Asymmetry of the Indian Ocean Dipole. Part II: Model Diagnosis*

CHI-CHERNG HONG

Department of Science, Taiwan Municipal University of Education, Taipai, Taiwan

TIM LI

IPRC/SOEST, University of Hawaii at Manoa, Honolulu, Hawaii

JING-JIA LUO

FRCGC, Japan Agency for Marine-Earth Science and Technology, Yokohama, Japan

(Manuscript received 6 September 2007, in final form 13 January 2008)

ABSTRACT

In this second part of a two-part paper, the mechanism for the amplitude asymmetry of SST anomalies (SSTA) between positive and negative Indian Ocean dipole (IOD) events is investigated through the diagnosis of coupled model simulations. Same as the observed in Part I, a significant negative skewness appears in the IOD east pole (IODE) in September–November (SON), whereas there is no significant skewness in the IOD west pole (IODW). A sensitivity experiment shows that the negative skewness in IODE appears even in the case when the ENSO is absent.

The diagnosis of the model mixed layer heat budget reveals that the negative skewness is primarily induced by the nonlinear ocean temperature advection and the asymmetry of the cloud–radiation–SST feedback, consistent with the observation (Part I). However, the simulated latent heat flux anomaly is greatly underestimated in IODE during the IOD developing stage [June–September (JJAS)]. As a result, the net surface heat flux acts as strong thermal damping. The underestimation of the latent heat flux anomaly in the IODE is probably caused by the westward shift of along-coast wind anomalies off Sumatra.

1. Introduction

This paper is the second of a two-part study of the Indian Ocean dipole (IOD) asymmetry. In Hong et al. (2008, hereafter Part I) we investigate dynamic and thermodynamic processes that give rise to the IOD asymmetry through observational analysis. With the same methodology of Part I, in Part II we examine the IOD asymmetry by diagnosing a fully coupled model outputs. In the following, we briefly review the main results from Part I.

The IOD is an east–west zonal mode of the interannual variability of the Indian Ocean SST, developing in northern summer and maturing in northern autumn (e.g., Saji et al. 1999; Webster et al. 1999). Measuring the magnitude asymmetry of SST anomalies (SSTA) in the Indian Ocean by skewness, we show that the IOD east pole (IODE) has significant negative skewness but the IOD west pole (IODW) almost no skew (Part I). As a result, the IOD asymmetry is primarily caused by the negative skewness in the east pole. A mixed layer heat budget diagnosis using the Simple Ocean Data Assimilation (SODA) data further shows that the magnitude asymmetry of SST anomalies (SSTA) in the Indian Ocean by skewness, we show that the IOD east pole (IODE) has significant negative skewness but the IOD west pole (IODW) almost no skew (Part I). As a result, the IOD asymmetry is primarily caused by the negative skewness in the east pole. A mixed layer heat budget diagnosis using the Simple Ocean Data Assimilation (SODA) data further shows that the negative skewness is mainly induced by (i) the nonlinear horizontal and vertical temperature advection and (ii) the asymmetry of the cloud–radiation–SST feedback.

A major limitation in the observational analysis is that the SODA does not provide surface heat fluxes, and thus our mixed layer heat budget has a significantly large residual term. Furthermore, the robustness may be limited by the small number of IOD events in the observations. It is anticipated that a better balanced...
mixed-layer heat budget can be achieved from high-resolution fully coupled model simulations. By diagnosing the long-term coupled model output, one may examine the robustness of the observational analysis.

The long-term simulations of a fully coupled global general circulation model, the SINTEX-F1 model, will be used for this study. The SINTEX-F1 was developed at the Frontier Research Center for Global Change (FRCGC). It well simulates the annual cycle of the Asian monsoon, IOD, and ENSO (Luo et al. 2005; Behera et al. 2006). Additional sensitivity experiments, including one with the ENSO variability being suppressed, may be used to investigate the remote ENSO impact on the IOD asymmetry.

The rest of this paper is organized as follows: In section 2 we describe the SINTEX-F1 model and experiments. The skewness of the IOD asymmetry is presented in section 3. In section 4 we describe the relationship between the IOD asymmetry and ENSO. In section 5, a mixed layer heat budget analysis is performed and mechanisms leading to the IOD asymmetry are discussed. Finally, a discussion and concluding remarks are given in section 6.

2. The model and experiment design

The SINTEX-F1 (SINTEX-FRCGC version 1.0) (Luo et al. 2005) is a fully coupled atmosphere–ocean general circulation model developed under the framework of European–Japanese collaboration based on the original European SINTEX model (Gualdi et al. 2003; Guilyardi et al. 2003). The atmospheric component, T106L19 ECHAM-4.6 (Roeckner et al. 1996), is coupled to the ocean component Ocean Parallélisé (OPA 8.2) (Madec et al. 1998), through the Ocean–Atmosphere–Sea Ice–Soil (OASIS 2.4) (Valeke et al. 2000) coupler. The spectral resolution (T106) of the atmosphere model is roughly equivalent to 1° × 1°. The OPA 8.2 uses the Arakawa C grid with longitude–latitude resolution of 2° × 2° cosine (latitude) with increased meridional resolution up to 0.5° near the equator. The coupled model has been integrated for 420 years, and the first 200 years will be used as the primary data in this study.

In addition to the 200-yr control run, a non-ENSO experiment, in which the atmosphere and ocean are decoupled in the tropical eastern Pacific (25°S–25°N, from 170°W to the eastern boundary) to suppress the ENSO variability, is conducted for 70 years to investigate how ENSO may affect the IOD asymmetry. The decoupling strategy is similar to that in Behera et al. (2006); that is, the tropical eastern Pacific is fixed with the climatological SST from the control run during the 70-yr non-ENSO simulation.

3. Negative skewness in IODE

Following Part I, we use the skewness to measure the amplitude of the IOD asymmetry. Here, zero skewness represents a normal distribution and a negative skewness indicates that the amplitude of negative anomalies is larger than that of positive anomalies in statistics. The statistical significance of skewness is estimated by the formula suggested by White (1980). A confidence level of 95% corresponds to the amplitude of the skewness exceeding ±0.35.

The distribution of the SSTA skewness (Fig. 1a) shows a significant negative skewness (skewness = −0.51) in IODE and a weak, insignificant positive skewness (skewness = 0.16) in IODW. This points out that the negative skewness in IODE is a primary cause of the IOD asymmetry, which is consistent with the observation (Part I). It is also found that the negative skewness is season dependent and it peaks in the IOD mature phase [September–November (SON)] and is less skewed during the IOD developing phase (skewness = −0.27).

Comparing with observations (Fig. 1b), the SINTEX-F1 well reproduces the spatial pattern of SSTA skew-
ness, a strong negative skewness in IODE, and near-zero skewness in IODW. The magnitude of the negative skewness in the model seems smaller compared to the observed (skewness = −1), possibly due to a larger model sample number (N = 200) than the observed (N = 52). Note that the maximum negative skewness shifts slightly to the west probably because of a westward shift of along-coast wind anomalies off the coast of Sumatra, which will be discussed in section 5. Such biases are primarily related to too weak surface westerly winds in the equatorial Indian Ocean in the model climatology, which leads to a flat thermocline and far-westward extended IOD signal along the equator (Luo et al. 2007).

Because of the westward shift of the negative skewness center, in the following model diagnosis, the IODE index is defined in the area 10°S–0°, 85°–110°E. The normalized IODE SSTA amplitude in mature phase (SON) exceeding ±1 σ is defined as an IODE event. A positive IODE event corresponds to a negative phase of IOD. A total of 38 negative and 31 positive IODE events are identified for the composite (Table 1). A 5-month running mean of the normalized Niño-3 index that exceeds ±1 σ in mature phase [November–January (NDJJ)] is defined as an ENSO event. About 30% of the IODE events co-occur with the ENSO (Table 1).

4. Possible ENSO impact on the IODE asymmetry

An interesting question is whether or not the negative skewness in the IODE is induced by the asymmetry of remote El Niño and La Niña forcing. In the following, we investigate their relationship based on both the control and non-ENSO experiments.

For the control experiment, we recalculate the skewness by removing all of the ENSO year. It turns out that the skewness just changes a bit (skewness = −0.52) and still passes the significance test at 95% confidence level (P_{0.05} = ±0.41), with a higher threshold due to the decreased sample size. This result indicates that the negative skewness in the IODE is not caused by the ENSO.

We further separate negative IODE events shown in Table 1 into three categories: Type I (−1.5σ ≤ SSTA ≤ −1σ), Type II (−2σ ≤ SSTA ≤ −1.5σ), and Type III (SSTA ≤ −2σ) (Table 2). While the SSTA amplitude increases linearly from Type I to Type III, the increase of the El Niño amplitude is nonlinear. From Type I to Type II, the El Niño strength increases rapidly, whereas from Type II to Type III, the magnitude of Niño-3 SSTA has little change. This result suggests that, for strong negative IODE events, the ENSO remote forcing just plays a minor role in the growth of SSTA in the IODE.

Spatial distributions of the SSTA skewness for the non-ENSO experiment are shown in Fig. 2. It displays a similar spatial pattern as that in the control run (Fig. 1a), a strong negative skewness in the IODE (skewness = −0.67) and a weak positive skewness (skewness = 0.14) in the IODW. The greater magnitude of negative skewness in the non-ENSO experiment may be attributed to a smaller sample number (N = 70). A t test shows that the negative skewness is significant at the 95% confidence level (P_{0.05} = ±0.57). Thus the non-ENSO experiment confirms that the negative skewness in the IODE arises from local air–sea interaction. In the next section, through a mixed layer heat budget analysis we intend to investigate specific processes that give rise to the IOD asymmetry.

5. A mixed layer heat budget analysis

To understand the relative roles of the ocean advection and surface heat fluxes in causing the SSTA amplitude asymmetry, we analyze the oceanic mixed layer heat budget and make composites for the positive and negative IODE events. The mixed layer temperature tendency equation may be written as (Li et al. 2002)

\[
\frac{\partial T'}{\partial t} = - (V' \cdot \nabla T + \nabla \cdot \nabla T') - (V' \cdot \nabla T') + \frac{1}{\rho C_p H} (Q_{SW} + Q_{LW} + Q_{LH} + Q_{SH}) + R,
\]

(1)
where $T$ denotes the mixed layer temperature; $\mathbf{V} = (u, v, w)$ is three-dimensional ocean current, defined as the vertical average from surface to the bottom of mixed layer; $(\cdot)'$ represents the anomaly variables and $\langle \cdot \rangle$ the climatological mean variables; term $-\nabla \cdot (\mathbf{V}' \cdot \nabla T' + \nabla \cdot \nabla T')$ is the summation of linear advection terms; $-\nabla \cdot (\mathbf{V} \cdot \nabla T)$ denotes the nonlinear temperature advection term; $Q_{SW}, Q_{LW}, Q_{LH}$, and $Q_{SH}$ represent the net downward shortwave radiation at the ocean surface, net downward surface longwave radiation, and surface latent and sensible heat fluxes; $R$ represents a residual term. Here a positive surface flux indicates heating of the ocean. The mixing layer depth (MLD) in the model varies from 30 to 40 m in the IODE during the developing phase. A variable MLD is used in the diagnosis of the mixed layer heat budget.

Figure 3 shows the composite SSTA and 850-hPa wind anomaly fields for positive and negative IODE events. An east–west dipole of SSTA is clearly seen in the Indian Ocean. The IODE has a larger SSTA magnitude than the IODW, suggesting that the IOD variability is primary determined by the variability of SSTA in the IODE ($\sigma_{IODE} = 0.6$, $\sigma_{IODW} = 0.26$). Whereas both of the composites have a similar horizontal pattern but an opposite mirror image, the magnitude of SSTA in the negative IODE is much stronger than that in the positive IODE.

The composite evolution of the mixed layer temperature (hereafter MLT) and MLT tendency $\partial T/\partial t$ is illustrated in Fig. 4. Note that initial SST perturbations in both positive and negative events have similar amplitude in April, but they diverge quickly after June, and the amplitude of MLT in the negative IODE composite reaches $-1.2^\circ$C in October compared to 0.8°C in the positive IODE composite. As in Part I, we further examine the dynamic and thermodynamic processes that give rise to the asymmetric MLT tendency during the developing phase [June–September (JJAS)].

The estimate of MLT tendency by the sum of 3D ocean temperature advection and surface heat flux terms is shown in Fig. 5. Note that the estimated temperature tendency from the heat budget is very close to the actual temperature tendency, in both the temporal evolution and amplitude. The magnitude of the residual term is much smaller compared to the SODA analysis.

**Fig. 2.** As in Fig. 1, but for the non-ENSO experiment.

**Fig. 3.** Composites of the model SSTA and 850-hPa wind anomaly during SON for (a) positive and (b) negative IODE.

**Fig. 4.** Composite mixed layer temperature (circles) and mixed layer temperature tendency (squares), unit: °C month$^{-1}$. Open (closed) marks denote positive (negative) IODE events.
Figure 6 reveals that the ocean temperature advection significantly contributes to the negative skewness in the IODE. In contrast to the SODA diagnosis, the net surface heat flux tends to damp the SSTA in the IODE during the developing phase. The cause of this inconsistency is attributed to a bias in the surface latent heat flux field. In the following, we investigate the specific process that gives rise to the IOD asymmetry and discuss why the net surface heat flux contributes negatively to the MLT tendency during the IODE developing stage.

a. Effect of nonlinear temperature advection

Following Part I, we decompose 3D ocean temperature advection into zonal, meridional, and vertical temperature advection components, and for each component we further decompose it into linear and nonlinear advection terms. The sum of both linear and nonlinear advection terms in contributing to the asymmetric MLT tendency in JJAS is listed in Table 3. Note that, while the linear advection terms contribute to the growth of both positive and negative IODE, the nonlinear terms cool the MLT in both warm and cold episodes, thus playing an important role in causing the negative skewness in the IODE. This nonlinear ocean dynamics effect is consistent with the observational analysis.

A further diagnosis indicates that both horizontal and vertical nonlinear advection terms contribute significantly to the negative skewness (Fig. 7). In particular, the vertical advection has a strong cooling tendency at the equator but is weaker near the coast of Java–Sumatra. This implies that both SINTEX-F1 and SODA may underestimate the effect of coastal upwelling. In general, the box-averaged vertical advection has comparable magnitude to the horizontal advection.

The role of nonlinear ocean advection in causing the IODE asymmetry may be further demonstrated from the time series of SSTA and the linear and nonlinear advection fields (Fig. 8). Note that the linear advection always contributes to the growth of both positive and negative SSTA, while the MLT tendency associated with the nonlinear advection is always negative and, thus, tends to enhance (weaken) the negative (positive) IODE episodes. This confirms that the asymmetry of the ocean advection–SST–wind feedback is one of major mechanisms that lead to the negative skewness.

b. Effect of the surface latent heat flux

As shown in Part I, the surface latent heat flux anomaly plays an important role in enhancing the amplitude asymmetry in the IODE. In contrast to observation, the latent heat flux anomaly in the model is much weaker during the developing stage (JJAS). As a result, the net surface heat flux is primarily determined by the shortwave radiation anomaly (Fig. 9) and, thus, acts as a thermal damping for IOD.

A comparison between the spatial distributions of the observed and simulated latent heat flux anomaly shows that the significant underestimation of the latent heat flux anomaly in the IODE is attributed to 1) the westward shift of maximum wind anomaly and thus the center of the negative latent heat flux anomaly and 2) occurrence of a positive latent heat flux center near the coast of Java–Sumatra (Fig. 10). While the observed SSTA and latent heat flux anomaly are approximately

<table>
<thead>
<tr>
<th>Event</th>
<th>Linear advection</th>
<th>Nonlinear advection</th>
</tr>
</thead>
<tbody>
<tr>
<td>Negative IODE</td>
<td>−0.39</td>
<td>−0.1</td>
</tr>
<tr>
<td>Positive IODE</td>
<td>0.35</td>
<td>−0.1</td>
</tr>
</tbody>
</table>
in phase, the simulated negative latent heat flux has a significant zonal phase difference with the cold SSTA center. The cause of this phase difference is primarily attributed to a westward shift of the wind anomaly, which leads to a near-zero wind speed anomaly near the coast of Java–Sumatra.

To further understand the influence of the westward shift of the wind anomaly on the surface heat flux, we
diagnose the latent heat flux by using the bulk formula. The latent heat flux is proportion to $U \cdot \Delta q$, where $U$ is the wind speed at 10 m, and $\Delta q = q_s - q_a$ denotes the specific humidity difference between the ocean surface and 10 m. The latent heat flux anomaly ($U \cdot \Delta q$) can be decomposed into the following three terms, that is, $(U \cdot \Delta q) = \bar{U} \Delta q + U' \Delta q + U' \Delta q'$. Here, the prime denotes the deviation from the climatological mean state as indicated by a bar. In general, the term $\Delta q'$ is proportion to SSTA, and the latent heat flux anomaly is dominated by the term $U' \Delta q$ (Fig. 11a). For example, during the developing phase of the negative IODE event, the observed wind anomaly is in phase with the summer mean flow. As a result, $U'$ is positive and creates a positive anomalous latent heat flux ($U' \Delta q > 0$), which cools the sea surface and enhances the magnitude of the negative SSTA. However, in the model simulation, due to the westward shift of $U'$, the anomalous wind speed is very small near the

Fig. 9. Time series of the contribution of the latent heat flux (circles) and the downward shortwave radiation (squares) anomalies averaged over the east pole for the positive (open marks) and negative (closed marks) IODE events.

Fig. 10. Comparison of the surface latent heat flux (contour), SST (shading), and 850-hPa wind anomalies in JJA for the negative IODE events between (a) the SINTEX-F1 and (b) the observation. Contour intervals are 5 W m$^{-2}$; positive contours denote a negative contribution to SSTA.

Fig. 11. Contributions of the terms (a) $U' \Delta q$ and (b) $\bar{U} \Delta q'$ to the latent heat flux anomaly shown in Fig. 10a. The latent heat flux is estimated by bulk formula (Fairall et al. 1996); $U$ is wind speed at 10 m, and $\Delta q = q_s - q_a$ denotes the specific humidity difference between the ocean surface and 10 m. The prime represents the deviation from the climatological mean state as indicated by a bar. Note that the sign of latent heat flux anomaly is just opposite with Fig. 10a. A positive anomaly means that the latent heat flux anomaly tends to cool SST. The contour interval is 10 m s$^{-1}$ in (a) and 2 g kg$^{-1}$ in (b).
coast of Java–Sumatra (Fig. 10a), where $\Delta q'$ is large (Fig. 11b). As a result, term $\overline{U} \Delta q'$ becomes important near the coast and has compatible magnitude but an opposite sign relative to term $U' \Delta \eta$. Thus, $\overline{U} \Delta q'$ tends to suppress the effect of $U' \Delta \eta$. Because of the opposite effects, the averaged latent heat flux anomaly in the east pole is weak and has little contribution to IODE growth and asymmetry.

The surface latent heat flux bias seems common in climate models, possibly owing to a common parameterization in which evaporation does not increase with wind until the wind reaches a threshold value. As a consequence, evaporation is strongly influenced by SST (Cai et al. 2005).

c. Effect of the cloud–radiation–SST feedback

Next, we pay special attention to the cloud–radiation–SST feedback. Following Part I, we focus on the relationship between $Q_{SR}$ and SSTA in SON. Table 4 shows a ratio asymmetry between amplitude of MLT and $Q_{SR}$: whereas the ratio of the magnitude of MLT between the negative and positive IODE is 1.4:1, the ratio of $Q_{SR}$ is only 1:1. This implies that the cloud–radiation–SST negative feedback is less efficient in negative IODE episodes. Thus, the asymmetric effect of the cloud–radiation–SST feedback is another important cause of the negative skewness in IODE.

The asymmetry of the cloud–radiation–SST feedback may be illustrated from the scatter diagrams of precipitation–SST and $Q_{SR}$–SST relationship (Fig. 12). In general, the SSTA are positively correlated with the precipitation anomaly ($r = 0.8$) while negatively correlated with the surface shortwave radiation anomaly ($r = -0.86$). However, the relationships are not simply linear. As shown in Fig. 12a, after negative SSTA reach a certain magnitude (say, $-1 \sigma$), the precipitation anomaly is saturated. This means that the precipitation anomalies stop decreasing even though the SSTA keep dropping. Similarly, the shortwave radiation anomaly is also saturated. This implies that the thermodynamic damping of the cloud–radiation forcing will be inefficient after the cold SSTA drop below a critical value.

To sum up, our mixed layer heat budget analysis indicates that the IOD asymmetry is primarily caused by the asymmetry of nonlinear ocean advection and the cloud–radiation–SST feedback. The former (latter) tends to force (damp) MLT with a larger (smaller) growth rate for the negative IODE events than the positive events. The combination of the two asymmetric processes leads to the asymmetric SSTA magnitude between positive and negative IODE episodes. In contrast to observation, the magnitude of latent heat flux anomalies in the model is weaker than that of the net downward shortwave radiation during the IODE developing phase (JJAS) owing to the westward shift of the wind anomaly. As a result, the net surface heat flux contributes negatively to the SSTA growth during the developing phase. Due to the weaker contribution of

<table>
<thead>
<tr>
<th>Event</th>
<th>MLT</th>
<th>$Q_{SW}$</th>
</tr>
</thead>
<tbody>
<tr>
<td>Negative IODE</td>
<td>-1.0</td>
<td>+0.36</td>
</tr>
<tr>
<td>Positive IODE</td>
<td>+0.7</td>
<td>-0.35</td>
</tr>
<tr>
<td>Ratio</td>
<td>1.4</td>
<td>1</td>
</tr>
</tbody>
</table>

TABLE 4. Comparisons of the net downward shortwave radiation ($Q_{SR}$) and the mixed layer temperature (MLT) in the mature phase (SON) between the positive and negative IODE event.
the surface latent heat flux, the magnitude of the negative skewness in the model IODE is smaller than observed (Part I).

6. Summary and conclusions

In Part II, we investigate the amplitude asymmetry of SSTA between the positive and negative IODE events by analyzing a long-term simulation from the SINTEX-F1 model and comparing the results with observations. As in Part I, we use skewness to measure the magnitude asymmetry. By comparing IODE events with and without ENSO and by designing an additional experiment in which ENSO is not present, we examine the possible role of ENSO on the IODE asymmetry. A mixed layer heat budget diagnosis is further conducted to understand specific dynamical and thermodynamical processes that lead to the asymmetry. The main results are summarized below:

1) A significant negative skewness of SSTA appears in the southeast Indian Ocean off Sumatra during the IOD mature phase, while an insignificant weak skewness appears in the western Indian Ocean. Similar to the observation, the IOD asymmetry is primarily caused by the SSTA magnitude asymmetry in the east pole.

2) Diagnosis of both the control experiment and the non-ENSO experiment reveals that the negative skewness in the IODE exists even in the absence of ENSO remote forcing. This suggests that the amplitude asymmetry is primarily induced by local air–sea interaction processes.

3) The mixed layer heat budget diagnosis confirms the observational result that the negative skewness in the IODE is primarily attributed to nonlinear horizontal and vertical ocean temperature advection and the asymmetry of the cloud–radiation–SST feedbacks between the positive and negative episodes.

4) In contrast to the observation, the net surface heat flux anomaly contributes negatively to SSTA growth during the developing phase, due to significant suppression of the surface latent heat flux effect. The westward shift of the along-coast wind anomaly is a primary reason for the weakening of the latent heat flux in IODE.

Both the model simulation and the observation show that the SSTA magnitude in IODE has a negative skewness. Because the negative skewness appears in the mature phase, we focus on our diagnosis of the mixed layer heat budget in the developing phase. This implies that the negative skewness in the mature phase is caused by the asymmetric forcing in the developing phase.

The mixed layer heat budget analysis reveals that nonlinear ocean advection plays a crucial role in the IOD asymmetry. The linear and nonlinear ocean advections play a distinctive role in forcing the MLT tendency. The former tends to enhance the MLT for both positive and negative events, thus contributing to the growth of IOD. The latter exerts an asymmetric effect; it tends to enhance cold events but weaken warm events, leading to the negative skewness. Both nonlinear horizontal and vertical advection contribute to the amplitude asymmetry. Whereas the nonlinear advection has a similar magnitude to the linear advection in the SODA analysis, the magnitude of nonlinear advection in the model is smaller compared to the linear advection. As a result, the negative skewness in model is somehow weakened.

The asymmetric effect of the cloud–radiation–SST feedback is another mechanism that leads to the negative skewness. Cloud shortwave radiation forcing always tends to damp SSTA. In general, this damping effect is linearly correlated with the SSTA; that is, a larger SST anomaly leads to a larger precipitation (cloud) anomaly, which further leads to larger thermal damping for the SST anomaly. Evidence from both the observation and the model simulation show an asymmetric scenario; that is, the positive correlation between precipitation and SST anomalies exists for the positive IODE episodes, but the relationship stops for the extreme negative episodes when the SSTA drop below a critical value. Below this critical value, precipitation anomalies no longer decrease. As a result, the thermal damping effect becomes inefficient and the cold SSTA may grow faster.

Whereas the observed latent heat flux anomalies play a role in enhancing the IODE asymmetry, the effect of the latent heat flux anomaly in the SINTEX-F1 model simulations is significantly weaker due to a westward shift of the model wind response. The wind shift leads to a near-zero wind speed anomaly near the coast of Java–Sumatra, resulting in a negative rather than positive wind–evaporation–SST feedback (Fig. 10a). As a result, the net surface heat flux contributes negatively to MLT growth during the IODE developing stage. Because of the lack of the efficient wind–evaporation–SST feedback, the strength of the negative skewness in the model is weaker than observed.

Acknowledgments. The authors thank Drs. A. Navara, S. Gualdi, and T. Yamagata for kindly providing the SINTAX-F1 model data. This study was completed when CCH visited IPARC, University of Hawaii at Manoa. CCH was supported by NSC 95-211-M133-001-AP4 and NSC-96-2745-M-002. TL was supported by
NSFC Grants 40628006/40675054 and ONR Grants N000140710145/N000140210532 and by the International Pacific Research Center, which is partially sponsored by the Japan Agency for Marine-Earth Science and Technology (JAMSTEC).

REFERENCES


