### Title
A possible bias of simulating the post-2000 changing ENSO




### Journal
Chinese Science Bulletin, 60(21)

### ISSN
2095-9273



### Authors
Zheng, Fei
Zhang, Wen
Yu, Jinyi
et al.



### Publication Date
2015-11-01

### DOI
10.1007/s11434-015-0912-y

Sci. Bull. (2015) 60(21):1850–1857
DOI 10.1007/s11434-015-0912-y

www.scibull.com
www.springer.com/scp

Article

Earth Sciences

# A possible bias of simulating the post-2000 changing ENSO

**Fei Zheng · Wen Zhang · Jinyi Yu · Quanliang Chen**

Received: 18 August 2015 / Accepted: 24 September 2015 / Published online: 15 October 2015


**Abstract** Since the late 1990s, a climate shift has occurred over the tropical Pacific that is characterized with a La Niña-like mean state. Coincident with this climate shift, climate models' skills in predicting the El Niño Southern Oscillation (ENSO) events in the 2000s are significantly lower than in the 1980s–1990s. A common bias is likely to exist in contemporary ENSO models that got amplified after the climate shift. In this study, we identify this model bias to be the wind–sea surface temperature coupling processes over the tropical Pacific. Evidence is presented to show that this coupling process experienced an obvious shift around year 2000 in its coupling strength and coupling center. A simple ENSO coupled model is used to demonstrate that the changing properties of the post-2000 ENSO events can be more realistically simulated if this model bias is alleviated.

**Keywords** ENSO · Wind–SST coupling · Bias correction · Climate shift

F. Zheng (✉) · W. Zhang
International Center for Climate and Environment Science (ICCES), Institute of Atmospheric Physics, Chinese Academy of Sciences, Beijing 100029, China
e-mail: zhengfei@mail.iap.ac.cn

W. Zhang · Q. Chen
College of Atmospheric Sciences, Chengdu University of Information Technology, Chengdu 610225, China

J. Yu
Department of Earth System Science, University of California, Irvine, CA 92697-3100, USA

## 1 Introduction

The El Niño Southern Oscillation (ENSO) is one of the important sources of climate variability on seasonal to interannual scales and has been extensively studied in the past few decades. Since the Zebiak–Cane (ZC) model first reproduced the main observed features of ENSO [1], models with various complexities of atmosphere–ocean coupling have been developed to simulate and predict ENSO events. Contemporary coupled models have now reached a stage at which accurate predictions can be made 6–12 months in advance [2–6]. However, the ENSO prediction skill was noticed to decline since around year 2000 [7, 8], which is about the time when a shift in the climate regime took place in the tropical Pacific that is characterized by a prominent La Niña-like mean state and enhanced trade winds [9–11]. Barnston et al. [7] suggested that decadal variations in ENSO properties may be a skill-determining factor.

It has been noticed that the central Pacific (CP) ENSO [12, 13] occurred more frequently in recent decades [14, 15]. This type of ENSO has its sea surface temperature (SST) anomaly center in the central equatorial Pacific and is distinct from the traditional eastern Pacific (EP) ENSO that has its SST anomaly center in the eastern equatorial Pacific. The CP type of ENSO is believed to be produced by a mechanism distinct from that of the traditional ENSO [16] and its increased occurrence is possibly linked to the mean state change after the year 2000 [17–19]. It is likely that the changing ENSO property (i.e., the ENSO type) after the climate shift in year 2000 causes the decline of ENSO prediction skills. This hypothesis is supported by Xue et al. [8] who analyzed the ENSO simulations in the Climate Forecast System, version 2 (CFSv2), model and noticed biases in simulating the Niño3.4 index [average

SST anomalies over the area (5°S–5°N, 170°–120°W)] and the maximum standard deviation (SD) of SST anomalies shifted along with the change of ENSO properties around the year 2000. Meanwhile, it is noticed that the CP ENSO pattern cannot be adequately simulated in the phase 5 of the Coupled Model Intercomparison Project (CMIP5) [20].

The climate shift near the year 2000 appears to have amplified some specific biases in contemporary ENSO models [21] and thus degrades their performances in simulating and predicting the changing ENSO events in the twenty-first century. Models that were turned for or trained with the observations before 2000 may not be able to reasonably simulate the post-2000 ENSO characteristics. Biases in a model can be attributed to imperfect physical formulation and/or improper parameterizations, among other errors. In this study, we examined the impacts of the year-2000 climate shift on ENSO simulation skills using a simple ENSO coupled model (i.e., the GMODEL, version 3.0) [22]. We show with evidence that a model bias associated with the air–sea interaction over the tropical Pacific can get amplified after the year-2000 climate shift. A bias correction scheme is developed to improve the model performance in simulating the changing ENSO events after the year-2000 climate shift.

## 2 Data and model

Several monthly observational/reanalysis datasets were used for the study period 1982–2013: SST data from the National Oceanic and Atmospheric Administration Extended Reconstructed SST (ERSST, v3b) dataset [23]; sea surface height (SSH) data, which are used to represent the variations in thermocline depth, from the National Centers for Environmental Prediction/Global Ocean Data Assimilation System (NCEP/GODAS); and zonal wind stress (TAUX) data from European Center Hamburg Atmospheric Model, version 4.5 (ECHAM4.5), ensemble simulations [24].

A simple linear coupled model is used in this study, which is the GMODEL, version 3.0 [22]. Its atmospheric component is a statistical atmosphere model that was trained by the observed monthly wind stress anomalies from Florida State University and the observed Niño3 and Niño4 indices [an average of SST anomalies over the Niño3 region (5°S–5°N, 150°–90°W) and the Niño4 region (5°S–5°N, 160°E–150°W)] during period 1982–1999. The ocean model component contains a 1.5-layer linear shallow-water model and a linear SST equation.

The temporal evolution of the SST anomalies in GMODEL is controlled by the following anomaly equation:

$$\frac{dT}{dt} = \alpha(x)h(x,y) + \beta(x)\tau_x(x,y) - \gamma(x)T(x,y), \qquad (1)$$

where $T$ represents the SST anomaly field, $h$ is the thermocline anomaly field, and $\tau_x$ is the zonal wind stress (TAUX) forcing anomaly field. The parameters $\alpha$, $\beta$, and $\gamma$ correspond to the thermocline feedback, Ekman pumping feedback, and heat flux feedback, respectively. These parameters can be determined by regressing the time rate of changes of SST anomalies onto the anomalies of thermocline depth, zonal wind stress, and SST. All three variables (i.e., $T$, $h$, and $\tau_x$) in Eq. (1) are two-dimensional, and the three parameters (i.e., $\alpha$, $\beta$, and $\gamma$) in Eq. (1) are one-dimensional, which are only varying considerably along the equator [22].

## 3 Climate shift in the wind–SST coupling process

As described in the introduction, the year-2000 shift in the tropical Pacific means climate may affect atmosphere–ocean couplings to alter ENSO properties. In order to examine the changes of tropical Pacific coupling across the year-2000 climate shift, we separate the analysis period into two sub-periods: 1982–1999 and 2000–2013. Figure 1a shows the longitudinal distributions of zonal wind stress ($\tau_x$) anomalies along the equatorial (5°S–5°N) Pacific during the two sub-periods. The center of the anomalous TAUX is noticed to shift from 170°W in 1982–1999 to 165°E in 2000–2013. This westward shift of the wind stress anomaly center together with the change of ENSO from the EP type to the CP type [13] indicates that the wind–SST coupling center of ENSO events has displaced westward after year 2000. We further examined the wind–SST coupling strength during the two sub-periods by finding the regression coefficient between the Niño4 TAUX and the Niño3.4 SST anomalies. As shown in Fig. 1b, the regression coefficient decreased from 4.49 in 1982–1999 to 3.77 in 2000–2013, suggesting that the coupling strength weakened after the year-2000 climate shift. The difference between these two regression coefficients is statistically significant at the 95 % confidence level using a Student's $t$ test. Figure 1a, b together indicates that, associated with the climate shift, the wind–SST coupling in the equatorial Pacific was observed to shift westward and became weaker after 2000.

## 4 Impacts of wind–SST coupling on ENSO characteristics

We next used the GMODEL to examine how the changes in the center and strength of the tropical Pacific wind–SST

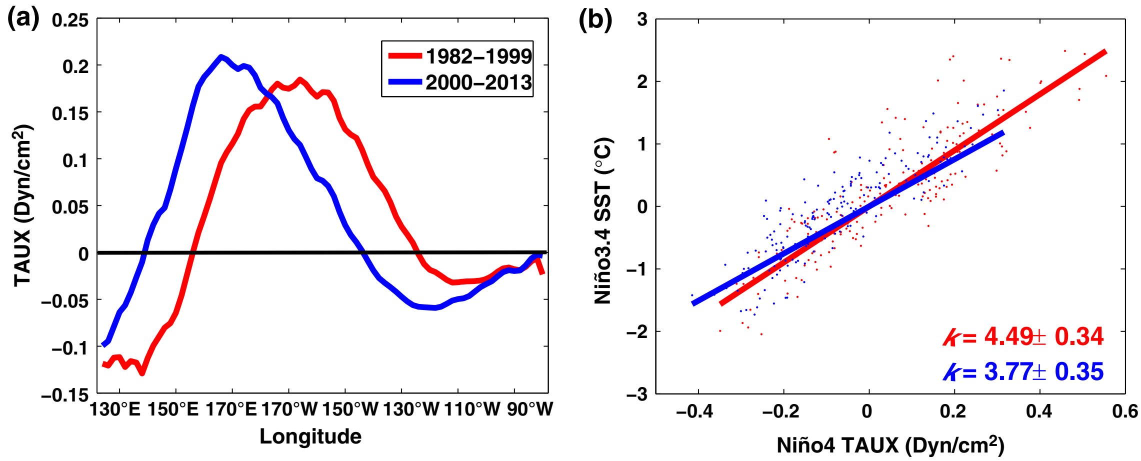


**Fig. 1** Observed shift in the wind–SST coupling progress. **a** The zonal structure for the anomalous TAUX averaged over 5°S–5°N in the period 1982–1999 (red lines/points) and 2000–2013 (blue lines/points). **b** Scatter diagram and the corresponding linear fitting lines (with the values of slopes plus and minus 1.96 standard errors, namely 95 % confidence for a Student's *t* test) between the Niño4 TAUX and Niño3.4 SST anomalies during the two sub-periods (1982–1999 and 2000–2013)

coupling can together and separately impact ENSO characteristics and simulations. This coupling process is represented in GMODEL by the parameter $\beta$ of Eq. (1). As shown in Sect. 3, the year-2000 climate shift displaced the wind–SST coupling center westward by about 20° and weakened the coupling strength by about 16 %. Four experiments were conducted with the GMODEL to evaluate the importance of the wind–SST parameter (i.e., $\beta$) in affecting the model simulation of the post-2000 ENSO (Table 1). In the control experiment, all the three parameters ($\alpha$, $\beta$, and $\gamma$) of Eq. (1) were determined by conducting regression analyses with the 1982–1999 observations. We refer to this experiment as the Scheme-original experiment. In the second experiment, we updated the $\beta$ parameter with a regression analysis of the 2000–2013 observations. This experiment is referred to as the Scheme-new experiment. To further identify the individual impacts of changing the center and the strength of the wind–SST coupling on ENSO simulations, we updated $\beta$ parameter in the control experiment to the values in the 2000–2013 period only for its coupling strength in a $\beta$-strength experiment and only for its coupling center in a $\beta$-center experiment. Table 1 summarizes the detailed setups of these four GMODEL experiments. All the four experiments were integrated for 60 years from a same initial condition, and the last 50-year results (i.e., avoiding the effects of the initial conditions) were used for the following analysis.

We compared in Table 2 the SDs of the SST anomalies calculated from the two sub-periods of the observations and the four GMODEL experiments over the Niño3, Niño3.4, and Niño4 regions. In the observations, the SD values reduced from the 1982–1999 to 2000–2013 sub-periods over both the Niño3 region (from 1.04 to 0.68 °C) and Niño3.4 region (from 0.93 to 0.75 °C). Similar reductions are found from the Scheme-original experiment to the Scheme-new experiments, whose SD values decrease from 0.93 to 0.82 °C in the Niño3 region and from 0.86 to 0.68 °C in the Niño3.4 region. The SD values produced by the Scheme-original experiment are close to the value observed during the 1982–1999 period, while the SD values produced by the Scheme-new experiment are close to those observed in the 2000s. These similarities indicate the importance and success of updating the values of the wind–

**Table 1** Description of the experiment schemes

| Scheme | Modified factors | | Description |
|---|---|---|---|
| | Strength | Center | |
| Scheme-original | | | The model is trained by the observations from 1982–1999 (the original setting) |
| Scheme-new | √ | √ | The parameter $\beta$ is updated using the observations from 2000–2013 |
| $\beta$-Strength | √ | | Only the coupling strength in $\beta$ is modified |
| $\beta$-Center | | √ | Only the coupling center in $\beta$ is modified |

SST coupling parameter in reproducing the changing ENSO characteristics in the past three decades.

Figure 2 further compares the power spectra of the Niño3.4 SST anomalies between the two sub-periods of the observations (Fig. 2a) and between the Scheme-original and Scheme-new experiments (Fig. 2b). Figure 2a shows that the dominant ENSO frequency decreases from once every 4.1 years in 1982–1999 to about once every 2.3 years in 2000–2013. Figure 2b shows a similar frequency decrease from the Scheme-original experiment (about 3.4 years) to the Scheme-new experiment (about 2.0 years). Table 2 and Figure 2 together show that, by updating the wind–SST coupling parameter ($\beta$) to the observed values in each sub-period, the same GMODEL model is able to realistically simulate the changing El Niño amplitude and frequency before and after the year-2000 climate shift. These results also indicate that the wind–SST coupling is a key process to cause the different characteristics between the post-2000 and the pre-2000 ENSOs.

To further understand why an updated wind–SST coupling parameter can produce a more realistic simulation of the post-2000 ENSO, we examined the main differences in the simulated TAUX, thermocline depth, and SST between the Scheme-original and of Scheme-new experiments. The differences were identified by applying an empirical orthogonal function (EOF) analysis to the differences of their simulations in each of the analyzed fields. The first EOFs of the structure differences are displayed in Fig. 3. The figures indicate that the main structure differences under the decadal changes of the interannual wind–SST coupling (i.e., the parameter $\beta$) are characterized by strengthened easterly wind stresses over the central Pacific; higher thermocline over the western Pacific and lower thermocline over the eastern Pacific; and La Niña-like SSTs over the eastern-to-central Pacific. These patterns depict the following wind–SST coupling process: First, the strengthened easterly winds over the central Pacific provide a mechanism to deepen the thermocline in the western Pacific and shoal the thermocline in the eastern equatorial Pacific. Colder seawater emerges in the eastern Pacific can then propagate to the west through the action of coastal upwelling and advection to produce a cold SST state (i.e.,

**Table 2** Standard deviation (SD) of the SST anomalies over the three Niño (Niño3, Niño3.4, and Niño4) regions, estimated from the four different schemes (Scheme-original, Scheme-new, $\beta$-strength, and $\beta$-center) and from the observations in two sub-periods (1982–1999 and 2000–2013)

| Region | Scheme-original | Scheme-new | $\beta$-Strength | $\beta$-Center | OBS (1982-1999) | OBS (2000-2013) |
|---|---|---|---|---|---|---|
| Niño3 | 0.93 | 0.82 | 0.81 | 0.96 | 1.04 | 0.68 |
| Niño3.4 | 0.86 | 0.68 | 0.67 | 0.91 | 0.93 | 0.75 |
| Niño4 | 0.60 | 0.50 | 0.43 | 0.76 | 0.59 | 0.66 |

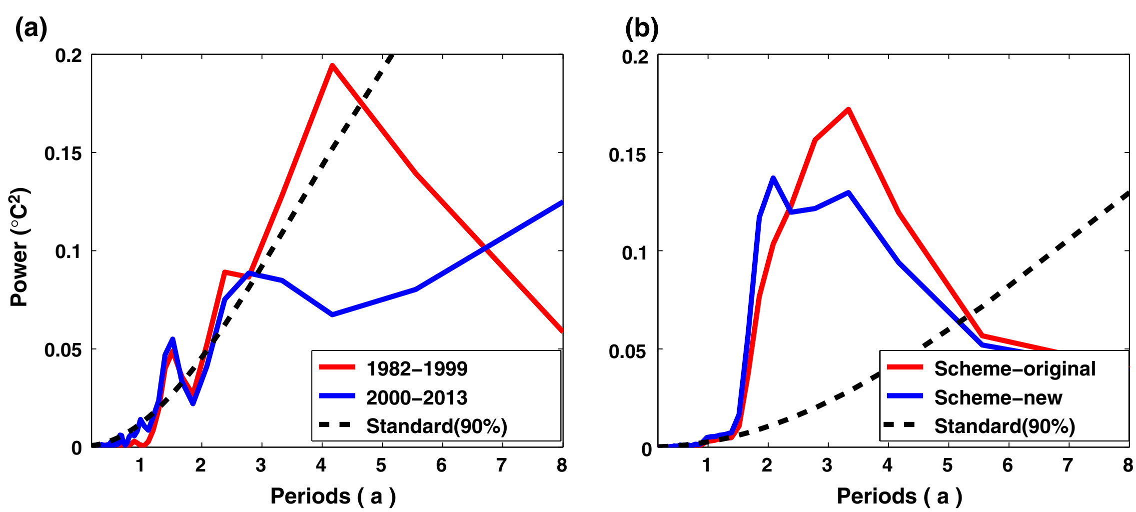


**Fig. 2** Power spectra of the Niño3.4 SST anomalies between two scenarios. **a** One from the two sub-periods of the observations and **b** the other from the two parameter schemes of the experiments. The red line in (**a**) is for the period 1982–1999, and the blue line is for the period 2000–2013; the red line in (**b**) is for the Scheme-original, and the blue line is for the Scheme-new; the black line in (**a**) and (**b**) represents the 90 % confidence standard

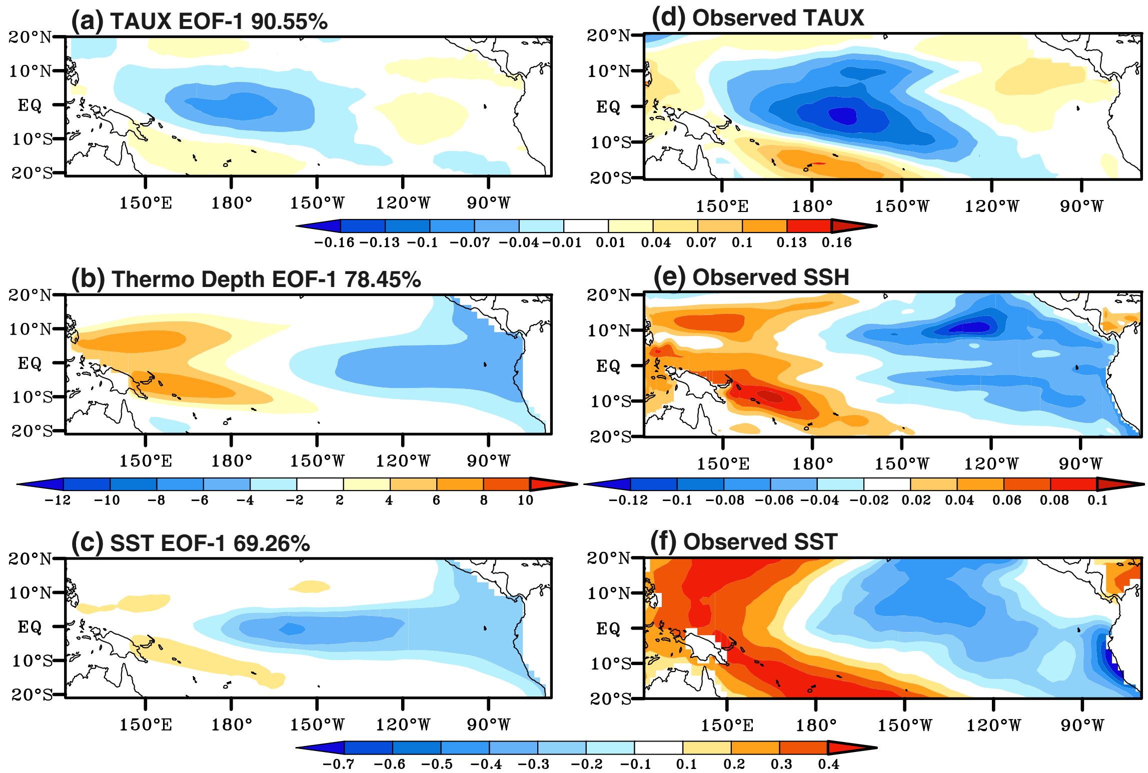


**Fig. 3** Leading EOF modes of the simulation differences in **a** TAUX (dyn cm$^{-2}$), **b** thermocline depth (m), and **c** SST (°C) between Scheme-new and Scheme-original, and mean state changes (2000–2013 minus 1982–1999) of anomalous **d** TAUX (dyn cm$^{-2}$), **e** SSH (m), and **f** SST (°C) from the observed data

the La Niña-like state) over most of the eastern-central equatorial Pacific, which in turn enhances the easterly wind state.

The main differences of simulated fields show a high degree of similarity with the observed mean state changes (i.e., 2000–2013 period minus 1982–1999 period) of TAUX, SSH, and SST (i.e., Fig. 3d–f), except for a weaker magnitude. This similarity further proves the critical role played by the wind–SST coupling parameter in improving the simulation of the post-2000 ENSO. This also suggests that the weakened ENSO cycle (i.e., decreased SD values of Niño3 and Niño3.4 SST simulated by the Scheme-new experiment) is related to the enhancement of easterly mean winds over the tropical Pacific (Fig. 3a), which hinders the transportation of warm water anomalies (Fig. 3b) from west to east to amplify ENSO events. Significantly, the observed cooling mean state over the tropical Pacific has been previously alluded to as the facilitator of the CP El Niño [10, 17, 25].

We next focused on isolating the individual roles of the coupling strength and the coupling center of $\beta$ in influencing the ENSO characteristics in the GMODEL simulations. We first compared in Table 2 (columns 4 and 5) the SD values of SST between the $\beta$-strength experiment and the $\beta$-center experiment over the Niño regions. We noticed that the observed decrease in the SD values across the 2000 over the Niño3 and Niño3.4 regions can only be produced when the $\beta$-strength is updated from the pre-2000 value (i.e., the Scheme-original experiment) to the post-2000 values (i.e., the $\beta$-strength experiment). However, the observed increase in the SD value across the climate shift over the Niño4 region can only be produced when the $\beta$-center is updated from the pre-2000 location (i.e., the Scheme-original experiment) to the post-2000 location (i.e., the $\beta$-center experiment). Therefore, the observed change in ENSO pattern (i.e., from the EP ENSO before the year-2000 climate shift to the CP ENSO afterward) involves changes in not only the strength but also the center of the wind–SST coupling in the tropical Pacific.

We repeated the EOF analysis of Fig. 3a–c with the simulation difference between the $\beta$-strength experiment and the Scheme-original experiment, and between the $\beta$-center experiment and the Scheme-original experiment. The results are shown in Fig. 4. This figure is used to examine the influence of modifying either the strength or the center of the parameter $\beta$ on the main differences of simulated states. The left-hand column shows that, when the strength of the wind–SST coupling is reduced from the Scheme-

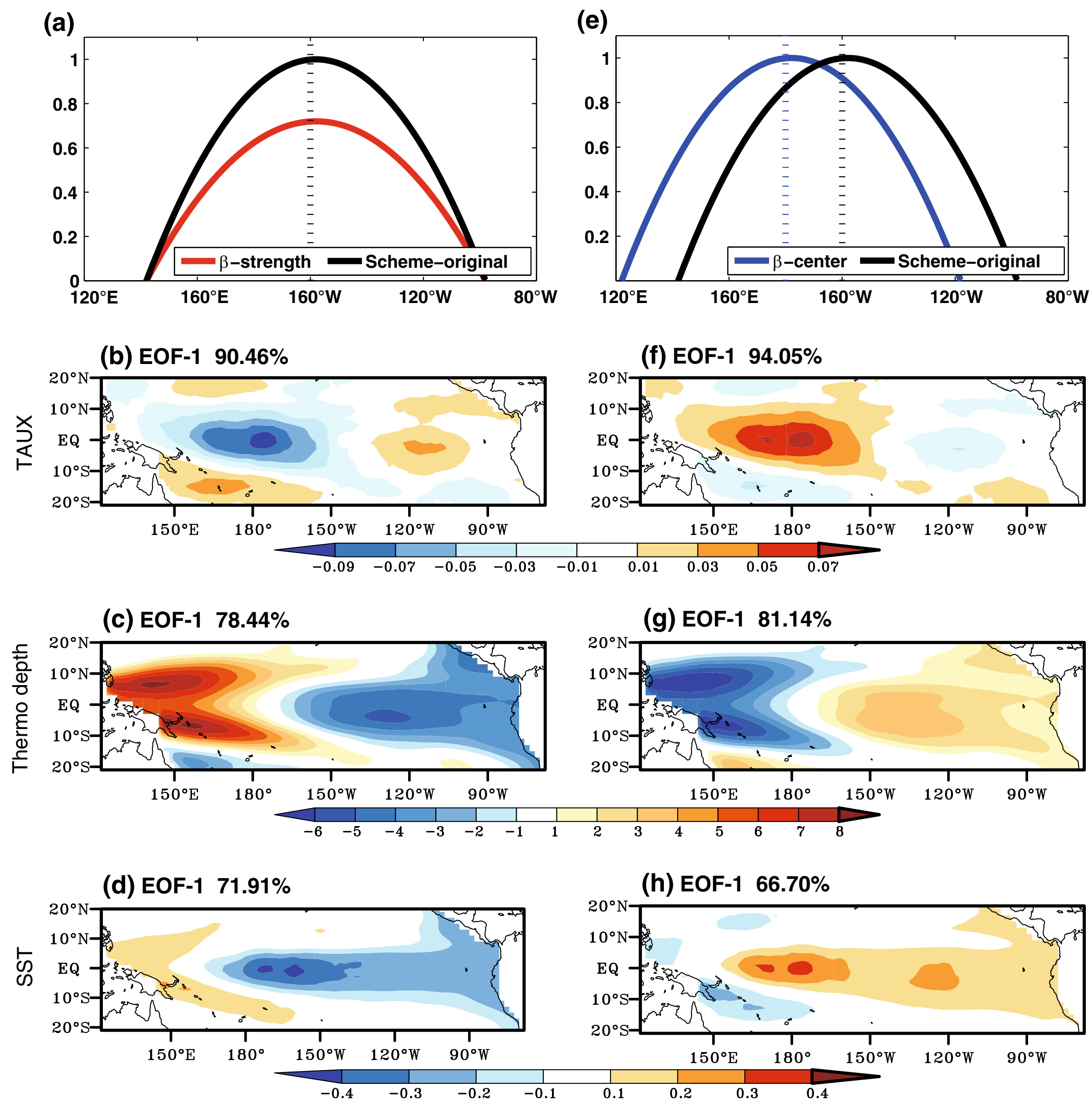


**Fig. 4** Leading EOF modes of the simulation differences in TAUX (dyn cm$^{-2}$; second row), thermocline depth (m; third row), and SST (°C; bottom row) between $\beta$-strength and Scheme-original (left column), and between $\beta$-center and Scheme-original (right column). And the top row is sketching the scheme differences between $\beta$-strength and Scheme-original (left), and between $\beta$-center and Scheme-original (right), respectively

original experiment to the $\beta$-strength experiment (Fig. 4a), the main simulation changes (Fig. 4b–d) between these two experiments are consistent with those from the Scheme-original to the Scheme-new experiments (Fig. 3a–c) and are also similar to the mean state changes observed from the pre- to post-2000 climate shift eras (Fig. 3d–f).

Figure 4 also shows that, when the coupling center of $\beta$ is shifted westward by 20° (Fig. 4e), the $\beta$-center experiment produces stronger westerly wind stress component in the central Pacific, which is accompanied with a flattened equatorial thermocline (i.e., negative anomalies over the western Pacific and positive anomalies over the eastern Pacific) and an El Niño-like SST pattern (Fig. 4f–h). Figure 4 indicates that reducing the wind–SST coupling strength is in favor of producing a cooling simulated state in the tropical Pacific, whereas shifting westward the coupling center contributes to the formation of a warm simulated state. Moreover, it is noticed that the La Niña-like simulated differences produced by the Scheme-new and $\beta$-strength experiments are similar (Figs. 3a–c, 4b–d). This high similarity indicates that the weakening of the wind–SST coupling strength dominates the zonal shift of the coupling center in controlling the post-2000 ENSO simulation.

## 5 Concluding remarks

A climate shift, which is characterized by a weakened Walker circulation and a shoaled flattened equatorial thermocline, is evident over the tropical Pacific Ocean around year 2000. In this study, we were able to quantify with observational data that this climate shift weakens the wind–SST coupling strength by about 16 % and displaces the coupling center westward around 20° from 170°W to around 165°E. We further used a simple coupled model (GMODEL) to demonstrate that these two changes in the wind–SST coupling are crucial to explaining the changing El Niño properties observed in the post-2000 era, which include a higher frequency of occurrence, weaker amplitudes, and the shift of the El Niño from the EP type to the CP type.

This robust weakened relationship between the atmospheric winds and the tropical SST in the post-2000 era has been explored in many previous studies [17, 25–28]. And one possible reason for inducing this weakened air–sea interaction at the interface might be from the variations in the background state of the tropical Pacific [10, 11, 26]. For example, cooler mean SST in the eastern and central equatorial Pacific results in reduced convection there together with a westward shift in the ascending branch of the Walker circulation [10, 11]. And this shift leads to a weakening in the relationship between eastern Pacific SST and longitudinally averaged equatorial zonal wind stress [26, 29]. However, the asymmetry of interannual variabilities can also modulate the mean state conditions, which will in turn affect the interannual variabilities, but this mechanism has been less investigated [11]. As demonstrated in Fang and Zheng [11], the interannual variabilities also can significantly affect the climate mean state, and the predominance of the EP and CP El Niño can be modulated by relationships between anomalous wind stresses and SST.

In this study, we further found that changing the strength and center of the wind–SST coupling can give rise to changes in the tropical Pacific mean state: A weakening of the coupling strength gives rise to a La Niña-like mean state, while shifting the coupling center westward gives rise to an El Niño-like mean state. And a common parameter bias exists in representing the changed relationship between wind and SST in ENSO models around 2000. Our GMODEL experiments conclude that weakening the wind–SST coupling strength dominates the westward shift of the wind–SST coupling center in controlling the cooling pattern over the tropical Pacific in the post-2000 era, and the changing properties of the post-2000 ENSO events can be more realistically simulated if this bias is reasonably reduced. Although the findings reported here are based on a simple coupled model, they can be used to understand and to alleviate biases of other more complex coupled models in simulating/predicting the changing El Niño observed in the twenty-first century [6, 30–32]. It should be noted that the possible impacts of the other two coupling parameters [i.e., $\alpha$ and $\gamma$ of Eq. (1)] remain a matter of major interest and merit further studies [33, 34].

**Acknowledgments** This work was supported by the National Program for Support of Top-notch Young Professionals, the National Basic Research Program of China (2012CB955202), the Chinese Academy Sciences' Project "Western Pacific Ocean System: Structure, Dynamics and Consequences" (XDA10010405), and the National Natural Science Foundation of China (41576019). We thank two anonymous reviewers for their valuable comments.

**Conflict of interest** The authors declare that they have no conflict of interest.

## References

1. Zebiak SE, Cane MA (1987) A model El Niño-Southern Oscillation. Mon Weather Rev 115:2262–2278
2. Latif M, Anderson D, Barnett T et al (1998) A review of the predictability and prediction of ENSO. J Geophys Res 103:14375–14393
3. Zheng F, Zhu J, Zhang RH (2006) Ensemble hindcasts of SST anomalies in the tropical Pacific using an intermediate coupled model. Geophys Res Lett 33:318–372
4. Jin EK, Kinter JL, Wang B et al (2008) Current status of ENSO prediction skill in coupled ocean–atmosphere models. Clim Dyn 31:647–664
5. Tippett MK, Barnston AG (2008) Skill of multimodel ENSO probability forecasts. Mon Weather Rev 136:3933–3946
6. Zheng F, Zhu J, Wang H et al (2009) Ensemble hindcasts of ENSO events over the past 120 years using a large number of ensembles. Adv Atmos Sci 26:359–372
7. Barnston AG, Tippett MK, L'Heureux ML (2012) Skill of real-time seasonal ENSO model predictions during 2002–2011: Is our capability increasing? Bull Am Meteorol Soc 93:631–651
8. Xue Y, Chen M, Kumar A (2013) Prediction skill and bias of tropical Pacific sea surface temperatures in the NCEP climate forecast system version 2. J Clim 26:5358–5378
9. Kosaka Y, Xie SP (2013) Recent global-warming hiatus tied to equatorial Pacific surface cooling. Nature 501:403–407
10. Xiang BQ, Wang B, Li T (2013) A new paradigm for the predominance of standing central Pacific warming after the late 1990s. Clim Dyn 41:327–340
11. Fang XH, Zheng F (2014) Effect of decadal changes in air–sea interaction on the climate mean state over the tropical Pacific. Atmos Ocean Sci Lett 7:400–405
12. Yu JY, Kao HY (2007) Decadal changes of ENSO persistence barrier in SST and ocean heat content indices: 1958–2001. J Geophys Res 112:125–138
13. Kao HY, Yu JY (2009) Contrasting eastern-pacific and central-pacific types of ENSO. J Clim 22:615–632
14. Lee T, McPhaden MJ (2010) Increasing intensity of El Niño in the central-equatorial Pacific. Geophys Res Lett 37:L14603
15. Yu JY, Kao PK, Paek H et al (2015) Linking emergence of the central-pacific El Niño to the atlantic multi-decadal oscillation. J Clim 28:651–662
16. Yu JY, Kao HY, Lee T (2010) Subtropics-related interannual sea surface temperature variability in the equatorial central pacific. J Clim 23:2869–2884

17. McPhaden MJ, Lee T, McClurg D (2011) El Niño and its relationship to changing background conditions in the tropical Pacific ocean. Geophys Res Lett 38:L15709–L15712
18. Yu JY, Kim ST (2011) Reversed spatial asymmetries between El Niño and La Niña and their linkage to decadal ENSO modulation in CMIP3 models. J Clim 24:5423–5434
19. Chung PH, Li T (2013) Interdecadal relationship between the mean state and El Niño types. J Clim 26:361–379
20. Taschetto AS, Sen Gupta A, Jourdain NC et al (2014) Cold tongue and warm pool ENSO events in CMIP5: mean state and future projections. J Clim 27:2861–2885
21. Kumar A, Chen M, Zhang L et al (2012) An analysis of the nonstationarity in the bias of sea surface temperature forecasts for the NCEP Climate Forecast System (CFS) version 2. Mon Weather Rev 140:3003–3016
22. Burgers G, van Oldenborgh GJ (2003) On the impact of local feedbacks in the central Pacific on the ENSO cycle. J Clim 16:2396–2407
23. Smith TM, Reynolds RW, Peterson TC et al (2008) Improvements to NOAA's historical merged land-ocean surface temperature analysis (1880–2006). J Clim 21:2283–2296
24. Zheng F, Du J, Zhu J (2009) A reconstructed wind stress dataset for climate research over the tropical pacific during a 153-year period. Atmos Ocean Sci Lett 2:277–283
25. Hu ZZ, Kumar A, Ren HL et al (2013) Weakened interannual variability in the tropical Pacific Ocean since 2000. J Clim 26:2601–2613
26. Lübbecke JF, McPhaden MJ (2014) Assessing the twenty-first-century shift in ENSO variability in terms of the Bjerknes stability index. J Clim 27:2577–2587
27. Zheng F, Fang XH, Yu JY et al (2014) Asymmetry of the Bjerknes positive feedback between the two types of El Niño. Geophys Res Lett 41:7651–7657
28. Fang XH, Zheng F, Zhu J (2015) The cloud radiative effect when simulating strength asymmetry in two types of El Niño events using CMIP5 models. J Geophys Res 120:4357–4369
29. Zhang RH, Chao JP (1993) Unstable tropical air–sea interaction waves and their physical mechanisms. Adv Atmos Sci 10:61–70
30. Zheng F, Wang H, Zhu J (2009) ENSO ensemble prediction: initial condition perturbations vs. model perturbations. Chin Sci Bull 54:2516–2523
31. Zheng F, Zhu J (2015) Roles of initial ocean surface and subsurface states on successfully predicting 2006–2007 El Niño with an intermediate coupled model. Ocean Sci 11:187–194
32. Feng LS, Zheng F, Zhu J et al (2015) The role of stochastic model error perturbations in predicting the 2011/12 double-dip La Niña. SOLA 11:65–69
33. Zheng F, Zhu J (2015) An observed splitting eastbound propagation of subsurface warm water over the equatorial Pacific in early 2014. Sci Bull 60:477–482
34. Jin TY, Li JC, Jiang WP et al (2012) Low-frequency sea level variation and its correlation with climate events in the Pacific. Chin Sci Bull 57:3623–3630