) Pacific ENSO, (2) western Indian Ocean warming, (3) equatorially asymmetric Indian Ocean warming, (4) northwestern Pacific SST dipole, and (5) the northeastern Pacific SST dipole. Therefore, we refer to this SST anomaly pattern as the "Indo-Pacific ENSO mode". By examining the generation mechanisms of each climate feature of this mode, we should be able to better understand how the

Pacific and Indian Oceans interact with other. Furthermore, we should also be able to learn more about the interactions between tropical and extratropical Pacific Ocean during the ENSO cycle. Further studies are being conducted to address these inter-basin and basin-wide interactions.

6. CONCLUSIONS

This study uses a CGCM to study the climate variability over the Indo-Pacific oceans during ENSO. In particular, the impact of the Indian Ocean on the ENSO cycle is addressed by comparing CGCM simulations performed with and without an active Indian Ocean. It is found that an active Indian Ocean increases the magnitude and prolongs the period of the ENSO cycle. A strong decadal modulation in ENSO activity is also produced through inter-basin interactions between the Pacific and Indian Oceans. During ENSO, significant climate variations are produced in the Indian Ocean. The major feature is the warming/cooling of the mean Indian Ocean SST. This warming/cooling is characterized by a east-west SST contrast along the equator and a north-south movement of SST anomalies. It is found that air-sea interactions over the Indian Ocean are very different from those over the Pacific Ocean. Surface heat flux is an active forcing to the interannual warming of the Indian Ocean, while it is a passive damping to the ENSO warming in the Pacific. This study also identified five major climate variability features in the Indo-Pacific region that are part of the ENSO SST pattern. This Indo-Pacific ENSO SST mode includes: the Pacific ENSO, Western Indian Ocean warming, equatorially asymmetric mode of the Indian Ocean SST, SST anomaly dipole in the western Northern Pacific, and SST anomaly dipole in the eastern Northern Pacific.

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