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Independence of SST skewness from thermocline feedback in the eastern equatorial Indian Ocean

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[1] The observed sea surface height (SSH)-sea surface temperature (SST) in east equatorial Indian Ocean (EEIO) shows a significant asymmetric relation between the positive and negative SSH anomalies during boreal autumn. Whether or not the thermocline- SST feedback is responsible for the negative SST skewness in the EEIO is explored by diagnosing various air-sea feedback processes and a mixed layer heat budget. Our analysis based on observations suggests that the SSH-subsurface temperature relation is approximately symmetric between the positive and negative episode, which is significantly different from the asymmetric SSH-SST relation. This implies that the observed SSH-SST asymmetry is not attributed to the ocean thermocline feedback. A further analysis of the SST-precipitation, precipitation-wind stress and wind stress-SSH relations demonstrates that the asymmetry arises from asymmetric atmospheric heating/wind responses to the SST anomaly. A mixed layer heat budget analysis reveals that the ratio of the mixed-layer temperature tendency between the positive and negative events keeps approximately unchanged with and without vertical temperature advection, suggesting that the thermocline-feedback is not crucial for generating the negative SST skewness in the EEIO. **Citation:** Hong, C.-C., and T. Li (2010), Independence of SST skewness from thermocline feedback in the eastern equatorial Indian Ocean, *Geophys. Res. Lett.*, *37*, L11702, doi:10.1029/2010GL043380.

1. Introduction

[2] The Indian Ocean Dipole (IOD) is one of dominant interannual modes in the Indian Ocean (IO) [e.g., *Saji et al.*, 1999; *Li et al.*, 2002; *Lau and Nath*, 2004]. The IOD exerts a significant impact on the Asian monsoon [e.g., *Li et al.*, 2003; *Ashok et al.*, 2004; *Li et al.*, 2006; *Wu et al.*, 2009] and areas beyond the monsoon region [e.g., *Guan and Yamagata*, 2003], including a preconditioning effect of Australian bushfires [*Cai et al.*, 2009].

[3] Observations show that a significant negative sea surface temperature (SST) skewness appears in the IOD east pole (hereafter IODE (Figure 1a)) during the IOD mature phase. The cause of this negative skewness is attributed to, based on a SODA (Simple Ocean Data Assimilation) data analysis, both the nonlinear ocean temperature advection and the asymmetry of the SST-cloud-radiation feedback [*Hong et al.*, 2008a, 2008b]. Because of the significant negative skewness in IODE, the impact of positive and negative IOD events to the circulation and rainfall anomalies over the Asian-western Pacific monsoon regions is likely asymmetric [e.g., *Hong et al.*, 2008c; *Cai et al.*, 2009].

[4] Recent study by *Zheng et al.* [2010] suggested that an asymmetric feedback between the sea surface height (SSH) and SST anomalies is responsible for the observed negative skewness in IODE. Figure 1b illustrates this asymmetric SSH-SST relationship. Note that for the one-unit change of SSHA, the corresponding SST variation is two times greater when the thermocline is shoaling than when the thermocline is deepening. This prompts *Zheng et al.* [2010] to suggest that the asymmetric thermocline feedback to SST may be responsible for the negative SST skewness in IODE. The premise behind this argument is that because the mean thermocline depth in IODE is relatively deep compared to that in the eastern equatorial Pacific, a shoaling of the thermocline may decrease the subsurface ocean temperature significantly whereas a deepening of the thermocline has a much less impact on the subsurface temperature; as a result, the thermocline induced subsurface temperature variation has a marked asymmetric effect on the SST.

[5] In this study we attempt to prove that the premise above is faulted. As shown in the following sections, observational evidences illustrate that there is little asymmetry between the SSH and subsurface ocean temperature anomalies in the region of interest and the slope difference between the positive and negative phases shown in Figure 1b is primarily due to the asymmetry of atmospheric heating/wind responses to the SST anomaly (SSTA) and the SSH variation is a result of the asymmetric wind forcing. A mixed layer heat budget analysis, in which we include and exclude the thermocline feedback effect, is further carried out to support our claim.

2. Data

[6] The SODA 2.0.2 [*Carton et al.*, 2005] is the major data source for this study. Forced by daily wind stresses and heat fluxes from ERA-40, SODA 2.0.2 assimilates all available hydrographic data including XBTs from 1958 to 2001. In the present study, a monthly mean climatology is first calculated for the period of 1958–2001 and anomalies are then defined as departures from this mean climatology. A positive (negative) IODE event is defined when the area-averaged SSTA over IODE (10°S–0°, 90°–110°E) during the IOD mature phase (SON) is greater than 0.75 (less than −0.75) standard deviation. The negative SST skewness is also observed in the western equatorial IO and other regions on shorter timescales [e.g., *Sura and Sardeshmukh*, 2008; *Lloyd and Vecchi*, 2010], But in this study we focus on the

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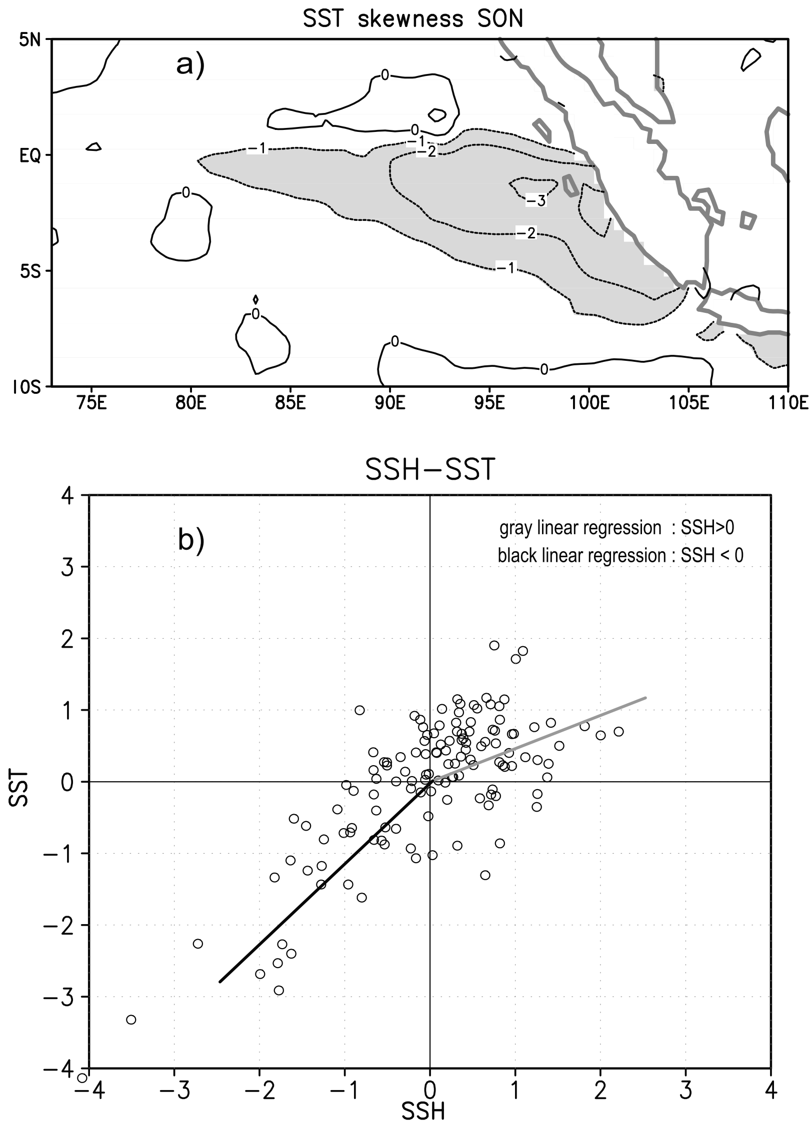

Figure 1. (a) Horizontal distribution of the SST skewness (defined as: $\sum_{i=1}^{N}\frac{(x_i-\overline{X})^3}{\sigma^3}$) of the Indian Ocean in SON. Shading indicates SST skewness greater than the 95% confidence level. (b) The SSH-SST scatter diagram in SON. The gray (black) line denotes the linear regression for the positive (negative) SSH anomalies. α_{positive} (α_{negative}) denotes the linear slope for the positive (negative) anomalies. The SST and SSH data are averaged over IODE (10°S–0°, 90°–110°E) and are normalized based on their standard deviations in the scatter diagram. The two separate linear regressions (SSH > 0 and SSH <0) are significantly different at the 95% confidence level under a Z-test.

negative skewness in IODE on the interannual timescale. Eight negative IODE events (1961, 1963, 1967, 1972, 1982, 1991, 1994, 1997) and eight positive IODE events (1958, 1980, 1989, 1990, 1992, 1996, 1998, 2001) are selected for a composite analysis. A negative (positive) IODE event is in general corresponding to a positive (negative) IOD phase. Following the previous study [*Zheng et al.*, 2010], the SSH anomaly is used as a proxy to represent the variation of the thermocline depth.

3. Diagnosis of Air-Sea Feedback Processes

[7] Figure 1b shows an asymmetric SSH-SST relation between positive and negative episodes. To examine the statistical significance of two linear slopes for SSH > 0 and SSH < 0 compared to a single slope, we conducted a Z test [*Bluman*, 2007] as the following:

$$z = \frac{Z_{r_p} - Z_{r_n}}{\sqrt{\frac{1}{n_P-3} + \frac{1}{n_n-3}}}, \quad (1)$$

where Z_r is the Fisher transfer:

$$z_r = \ln\sqrt{\frac{1+r}{1-r}}, \quad (2)$$

$r_p(r_n)$ and $n_p(n_n)$ denote the SST-SSH correlation coefficients and the sample number for positive (negative) SSH anomaly cases individually. Our calculation shows that the correlation coefficient $r_p(r_n)$ is 0.13 (0.84) and the sample

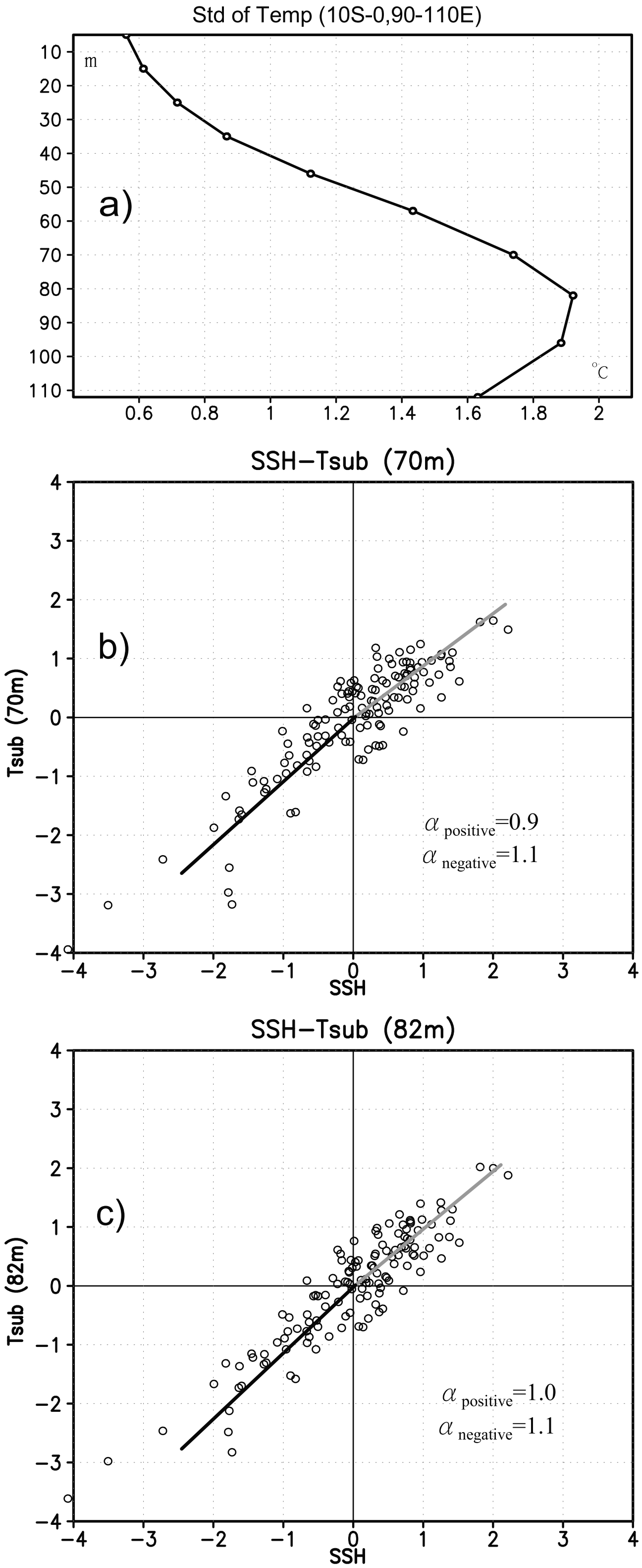

Figure 2. (a) The vertical profile of the standard deviation of the temperature averaged over IODE in SON. Same as in Figure 1b but for the anomalous SSH and subsurface temperatures at (b) 70m and (c) 82m.

number n_p (n_n) is 75 (57) respectively. Based on the equations above, the calculated Z value is 5.87, which exceeds the 95% confidence level. (The 95% level corresponds to a Z value of $Z_{0.95}$ = 1.96).

[8] The asymmetric SSH-SST relation in Figure 1b implies two possibilities. Firstly, the SST response to the ocean thermocline forcing is asymmetric. In this scenario, the thermocline plays an active role in modulating the vertical temperature advection and SST. Secondly, the thermocline asymmetry results from the asymmetric response of the atmospheric heating and wind to the SSTA. In the second scenario, the thermocline plays a passive role in the asymmetric SSH-SST relation. In the following we diagnose the nature of the air-sea feedback process in IODE based on the observational data in the context of the aforementioned two possibilities. Regarding to the first possibility, a key element is to examine the relationship between the SSHA and the subsurface temperature (hereafter Tsub) anomaly, since the thermocline primarily affects the SST through the change of the ocean subsurface temperature and associated vertical temperature advection [*Li*, 1997; *Hong et al.*, 2008a]. If the negative skewness in IODE is attributed to the thermocline feedback, then the SSH-Tsub relation should be asymmetric too. Note that the maximum Tsub variability in IODE appears around the depth of 80 m (Figure 2a). Thus in the following the observed ocean temperatures at 70m and 82m from SODA are used to examine the SSH-Tsub relationships. Figures 2b and 2c illustrate scatter diagrams between the anomalous SSH and Tsub at 70m and 82m respectively. It is interesting to note that the SSH-Tsub relation is almost symmetric between the positive and negative SSHA phases (Figures 2b and 2c), significantly different from the SSH-SST relation (Figure 1b). The fact that the SSH-Tsub relation is nearly symmetric implies that the thermocline feedback cannot play an active role in contributing to the negative SST skewness or the observed SSH-SST asymmetry in IODE.

[9] To examine the second possibility, we analyze the observed SST-precipitation, precipitation-wind stress and wind stress-SSH relations (Figure 3). The SST-precipitation scatter diagram exhibits a significant asymmetric relation between positive and negative SSTA events (Figure 3a). The slope difference between the positive and negative events is even greater than the asymmetry in the SSH-SST relation. The cause of this asymmetric SST-precipitation relation was discussed in *Hong et al.* [2008a], who found that the negative skewness in IODE is partly attributed to the asymmetry of the SST-cloud-radiation (SCR) feedback. For a positive IODE, the negative SCR feedback continues with the increase of warm SSTA. For a negative IODE, the same negative SCR feedback works when the amplitude of SSTA is small. After reaching a critical value, the cold SSTA may completely suppress the mean convection and lead to cloud-free; a further drop of the cold SSTA does not lead to additional thermal damping so that the cold SSTA may grow faster.

[10] The relationship between the precipitation anomaly in IODE and the wind stress anomaly in the central equatorial Indian Ocean also exhibits an asymmetric feature (Figure 3b). The reason to use the central equatorial IO wind stress is that maximum zonal wind anomalies associated with the IOD appear in the central not eastern equatorial IO [*Saji et al.*, 1999; *Li et al.*, 2003]. Figure 3b shows that given the same

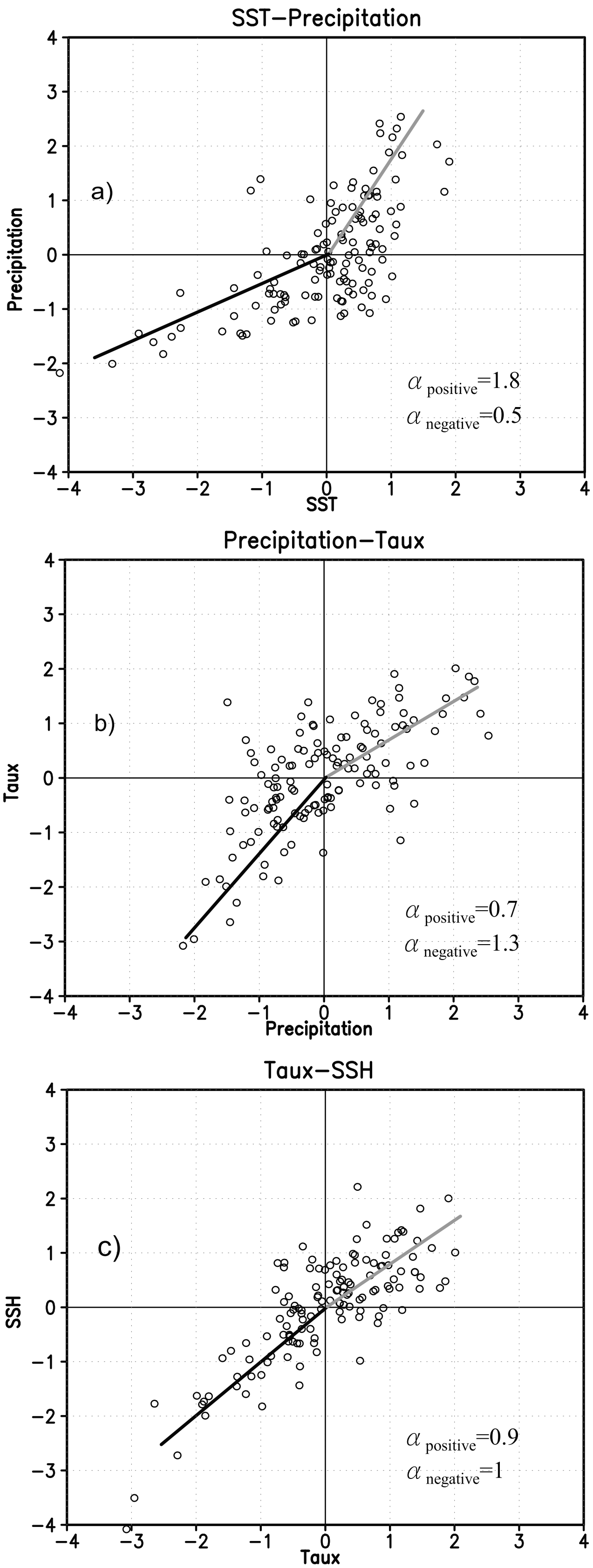

Figure 3. Same as in Figure 1b except for (a) SST-precipitation, (b) precipitation-wind stress, and (c) wind stress-SSH relations. The wind stress anomaly is averaged over the equatorial central Indian Ocean (5°S–5°N, 70°–90°E), whereas other variables are averaged over IODE.

one-unit precipitation anomaly, a larger (smaller) wind stress anomaly response occurs during the negative (positive) precipitation anomaly phase. This is because the wind in the central equatorial IO depends on not only the mid-tropospheric heating anomaly but also the zonal SSTA gradient.

[11] The relation between the anomalous wind stress and SSHA is approximately symmetric between the positive and negative phases (Figure 3c). This implies that the zonal wind stress anomaly in the central equatorial Indian Ocean and the thermocline depth anomaly in the eastern equatorial Indian Ocean are approximately in a Sverdrup balance.

[12] Given the aforementioned SST-precipitation, precipitation-wind stress and wind stress-SSH relations, one may estimate the asymmetric relationship between the SSTA and SSHA through the atmospheric "bridge", by multiplying the ratios ($R = \alpha_{positive}/\alpha_{negative}$) of three feedback slopes:

$$R_{SST-SSH} \cong R_{SST-precipitation} {}^{*} R_{precipitation-wind\cdot stress} {}^{*} R_{wind\cdot stress-SSH}, \quad (3)$$

[13] The product ratio above is equal 1.1:0.6, which is close to the reversed ratio shown in Figure 1b (1.1: 0.5). (Note that Figure 1b shows the SSH-SST relation, not a reversed SST-SSH relation.) The results above suggest that it is the asymmetric atmospheric response to the SSTA through the asymmetric SST-precipitation and precipitation-wind stress relations that eventually cause the asymmetry of the SSH-SST relation.

[14] To sum up, the observational evidences presented above point out the active role of the atmosphere in causing the SSH-SST asymmetry and the thermocline induced Tsub is approximately symmetric and thus its contribution to the negative SST skewness is insignificant. In the following section, we further demonstrate, through a mixed layer heat budget analysis, that the thermocline variation induced Tsub change is not essential for generating the negative SST skewness in IODE.

4. A Mixed Layer Heat Budget Analysis

[15] The mixed layer temperature tendency equation may be written as [*Li et al.*, 2002; *Hong et al.*, 2008a]:

$$\frac{\partial T'}{\partial t} = -(V \cdot \nabla T)' + \frac{Q'_{net}}{\rho C_P H} + R, \quad (4)$$

where T denotes the mixed layer temperature. $V = (u, v, w)$, is 3 dimensional (3D) ocean current, and term $-(V \cdot \nabla T)'$ denotes the anomalous 3D temperature advection integrating vertically from the surface to the bottom of the mixed layer. Q_{net} is the summation of the net downward shortwave radiation (Q_{SW}), surface longwave radiation(Q_{LW}), surface latent heat (Q_{LH}) and sensible heat (Q_{SH}) fluxes at the ocean surface. R represents the residual term. ρ is the density of water,C_P is the specific heat of water, and H denotes the mixed layer depth that varies with time and space. In the heat budget analysis, the composite fields are derived first and then each term in equation (4) is calculated. We also did the budget analysis for individual events first and then made a composite. The results are quite similar.

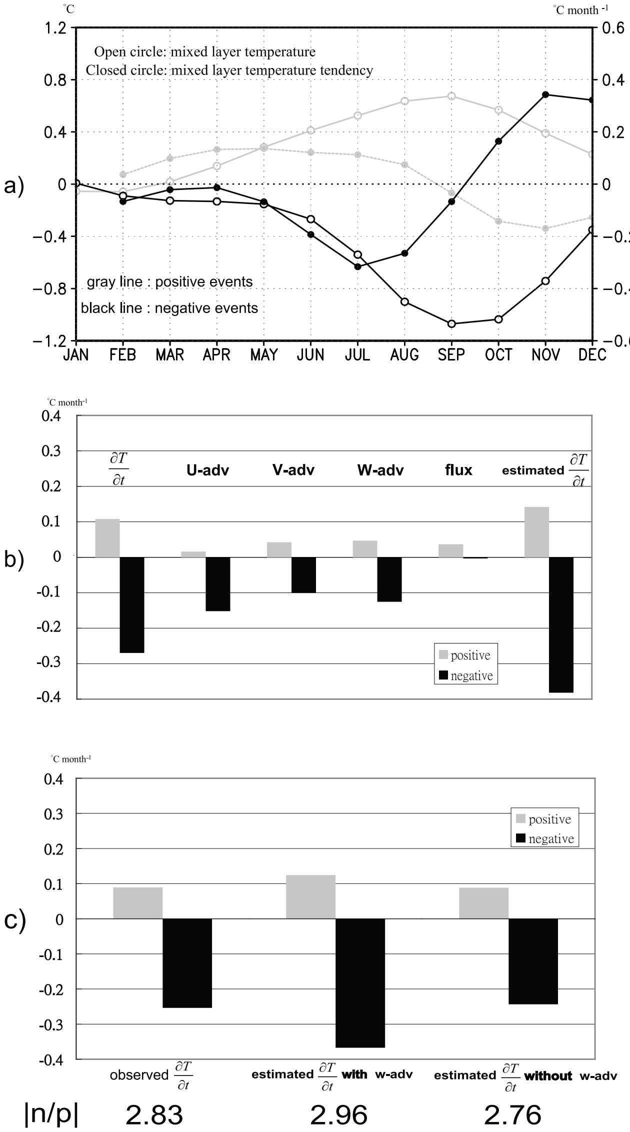

Figure 4. (a) Composite time series of the mixed layer temperature (marked with "○") and the mixed layer temperature tendency (marked with "•"). (b) From left to right, the observed mixed layer temperature tendency, the 3D temperature advections, the downward net surface flux, and the estimated mixed layer temperature tendency (i.e., the sum of 3D temperature advections and the downward net surface heat flux). (c) Same as in Figure 4b except for the observed mixed layer temperature tendency, the estimated mixed layer temperature tendency, and the estimated mixed layer temperature tendency excluding the vertical temperature advection. Gray (black) bars represent the composite results for the positive (negative) IODE events. All the terms are averaged over the IODE for the period of June–August. The numbers in the bottom denote the amplitude ratio of the temperature tendency between the negative and positive events.

[16] The composite evolution of the mixing layer temperature (hereafter MLT) and its tendency ($\partial T/\partial t$) is illustrated in Figure 4a. Note that at the peak phase (September) the amplitude of MLT in the negative IODE composite (−1.1°C) is almost twice as large as that in the positive IODE composite (0.6°C). From the time evolution of the MLT tendency terms, one may clearly see that the maximum difference of the temperature tendency between the positive and negative composites appears in JJA. Therefore, examining the cause of the asymmetric MLT tendency during the developing phase (JJA) is crucial to understand the negative SST skewness in IODE during the mature phase.

[17] The MLT tendency in JJA due to the sum of 3D ocean temperature advection and the surface heat flux terms is shown in Figure 4b. Comparing to the observed MLT tendency (left), the estimated heat budget (right panel) is slightly overestimated for both the positive and negative composites. The ratio of the MLT tendency between the negative and positive IODE events, however, is well reproduced. While the ratio of the observed MLT tendency between the negative and positive events is 2.83:1, the ratio of the estimated tendency is 2.96:1 (see the numbers at the bottom of Figure 4c). The asymmetric tendency is primarily attributed to the 3D ocean temperature advections, whereas the net heat flux term plays a minor role. The asymmetric tendency eventually leads to the negative skewness.

[18] The heat budget above includes all dynamic and thermodynamic contributions. How does the tendency ratio change when the thermocline feedback process is excluded? To address the question, we recalculate the mixed layer heat budget in which we remove the vertical temperature advection contribution (right in Figure 4c). Although the amplitude of the MLT tendency is decreased by 20–30% for both the positive and negative events, the ratio of the MLT tendency between the negative and positive events barely changes. This indicates that the asymmetry of the MLT tendency between the positive and negative events keeps largely unchanged. Thus, by comparing the mixed layer head budgets with and without the vertical advection, we demonstrate that the thermocline-SST feedback is not crucial for generating the negative SST skewness in IODE.

5. Summary and Discussion

[19] A significant negative SST skewness appears in the eastern equatorial Indian Ocean, where the observed SSH-SST relation is asymmetric between the positive and negative SSH anomalies. Whether or not this asymmetric thermocline-SST feedback is responsible for the negative SST Skewness in IODE is explored by diagnosing the various air-sea feedback coefficients and the ocean mixed layer heat budgets. The main results are summarized as below:

[20] 1. The relationship between the observed anomalous SSH and subsurface temperature in IODE is approximately symmetric, which is markedly different from the asymmetric SSH-SST relation. This implies that the thermocline induced subsurface temperature variation may not directly contribute to the negative SST skewness. Our analysis of the SST-precipitation, precipitation-wind stress and wind stress-SSH relations further demonstrates that the SSH-SST asymmetry is primarily attributed to the atmospheric "bridge" due to the asymmetric atmospheric heating/wind responses to the SSTA in IODE.

[21] 2. A mixed layer heat budget analysis reveals that the negative SST skewness is attributed to the asymmetry of the MLT tendency during the IODE developing stage (JJA), and that ocean horizontal temperature advections primarily contribute to the tendency asymmetry. The comparison of

the mixed layer heat budgets with and without the vertical advection shows that the asymmetry of the temperature tendency between the positive and negative events remains unchanged, suggesting that the thermocline-feedback is not crucial for generating the negative SST skewness.

[22] Sensitivity tests with different criteria (0.75σ, 1σ, and 1.5σ) of IODE event were performed. The ratios of the temperature tendency between positive and negative events are quite similar. This confirms that the result shown in Figure 4b is robust. Our analysis based on observations suggests that the asymmetric SSH-SST relation is primarily attributed to the asymmetric atmospheric response to the SSTA in IODE, not attributed to the asymmetric subsurface ocean temperature response to the thermocline variation. In fact, the SSH-Tsub relation is approximately symmetric, that is, given the same amount of the thermocline change (either shoaling or deepening), the amplitude of the positive or negative subsurface temperature anomaly is almost same.

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