Dynamical mechanisms for asymmetric SSTA patterns associated with some Indian Ocean Dipoles

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Abstract Indian Ocean Dipole (IOD) can be divided into two types according to their SST anomaly (SSTA) patterns: the symmetric IODs and the asymmetric IODs. Dynamical mechanisms for the two types of IODs are investigated using an ocean general circulation model, and the numerical experiments indicate that the setup time of the equatorial easterly wind anomalies (EEWA) associated with IODs is crucially important for the symmetrical characteristics of the SSTA patterns. Early setup of the EEWA in spring can induce intense cooling in the east pole but weak warming in the west pole, making the two poles asymmetric. The intense cooling in the east pole is linked to the seasonal variations of thermocline depth, horizontal SST gradient, and unusually long duration of the EEWA, and the weak warming in the west pole is due to unusually cold zonal advection resulted from zonal SST gradient change. The numerical experiments demonstrate that the strength of the EEWA also plays an important role in the symmetrical characteristics of IODs. The SSTA in the two poles both intensify as the EEWA strength increases only when the EEWA speed is below a critical value. Above the critical value, the warming in the west pole starts to decrease while the cooling in the east pole still keeps increasing, leading to an asymmetric SSTA pattern. The mechanism behind this phenomenon is similar to the one in the situation when EEWA sets up earlier.

1. Introduction

Indian Ocean Dipole (IOD) is an air-sea coupled phenomenon occurring in the tropical Indian Ocean [Saji et al., 1999; Webster et al., 1999]. A positive IOD, which is tightly coupled with the equatorial easterly wind anomaly (EEWA), is characterized by anomalous cooling in sea surface temperature (SST) in the southeastern tropical Indian Ocean and anomalous warming in SST in the western tropical Indian Ocean. The IODs not only have strong impacts on local climate but also influences various parts of the globe via atmospheric bridge effects [Saji and Yamagata, 2003]. And extreme IOD may significantly enhance El Niño [Luo et al., 2010].

IODs can be divided into two types according to their SST anomaly (SSTA) patterns: the symmetric IODs and the asymmetric IODs. The criterion we used to distinguish these two types of IODs is as follows: if the amplitude of mean SSTA in the east pole does not exceeds twice the amplitude of mean SSTA in the west pole during the peak of an IOD, this IOD is considered to be a symmetric IOD (the east and the west poles are defined as in Saji et al. [1999]); otherwise, it is considered to be an asymmetric IOD. In symmetric IODs, although the SSTA is usually weaker in the west than in the east, the cooling in the east pole and the warming in the west pole are both significant. In asymmetric IODs, the warming in the west pole is very weak or absent while the cooling in the east pole is still intense. Based on the dipole mode index (DMI, see Saji et al. [1999]) derived from the 7 year high-pass filtered SSTA from ERSST. V3 [Xue et al., 2003; Smith et al., 2008], totally six significant IODs (1961, 1972, 1982, 1994, 1997, and 2006), whose DMI exceeds 1.5 standard deviation of the DMI time series, can be identified during 1950–2010. If we apply the above criterion to the six IODs, the IODs in 1972, 1982, 1997, and 2006 are symmetric IODs while the ones in 1961 and 1994 are asymmetric IODs.

For the symmetric IODs (Figure 1a), the warm SSTA in the western Indian Ocean and the cold SSTA in the southeastern Indian Ocean are both notable, with SSTA showing a typical dipole pattern. For the asymmetric IODs (Figure 1b), the intense cold SSTA in the southeastern Indian Ocean, in contrast to the much weaker warm SSTA in the western Indian Ocean, becomes the major feature of the SSTA pattern, making the SSTA distribution more like a monopole rather than a dipole. Since the cold SSTA in the southeastern Indian Ocean are obvious in all the six IODs, the most distinct difference between the symmetric and the...
asymmetric IODs is the amplitude of SSTA in the western Indian Ocean [Drbohlav et al., 2007]. Based on the facts that the symmetric IODs all happened together with El Niño (ENSO-IOD) and the two asymmetric IODs happened without El Niño (independent IOD), some studies thus conclude that the asymmetric SSTA pattern is only associated with the independent IODs [Hong et al., 2008; Drbohlav et al., 2007].

The temporal evolutions of the symmetric and the asymmetric IODs are also different from each other. One can see that (Figure 2a) the SSTA of the two poles of the symmetric IODs grow synchronously during their developing stage. After both poles reach their peaks in October-November, the negative SSTA of the east pole warms up quickly and turns to positive, with the warm SSTA of the west pole still persists. So the entire tropical Indian Ocean is in basin warming mode during boreal winter and the following spring. As for the asymmetric IODs, however, the cold SSTA of the east pole is much stronger than the warm SSTA of the west pole. It is worth to note that the cold SSTA not only reaches its peak earlier (in August) than that of the symmetric IODs but also persists longer (turns to positive until in boreal spring). Similar evolutional characteristics of the east/west poles of symmetric and asymmetric IODs can also be found in the SSTA derived from the HadISST [Rayner et al., 2003] (Figure 2b).

Symmetric and asymmetric IODs can lead to different climate responses. Since the western Indian Ocean is an important moisture source of Indian summer monsoon, different SSTA in this region can induce different anomalous rainfall patterns in the Indian monsoon region [Drbohlav et al., 2007]. Hong et al. [2008] demonstrate that the summer rainfall anomalies in the Indian monsoon region show opposite signs for ENSO-IODs and independent IODs. Loschnigg et al. [2003] find that the intense and long-lasting warm SSTA in the western Indian Ocean associated with ENSO-IODs can result in stronger-than-normal summer monsoon in the
following year, while weak warm SSTA associated with independent IODs has little influence on the summer monsoon in next year. Therefore, studying the mechanisms of symmetric and asymmetric IODs is not only important for understanding the IOD itself but also helpful for improving forecasting skill of Indian summer monsoon and its associated rainfall.

Different hypotheses have been proposed to explain how the SSTA patterns of the asymmetric IODs arise. Drbohlav et al. [2007] found that a monsoon-like anomalous wind flow, which does not exist during ENSO-IODs, develops during the developing phase of independent IODs. The ocean advection forced by this anomalous wind flow could induce cold advection in both the southeastern and the western Indian Ocean, thus suppress the warming of the west pole. Hong et al. [2008] noted that the EEWA is more restricted to the eastern Indian Ocean during independent IODs, and thus has little contribution to the warming in the west pole. In addition, the difference in sea surface heat flux between independent IODs and ENSO-IODs may also play a role in symmetrical characteristic of SSTA patterns. These studies attribute the main causes of asymmetric IODs to different wind spatial distributions, but we noticed that the temporal evolutions of the wind anomalies of the two types of IODs are distinct: the EEWA sets up much earlier in asymmetric IODs than in symmetric ones (Figure 3). Vinayachandran et al. [2002] also noticed that the wind anomalies appear few months earlier in 1994 than in 1997. However, the effect of this factor has not been considered yet. Moreover, if we compare the zonal wind anomaly of symmetric IODs with that of asymmetric ones during their peak period (Figure 4), we can find that the differences in the anomalous wind patterns is rather obscure: not only the pattern and the intensity of the EEWA are similar in both types of IODs, even the distributions of wind anomalies in adjacent regions, like Bay of Bengal, Arabian Sea, and South China Sea, are also similar. Therefore, whether the remarkable SSTA asymmetry in 1961 and 1994 are merely caused by wind pattern change, as argued by previous studies, is still an issue worth to discuss.

Can the setup time of the EEWA influence the symmetrical characteristic of the SSTA associated with IODs? If so, how different temporal evolutions of EEWA are translated into different spatial distributions of SSTA? And what is the role of the EEWA intensity in causing the SSTA asymmetry? To answer these questions, we investigate the dynamical effects of the wind anomalies on SSTA patterns associated with IODs using an ocean general circulation model (OGCM). The model used in this study is introduced in section 2; section 3 describes how the numerical experiments are designed and the results of the numerical experiments are analyzed; then summary and discussion are given in section 4.

2. Numerical Model

The OGCM used in this study is the Hybrid Coordinate Ocean Model (HYCOM) [Bleck, 2002]. The model domain covers the tropical Indian Ocean (30°S–25°N, 30°E–120°E) with a horizontal resolution of 0.5° × 0.5° cosθ in longitude and latitude (θ is latitude), 33 hybrid levels in vertical, and realistic bottom topography from the ETOPO5 5 min gridded earth topography data (available from NOAA’s National Geophysical Data Center). Along continental boundaries, no-slip boundary conditions are applied. Near the open boundaries,
sponge layers of $5^\circ$ are applied to relax the model temperature and salinity to the Levitus climatologies [Levitus and Boyer, 1994; Levitus et al., 1994]. The climatology run is forced by 6 hourly climatological wind stress derived from the Version 2 Forcing for Common Ocean-ice Reference Experiments (CORE) [Large and Yeager, 2009] and climatological net ocean surface heat flux from the objectively analyzed air-sea Fluxes (OAFlux) [Yu and Weller, 2007]. The climatology run is integrated for 20 years from a state of rest. Then a control run is initiated from year 20 of the climatology run. The control run is forced by CORE 6 hourly reanalysis wind data, air temperature and specific humidity from OAFlux [Yu and Weller, 2007], shortwave and longwave radiation from ISCCP [Zhang et al., 2004]. The control run is integrated from 1990 to 2008. Table 1 lists the experiments reported in this paper.

In addition to the control run, a dynamical run, which is forced by interannual wind stress but climatological sea surface heat flux, is conducted for the same period to investigate the role of dynamical processes in the IOD development. Since the use of air temperature and humidity could force the SST simulations toward observations [Vinayachandran et al., 2002], the dynamical run is forced by CORE 6 hourly reanalysis wind stress and OAFlux climatological net ocean surface heat flux.

**Table 1. HYCOM Experiments**

<table>
<thead>
<tr>
<th>Experiment</th>
<th>Wind Forcing</th>
<th>Surface Heat Flux Forcing</th>
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<tr>
<td>Control run</td>
<td>CORE 6 hourly reanalysis wind stress and speed</td>
<td>Daily air temperature and specific humidity from OAFlux; Shortwave and longwave radiation from ISCCP</td>
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<tr>
<td>Dynamical run</td>
<td>CORE 6 hourly reanalysis wind stress</td>
<td>Daily climatological net surface heat flux derived from OAFlux</td>
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<tr>
<td>Experiment 1</td>
<td>CORE 6 hourly climatological wind plus ideal EEWA</td>
<td>Daily climatological net surface heat flux derived from OAFlux</td>
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<td>(with $\sigma_2$ varies from 10 to 90; $A = 9$ m/s)</td>
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<tr>
<td>Experiment 2</td>
<td>CORE 6 hourly climatological wind plus ideal EEWA</td>
<td>Daily climatological net surface heat flux derived from OAFlux</td>
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<td></td>
<td>(with $\sigma_2 = 30$; $A$ varies from 1 to 15 m/s)</td>
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*See text for detailed description.*
In order to validate the capability of our model in simulating IODs, we compare the DMI derived from observations with the DMI derived from the model simulations. Figure 5 shows the time series of observed (NOAA optimally interpolated SST (OISST) version 2 monthly data [Reynolds et al., 2002] and HadISST) and modeled (control run and dynamical run) fields for 1990–2008, showing DMI (top panel), SSTA in the east pole (middle panel), and SSTA in the west pole (bottom panel). The SSTA data are computed for each month by subtracting their climatological values computed over 1990–2008. The observed IODs in 1994, 1997, 2006, 2007, and 2008 are well reproduced by the control run, with the DMI agreeing in both time variations and amplitude. The correlation coefficients between the DMI derived from control run and that derived from the NOAA OISST (HadISST) is 0.81 (0.78), exceeding the 99.9% significance level. The interannual variability of the SSTA in east and west poles are also simulated reasonably well in the control run. The correlation coefficient between SSTA derived from control run and NOAA OISST is 0.78 for the east pole and 0.61 for the west pole, both values exceed the 99.9% significance level.

The simulated results of the dynamical run are also compared with observations in Figure 5. One can see that, although there are some discrepancies in IOD intensity, the model well reproduces the 1994, 1997, and 2006–2008 IODs even the surface heat flux forcing is of climatology (Figure 5a). The correlation coefficient between the DMI derived from NOAA OISST and that from the dynamical run is 0.7. These results
suggest that the dynamical processes induced by wind anomalies play a dominant role in the IOD development. This is consistent with previous finding that upwelling and downwelling are the most important mechanisms during the IODs in 1994 and 1997 [Vinayachandran et al., 2002]. Differences between the dynamical run and observations, however, do exist. The warming of the east pole after the peak of IOD in the dynamical run is much weaker and slower than that in the observations and control run, which can be seen clearly in the results of 1994 and 1997. This phenomenon is consistent with the previous findings that the damping of the east pole is primarily due to the surface heat flux [Li et al., 2002; Vinayachandran et al., 2002]. Such discrepancies also exist in the result of the west pole. Numerical experiment conducted by Murtugudde and Busalacchi [1999] suggests that the SSTA anomalies in Bay of Bengal and the eastern south tropical Indian Ocean are significantly affected by anomalies in solar radiation and cloudiness. Nevertheless, the dynamical run produces reasonable interannual SST variations, which indicate that it captures the major processes that determine the SST variability in this region. According to the previous findings by Li et al. [2002] and Hong et al. [2008], the warming of the west pole is mainly caused by dynamical processes. Since the west pole is the key area for the symmetrical characteristic of IODs, applying the climatological heat flux forcing to our numerical experiments is justified, and the focus of this paper is to study the dynamical processes.

3. Experiments and Results

3.1. Idealized EEWA

To investigate the roles of the intensity and the setup time of the EEWA in influencing the asymmetrical characteristic of IODs, idealized anomalous wind fields are constructed based on the characteristics of actual wind anomalies during IODs. Since the EEWA is strongest in central equatorial Indian Ocean (70°E–90°E, 10°S–10°N) and plays a dominant role in IOD development [Saji, et al., 1999; Gadgil et al., 2004], idealized wind fields are constructed in the central equatorial Indian Ocean region (surrounded by the black rectangle in Figure 4) and their meridional variation is approximated with a normal distribution function:

\[
U(y) = \frac{A}{\sigma_1 \sqrt{2\pi}} e^{-\frac{(y-y_0)^2}{2\sigma_1^2}},
\]

where \(y\), in our case, is latitude ranging from 10°S to 10°N, \(y_0\) is the location where the maximum wind speed locates, \(\sigma_1\) controls the meridional distribution of the wind speed, and \(A\) is the coefficient for EEWA speed. The EEWA speed does not vary with longitude at any latitude. In our experiments, \(y_0\) is set to 0, means that the maximum EEWA locates right at the equator and the wind speed decreases as latitude increases (Figure 6). The mean value of the idealized EEWA speed during its peak month in the central equatorial Indian Ocean is about half of \(A\).

Similarly, the temporal evolution of the EEWA can also be approximated with a normal distribution function:
where $t$ is the day of year, $t_0$ is the date when the EEWA speed reaches its peak, and $\sigma_2$ is the standard deviation, a parameter controls the temporal evolution of the EEWA speed. Figure 7 shows the 30 day running mean of the time series of EEWA (averaged over $70^\circ E$–$90^\circ E$, $10^\circ S$–$10^\circ N$) associated with the symmetric and the asymmetric IODs. It is interesting to note that the EEWAs of all the six IODs peak in November (around day 315) and decay in a similar way. But the EEWA associated with the 1961 and 1994 IODs starts in May (around day 120), earlier than those associated with the 1972, 1982, 1997, and 2006 IODs, which become stable easterly wind anomalies till September (around day 240). According to this unique characteristics of the EEWA evolution, $t_0$ in equation (2) is thus set to 315 and different $\sigma_2$ will be used to represent different EEWA setup time (e.g., $\sigma_2 = 30$ for ENSO-IODs; $\sigma_2 = 80$ for independent IODs), but after day 315, $\sigma_2$ is fixed at 20 for both types of IODs. The idealized EEWA time series with different $\sigma_2$ are shown in Figure 8.

Therefore, the spatial and temporal variations of the idealized EEWA, $W(y, t)$, can be constructed using the following formula:

\[
W(y, t) = U(y)T(t) = \frac{A}{2\pi \sigma_2} e^{-\frac{(y-y_0)^2}{2\sigma_2^2}} e^{-\frac{(t-t_0)^2}{\sigma_2^2}}.
\]

The strength and the setup time of the EEWA can be easily adjusted in numerical experiments by tuning the values of $A$ and $\sigma_2$, respectively.

### 3.2. Role of EEWA Setup Time

We first explore the role of EEWA setup time in influencing the symmetrical characteristic of the SSTA pattern with a sensitivity experiment (hereafter EXP1), which consists of 9 runs. In EXP1, $A$ in equation (3) does not change (9 m/s), but $\sigma_2$ varies from 10 to 90 before the day 315, representing different setup time of EEWA. All the runs are initialized with the last year’s output (year 20) of the climatology run and then integrated for 2 years, forced with the idealized EEWA superimposed onto climatological wind and the climatological sea surface heat flux. The
climatology run is also integrated for another 2 years from year 20, and this 2 year simulation stands for climatological situation. Since the initial conditions of all the 9 runs and the climatology run are exactly the same, the differences between the EXP1 and the climatology run can be used to evaluate the impacts of EEWA with different setup time.

The results of EXP1 are shown in Figure 9. One can see that when $\sigma_2 \leq 30$, or the setup time of EEWA is later than August, the SSTA intensities of the east pole is similar to or weaker than that of the west pole. The temporal evolutions of the two poles are in phase, both reaching their peak in January/February. When $\sigma_2 > 30$, or EEWA setup time is earlier than August, the cooling of east pole is dominant; and when $\sigma_2 = 40$, the SSTA intensity of the east pole is nearly twice as large as that of the west pole. As $\sigma_2$ increases, the proportion of the SSTA intensity of the east pole to that of the west pole increases remarkably and the SSTA of the two poles become significantly asymmetric. In addition, the peaking time of the east pole is also shifted to October/November as $\sigma_2 > 50$, about 2 months earlier than those in the runs with $\sigma_2 \leq 30$. This result is consistent with the real situation, in which the peaking time of east pole cooling during independent IODs is
about 2 months earlier than that of ENSO-IODs according to the ERSST data (Figure 2a) or about 1 month earlier according to the HadISST data (Figure 2b).

The relationship between SSTA variation and EEWA setup time can be seen more clearly in Figure 10a, which shows the SSTA peak values of the east and the west poles of EXP1. One can see that the SSTA peak value of the east pole increases rapidly to \(3.8^\circ C\) as \(\sigma_2\) increases from 0 to 90. This consistently increasing trend, however, cannot be found in the SSTA peak value of the west pole, which grows slowly when \(\sigma_2 < 40\) but starts to decrease after that. Consequently, the SSTA of the two poles are basically symmetric when \(\sigma_2 > 30\) because the magnitudes of SSTA of the east and the west pole both increase during this stage. However, this symmetric characteristic cannot be kept when \(\sigma_2 > 50\), because during this stage the magnitude of the west pole starts to decrease as that of the east pole keeps growing. The difference in SSTA patterns between the ENSO-IODs and the independent IODs can be well explained by the above findings: the EEWA of the ENSO-IODs usually set up in August, equivalent to the situation of the run with \(\sigma_2 = 30\), and thus the SSTA in the tropical Indian Ocean shows a typical dipole pattern during these IODs; while for the independent IODs, the setup time of EEWA is in May, similar to the situation of the run with \(\sigma_2 = 80\), that is why the SSTA pattern induced by such EEWA is asymmetric and more like a monopole rather than a dipole.

Previous findings show that although the SSTA patterns are different for different types of IODs, the variations of thermocline depth are characterized by a typical dipole pattern during all IODs [Rao et al., 2002]. Our results support this view, the thermocline depth (depth of the 20°C isotherm, D20) anomalies (D20A) of the two poles are symmetric for all the 9 runs of EXP1 (Figure 11). It is worth to note that the magnitudes of D20A in the east and the west poles, unlike the intensity of SSTA, both increase as the EEWA setup time gets earlier though their growth rate slows down when \(\sigma_2 > 40\) (Figure 10b). While the negative D20A are always related to cold SSTA, the deepening of D20 does not necessarily corresponds to warm SSTA [Vinayachandran et al., 2002]. The inconsistency between the increase in the magnitude of D20A and the decrease in the SSTA intensity in the west pole implies that the warming effect of the downwelling due to thermocline variation on the SST in the west pole is quite limited when \(\sigma_2 > 40\), the horizontal temperature advection might be more important.

Kelvin and Rossby waves play an important role on the dynamics and thermodynamics of the tropical Indian Ocean during IOD. The propagation of these ocean waves, and their contribution to the evolution of IOD has been elaborated in previous studies [e.g., Murtugudde and Busalacchi, 1999; Vinayachandran et al., 1999; Webster et al., 1999; Rao et al., 2002; Vinayachandran et al., 2002; Han et al., 2006; Yuan and Liu, 2009]. The results of our simulations are consistent with previous findings. The D20 variations in our experiments are also dominated by such processes. Take the D20 evolutions in the run with \(\sigma_2 = 30\), for example (Figure 12), the EEWA excites a upwelling Kelvin wave along the equator and a pair of off-equatorial Rossby waves. The thermocline of the eastern tropical Indian Ocean is lifted when the upwelling Kelvin wave reaches the eastern boundary (Figure 12a). As the EEWA intensifies, the D20A induced by the corresponding Rossby and Kelvin waves also increases. In November, when the EEWA is strongest, the D20A of the east pole reaches its peak (Figure 12b). The D20A of the west pole reaches its peak value in the following month,
December (Figure 12c). The D20A peak of west pole is 1 month later than that of the east pole because the speed of equatorial Kelvin wave is faster than that of the Rossby wave. It takes about 1 month for the downwelling Rossby wave, which is generated in the central equatorial Indian Ocean, to propagate to the west pole. When the downwelling Rossby waves reach the western boundary, they reflect as a downwelling Kelvin wave, which propagates eastward along the equatorial Indian Ocean (Figure 12d). When the downwelling Kelvin wave reaches the eastern boundary, the original negative D20A of the east pole is damped by this wave. With the retreat of EEWA after November, the equatorial D20 comes back to its normal position gradually.

The D20 evolutions in other runs are similar to that in the run with $\sigma_2 = 30$. However, there are still some differences in the strength and temporal evolution of D20A. These differences are also associated with ocean waves. Figure 13 shows the D20A along the equator, 5°S, 12°S, and 5°N in the run with $\sigma_2 = 30$ and 90 of EXP1. The D20A along 5°S, 12°S, and 5°N are dominated by westward Rossby waves, while the D20A along the equator is dominated by eastward Kelvin waves. Decreasing phase speed (derived from the slope of the D20A) with increase in latitude, which is an important characteristic of Rossby wave propagation.
Rao et al., 2002, is evident from these figures. The major difference between the D20A in the two runs is that the appearance of D20A is about 4 months earlier when $r_2 = 90$, which is consistent with the earlier development of EEWA. And the earlier setup of EEWA in the run with $r_2 = 90$, also leads to the longer persistence of D20A in the Indian Ocean.

What causes the dramatic increase in SSTA intensity in the east pole when the setup time of the EEWA gets earlier? To answer this question, the processes that determine the cooling of the east pole and their changes corresponding to the earlier setup of EEWA need to be considered. Previous studies suggest that the oceanic processes, especially the upwelling of cold water is responsible for cooling of the east pole. Upwelling brings cold water upward and cools the sea surface [e.g., Murtugudde et al., 2000; Vinayachandran et al., 2002, 2007; Rao et al., 2009]. As for the contribution of surface heat flux, although the anomalous sea surface latent heat flux associated with enhanced southeasterly wind off Sumatra also contributes to the cooling, the shortwave radiation flux tends to damp the SSTA. So the contribution of surface heat flux is relatively small during the developing phase of east cooling. But decay of the east pole is primarily due to the surface heat flux [Li et al., 2002; Vinayachandran et al., 2002, 2007].

The earlier setup of EEWA could greatly modulate the contribution of the three-dimensional temperature advection in the east pole, thus leading to dramatic increase in SST. First, the climatological thermocline depth in the east pole increases by about 15 m from September to November (Figure 14). When thermocline depth is shallow, the cold subsurface water is closer to the mixed layer base, enhancing the vertical temperature gradient beneath the mixed layer and making the cooling effect of upwelling on SST stronger. Therefore, in the years when the setup time of EEWA is relatively early (as in 1961 and 1994), the EEWA is already notable during September, so the cooling effect of the upwelling in the east pole induced by the EEWA is enlarged by the sharp vertical temperature gradient, and thus the SSTA in the east pole are unusually strong during these IODs. Second, under the circumstance of same wind speed and same peak time, the earlier the EEWA sets up, the longer it sustains. It would intensify the upwelling in the east pole through enhanced upwelling Kelvin waves. This also helps to enhance the cooling in the east pole. Third, since the horizontal SST gradient in the southeastern Indian Ocean is sharpest in boreal summer (Figure 15), the cold
temperature advection by anomalous northward offshore current induced by the EEWA will be strengthened. This favors the development of the cold SSTA in the east pole during this season. Fourth, the appearance of the eastward equatorial jets (Wyrtki jet) during the transition period between monsoons is an important feature of the equatorial Indian Ocean [Wyrtki, 1973]. The Wyrtki jets accumulate warm water in the eastern Indian Ocean leading to a warm SST and a deep mixed layer and thermocline [Hastenrath et al., 1993]. The jets are anomaly weak during IODs [Vinayachandran et al., 2002]. In 1994, when the EEWA develops as early as in May, the spring jets were very weak, leading to unusually cold SST in the east pole [Vinayachandran et al., 1999]. Therefore, in the IOD years when the setup time of EEWA is relatively early (as in 1961 and 1994), the Wyrtki jet are substantially weakened. It is also helpful for intensify the cooling in the east pole.

As for the west pole, the warming is mainly due to horizontal advection and downwelling [Webster et al., 1999; Li et al., 2002; Vinayachandran et al., 2002]. Drbohlav et al. [2007] suggest that the weak west pole warming during Independent IODs is caused by changes in horizontal temperature advection. The contribution of surface heat flux to the west pole warming varies with seasons and events [Vinayachandran et al., 2002]. Surface heat flux plays a more important role in ENSO-IODs than in independent IODs [Hong et al., 2008]. The westward propagating downwelling Rossby waves play an important role in the persistence of warm SSTA in the west pole [Murtugudde et al., 2000; Du et al., 2009]. When the EEWA setup time becomes earlier, the strong cooling in the east pole overturns the original zonal temperature gradient in the equatorial Indian Ocean, the SST in the eastern Indian Ocean become colder than that in the western Indian Ocean. Under this situation, the anomalous equatorial westward current forced by EEWA will induce cold advection to cool the west pole, and the west pole warming is thus weakened instead of being intensified in the years when EEWA sets up earlier. However, while the cold water is transported from the eastern Indian Ocean to the western Indian Ocean by anomalous westward surface current, the positive subsurface temperature
anomaly in the west pole remains even the SSTA above it already turns to negative (Figure 16b). Positive subsurface temperature anomaly remaining beneath negative SSTA further suggests that the weakening of the SSTA in the west pole is mainly caused by horizontal temperature advection. This is quite different from the cases when the EEWA setup is late, e.g. $\sigma_2 = 30$ (Figure 16a), which corresponds to ENSO-IODs.

To assess the relative importance of different dynamical processes in influencing SSTA patterns, mixed layer heat budget of the EXP1 is analyzed. In general, the change in SST during IODs is caused by both surface heat flux and three-dimensional ocean temperature advection [Li et al., 2002]. Since the surface heat flux in EXP1 is of climatology, the change in SST is mainly induced by ocean temperature advection, which consists of three parts: the zonal, meridional, and vertical temperature advection. We diagnose the heat budget for the upper 50 m, a depth commonly used as a typical mixed layer depth in studies about Indian Ocean [e.g., Behera and Yamagata, 2001; Baquero-Bernal et al., 2002; Vinayachandran et al., 2007]. The simplified temperature equation can be written as:

$$\frac{\partial <T>}{\partial t} = - <u \frac{\partial T}{\partial x}> - <v \frac{\partial T}{\partial y}> - <w \frac{\partial T}{\partial z}> + \frac{Q_{\text{net}}}{\rho C_p h} + R,$$

where $u$, $v$, and $w$ are the zonal, meridional, and vertical ocean current velocities, respectively, $T$ is the mixed layer temperature, $t$ is the time, $Q_{\text{net}}$ is the net surface heat flux, $\rho$ is the density of water, $C_p$ is the specific heat of water, $h$ is the mixed layer depth, and $R$ is a residual term representing model errors and neglected processes such as diffusion, mixing, and so on. For a variable $M$, $<M>$ is defined as the vertical average of $M$.

Figure 14. Time-depth section of climatological temperature (Unit: °C) in the east pole of IOD. The 20°C isotherm is used to indicate the depth of the thermocline, and is shown in thick black contour. (The climatological temperature data are obtained from World Ocean Atlas 2009 [Locarnini et al., 2010].)

Figure 15. SST (Unit: °C) climatology of the Indian Ocean in (a) August and (b) November based on World Ocean Atlas 2009 [Locarnini et al., 2010].
M from ocean surface to 50 m. All terms are calculated from the monthly mean model outputs. The anomalies are derived by subtracting the results of the climatology run.

The results of heat budget analysis of runs with $\sigma_2 = 30$ and 90 are shown in Figure 17. The sum of three-dimensional temperature advection terms well represents the temperature time tendency in both the east and the west poles. It is worth to note that there are still some discrepancies between the sum of temperature advection terms and the temperature time tendency. The discrepancies are probably induced by the omitting of heat flux term. Although the experiments are forced by climatology net heat flux, the changes in mixed layer and thermocline depth can modulate the heat flux effect on SSTA [Li et al., 2002]. Since the
Figure 18. Time series of SSTA (Unit: °C) calculated from each runs of EXP2 (dashed lines indicate the SSTA in the west pole; solid lines indicate the SSTA in the east pole).
climatology net surface heat flux is positive in both poles during the period that IOD develops, the heat flux term could induce anomalous warming (cooling) tendency in the east (west) pole where the thermocline depth is anomalously shallow (deep). The effect of the heat flux term is also modulated by the magnitude of net surface heat flux in the two poles as well. When $r_2 = 30$, strong cooling tendency in the east pole appears in October-December (Figure 17a), in which vertical temperature advection is the largest contributor and meridional temperature advection is secondary. For the case of $r_2 = 90$ (Figure 17c), in which the EEWA setup time is earlier, the cooling tendency in the east pole is most notable in August-September, and the three temperature advection terms all contribute to the development of the cold SSTA. In this case, all the three advection terms in equation (4) contribute to the cooling tendency in the east pole, and their magnitudes are about 3–4 times as large as those in the case of $r_2 = 30$. The role of zonal temperature advection is quite different in these two cases: it cancels the cooling tendency when $r_2 = 30$ but enhances that in the case of $r_2 = 90$. This difference is primarily due to the seasonal changes in horizontal isotherm direction and horizontal SST gradient as discussed above.

As for the west pole, however, the warming tendency appears in October-December in both cases (Figures 17b and 17d) with similar magnitudes. The vertical temperature advection plays a dominant role in the west pole warming no matter when EEWA sets up. But the effect of horizontal temperature advection is strongly influenced by the setup time of the EEWA. When $r_2 = 30$, the contribution of zonal temperature advection is rather small considering its small magnitude during the developing stage of the west pole. When $r_2 = 90$, the cooling effect of zonal temperature advection becomes notable during the developing stage of the west pole warming owing to the reversal of horizontal SST gradient and the enhancement of anomalous westward current due to the earlier EEWA setup. Therefore, the warming tendency of SSTA in the west pole is weakened by cooling effect of the zonal temperature advection.

### 3.3. Role of EEWA Strength

To test the relationship between EEWA strength and SSTA asymmetry during IODs, another numerical experiment (hereafter EXP2) consisting of 15 runs is conducted. In the EXP2, the temporal evolution of the EEWA follows that of the EEWA associated with ENSO-IODs, that is, the $r_2$ in equation (3) is set to 30 before the peak of the EEWA (day 315) and set to 20 after that. And the EEWA speed coefficient, $A$ in equation (3), varies from 1 to 15 m/s in the 15 runs. Results of the EXP2 are shown in Figure 18. One can see that the SSTA of the east and the west poles are basically symmetric when $A$ is under 9 m/s, and become more and more asymmetric as EEWA velocity strengthens. Similar to the results of EXP1, the cooling in the east pole is substantially intensified as EEWA becomes stronger, while the warming in the west pole does not change very much. The peaking time of the east pole gets earlier by 1–2 months as the EEWA speed increases. The peak values of the SSTA in the two poles of the EXP2 are summarized in Figure 19a. The SSTA of the east and the west poles both intensify as the EEWA strengthens when $A$ is less than 9 m/s, but after that the SSTA intensity of the west pole starts to decrease, causing the cooling in the east pole being much stronger than the warming in the west pole, and thus the asymmetric SSTA pattern.

Figure 20 shows the variation of D20A simulated in the 15 runs of the EXP2. One can see that the magnitudes of the D20A of the two poles both intensify as EEWA velocity strengthens, making the D20A
symmetric in all the 15 runs. This is also clearly shown in Figure 19b. The D20A in the east and west poles basically change linearly with the EEA speed. When $A$ is increased by 1 m/s, the D20A of the east and west pole will enlarge about 4 and 3 m, respectively. The D20A along the equator, $5^\circ S$, $12^\circ S$, and $5^\circ N$ in the

Figure 20. Time series of thermocline depth (depth of the 20°C isotherm, D20; Unit: m) anomalies (D20A) calculated from each runs in EXP2 (dashed lines indicate the D20A in the west pole; solid lines indicate the D20A in the east pole).
run with $A = 8$ and $14 \text{ m/s}$ of EXP2 are shown in Figure 21. Similar to the situation in EXP1 (Figure 13), the D20A along $5^\circ S$, $12^\circ S$, and $5^\circ N$ are dominated by westward Rossby waves, while the D20A along the equator is dominated by eastward Kelvin waves. The temporal evolutions of D20A in all the latitudes are all similar for the two runs. The major difference between the D20A in the two runs is that the magnitude of D20A in the run with $A = 14 \text{ m/s}$ is larger than that in the run with $A = 8 \text{ m/s}$.

The relationship between the EEWA strength and the SSTA asymmetry can be explained as follows. Considering the maximum SSTA in the west pole always appears in December-February in the EXP2 (Figure 18),

Figure 21. Time-longitude plots of the model D20A along (a) equator, (b) $5^\circ S$, (c) $12^\circ S$, and (d) $5^\circ N$ in the run with $A = 8 \text{ m/s}$ in EXP2. (d–g) same as Figures 21a–21d but in the run with $A = 14 \text{ m/s}$ in EXP2.

Figure 22. Depth-longitude sections of subsurface temperature anomalies (Unit: $^\circ C$) of the equatorial Indian Ocean (averaged between $5^\circ S$ and $5^\circ N$) during the peak month of IOD simulated in the runs with anomalous wind speed of (a) $8 \text{ m/s}$ and (b) $14 \text{ m/s}$ of EXP2. The zero contour has been added as a solid black line.
we take December as an example to investigate the vertical distribution of temperature anomaly in the equatorial Indian Ocean (Figure 22). For the case of $A = 8$ m/s (Figure 22a), the signs of the surface and subsurface temperature anomalies are the same for both the eastern and the western equatorial Indian Ocean. When $A$ is increased to 14 m/s (Figure 22b), the upwelling in the eastern Indian Ocean and the anomalous westward current in the surface layer of the equatorial Indian Ocean both strengthens, making the cooling in the east pole much more intense than that in the case of $A = 8$ m/s and transporting colder water to the west pole by horizontal advection. In this case, the SST warming in the west pole is damped and even turns to a weak cooling in the surface layer, showing a monopole pattern in SSTA.

Mixed layer heat budget analysis of the EXP2 is also conducted to investigate the roles of different dynamical processes in the SST variations in the east and the west poles, and the results of runs, $A = 8$ m/s (weak EEWA) and $A = 14$ m/s (strong EEWA), are shown in Figure 23. Similar to EXP1, the sum of three-dimensional temperature advection terms also well represents the time tendency of temperature in both the east and west poles, which indicates that the temperature anomalies are dominated by dynamical processes. The discrepancy between the sum of three-dimensional temperature advection terms and the temperature time tendency may also related to the changes of heat flux terms as described in section 3.2. For the east pole, cooling tendency is strong in October-December in both runs. When $A = 8$ m/s, both the vertical and the meridional temperature advection contribute to the cooling tendency, while the effect of the zonal temperature advection is against it; when $A = 14$ m/s, the magnitude of the vertical temperature advection increases dramatically and becomes the dominant contributor to the cooling tendency in the east pole. As for the west pole, when $A = 8$ m/s, the vertical temperature advection term is much larger than the two horizontal temperature advection terms, and plays a dominant role in the west pole warming. But the situation changes in the case of $A = 14$ m/s: the cooling effect of the zonal temperature advection is not negligible due to the change in zonal SST gradient caused by severe east pole cooling and the strengthening of anomalous westward equatorial current. This unusually strong cold zonal temperature advection partly offsets the
warming in the west pole caused by vertical temperature advection, and thus makes the SSTA pattern asymmetric.

4. Summary and Discussion

The SSTA patterns of the six strongest IODs in the past 60 years are significantly different. During the IODs in 1972, 1982, 1997, and 2006, the intensities of the warm SSTA in the western Indian Ocean and the cold SSTA in the southeastern Indian Ocean both are notable and comparable, and SSTA pattern in the tropical Indian Ocean shows a typical dipole distribution. While in 1961 and 1994, the intense cold SSTA in the southeastern Indian Ocean becomes the major feature of the SSTA pattern in contrast to the much weaker warm SSTA in the western Indian Ocean, making the SSTA pattern more like a monopole rather than a dipole. Dynamical mechanisms of the formation of these different SSTA patterns are explored in this research using an OGCM.

The results of numerical experiments suggest that the setup time of the EEWA associated with IODs is crucially important for the symmetrical characteristics of SSTA patterns. Early setup of the EEWA can induce intense cooling in the east pole but only relatively weak warming in the west pole, causing the two poles of the IOD are thus asymmetric. The intense cooling in the east pole is mainly caused by seasonal variation of thermocline depth, horizontal SST gradient in IOD developing season, and longer duration of the EEWA. And the weak warming in the west is mainly due to the unusual cold zonal advection resulted from the zonal SST gradient change, which is induced by severe east pole cooling, and the enhanced anomalous westward current in the equatorial region.

In addition, numerical experiment further demonstrates that the strength of the EEWA also plays an important role in the symmetrical characteristics of IODs. The SSTA in the east pole and the west pole both intensify as the EEWA speed increases only when the EEWA speed A is below a critical value, which is 9 m/s. Above this critical value, the magnitude of the warming in the west pole starts to decrease as the magnitude of the cooling in the east pole still keeps increasing, leading to an asymmetric SSTA pattern. The mechanism behind this phenomenon is similar to the one in the situation when EEWA sets up earlier—the warming in the west pole is weakened by the cold horizontal advection resulted from the zonal SST gradient and the enhanced anomalous westward current, while the intense cooling in the east pole is mainly caused by the strong upwelling induced by the strengthened EEWA.

Unlike the SSTA, the thermocline depth anomalies in the two poles are always symmetric, consistent with previous findings, and their magnitude increases synchronously as the setup time of the EEWA gets earlier or the strength of the EEWA gets stronger. This implies that the asymmetric characteristic of the SSTA during IOD events is not induced directly by the anomalous thermocline variations.

The above mechanisms well explain why the IODs in 1972, 1982, 1997, and 2006 are symmetric IODs, while the ones in 1961 and 1994 are asymmetric IODs. Since the IODs in 1972, 1982, 1997, and 2006 are ENSO-IODs, the temporal evolution and the strength of the EEWA associated with these IODs are quite similar (Figure 7a): they usually setup in September and peak in November, and the maximum EEWA speed in the central equatorial Indian Ocean (70°E–90°E, 10°S–10°N, 30 day running mean) is about 5 m/s, equivalent to $A = 10$ m/s in equation (3). According to the results of numerical experiments, EEWA with such characteristics is expected to result in symmetric SSTA dipole patterns. For the IODs in 1961 and 1994 (Figure 7b), however, the setup time of the EEWA is around May, equivalent to $\sigma_2 = 80$ in equation (3), and thus asymmetric SST patterns are expected.

It is well known that the tropical Indian Ocean will turn into basin-wide warming mode during an El Niño year, which is mainly caused by ENSO induced heat flux changes [Klein et al., 1999]. The basin-wide warming induced by El Niño will contribute to the western pole warming. However, the basin-wide warming lags 2–4 months behind El Niño warming in the Pacific, and peaks during spring (reviewed by Schott et al. [2009]). So this basin-wide warming may has relatively less impact on the Indian Ocean SSTA during the developing stage of IOD, which is about half year before the peak of El Niño induced basin-wide warming.

It is worth to note, however, our numerical results cannot explain the symmetrical characteristics of all the independent IODs because the temporal evolutions and intensities of EEWA during independent IODs are highly variable while the anomalous wind fields constructed in our numerical experiments are idealized.
The EEWAs associated with the independent IODs, other than the 1961 and 1994 IODs, are either very weak or have completely different temporal evolutions. For example, the EEWAs associated with the independent IODs in 2007 and 2008 underwent a rapid growth in April to May but decay unusually early [Cai et al., 2009] and fade out before boreal fall, which is usually the peaking season of EEWAs. Under this situation, the causes of symmetrical characteristics cannot be explained by our results alone. Other factors such as different patterns of wind anomalies [Hong et al., 2008; Drbohlav et al., 2007] and sea surface flux may play more important roles in these independent IODs.

Acknowledgments
Ocean heat flux and evaporation products were provided by the WHIO OAFlux project (http://oafux.whoi.edu) funded by the NOAA Climate Observations and Monitoring (COM) program. CORE wind data were obtained from http://data1.gfdl.noaa.gov/nomads/forms/core/Corev2.html, which is maintained by GFDL scientists in collaboration with NCAR. NOAA_OI_SST_V2 and NOAA_ERST_v2 data were provided by the NOAA/OAR/ESRL PSD, Boulder, Colorado, USA, from their Web site at http://www.esrl.noaa.gov/psd/. HadISST data were obtained from http://www.metoffice.gov.uk/hadobs/hadisst/, hosted by Met Office Hadley Centre for Climate Change. This work was supported by the Basic Scientific Research Fund for National Public Institutes of China (GY02–2012G04, GY02–2010T02), Strategic Priority Research Program of the Chinese Academy of Sciences (XDA11010102), and National Natural Science Foundation of China (41176030). We wish to thank the three reviewers for their valuable comments, which helped to improve the manuscript.

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