Response of the equatorial basin-wide SST to non-breaking surface wave-induced mixing in a climate model: An amendment to tropical bias

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[1] One of the common problems of the coupled atmosphere-ocean general circulation models (AOGCMs) without flux correction is that the simulated sea surface temperature (SST) deviates noticeably from the observation especially in the tropics, such as the too cold tongue in the eastern Pacific and a reversed SST zonal gradient in the equatorial Atlantic. The coupled atmosphere-wave-ocean general circulation model, which incorporates the non-breaking surface wave-induced mixing into the CCSM3 through a coupler, can improve the simulation of the tropical SST. On the ocean-basin scale, the wave-induced vertical mixing can generate "West-Positive and East-Negative" pattern for the equatorial SST that much alleviates the tropical bias. The formation mechanism for this basin-wide response to the wave-induced mixing is analyzed through sensitive experiments of AOGCMs and stand-alone ocean general circulation models (OGCMs). First, in each basin, the SST becomes colder under the direct effect of the wave-induced mixing, and the SST in the eastern part of each basin is colder due to the shallower ocean mixed layer than that of the western part. The SST in the western basin (or central basin in the Pacific Ocean) increases due to the weakened eastward zonal current. Then, the pattern of warm SST in the west and cold SST in the east is amplified due to the Bjernkes feedback in a climate system. The net heat flux feedback plays a negative role in this kind of SST response.

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1. Introduction

[2] The tropical ocean is a region with the world's warmest sea surface temperature (SST) and the most intensive air-sea interaction, which can much influence the global climate system. The coupled atmosphere-ocean general circulation models (AOGCMs) is one of the most powerful tools in the climate research and projection. Although AOGCMs are able to reconstruct the basic features of the climate system [*Covey et al.*, 2003; *Meehl et al.*, 2005], systematic model biases still exist, especially in the tropic region, such as the too-cold tongue in the central tropical Pacific Ocean, warmer tropical ocean temperature in the east part of each basin, reversed SST gradient along equator of the Atlantic Ocean, among others [*Mechoso et al.*, 1995; *Davey et al.*, 2002; *Covey et al.*, 2003; *Bretherton*, 2003; *Xie et al.*, 2007; *de Szoeke and Xie*, 2008]. The above deviations faced by nearly all AOGCMs are some components of the "tropical bias."

[3] One of the reasons for these biases is due to the vertical mixing scheme in the ocean general circulation models (OGCMs) [*Mechoso et al.*, 1995; *Bretherton*, 2003; *Xie et al.*, 2007; *de Szoeke and Xie*, 2008]. Previous studies suggest that the global coupled atmosphere-wave-ocean general circulation model including the non-breaking surface wave-induced mixing [*Qiao et al.*, 2004] can serve as a solution to improve the simulations of the AOGCMs [*Song et al.*, 2007; *Huang et al.*, 2008; *Song et al.*, 2011]. The improvements include alleviated cold bias in the eastern tropical Pacific [*Song et al.*, 2007], removing spurious semi-annual SST cycle in the eastern tropical Pacific [*Song et al.*, 2011], cure of the global mean temperature drifting [*Huang et al.*, 2008], and much improvement in water vapor transport and precipitation simulation for summer Asian Monsoon [*Song et al.*, 2012]. Additionally, the latest simulation results (Figure 1) from the NCAR coupled model of the Community Climate System Model version 3 (CCSM3) show that the equatorial Pacific cold tongue can be improved by considering the wave-induced mixing. Moreover, climate

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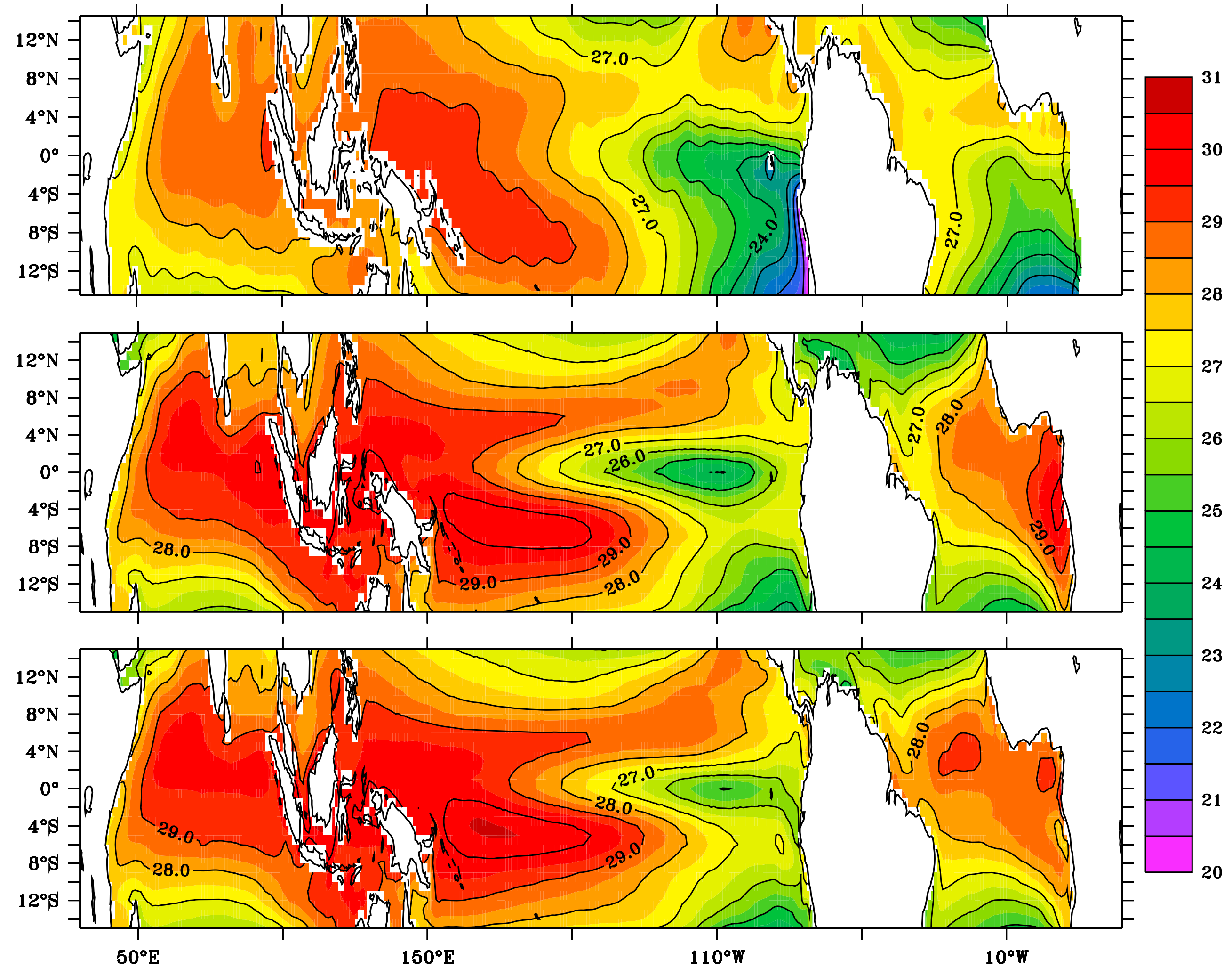

Figure 1. (top) Climatological annual-mean SST in the equatorial region from Levitus data set, (middle) model years of 251–300 from Exp NoWAVE and (bottom) model years of 251–300 from Exp WAVE.

prediction experiments show that the consideration of the wave-induced mixing can help improve forecasting skill [*Song et al.*, 2009]. Although the surface wave-induced vertical mixing improves the performance of two kinds of AOGCMs, the mechanism of basin-wide SST response to the wave mixing in climate models remains unclear.

[4] Compared with the responses of stand-alone OGCMs to the wave-induced mixing, the responses of a coupled model are quite different. First, the ocean surface waves are relatively small in the tropical ocean comparing with mid and high latitudes, so that the impact of the wave-induced mixing on stand-alone OGCMs in the tropics is not so obvious compared with that in extra-tropical areas [*Qiao et al.*, 2010]. However, the effect of the wave-induced mixing on an air-sea coupled model may be large because of the feedback process of the coupled system associated with the strong air-sea interaction in the tropics. Second, for a stand-alone OGCM, the external forcing on the ocean is fixed, so ocean variations will not have any feedback to the external forcing. In an air-sea coupled system, the variability in the ocean will influence the atmosphere through air-sea interaction; as a consequence, the external forcing on the ocean will change accordingly. Since the air-sea coupled system is quite complex, so to understand the physical mechanism and feedback process related to the wave-induced mixing remains a big challenge. Previous studies conducted the analysis on the local effect of the wave-induced mixing on the cold tongue simulation [*Song et al.*, 2007] and eastern Pacific SST annual cycle simulation [*Song et al.*, 2011] in the climate model. The key factors and processes causing the SST response of the "West-Positive and East-Negative" pattern (Figure 2) in the ocean basin are the foci of the present paper.

[5] The numerical experiments design is introduced in section 2. The experiment results are presented in section 3, in which the SST responses in AOGCMs and stand-alone OGCMs are presented, and the mechanism is analyzed by comparing results of numerical experiments. Section 4 is the discussion and conclusions of this study.

2. Numerical Experiment Design

[6] To analyze the effects of the wave-induced mixing on the SST in the equatorial region, two sets of numerical

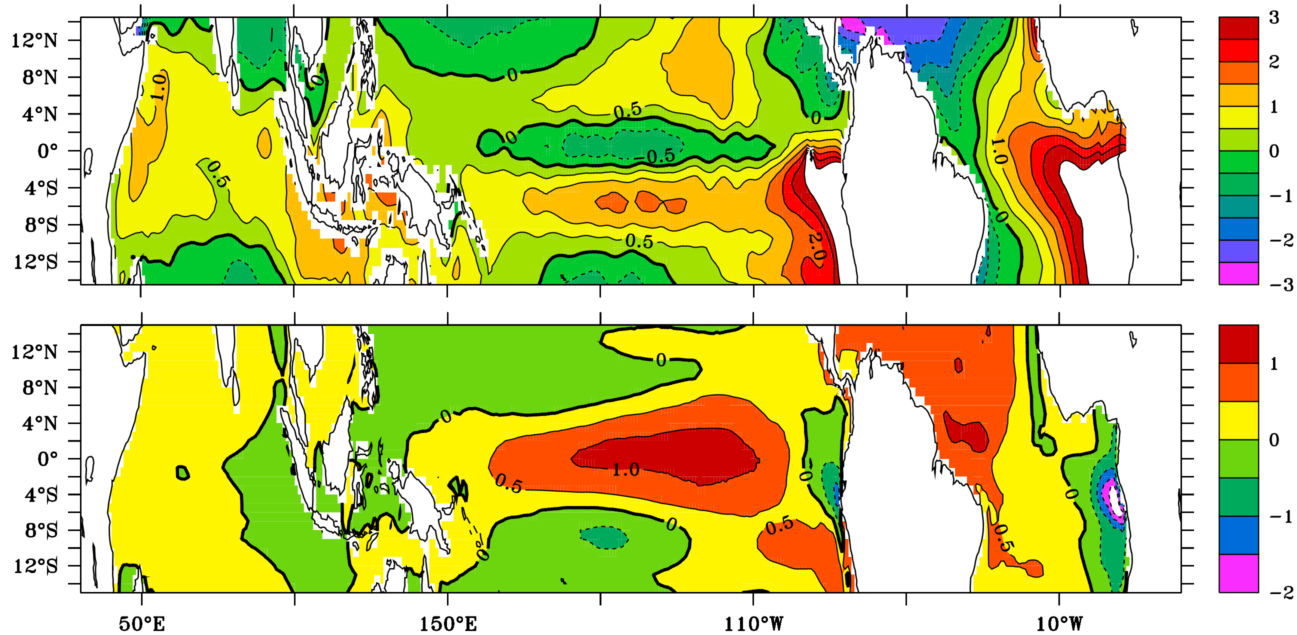

Figure 2. (top) Climatological annual-mean SST differences of the simulation from Exp NoWAVE with respect to Levitus data set, and (bottom) the simulation from Exp WAVE with respect to Exp NoWAVE (which can be regarded as wave effects).

model experiments are performed. The first set is numerical experiments based on climate model by employing the original CCSM3 [*Collins et al.*, 2006a] that does not have wave effect (hereafter Exp NoWAVE) and the atmosphere-wave-ocean coupled model [*Song et al.*, 2011] which is based on the CCSM3 and coupled with the surface wave model through incorporating the wave-induced mixing (hereafter Exp WAVE). The atmosphere, land surface, sea ice, ocean and wave model components are the Community Atmosphere Model Version 3 (CAM3) [*Collins et al.*, 2006b], the Community Land Model Version 3 (CLM3) [*Dickinson et al.*, 2006], the Community Sea-ice Model Version 5 (CSIM5) [*Briegleb et al.*, 2004], the Parallel Ocean Program Version 1.4.3 (POP1.4.3) [*Smith and Gent*, 2002], and the MASNUM Wave model [*Yang et al.*, 2005], respectively. The resolution for coupled model is T42_gx1v3, which means the horizontal resolution for CAM3 and CLM3 is the T42 spectral truncation and a nominal 1° for POP and CSIM, with the northern pole displaced to the Greenland. The surface wave model has resolution of 2° by 2°.

[7] The second set is stand-alone OGCMs experiments, using the POP (hereafter Exp OCEAN),which is same as the ocean component of the coupled model of Exp NoWAVE, and the POP coupled with the wave model (hereafter Exp OCEAN-WAVE). In these numerical experiments, the ocean

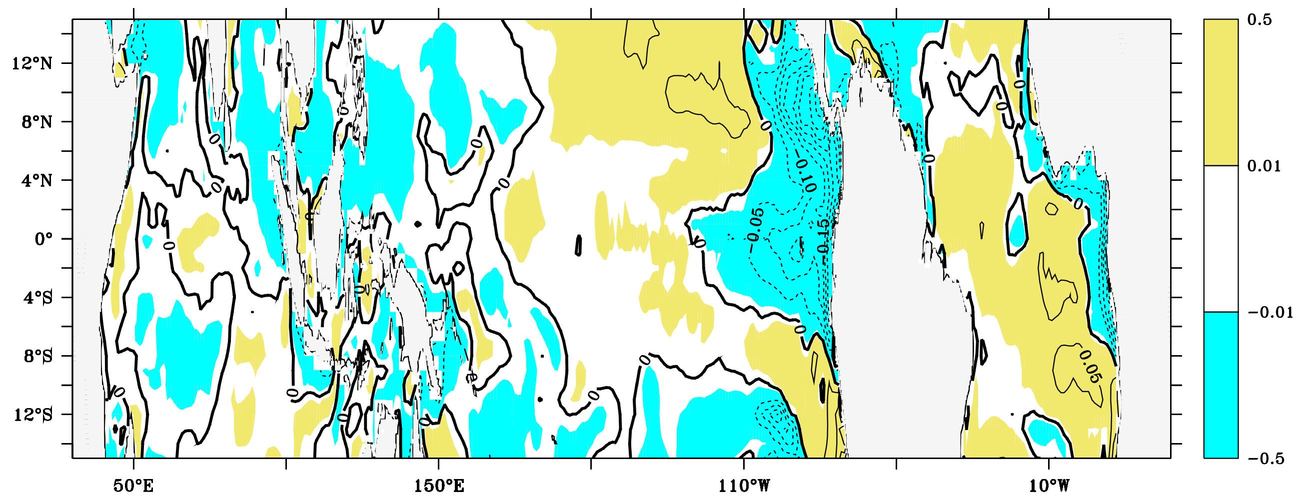

Figure 3. Climatological annual-mean SST difference of simulations from Exp WAVE-OCEAN with respect to Exp OCEAN in the stand-alone ocean model (units: °C).

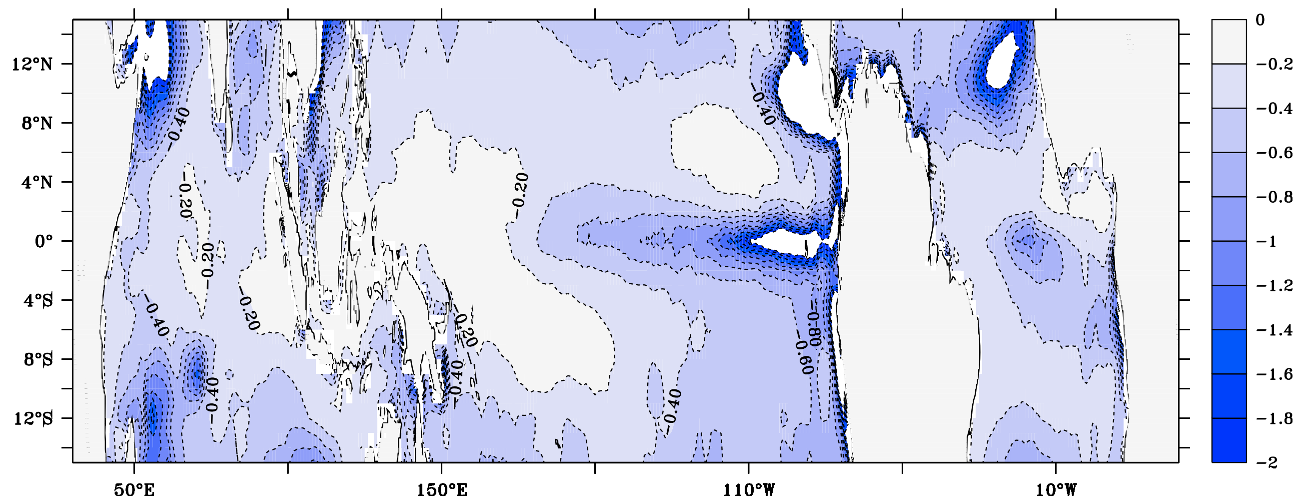

Figure 4. The wave-induced vertical diffusion effect in equation (1) in the stand-alone ocean model (Units: °C $month^{-1}$).

models adopt the same resolutions and parameters as those of the coupled model experiments.

[8] The coupled models are run for 300 years, and the stand-alone OGCMs are run for 30 years. The effects of the wave-induced mixing on the equatorial SST are investigated by diagnosing the coupled models outputs for the last 50 years (i.e., for model years of 251–300) and stand-alone OGCMs outputs for the last 10 years (i.e., for model years of 21–30).

3. Results

3.1. Analysis of Model Results

[9] This paper focuses on the tropical SST, so we select the target area between 15°S and 15°N. From multiyear averaged SST (Figure 1), the simulated equatorial Pacific SST from Exp NoWAVE (Figure 1, middle) is too cold in the central Pacific around equator compared with the Levitus observation (Figure 1, top) and the 27°C isotherm stretches westward to nearly 160°W, which is the typical problem of the "too cold tongue." Additionally, because the model SST is lower along the northeast Pacific coast and higher in the southeast Pacific coast, it fails to reproduce the cold tongue spatial pattern that extends from the southeast Pacific coast to the equator and then to the west. However, the simulated 27°C isotherm of the equatorial Pacific SST from Exp WAVE (Figure 1, bottom) extends to 140°W, which is consistent with the observed 27°C isotherm distribution at the equator. Additionally, the simulated temperature along the northeast Pacific coast is increased, so the difference between the model results in Exp WAVE and the observation is reduced by including the wave-induced mixing. Similar improvements appear along the southeast Pacific coast and from eastern to the central Pacific in the cold tongue region. It is noticed that the simulated SST along the southeast Pacific coast in Exp WAVE remains higher than the observation. Maybe it has to do with the coarse resolution of 1 degree in the ocean general circulation model.

[10] The observed SST in the equatorial Atlantic is higher in the west and lower in the east, similar to that in the equatorial Pacific. However, the SST simulated by Exp NoWAVE has the warmest area along the east coast of the equatorial Atlantic and the coldest on the west coast, which is opposite to the observation. So, the simulated SST gradient along equator is completely wrong, which is a common problem of AOGCMs. Compared with Exp NoWAVE, the simulated SST in the equatorial Atlantic from Exp WAVE is improved (Figure 1, bottom). Although the model biases

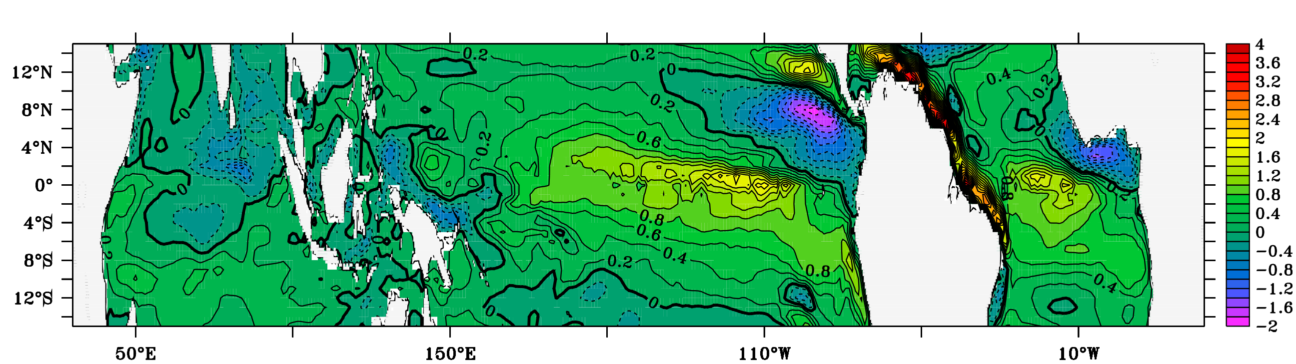

Figure 5. Climatological annual-mean zonal currents difference of simulations from Exp WAVE-OCEAN with respect to Exp OCEAN in the stand-alone ocean model (Units: cm s^{-1}).

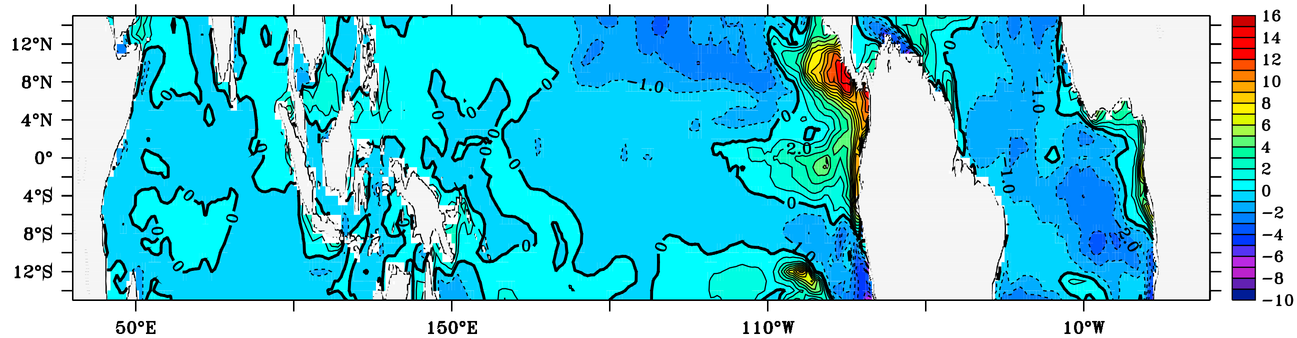

Figure 6. Climatological annual-mean net heat flux difference of simulation from Exp WAVE-OCEAN with respect to Exp OCEAN in the stand-alone ocean model (Units: Wm^{-2}).

have not been totally eliminated by including the wave-induced mixing, the model SST is much closer to the observation than that from Exp NoWAVE.

[11] Figure 2 (top) shows the SST difference between the model simulation of Exp NoWAVE and the observation. In the Indian Ocean, the simulation bias of Exp NoWAVE is greater than 0.5°C in most area, and the maximum bias is greater than 1°C in the western equatorial Indian Ocean and the eastern Indian Ocean. In the Pacific, the simulated SST in Exp NoWAVE has a cold bias within a great range of the eastern equatorial Pacific (150°E–110°W), especially in the region of (170°E–130°W, 2°S–2°N), reaching the maximum of more than 0.5°C. This is consistent with the cold tongue extending too far westward. The banded region near 4°S has a significant warm bias, especially along the southeast coast of the Pacific with the warm bias exceeding 2°C, whereas the northeast Pacific coast (100°W–60°W, 4°N–15°N) has a cold bias of more than 0.5°C. As displayed in Figure 2 (bottom), the contribution of the wave-induced vertical mixing generally makes compensation to the weak points of original CCSM3; in other words, the model produces a better SST by considering the wave-induced mixing. The cold bias of SST has been reduced in the equatorial eastern Pacific, especially in the (170°E–110°W, 2°S–2°N) region, with the increase of SST by 1°C. The cold bias of SST in the northeast Pacific coastal region is also improved. In addition, the region with warm bias simulated by Exp NoWAVE is reduced by 0.5°C along the southeastern Pacific coast.

[12] For the SST simulation in the Atlantic Ocean, the simulated equatorial SST in Exp NoWAVE is colder in the western Atlantic and warmer in the eastern Atlantic compared with the observation. Specifically, the SST difference can be greater than 1.0°C along the western Atlantic coast and up to 3.0°C along the eastern Atlantic coast, which produces an opposite SST gradient along the Atlantic equator. The cold bias in the western Atlantic is reduced by more than 0.5°C, while the warm bias in the eastern Atlantic is decreased by more than 1°C. The model incorporated with the wave-induced mixing (Exp WAVE) can give much better results. However, the problem of the reversed SST gradient along Atlantic equator still remains, although alleviated by the wave-induced mixing.

3.2. Mechanism Analysis

[13] Figure 2 (bottom) shows that the wave-induced mixing in the climate model of CCSM3 can generate the basin-wide “West-Positive and East-Negative” SST pattern in the Indian, Pacific, and Atlantic oceans, which is favorable for improving climate model. Why does this kind of pattern appear in a climate model?

[14] To understand the effect of the wave-induced mixing, the SST response to the wave mixing in a stand-alone OGCM is analyzed first. Figure 3 shows the 10-yr mean SST difference between the two stand-alone ocean model experiments of with and without the wave-induced mixing. Comparing with the SST response in the coupled model (Figure 2, bottom), the response of SST of stand-alone ocean model is similar, while the response range of −0.5 to 0.5°C in the stand-alone OGCM is relatively smaller than that in the coupled model of CCSM3, which may be due to no air-

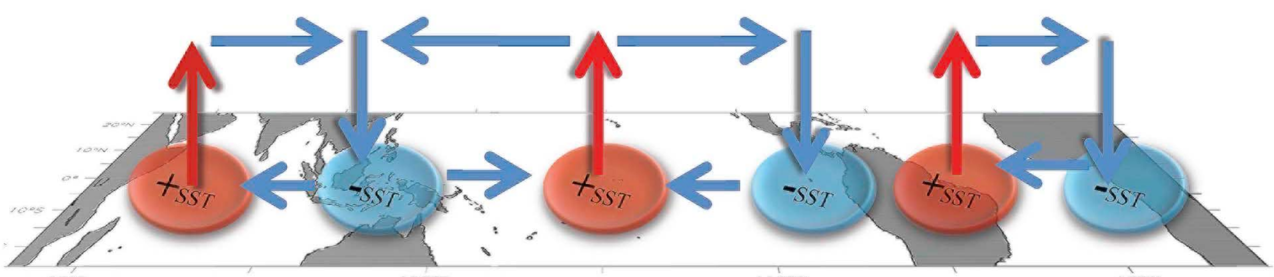

Figure 7. Schematic responses of SST anomaly and wind (arrow) anomaly to the wave-induced mixing in a climate system. The cold (warm) anomalies of SST in the eastern (western) Ocean drive the Walker-like anomaly circulations and are enhanced by the Bjerknes feedback.

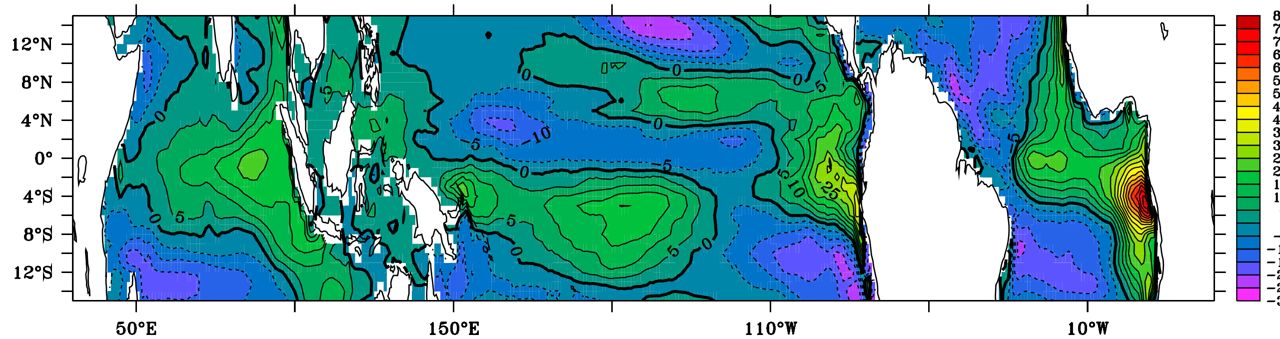

Figure 8. Climatological annual-mean net heat flux difference of simulation from Exp WAVE with respect to Exp NoWAVE in the coupled model (units: Wm^{-2}).

sea interaction feedback in the stand-alone ocean model. In contrast, in the coupled model, the SST response is from −2.0 to 1.5°C, which indicates that the feedback processes of the air-sea coupled system can amplify the wave-induced mixing effect in the tropical oceans.

[15] Why does the stand-alone OGCM experiment display the basin-scale SST anomalies pattern of warm in the west and cold in the east? To answer this question, the heat budget in the ocean surface layer is analyzed. The temperature control equation for the ocean surface layer is as follows:

$$\frac{\partial T}{\partial t} = -u\frac{\partial T}{\partial x} - v\frac{\partial T}{\partial y} - w\frac{\partial T}{\partial z} + \frac{A_{hv}}{\Delta z_1}\frac{\partial T}{\partial z}\bigg|_{z=\Delta z_1} + \frac{F_A}{\rho_0 c_p \Delta z_1}, \quad (1)$$

where T is the ocean surface layer temperature, u, v and w are the velocity components of surface-layer ocean currents in x, y and z directions, respectively, A_{hv} is the vertical diffusion coefficient ($A_{hv} = A_{hv0} + Bv$, for the Exp WAVE-OCEAN, and Bv is removed in Exp OCEAN. where Bv is calculated from the wave model), Δz_1 is surface layer depth, ρ_0 is seawater density, c_p is the specific heat of seawater, and F_A is the net surface heat flux. The term on the left-hand side of equation (1) is local change rate of temperature. On the right-hand side of equation (1), the first and second terms are the zonal and meridional advections; the third term represents the vertical advection; the fourth term is the vertical diffusion which includes the wave-induced mixing in the Exp WAVE-OCEAN; and the last term stands for the surface net heat flux term, which contains the process of shortwave radiation penetration. In equation (1), we have ignored the horizontal diffusion term which is relatively small.

[16] The vertical diffusion term expressed as $\frac{A_{hv}}{\Delta z_1}\frac{\partial T}{\partial z}\big|_{z=\Delta z_1}$ is changed by the wave-induced mixing, which is always the negative value (Figure 4) indicating that the wave-induced mixing has directly cooling effect on SST. In addition, Figure 4 shows that the wave-induced mixing plays a more important role in the eastern ocean. From equation (1), the direct effect of wave-induced mixing is determined by A_{hv} of the vertical mixing coefficient, and $\frac{\partial T}{\partial z}\big|_{z=\Delta z_1}$ of the vertical gradient of ocean temperature. In the eastern part of each basin, both the wave-induced mixing and the vertical gradient of temperature are larger than those in west (not shown), as a result, the effect of the wave-induced mixing is much stronger in eastern basin. On the other hand, the wave-induced vertical mixing deepens the ocean upper mixed layer, and the larger inertia of upper ocean results in the weakened zonal current in the tropical ocean (Figure 5). Therefore, the warm SST anomalies appear in the western Indian and western Atlantic Oceans, and central Pacific. In the meantime, the net heat flux damps the SST change, in other words, the ocean gets more heat flux from external forcing when SST decreases, and vice versa (Figure 6).

[17] After understanding the SST response in an OGCM, we come back to the climate system. First, the cold anomaly of SST in the eastern Atlantic Ocean drives high surface air pressure, warm SST anomaly in the western Atlantic drives low surface air pressure. As a result, an easterly surface wind anomaly and westward sea surface ocean current anomaly appear, in accordance with the Bjerknes feedback. This process enhances the cold anomaly in the eastern Atlantic Ocean and warm anomaly in the western Atlantic Ocean. Because there is no continental mass separating the equatorial Pacific and the equatorial Indian Ocean, the two regions can be regarded as a whole that change simultaneously. Therefore, the cold SST anomalies in the eastern Indian Ocean and the western Pacific Ocean generate high air pressure; meanwhile the warm anomalies in the western Indian Ocean and the central Pacific generate low air pressure anomaly. Then the cold and warm anomalies will be enhanced by the Bjerknes positive feedback. The schematic diagram of the above SST and wind anomaly responses to the wave-induced mixing is shown in Figure 7. Second, net heat flux always plays a role of negative feedback in climate system (Figure 8). The warm (cold) SST is accompanied by the decrease (increase) of the local net heat flux, and vice versa.

4. Conclusions and Discussion

[18] This study analyzes the equatorial basin-wide SST response to the non-breaking surface wave-induced vertical mixing through numerical experiments of climate models and stand-alone ocean models. The SST biases in the CCSM3, such as "too cold tongue" in the eastern tropical Pacific and the reversed equatorial SST gradient in the Atlantic, can be improved by including the wave-induced mixing. The "West-Positive and East-Negative" SST pattern is responsible for the amendment of the climate model of CCSM3.

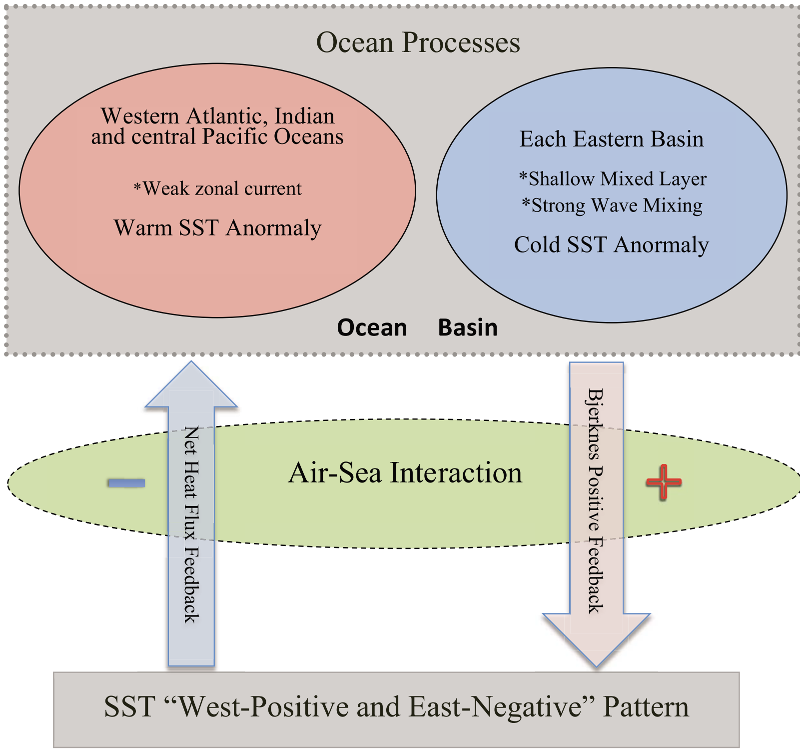

Figure 9. Schematic response of the equatorial basin-wide SST to the wave-induced mixing in climate system. In each eastern basin, the effect of the wave-induced mixing is strong because of the large wave-induced mixing coefficient and the shallow mixed layer (the latter is equivalent to the large vertical gradient of temperature). As a result, the SST decreases and exhibits cold SST anomaly. Meanwhile, the wave-induced mixing weakens the zonal surface ocean current that results in warm SST anomaly in western Atlantic and Indian Oceans, while this warm signal appears in central Pacific Ocean. In a climate system, the above SST anomaly pattern generates surface easterly wind responses through changing surface air pressure, and this kind of wind anomaly will enhance the above SST changes. That is the Bjerknes positive feedback. Then the "West-Positive and East-Negative" SST patterns in three basins appear in the equatorial region. The net heat flux plays a role of negative feedback.

[19] The influence of the wave-induced mixing on the tropical basin-wide SST in the climate model can be summarized as follows (Figure 9). In each eastern basin, the effect of the wave-induced mixing is strong because of the large wave-induced mixing and the shallow mixed layer, the latter is equivalent to the large vertical gradient of temperature. As a result, the SST decreases and exhibits cold SST anomaly in the tropical eastern part. Meanwhile, the wave-induced mixing weakens the zonal surface ocean current that results in warm SST anomaly in western Atlantic and Indian Oceans, while this warm signal appears in central Pacific Ocean. In a climate system, the above SST anomaly pattern generates surface easterly wind anomaly through changing surface air pressure, and this kind of wind anomaly will enhance the above SST changes. That is the kind of Bjerknes positive feedback. Then the "West-Positive and East-Negative" SST patterns in three basins appear in the equatorial region. The net heat flux plays a role of negative feedback.

[20] In this paper, we focus on the tropical region between 15°S and 15°N. The "West-Positive and East-Negative" SST pattern can enhance the Walker circulation. Although the SST response phenomena occur in the equatorial ocean, the processes beyond tropics may also contribute. The factors beyond the tropics need to be identified in future study.

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