RESEARCH ARTICLE

Response of the tropical Pacific Ocean to wind changes related to global warming from simulations with an ocean general circulation model

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Abstract: A suite of numerical experiments is implemented with an ocean general circulation model (OGCM) to examine the roles of wind stress and wind speed for oceanic changes in the tropical Pacific under global warming. In particular, we turned off the changes of wind stress and/or wind speed in the model to identify the effects of wind-driven ocean circulation and air-sea latent heat flux (i.e., its portion through the wind speed influence on the efficiency of latent heat flux). Results show that 1) the wind stress change appears to be a key forcing mechanism for weakening the tropical surface currents as well as for the oceanic changes in the equatorial thermocline, while it only contributes secondarily to the sea surface temperature (SST) pattern formation in the tropics; 2) the wind speed change is the leading cause for the minimum warming over the southeast subtropics and for a stronger surface warming in the northern hemisphere than in the southern hemisphere; and 3) the enhanced surface warming along the equator is mainly due to the effect of warming in the absence of wind stress and wind speed changes, and this effect also plays a significant role for changing the equatorial thermocline.

Keywords: Tropical Pacific Ocean, global warming, thermocline

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1. Introduction

Climate models have reached consensus on oceanic changes in the tropical Pacific under global warming, including an enhanced surface warming, a weakening of the equatorial currents, and a significant change in the thermocline (Vecchi and Soden, 2007; Luo, Rothstein and Zhang, 2009). However, our understanding about their formation mechanisms is still very limited although these changes are known to be of great importance to global climate and climate change.

Several hypotheses have been proposed to explain the SST pattern formation in the tropical Pacific. For example, Liu *et al*. (2005) argued that the primary contribution to the enhanced equatorial warming in the Pacific is through the influence of the climatological mean wind speed on the efficiency of latent heat flux. It is easy to cool off through latent heat flux in the trade wind regions due to high wind speed there, resulting in a smaller sea surface temperature (SST) change. However, it is hard to cool off at the equator due to low wind speed, resulting in larger SST change. However, this argument does not apply in regions where the wind speed change is significant such as the south eastern Pacific. Through careful heat budget diagnoses of the climate model outputs, DiNezio *et al*. (2009) found that the largest warming appeared in the central equatorial ocean and the ocean dynamics are important for the equatorial warming pattern. Meanwhile, Xie *et al*. (2010) suggested that the equatorial peak in SST warming is resulted from the mean evaporation that sets the thermal damping coefficient and is much weaker on the equator than in the subtropics. Although the heat budget analysis is helpful for identifying the major balance and forming hypotheses, it is ineffective when it comes to resolving issues of debate as above. Recently, Lu *et al.* (2012) employed a partially coupled model to demonstrate that the wind-evaporation-SST (WES) feedback is the main formation mechanism for the tropical warming in the Pacific. However, the ocean component in their partially coupled experiments has a coarse resolution of 3° × 3° which does not resolve the ocean dynamics in the tropical Pacific.

All the above mentioned studies left subsurface ocean unexplored. The thermocline changes in the tropical Pacific under global warming include a shoaling and sharpening of the equatorial thermocline, a minimum warming or even cooling at the thermocline, and an companying change in the structure of the Equatorial Undercurrent (EUC). It is generally viewed that the oceanic changes are a direct response to a weakening of the Pacific equatorial easterlies associated with the slowdown of the Walker circulation, a robust signature of the atmospheric response to global warming (Vecchi and Soden 2007). However, this view has not been carefully examined. In this study, we employed an ocean general circulation model (OGCM) with a high resolution to understand the formulation mechanisms of the oceanic changes not only near surface but also at subsurface in the tropical Pacific under global warming. More specifically, we turn off the wind-related changes to identify the wind stress effect (i.e., wind-driven ocean circulation) and/or wind speed effect on evaporation (WES feedback) on those robust features of the tropical Pacific. The rest of the paper is structured as follows; section 2 introduces the model configuration and experimental design; section 3 examines the effects of the wind stress and wind speed changes on the tropical SST, sea surface currents and the thermocline structure in response to global warming; a summary is given in Section 4.

2. Experiment Design

The surface energy budget has been widely used to examine the mechanisms for the SST pattern formation under global warming. Based on studies by Xie *et al.* (2010) and Lu *et al.* (2012), the leading-order energy balance that maintains the tropical SST change under global warming can be written as:

$$\delta T = \frac{\delta D_O^W + \delta D_O^M - (\partial \bar{Q}_E / \partial W)\delta W + \partial Q_A}{\partial \bar{Q}_E / \partial T} \tag{1}$$

Where δD_O^W is the SST variation resulted from the ocean circulation change driven by wind stress, and δD_O^M is the SST variation contributed by the heat divergence/convergence due to the mean ocean circulation, resembling the ocean dynamical thermostat (Clement, Seager, Cane *et al.*, 1996); Q_E is the latent heat and $(\partial \bar{Q}_E / \partial W)\delta W$ represents the contribution of the latent heat due to wind speed change, referred to as WES feedback; ∂Q_A represents the contribution from all other atmospheric forcing fields than wind stress and wind speed. In addition, the denominator of the equation, $\partial \bar{Q}_E / \partial T$ is the thermal damping which measures the resistance to the SST warming through evaporative cooling which exerts a strong influence on the pattern of the SST (Knutson and Manabe, 1995; Liu, Vavrus, He *et al*., 2005). This equation is used to guide our experimental design. In particular, we will design a suite of process-oriented numerical experiments with the Hybrid Coordinate Ocean Model (HYCOM) in order to identify the effects of wind stress change and/or wind speed change for the oceanic changes under global warming.

The HYCOM model is configured for the Pacific Ocean from 124°E to 72°W and 55°S to 60°N, with a constant horizontal resolution of 0.5° × 0.5° and 20 layers in the vertical. The atmospheric forcing and open boundary conditions are provided by ensemble means from eleven IPCC AR4 coupled models (CGCM3.1, CNRM−CM3, CSIRO−MK3.0, FGOALS−g1.0, GFDL−CM2.0, GFDL−CM2.1, HADCM3, IPSL−CM4, MIROC3.2, MRI−CGCM2.3.2, and PCM1). Specifically, the means from 1951 to 2000 in 20C3M are used to represent the present-day climate, and the means from 2151 to 2200 in SRESA1B are used to represent the future warmer climate. The 20C3M experiments simulate the 20th century climate where atmospheric CO_2 concentrations and other input data are based on historical records. The SRESA1B scenarios represent a climate in which atmospheric CO_2 concentrations double their present-day level in the year 2100 and are then fixed and maintained to years 2200. The differences of wind stress and its curl between SRESA1B and 20C3M are shown in Figure 1. It is found that global warming induces a weakening of equatorial easterlies through weaker trade winds in the northern hemisphere but stronger trade winds in the southern hemisphere.

In more details, based on the eleven IPCC model solutions from the 20C3M and SRESA1B experiments, we create the monthly climatology of temperature and salinity to be used as the HYCOM's initial and open boundary conditions, and of atmospheric fields (wind stress, air temperature, longwave and shortwave radiation, and specific humidity) to be used as the HYCOM's surface forcing. It is worth to note that in HYCOM evaporation, the latent and sensible heat fluxes are calculated using bulk formula in which wind speed as an input atmospheric variable is derived from wind stress. Four experiments are performed and their atmospheric forcing fields are listed in Table 1. Based upon Equation. (1), the wind stress contribution to SST and oceanic changes can be assessed by STRS – CTRL, the wind speed contribution or the WES feedback can be inferred from WIND – STRS, and FULL – WIND represents the effect of warming in the absence of wind stress and wind speed changes, including the contribution from changes in other atmospheric forcing fields, the thermal damping, and the ocean dynamical thermostat. FULL – CTRL is the full response, encompassing all the effects. All the above mentioned experiments were integrated for 25 years, and the analysis is conducted using the output of the last 5 years.

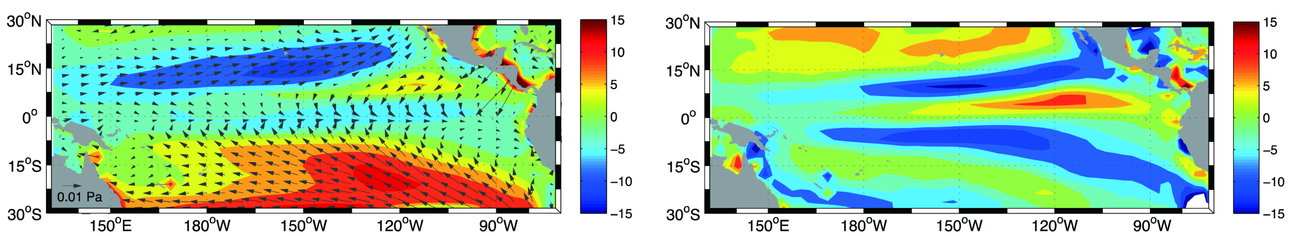
3. Results

3.1 Response of SST

The modeled full response of the tropical and subtropical Pacific SST to global warming (Figure 2A) is characterized by an enhanced warming along the equator as well as a minimum warming over the southeast subtropics, consistent with the climate model results (Liu, Vavrus, He *et al.*, 2005; Meehl, Averyt, Tignor *et al.*, 2007; Lu, Chen, and Frierson *et al.*, 2008; DiNezio, Clement, Vecchi *et al.*, 2009; Xie, Deser, Vecchi *et al.*, 2010). Its worthy to note that the equatorial warming in this model consists of two centers: one in the central equator around 160°W and another in the eastern equator.

The full response can be partitioned into the wind stress effect (Figure 2B), the WES feedback (Figure 2C), and the effect of warming in the absence of the wind stress and wind speed changes (Figure 2D). Without the wind-related effects, we find that the model reproduces the full response in the tropics, suggesting that the changes in wind stress and wind speed contribute marginally to the enhanced warming pattern along the equator.

The comparison of zonal-mean SST changes among these experiments (Figure 3) provides further evidence.



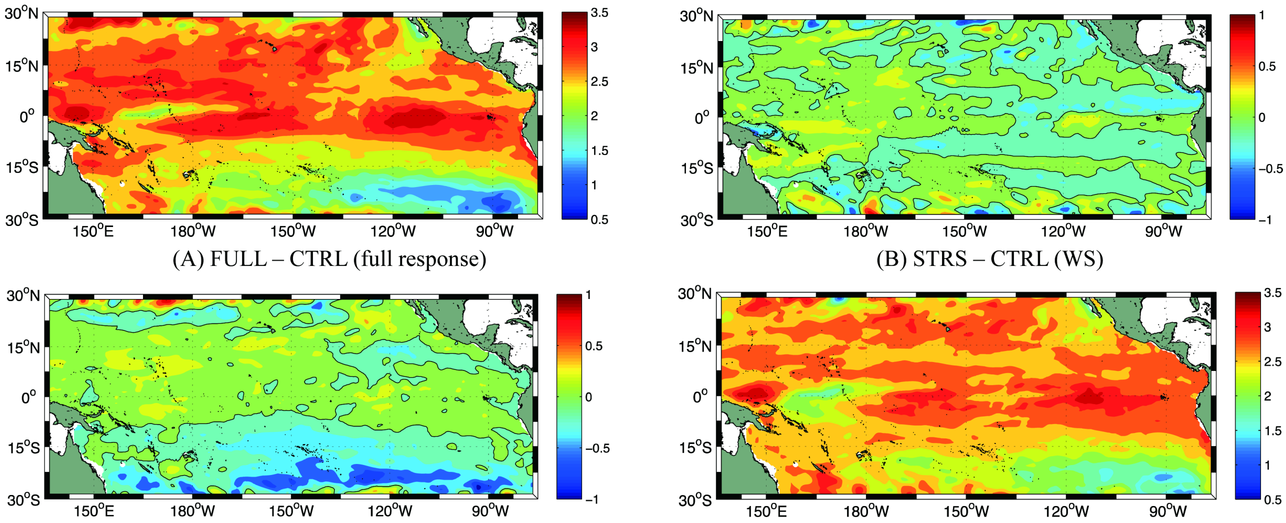
(A) Changes in wind stress and its magnitude

(B) Changes in wind stress curl

Figure 1. Changes of eleven-model ensemble-mean (A) wind stress (arrows) and its magnitude (color in 10^{-2} Pa), and (B) wind stress curl (color in 10^{-9} Pa m^{-1}) from 20C3M to SRESA1B.

Table 1. Experiments with HYCOM

Name	Atmospheric forcing			Motivation
	Wind stress	Wind speed	Other fields	
CTRL	20C3M	20C3M	20C3M	Control run
FULL	SRESA1B	SRESA1B	SRESA1B	Response to global warming
WIND	SRESA1B	SRESA1B	20C3M	Roles of both wind stress and wind speed
STRS	SRESA1B	20C3M	20C3M	Role of wind stress only



(A) FULL – CTRL (full response) (B) STRS – CTRL (WS)

(C) WIND – STRS (WES) (D) FULL – WIND (w/o WS & WES)

Figure 2. Differences of SST (color in °C) between the experiments: (A) FULL – CTRL, (B) STRS – CTRL, (C) WIND – STRS, and (D) FULL – WIND.

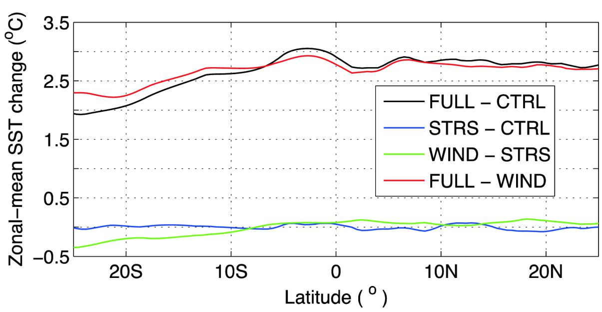


Figure 3. Differences of zonal-mean SST between the experiments.

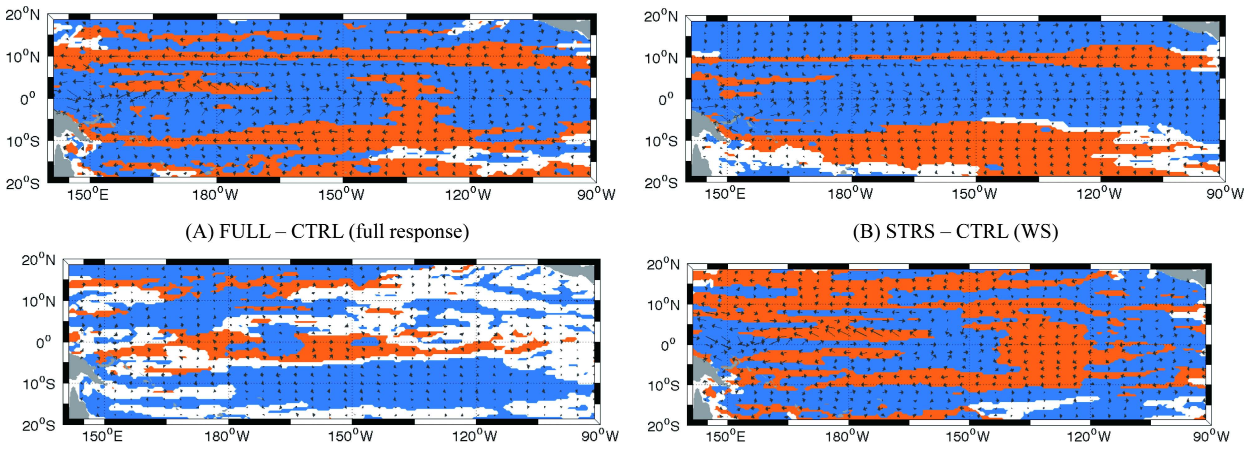
Therefore, the enhanced equatorial SST warming is mainly due to warming mechanisms other than the wind stress and wind speed changes.

Regarding the minimum warming over the southeast subtropics, the model shows that the WES feedback plays a leading role for its formation, in agreement with the results from the heat budget analysis by Xie *et al*. (2010) and the partially coupled modeling by Lu *et al.* (2012). In addition, the model also indicates that the asymmetry in wind speed change (a strengthening of the southeast trades and a weakening of the northeast trades; see Figure 1A) leads to the SST asymmetry between the northern and southern subtropics, i.e., a warming in the north and a cooling in the south. Note that our modeling result is different from the result from the partially coupled experiments by Lu *et al.*(2012) in which they argued that the WES feedback plays an important role for the equatorial enhanced warming. One reason for the weaker WES-induced SST warming could be the lack of atmospheric feedback in our ocean-alone experiment.

As shown in Figure 2B, the wind stress change results in a warming in the western tropics but a cooling in the central and eastern tropics. This is in contrast to what one might picture from the weakening of the tropical easterlies alone (Figure 1A), which shoals the thermocline in the west and deepens the thermocline in the east, and should lead to a cooling in the western tropics and a warming in the central and eastern tropics through the thermocline and Bjerknes feedbacks (Vecchi and Soden, 2007; Collins, An, Cai *et al*., 2010). Similar pattern of the SST response to wind stress change also appears in the coupled model experiments implemented by Lu *et al.* (2012) who suggested that it might be related to the feedbacks via radiative flux and latent heat flux. However, in our current experiments, there are no differences in the radiative flux and latent heat flux between STRS and CTRL, so the SST response pattern in our model should be resulted from other factors.

3.2 Response of Sea Surface Currents

The model captures major features of the sea surface current change under global warming (Figure 4A), including a weakening of the South Equatorial Current (SEC), the North Equatorial Countercurrent (NECC), and the North Equatorial Current (NEC), and a strengthening of westward currents in the southern tropics roughly between 10°S and 20°S. Comparing Figure 4B-4D with Figure 4A, it is clear that such a response



(A) FULL – CTRL (full response)
(B) STRS – CTRL (WS)
(C) WIND – STRS (WES)
(D) FULL – WIND (w/o WS & WES)

Figure 4. Differences of sea surface velocity between the experiments: (A) FULL – CTRL, (B) STRS – CTRL, (C) WIND – STRS, and (D) FULL – WIND. Blue, orange, and white colors denote zonal flows being weakened, intensified, and having no significant change, respectively.

of the sea surface velocity is due mainly to the change of the trade winds, which is weakened in the northern hemisphere and strengthened in the southern hemisphere under global warming (Figure 1A). Quite different from the SST response, the WES effect on the sea surface velocity is negligible. Without the wind-related effects, the magnitude of change in the sea surface currents is an order smaller than that due to wind stress effect. However, the effect of warming in the absence of the wind stress and wind speed changes plays a significant role for modifying the equatorial thermocline structure. This will be discussed further in next section.

3.3. Response of the Thermocline Structure

In addition to the changes in sea surface temperature and velocity, the thermocline at the equator is also projected to have significant changes under global warming by the coupled climate models (Vecchi and Soden, 2007; Luo Rothstein and Zhang, 2009), including a reduction of the mean depth of the thermocline, a cooling or minimum warming in the thermocline of the western and central equator, as well as an accompanied change in the Equatorial Undercurrent (EUC) with an increased flow in its upper flank but a decreased flow in its lower flank. All these major features are captured in the modeled full response to global warming (Figures 5A, 6A, and 7A).

Figure 5 shows the temperature differences along the equator between these experiments. It can be observed that the wind stress change plays a leading role for the cooling of the equatorial thermocline as well as the reduction of the thermocline depth. This can be attributed to local dynamics, i.e., the thermocline shoals in response to a weakening of the Pacific equatorial easterlies induced by a slowing Walker circulation (Vecchi and Soden, 2007). However, on closer inspection of the temperature changes in the tropics (Figure 6), it is found that the strongest cooling is not exactly on the equator but instead appears off the equator by a few degrees. This feature is mainly caused by large wind stress curl changes off the equator (Figure 1B) where a positive anomaly is seen to the north and a negative anomaly to the south, both of which lead to a shoaling of the tropical thermocline. The mechanism by which wind stress curl affects thermocline depth locally is through Ekman pumping (Gill, 1982), even in regions near the equator. In this process, positive (negative) wind stress curl in the northern (southern) hemisphere causes divergence of the local Ekman currents that, in turn, induces upwelling beneath the Ekman layer, thereby shoaling the depth of the thermocline, or equivalently, decreasing temperature at a fixed depth within the thermocline. In addition, we also note a local maximum warming around 10°N at subsurface of ~150 m (Figure 6B) that is induced by the large negative wind stress curl there (Figure 1B).

Significant contribution of the wind stress change to the thermocline water can also be seen from the response of the EUC whose upper portion increases and lower portion decreases (Figures 7A and 7B). Comparing Figure 7D with Figure 7A, however, the effect of warming in the absence of the wind stress and wind speed changes also appears to be important for the EUC change.

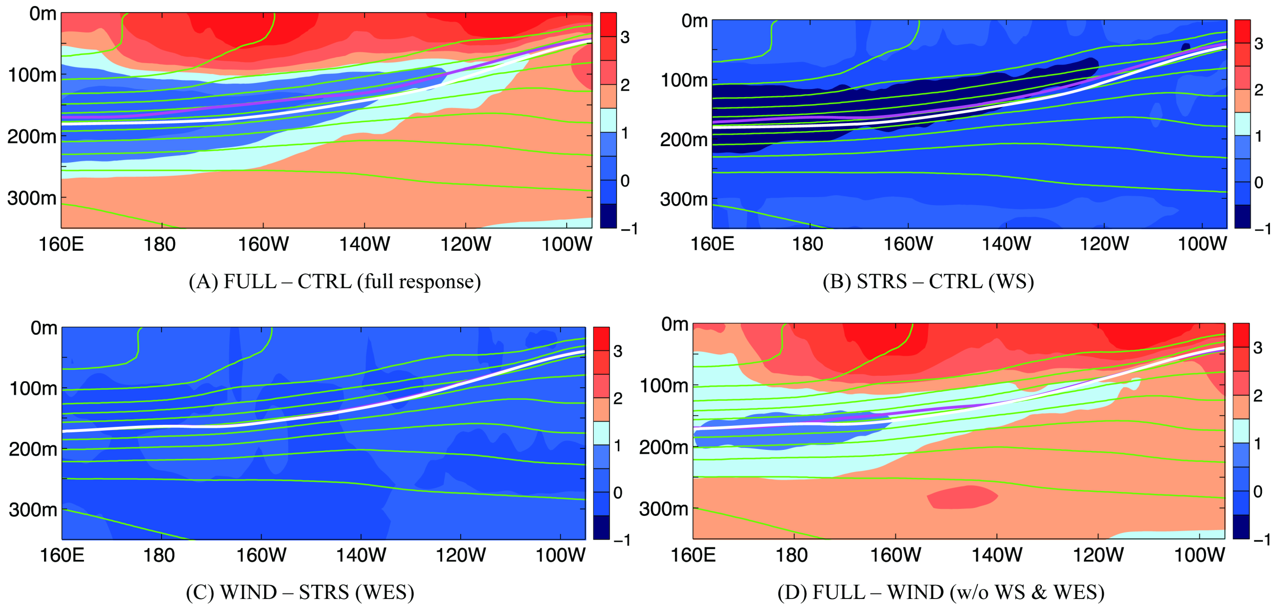


Figure 5. Differences of temperature (color in °C) along the equator between the experiments: (A) FULL – CTRL, (B) STRS – CTRL, (C) WIND – STRS, and (D) FULL – WIND. Superimposed are the thermocline depths (red thick lines for the experiments in front of the minus signs and white thick lines for the experiments behind the minus signs), and the climatological fields of the experiments behind the minus signs (contour interval (CI) = 2 °C).

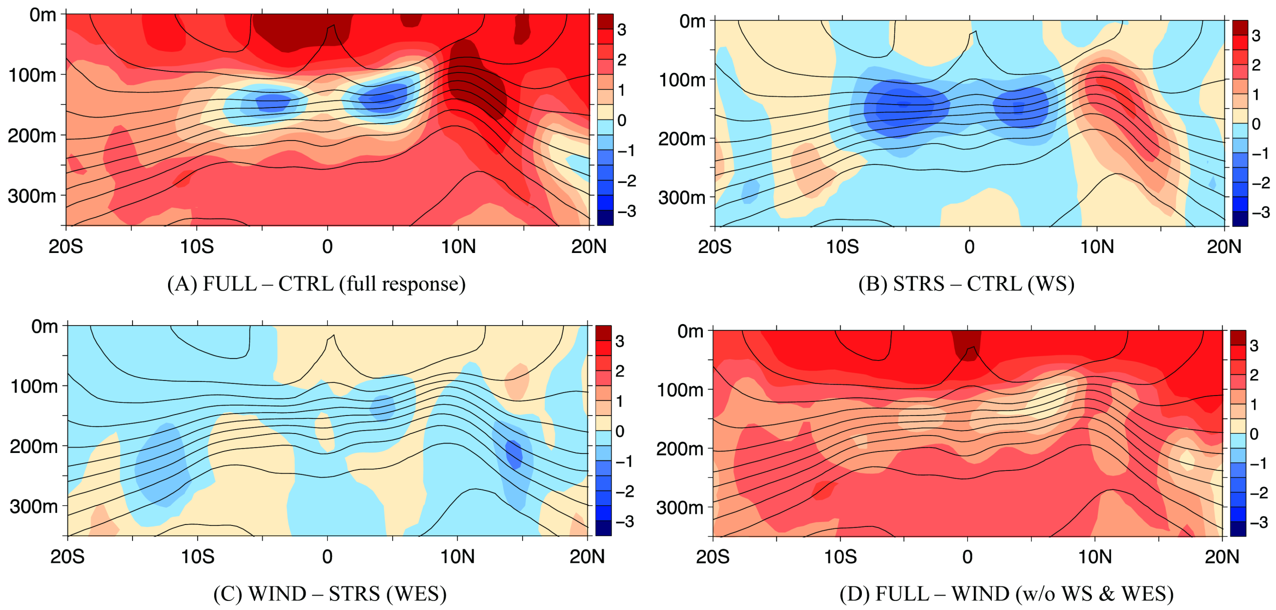


Figure 6. Differences of temperature (color in °C) along 160°W between the experiments: (A) FULL – CTRL, (B) STRS – CTRL, (C) WIND – STRS, and (D) FULL – WIND. Superimposed are the climatological fields of the experiments behind the minus signs (CI = 2 °C).

In addition, a comparison of Figure 7B and Figure 7A confirms that the wind stress change is the dominant factor for the surface velocity changes around the equator (i.e., the weakening of SEC, NECC, and NEC). Another finding from these experiments (comparing Figures 5C to 5A, 6C to 6A, and 7C to 7A) is that the effect of the wind speed change is only confined to the SST and it plays negligible role for the subsurface changes of the tropical Pacific Ocean.

4. Summary

By implementing a suite of experiments with HYCOM configured for the Pacific Ocean, we have investigated the effects of wind stress and wind speed

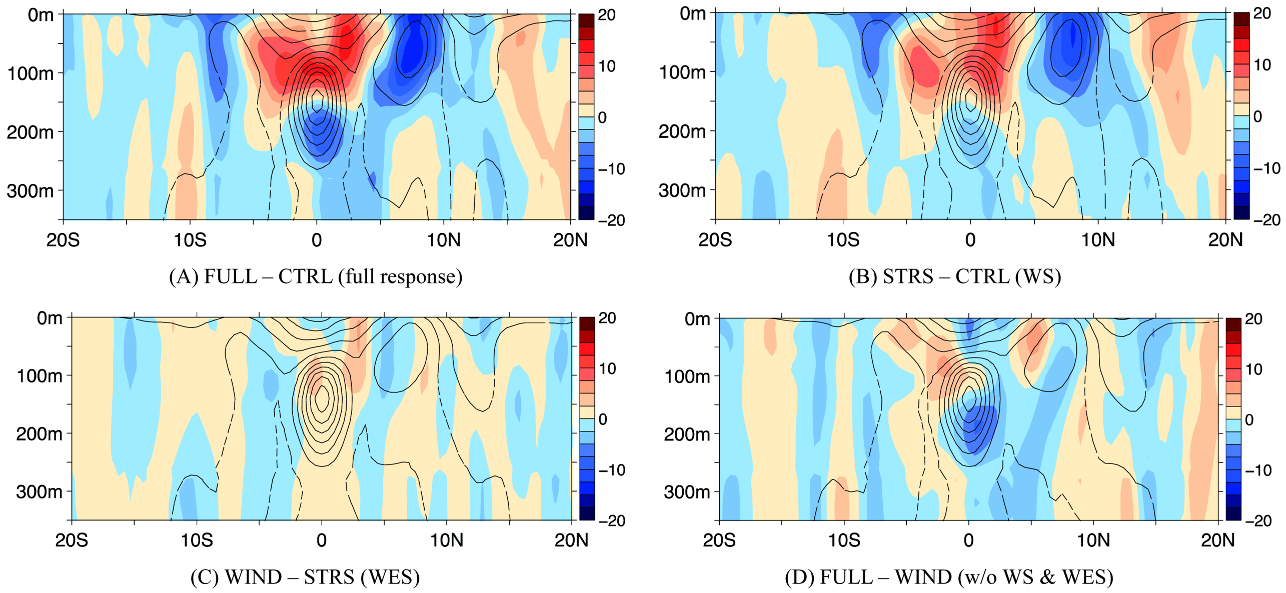


Figure 7. Differences of zonal current (color in cm/s) along 160°W between the experiments: (A) FULL – CTRL, (B) STRS – CTRL, (C) WIND – STRS, and (D) FULL – WIND. Superimposed are the climatological fields of the experiments behind the minus signs (CI = 10 cm/s).

changes in the tropical Pacific Ocean response to global warming. It is found that, while only contributing secondarily to the SST pattern formation in the tropics, the wind stress change appears to be a key forcing mechanism for weakening the surface westward currents as well as for the oceanic changes in the equatorial thermocline. The wind speed change contributes only to the SST warming pattern and its contribution to the subsurface ocean changes is negligible.

Our modeling result suggests that the wind-related effects contribute only marginally to the equatorial SST warming. However, this result should be interpreted with great caution since the SST pattern in FULL – WIND (w/o WS & WES) could be dictated by the surface energy fluxes which themselves might be partially originated from WS and/or WES feedbacks in a coupled system. Similar overriding experiments with wind stress and wind speed using CCSM3 (Lu and Zhao, 2012) suggests a much greater role of WES in shaping the equatorial SST pattern than the WES isolated here using an ocean-alone model. While the model by Lu *et al.*(2012) has too coarse resolution and many tropical processes are not well captured, the present study employs an ocean-alone model in which the full WES effect is compromised by prescribing the atmospheric conditions. Thus, further studies require a coupled or partially coupled system with higher resolution to better quantify the WES effect in the tropical SST response to global warming.

Although these experiments above are designed to examine the individual effect of several forcing factors for the oceanic changes under global warming, their effects may not be fully separable, i.e., each effect presented in the paper is not "pure" and may be contaminated by other factor's effect.

Conflict of Interest

No conflict of interest was reported by the author.

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