Asymmetry of the Indian Ocean Basinwide SST Anomalies: Roles of ENSO and IOD*

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ABSTRACT

A basinwide warming (cooling) in the Indian Ocean is observed following the El Niño (La Niña) mature phase, with the amplitude of the warming being significantly larger than the cooling. A composite analysis reveals that the amplitude asymmetry (positive skewness) between the warm and cold Indian Ocean basinwide sea surface temperature anomaly pattern (IOB) appears only when ENSO is concurrent with the Indian Ocean dipole (IOD). The amplitude asymmetry becomes insignificant during the ENSO-only and the IOD-only events.

The physical mechanism for the amplitude asymmetry is investigated by analyzing the mixed layer heat budget based on the Simple Ocean Data Assimilation (SODA) 2.0.2 data. It is found that the positive skewness in the IOD west pole (IODW) is mainly caused by the asymmetry of ocean temperature advection, whereas the positive skewness in the IOD east pole (IODE) is caused by the asymmetry of the surface heat flux anomaly (primarily shortwave radiation) in response to the ENSO remote forcing.

The asymmetry of the mixed layer depth (MLD) between warm and cold events is another factor contributing to the IOB positive skewness. The MLD in IODE during the warm events (27 m) is shallower than that of the cold events (45 m), resulting a larger (smaller) temperature tendency during the warm (cold) events. In contrast, the MLD in IODW during the warm events (44 m) is deeper than that of the cold events (37 m). Because the positive skewness in IODW is caused by the ocean temperature advection and the surface heat flux plays a damping role, a larger (smaller) MLD leads to a weaker (stronger) thermodynamic damping. Thus the asymmetry of MLD in both IODE and IODW favors a greater basinwide warming than cooling.

1. Introduction

Like an El Niño in the Pacific, the Indian Ocean (IO) sea surface temperature anomaly (SSTA) exerts a marked impact on the tropical and extratropical atmospheric general circulation. For example, the Indian Ocean dipole (IOD) affects not only the Asian monsoon precipitation (e.g., Vinayachandran et al. 1999; Li et al. 2003; Zubair et al. 2003; Ashok et al. 2004; Kripalani and Kumar 2004; Harou et al. 2006; Hong et al. 2008c) but also areas beyond the monsoon region (Guan and Yamagata 2003; Saji and Yamagata 2003b). The Indian Ocean basinwide SST anomaly pattern (IOB), characterized by a basinwide warming or cooling, also has a great impact on the South Asian summer monsoon (Chang and Li 2000; Li et al. 2001; Li and Zhang 2002) and a low-level anticyclonic

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anomaly over Philippines, the latter of which appears frequently during the El Niño decaying summer (e.g., Yang et al. 2007; Wu et al. 2009a; Xie et al. 2009).

Observational analysis revealed that the interannual variability of the Pacific SST is dominated by the El Niño pattern with a maximum SSTA in the eastern equatorial Pacific, while the SST leading mode in IO exhibits a season-dependent characteristic; that is, the SSTA is controlled by IOD during June–August (JJA) and September–November (SON) and by IOB in boreal winter [December–February (DJF)] and spring [March–May (MAM)]. This seasonality leads to season-dependent remote forcing effects of IOD and IOB. For example, the negative SSTA in the southeastern IO associated with a positive IOD event tends to enhance the western North Pacific (WNP) monsoon during the El Niño developing summer through a Philippine–Sumatra pattern (Li et al. 2003; Behera et al. 2006; Kug et al. 2006).

The fact that IOB peaks in early spring and always follows the ENSO mature phase (Saji and Yamagata 2003a; Chowdary and Gnanaseelan 2007; Yang et al. 2007) suggests that the ENSO remote forcing is one crucial factor that causes IOB. Besides, ocean current anomalies associated with IOD may exert a great impact on the WNP basin and reinforce the Indian Ocean basin warming through oceanic dynamic processes (Chowdary and Gnanaseelan 2007). Thus, both IOD-induced local process and ENSO-induced remote forcing may work together to contribute to the basinwide warming, as the strong ENSO event is often concurrent with IOD (Saji and Yamagata 2003a; Ashok et al. 2004), and the tropical Indian Ocean and tropical Pacific Ocean are tightly coupled (Li et al. 2003; Lau and Nath 2004; Zhong et al. 2005; Behera et al. 2006; Kug et al. 2006).

Based on a mixed layer heat budget analysis, Chowdary and Gnanaseelan (2007) examined the processes that lead to a basinwide warming. As revealed by the present study, the observed IOB shows a clear amplitude asymmetry between the basinwide warming and cooling. The physical processes that lead to the SST amplitude asymmetry between the warm and cold IOB events are not clear. As the amplitude of ENSO and IOD is asymmetric (An and Jin 2004; Hong et al. 2008a,b; Su et al. 2010), a natural question is whether the SST amplitude asymmetry of IOB is caused by the asymmetry of ENSO and IOD.

The objective of the present study is to reveal physical mechanisms responsible for the IOB amplitude asymmetry. Many previous studies are based on the positive minus negative IOB composites, which could not address this asymmetry issue. Here we investigate specific dynamic and thermodynamic processes that give rise to the IOB amplitude asymmetry by analyzing observational data. This paper is organized as follows: In section 2, we describe the data to be used. In section 3, we use the skewness to measure the amplitude asymmetry of IOB. A composite analysis is followed to investigate the relative impact of ENSO and IOD on the IOB asymmetry in section 4. A mixed layer heat budget diagnosis is put forth in section 5 to find out the specific dynamic and thermodynamic processes that give rise to the asymmetry of SSTA tendencies between the basinwide warm and cold phases. Finally, a concluding remark and discussion are given in the last section.

2. Data

The Simple Ocean Data Assimilation (SODA) version 2.0.2 (Carton et al. 2005) is used as a major data source in this study. The ocean model in the data assimilation is based on the Parallel Ocean Program (POP; Dukowicz and Smith 1994) with a horizontal resolution of 0.4° longitude by 0.25° latitude. There are 40 levels in the vertical, with a resolution of approximately 10 m in the upper 100 m. The output is in monthly averaged form, mapped onto a uniform 0.5° × 0.5° × 40-level grid. Forced by daily wind stresses and heat fluxes from 40-yr European Centre for Medium-Range Weather Forecasts (ECMWF) Re-Analysis (ERA-40), SODA 2.0.2 assimilates all the available hydrographic data including XBTs from 1958 to 2000. In addition, the ERA-40 (Uppala et al. 2005) and the Hadley Centre Sea Ice and Sea Surface Temperature (HadISST) dataset (Rayner et al. 1996) is used for diagnosing the surface heat fluxes and the asymmetry of SSTA.

In the present study, the monthly mean climatology is first calculated for the period of 1958–2001 and anomalies are then defined as departures from this climatology. A procedure is applied to the SST to remove a linear warming trend in the IO (Saji and Yamagata 2003a). A 3-month running mean is then applied to all datasets to filter out the intraseasonal variation. The definition of IOD is same as in Saji et al. (1999) and the IODE and IODW represent the IOD east pole and west pole, respectively. The IOB event is defined when area-averaged (20°S–20°N, 40°–105°E) SSTA is greater than 0.75 (less than −0.75) standard deviation. The ENSO event is defined when the normalized Niño-3.4 index in November–January (NDJ) is larger than 0.75σ. The so-defined ENSO events are similar to Trenberth (1997).

3. Measuring the IOB asymmetry

The skewness is a measure of the asymmetry of a probability distribution function and a value of 0 represents...
a normal distribution (White 1980). The skewness is defined as follows:

\[
\text{Skewness} = \frac{m_3}{(m_2)^{3/2}},
\]

where \(m_k\) is the \(k\)th moment,

\[
m_k = \frac{1}{N} \sum_{i=1}^{N} (x_i - \bar{X})^k,
\]

and \(x_i\) is the \(i\)th observation (seasonal mean), \(\bar{X}\) is the climatological mean, and \(N (=44)\) is the number of observations. The statistical significance of the skewness may be estimated if the number of independent samples is known (White 1980). Because the time series of SSTA is not statistically independent, a range of the independent sample number (N/2 ~ N) is used to estimate the significance level. It is estimated that a confidence level of 95% (90%) corresponds to the amplitude of the skewness exceeding \(\pm 0.72\) (\(\pm 0.6\)).

The distributions of the SSTA skewness in the tropical Indo-Pacific Ocean during different seasons are shown in Fig. 1. In IO, there appears a significant negative skewness off the coast of Sumatra (the box marked by IODE) during the IOD mature phase (SON). The cause of this IOD asymmetry was discussed in Hong et al. (2008a). Following the IOD mature phase, a positive skewness develops quickly over the western IO (the box marked by IODW) during IOD decaying phase (DJF). The positive skewness then extends gradually from...
western IO to eastern IO and finally spreads the whole IO in MAM (box marked by IOB). Note that the negative skewness over IODE in SON had fully terminated and switched into a positive skewness in MAM. In contrast to the distributions of SST skewness in IO, which exhibits a high seasonality, the SST skewness pattern over the equatorial eastern Pacific Ocean is characterized by a persistent positive skewness (Su et al. 2010). We recalculate the SST skewness by using the other data sources, such as National Oceanic and Atmospheric Administration (NOAA) extended reconstructed SST (Smith et al. 1996). The results show a consistency with Fig. 1 (not shown), indicating that the SST positive skewness in IOB during MAM is robust.

4. Composite analysis

The time series of IOB and Niño-3.4 (Fig. 2) show that most of the warm (cold) episode associated with IOB is followed by the El Niño (La Niña) episode and that the basinwide warming seems to attain a larger amplitude when ENSO is strong and concurrent with IOD (such as 1987 and 1997). Does the positive skewness in IOB depend on the phase and amplitude of ENSO and IOD? To investigate the impact of IOD and ENSO phases on the amplitude asymmetry of IOB, a composite analysis is conducted. Here, we divided the total ENSO and IOD cases into three categories: IOD-only, ENSO-only and the combined ENSO–IOD (Table 1). We note that for the category of ENSO with IOD, the El Niño is concurrent with a positive IOD [i.e., a cold (warm) SST in eastern (western) IO], while the La Niña is concurrent with a negative IOD, consistent with previous studies (e.g., Saji and Yamagata 2003a).

The Hovmöller diagram of the SSTA averaged over 20°S–20°N shows that a basinwide SSTA in IO is clearly seen for the ENSO-only and the combined ENSO–IOD events (Fig. 3), and the basinwide warming (cooling) is followed by the El Niño (La Niña) episode. Though the IOD-only composite also evolves into a basin-like pattern, the sign of SSTA is reverse and its amplitude is much weaker compared with the ENSO-only and the combined ENSO–IOD composites. As for the IOB amplitude, the basinwide warming is generally equal to the basinwide cooling for the ENSO-only and IOD-only composites, while the warming is significantly larger than the cooling for the combined ENSO–IOD composite. The result suggests that the SST positive skewness in IOB primarily results from the amplitude asymmetry of the combined ENSO–IOD events.

We then recalculate the SST skewness by removing the years of ENSO with or without IOD to evaluate the ENSO remote forcing effect on the IOB positive skewness. For example, years 1965, 1976, 1986, and 1991 are removed in estimating the influence of the El Niño–only events on the total skewness. The impact would be crucial if the distribution of the SST skewness significantly changes compared with the original one. It turns out that the basinwide positive skewness decreases dramatically when the combined El Niño–IOD events are removed, whereas the basinwide positive skewness just changes slightly when the El Niño–only events are removed (Fig. 4). Again, the above result demonstrates that the SST positive skewness in IOB primarily results from the amplitude asymmetry of the combined ENSO–IOD events. In absence of the IOD local impact, the ENSO-only cases (which are composed of relatively weak ENSO episodes) cannot cause the positive IOB skewness. In the next section we will reveal, through a detailed mixed layer heat budget analysis, the specific processes that give rise to the amplitude asymmetry.

5. Cause of the IOB asymmetry

To understand the relative roles of ocean temperature advections and surface heat fluxes in causing the SSTA amplitude asymmetry in IOB, we analyze the oceanic mixed layer heat budget for the combined ENSO–IOD composite. The mixed layer temperature tendency
Fig. 3. Hovmöller diagram of the monthly SSTA averaged over 20°S–20°N for the IOD-only, the combined ENSO-IOD, and the ENSO-only composites (see Table 1). (a)–(c) The El Niño and/or positive IOD composite; (d)–(f) La Niña and/or negative IOD composite. The x axis is the month of year, with (0) being the year of ENSO and/or IOD development and (1) being the year after.
equation may be written as (Li et al. 2002; Hong et al. 2008a)

\[
\begin{align*}
\frac{\partial T'}{\partial t} &= -(V \cdot VT') + \frac{Q_{\text{net}}'}{\rho C_P H} + R,
\end{align*}
\]

where \( T \) denotes the mixed layer temperature; \( V = (u, v, w) \) is three-dimensional (3D) ocean current, which is defined as the vertical average from surface to the bottom of mixed layer; \( \nabla = (\partial / \partial x, \partial / \partial y, \partial / \partial z) \) denotes 3D gradient operator; \( ' \) represents the anomaly variables’ departure from the climatological mean term; \( -(V' \cdot VT') \) denotes anomalous 3D temperature advection and can be decomposed into the linear advection terms \( -(V' \cdot VT + V \cdot VT') \) and nonlinear advection term \(- (V' \cdot VT')\), where \( ' \) denotes climatological mean variables; \( Q_{\text{net}} \) is the summation of the net downward shortwave radiation \( Q_{\text{SW}} \), surface longwave radiation \( Q_{LW} \), and surface latent heat \( Q_{LH} \) and sensible heat \( Q_{SH} \) fluxes at the ocean surface; \( R \) represents the residual term; \( \rho = 10^3 \text{ kg m}^{-3} \) is the density of water; \( C_P = 4000 \text{ J kg}^{-1} \text{ K}^{-1} \) is the specific heat of water, and \( H \) denotes the mixed layer depth. Here, a positive heat flux indicates heating the ocean, and \( H \) is defined as the depth at which the temperature is 0.8°C lower than the sea surface temperature, following Wang and McPhaden (2000).

Figure 5 shows the comparisons of the composite temperature and wind stress anomalies over the tropical Indo-Pacific Ocean between the IOB warm and cold events in DJF. For the positive events, a basinwide warming over IO and an El Niño–induced warm SST in the equatorial eastern Pacific are clearly seen. The spatial patterns of the cold events are generally the mirror image of the warm events but with smaller amplitude, which is also shown in Fig. 3. In contrast to the horizontal temperature anomaly in IO, which distributes uniformly in space, the vertical temperature structure, particularly for the warm events, is significantly different between eastern IO and western IO; that is, the temperature anomaly extends from the surface to the subsurface layer in western IO but is limited in near the surface in eastern IO (Fig. 5, right panels). Figure 5 also indicates the mixed layer depth in IODW is much deeper than that in IODE for the warm IOB composite (Table 2). Because the vertical structure of the ocean temperature anomaly significantly differs between the IODE and IODW, the heat budget in IODW and IODE is calculated separately and a realistically varying mixed layer depth is used in the diagnosis. Here, the IODE (15°S–0°, 85°–110°E) and IODW (15°–0°N, 50°–75°E) domains are determined based on the distribution of SST skewness in Fig. 1c, which is slightly different from Saji et al. (1999).

The composite evolution of the mixing layer temperature (MLT) and its tendency \( \partial T'/\partial t \) for IODE and IODW is illustrated in Fig. 6. Note that initial SST perturbations in IODW during summer for both warm and cold events have similar amplitude, but they diverge quickly after autumn, and the amplitude of MLT of warm events (0.9°C) is almost 2 times larger than that of cold events (−0.5°C) in the mature phase. The time evolution of the MLT and MLT tendency in IODE is similar to IODW but with a sharp transition from negative (positive) SST to positive (negative) SST during the IOB developing stage (Fig. 6b). Figure 6 shows that the MLT asymmetry in the mature phase is obviously attributed to the asymmetry of the MLT tendency during the developing stage. Note that the maximum
warming rate in IODE lags the maximum warming rate in IODW by 1–2 months (Fig. 6). Considering the difference of the peak warming between IODW and IODE, we define the developing stage as September–January for IODW and October–February for IODE.

a. Cause of the positive skewness in IODW

The heat budget analysis indicates that the warming and cooling in IODW are attributed to different physical mechanisms. Whereas the warming is forced by the ocean temperature advection, both the ocean temperature advection and the heat flux contribute to the cooling (Fig. 7a). The net surface heat flux terms, dominated by the shortwave radiation (not shown), actually tend to cool the SST for both warm and cold episodes, which acts to decrease the SST positive skewness in IOB. Note that the contribution of surface heat flux to the MLT tendency (−0.06°C month⁻¹) is much larger than that of the ocean temperature advection (−0.02°C month⁻¹) for the cold events, indicating the cooling is primarily forced by the atmospheric processes (heat flux). Although the heat budget is not exactly in balance because of the uncertainty of the surface heat fluxes and oceanic subgrid processes, the asymmetry in the MLT tendency is adequately demonstrated and is consistent with the observed; that is, the amplitude of the positive MLT tendency during the warming is much greater (almost double) than its cooling counterpart.

Figure 7a shows that the SST positive skewness in IODW is primarily attributed to the asymmetry of ocean dynamics between the warm and cold events. As the ocean dynamics consist of linear and nonlinear advection terms, it is necessary to reveal their relative importance. The sum of the linear and nonlinear advection terms in contributing to the asymmetric MLT tendency

<table>
<thead>
<tr>
<th>Area/phase</th>
<th>Warm phase</th>
<th>Cold phase</th>
<th>Climatology mean</th>
</tr>
</thead>
<tbody>
<tr>
<td>IODE</td>
<td>27</td>
<td>45</td>
<td>42</td>
</tr>
<tr>
<td>IODW</td>
<td>44</td>
<td>37</td>
<td>40</td>
</tr>
</tbody>
</table>
is shown in Fig. 8a. Note that the linear advection terms are $0.25 \pm 0.02$ °C month$^{-1}$ for the warm IOB and only $0.02 \pm 0.01$ °C month$^{-1}$ for the cold IOB, illustrating a great asymmetry. The nonlinear advection terms, on the other hand, are negative for both warm and cold events (both are $-0.01 \pm 0.01$ °C month$^{-1}$), indicating that the nonlinear advectons tend to cool the SST for both the cold and warm events. Thus, unlike the IOD and ENSO asymmetry during which the nonlinear advection plays a crucial role in causing the asymmetric MLT tendency (Hong et al. 2008a; Su et al. 2010), positive skewness associated with IOB in the western IO is primarily attributed to the asymmetry of the linear temperature advection.

The linear advection terms can be further decomposed into the zonal, meridional, and vertical advection terms. It is found that the horizontal advection $-u\partial T/\partial x$ and the vertical advection $-w\partial T/\partial z$ are the dominant terms (Fig. 8b). The asymmetry of $-u\partial T/\partial x (-u' < 0, \partial T/\partial x > 0)$ and $-w\partial T/\partial z (-w' < 0, \partial T/\partial z > 0)$ is caused by the asymmetry of local ocean current anomalies (Fig. 9). Because both the IOD and ENSO may affect the ocean current anomalies in IO, a partial correlation analysis is conducted to reveal their relative importance. The result shows that the ocean current anomaly in IODW is primarily affected by IOD (figure not shown). Keep in mind that the horizontal mean temperature gradient $\partial T/\partial x$ and vertical gradient $\partial T/\partial z$ are always positive in the equatorial IO. Because of the IOD asymmetry, the amplitude of westward and downward current anomalies is larger than that of eastward and upward current anomalies. As a result, the sum of $-u\partial T/\partial x$ and $-w\partial T/\partial z$ during the warm events has larger magnitude than that during the cold events. The annual cycle of the climatological mean vertical velocity over IODW also plays a role in the asymmetry of $\partial T/\partial z$. During the development of warm IOB events, the local ocean wave anomaly (not shown) results in a maximum positive temperature anomaly at the subsurface layer in IODW (Fig. 10a), which generates a significant negative vertical temperature gradient anomaly ($\partial T/\partial z < 0$) near the base of the mixed layer. The pattern during the cold events is generally a mirror image of the warm events except with smaller amplitude (Fig. 10b). As seen in Fig. 10a, the negative term $\partial T/\partial z$ persists through the IOB development phase for the warm event. The term $-\bar{W}\partial T/\partial z$ changes from a negative to positive value in September when the mean vertical velocity $\bar{W}$
turns from downwelling to upwelling (Fig. 10c). Because the contribution of $-\bar{W}\partial T'/\partial z$ to the asymmetric MLT tendency in IODW initiates in late autumn, the positive skewness in IODW lags the IOD peak phase (SON) and occurs in boreal winter and spring.

b. Cause of the positive skewness in IODE

The relative contribution of the net surface heat flux and ocean temperature advection to the warming (cooling) in IODE (Fig. 7b) shows that the surface heat flux is a main contributor to the amplitude asymmetry while the ocean advection terms tend to oppose the observed asymmetry. Note that the amplitude of the net surface heat flux for the warm events ($0.2^\circ$C month$^{-1}$) is significantly larger than that of the cold events ($-0.07^\circ$C month$^{-1}$). In contrast to the process in IODW, the warm SSTA in IODE is followed by a great cold SSTA in SON, and the positive skewness in IODE is caused by the asymmetric heat flux anomaly between the warm and cold events. The warming is not attributed to the thermocline process, as the positive temperature anomaly only appears in near the surface and a significantly large cold temperature anomaly appears in the subsurface layer as shown in Fig. 5a.

The heat flux is further decomposed into four terms: $Q_{SW}$, $Q_{LW}$, $Q_{LH}$, and $Q_{SH}$. Figure 11 shows that the shortwave radiation is the dominant term. Note that the peak of the net heat flux occurs in December, which lags the maximum shortwave radiation by 1–2 months for the warm episodes. The evaporation–wind–SST is a positive feedback during the IOD developing phase (Li et al. 2003) but switches into a negative feedback in boreal winter. The time series of $Q_{SW}$ (Fig. 11a) shows that the shortwave radiation anomaly is positive (less convection) in IODE, whereas $Q_{SW}$ is negative (more convection) in IODW (Fig. 7a) during the warm IOB developing stage.
Thus, the air–sea interaction undergoes in a distinctive dynamic regime in IODE and IODW. For the IODW, the SST is active; that is, the atmosphere is primarily in response to SSTA forcing. A positive SSTA tends to reinforce the convection, while the enhanced convection feedback weakens the SSTA from so-called cloud–radiation–SST (CRS) negative feedback process (Ramanathan and Collins 1991; Li et al. 2000). However, the SST is passive in IODE where the warm SSTA is a passive response to the atmospheric forcing (e.g., subsidence anomalies) remotely controlled by the El Niño over the equatorial eastern Pacific (Fig. 12). The result above is consistent with the thermodynamic nature of ENSO influence on the IO, suggested by previous studies (e.g., Klein et al. 1999).

Because the amplitude of El Niño in DJF is in general larger than that of La Niña, the resulting subsidence in IODE is also greater than the amplitude of the ascending motion (Fig. 12c). This asymmetry of anomalous vertical motion in IODE leads to an asymmetric surface heat flux anomaly (dominated by the shortwave radiation), which results in the SST positive skewness in IODE. Figure 12 also illustrates that the local Walker circulation in IO has a wider longitudinal extent during the warm events than during the cold events. This implies that the amplitude asymmetry in IODW may reinforce the asymmetry in the anomalous vertical velocity in IODE and thus further enhance the local SST positive skewness. Therefore, it is the combined effect of the remote ENSO forcing and local Walker circulation in IO that leads to the amplitude asymmetry in the shortwave radiation anomaly and thus in SSTA in IODE.

c. Effect of the mixed layer depth change

Next, we pay special attention to the impacts of MLD on the IOB positive skewness. The mixed layer heat budget equation shows that the MLT tendency is oppositely proportional to the mixed layer depth; that is, for given a fixed net heat flux anomaly, a shallower MLD would create a larger temperature tendency. The comparison of MLD between the warm and cold events is shown in Table 2. For IODE, the MLD of the cold events (45 m) is much deeper than that of warm events (27 m). This difference is also clearly seen in the right panel of Fig. 5: that is, a sharp vertical temperature gradient...
appears in the upper ocean in IODE for the warm events while the vertical temperature gradient is much shallower for the cold events. As the amplitude asymmetry in IODE is primarily attributed to the heat flux anomaly, the shallower MLD during the warm events may help accelerate the warming rate (1.6 times greater than the cooling rate) for given the same amplitude of the heat flux anomaly.

In contrast, the MLD during the warm events is deeper (44 m) than that during the cold events (37 m) in IODW. This implies that the heat flux anomaly is less efficient in contributing to the temperature tendency during the warm events. However, the MLT tendency in IODW is primarily controlled by the ocean temperature advection process while the heat flux tends to damp the SST positive skewness. Thus a deeper MLD...
in IODW may favor the development of the positive skewness.

6. Summary and discussion

In this study we investigate the amplitude asymmetry between the basinwide warm and cold events in the tropical IO by diagnosing the SODA2.0.2 and ERA-40 data. The strength of the asymmetry is measured by the skewness. A composite analysis is conducted, in which we separate all events into three groups—ENSO-only, IOD-only, and combined ENSO–IOD—in order to investigate the relative contributions of IOD and ENSO on the SSTA skewness. A mixed layer heat budget analysis is further conducted to investigate specific dynamic and thermodynamic mechanisms that lead to the amplitude asymmetry. The main results are summarized as below:

1) A significant basinwide positive skewness of SSTA is identified over IO. This basinwide skewness initiates at western IO in boreal late autumn, develops gradually into the eastern IO during boreal winter, and finally extends to the whole tropical IO in boreal spring.

2) A composite analysis reveals that the SST positive skewness in IOB primarily results from the asymmetry during the combined ENSO–IOD events. The contributions of the ENSO-only or IOD-only events to the basinwide positive skewness are insignificant.

3) The mixed layer heat budget analysis shows that the basinwide warming is caused by different mechanisms in the western and eastern IO. The SST positive skewness in IODW is primarily attributed to the asymmetric ocean temperature advection caused by the IOD-asymmetry-induced ocean current and thermocline anomalies. The SST positive skewness in IODE, on the other hand, is attributed to the asymmetric surface heat flux (primarily shortwave radiation) anomaly caused by the asymmetry of the ENSO-induced remote forcing and local Walker circulation.

4) The mixed layer depth (MLD) is another factor contributing to the IOB positive skewness. The MLD in IODE during the warm events (27 m) is shallower than that during the cold events (45 m), which leads to a larger temperature tendency during the warm events for a given surface heat flux anomaly. The MLD in IODW during the warm events (37 m), on the other hand, is deeper than that of cold events (37 m). Because the positive skewness in IODW is primarily caused by the ocean temperature advections and the surface heat flux plays a damping effect, the deeper MLD in IODW may favor a greater basinwide warming than cooling.
The fact that the positive skewness in IOB is followed by a significant negative skewness in IODE (appears in SON) and a positive skewness in equatorial eastern Pacific Ocean (peaks in NDJ) suggests that the SSTA amplitude asymmetry is possibly related to both IOD and ENSO asymmetries. A composite analysis reveals that the SST positive skewness in IOB primarily results from the combined ENSO–IOD events. The amplitudes of positive and negative IOB events are approximately symmetric for the ENSO-only composite.

The mixed layer heat budget for the combined ENSO–IOD events indicates that the asymmetry of the ocean temperature advection anomalies are responsible for the IOD positive skewness, while the positive skewness in IODE is primarily attributed to the asymmetric surface heat flux anomalies induced by the asymmetry of the remote ENSO forcing and local Walker circulation. It is worth emphasizing that in the combined ENSO–IOD events, it is hard to separate the relative roles of the remote ENSO forcing and the local air–sea coupling effects. A partial correlation analysis was conducted to estimate the relative contribution of ENSO and IOD. It turns out that both IOD and ENSO contribute to the ocean sea surface height (SSH) anomaly in the eastern IO (figure not shown). However, the ENSO remote impact on the SSH anomaly is confined in the eastern IO, whereas the IOD impact may be extended to the western IO. As the positive skewness in the western IO is primarily attributed to the asymmetric ocean temperature advection (Fig. 7a), the result above suggests that the IOD asymmetry may at least partially contribute to the positive skewness inIODW. Figure 13 shows the partial correlation of the equatorial IO SSTA to the Niño-3.4 and IOD index, respectively. It illustrates that the ENSO-induced basinwide warming (cooling) is greater than that induced by IOD for the period of December of the year of development through May of the following year. However, the partial correlation analysis does not tell whether the basinwide SSTA is positively or negatively skewed or the causes of the skewness.

We note that most of ENSO-only cases are of modest amplitude and as a result their impact on the IOB asymmetry is also modest (Fig. 4). The composite mixed layer heat budget for ENSO-only cases revealed that the basinwide warming (cooling) in IO is primarily attributed to the ENSO-induced basinwide surface heat flux anomalies, and the heat budget between warm and cold events does not show the observed positive skewness in either IODW or IODE (Fig. 14a). Our budget analysis result confirms the thermodynamic nature of remote ENSO influence on the IO as suggested by Klein et al. (1999) and others.

As the IOB events do not always occur with ENSO, it should be interesting to compose IOB events with and without ENSO. Our composite analysis shows that there are a few IOB events occurring independent of ENSO, such as the warm IOB events in 1959, 1969, and 1970 and the cold events in 1968, 1994, and 1997. The SSTA amplitude of the IOB-only events is modest and there is no obvious amplitude asymmetry between the warm and cold phase (Fig. 14b). A mixed layer heat budget analysis of the IOB-only cases shows that both the ocean temperature advection and the surface heat flux anomalies contribute to the basinwide warming/cooling (Fig. 14b). The lack of the amplitude asymmetry during the IOB-only events implies that the asymmetric ENSO remote forcing (i.e., the amplitude asymmetry between El Niño and La Niña) does play a role in causing the positive skewness in the IOB.

The robustness of observational analysis may be limited because of the smaller number of composite events. The same methodology is currently applying to long-term fully air–sea coupling simulations of the ECHAM5/Max Planck Institute Ocean Model (MPI-OM), which can successfully simulate both the IOD negative skewness and the IOB positive skewness. The simulations are in general consistent with the observations and an in-depth analysis of the model output will be reported elsewhere.

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