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A Note on the Role of Meridional Wind Stress Anomalies and Heat Flux in ENSO Simulations

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ABSTRACT

Four comparative experiments and some supplementary experiments were conducted to examine the role of meridional wind stress anomalies and heat flux variability in ENSO simulations by using a high-resolution Ocean General Circulation Model (OGCM). The results indicate that changes in the direction and magnitude of meridional wind stress anomalies have little influence on ENSO simulations until meridional wind stress anomalies are unrealistically enlarged by a factor of 5.0. However, evidence of an impact on ENSO simulations due to heat flux variability was found. The simulated Niño-3 index without the effect of heat flux anomalies tended to be around 1.0° lower than the observed, as well as the control run, during the peak months of ENSO events.

Key words: ENSO simulation, meridional wind stress, heat flux, OGCM

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1. Introduction

The El Niño-Southern Oscillation (ENSO), as a coupled oscillation phenomenon in the tropical Pacific Ocean, influences the global climate, and so it has evoked much attention. Around thirty years ago, Bjerknes (1969) postulated that ENSO could be explained as a self-sustained cycle based on the coupling between sea surface temperature (SST) and trade winds. Since then, many studies have been carried out to investigate the role of atmospheric wind stress on El Niño (e.g., Wyrtki, 1975; Rasmusson and Carpenter, 1982; Philander, 1990; Zhang and Huang, 1998). It is generally now agreed that zonal wind stress anomalies play the most important role in the occurrence and disappearance of El Niño (Schopf and Suarez, 1988; Philander, 1990; Huang and Zhang, 2001), and thus most of the conceptual or modeling approaches used for ENSO ignore the meridional wind stress component (e.g., Lau, 1981; McCreary and Anderson, 1984; Chao and Chao, 2002).

McCreary (1976) pointed out that meridional wind stress anomalies were not important in ENSO because they could not excite the oceanic Kelvin wave, which was regarded as one of the key dynamic processes in El Niño events. Fang and Yang (2003) indicated that unstable air-sea interactions are dominated by the zonal component of wind stress and ignoring the meridional wind stress is generally legitimate in tropical unstable air-sea interactions. However, no consensus has been reached on the role of meridional wind stress in ENSO (Périgaud et al., 1997; Zhang et al., 2001; Zhang and Zhao, 2001). Périgaud et al. (1997) found that meridional wind stress anomalies played a key role in maintaining finite amplitude inter-annual variability in coupled simulations by using the Zebiak-Cane model (Zebiak and Cane, 1987). Zhang et al. (2001) and Zhang and Zhao (2001) also reported, with observational and dynamical analyses, that preceding meridional wind stress anomalies could be important in the occurrence of El Niño events.

In addition to the thermodynamic effect of wind fields, heat flux through the interface of ocean and atmosphere is another important forcing in driving ocean circulations. Indeed, for the seasonal cycle, even in the equatorial cold tongue in the eastern Pacific, over which dynamical processes substantially control the SST, heat flux also acts as a critical role besides ocean

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mixing processes (Stockdale et al., 1998). While on the inter-annual timescale, it is usually considered that the heat flux plays a minor role (Stockdale et al., 1998). In fact, in many El Niño simulations, even by Ocean General Circulation Models (OGCMs), the inter-annual variability of heat flux is ignored (e.g., Miller et al., 1993; Zhang and Zebiak, 2004; Yu et al., 2001; Zhao et al., 1997). On the other hand, latent heat flux is reduced because of weaker winds in the central Pacific during a warm event, and this is gainful in reinforcing SST warming. Net incoming solar radiation and outgoing longwave radiation through the ocean surface are also changed because of the eastward shift of deep convection during El Niño. Therefore, their combined effects on tropical SST are complex and regionally distinct.

In the present paper, we examine the impacts of meridional wind stress anomalies and heat flux on the inter-annual variability in the tropical Pacific Ocean by using a high-resolution OGCM. The numerical model is briefly described in section 2, together with some observational data used and the experimental design. In section 3, the results of the experiments are compared. Conclusions and remarks are provided in section 4.

2. Model, data and experiments

2.1 *Ocean model*

The ocean model used in this study was first developed by Zhang and Endoh (1992), which has been used for ENSO prediction at the Institute of Atmospheric Physics, the Chinese Academy of Sciences (IAP/CAS) (Zhou and Zeng, 2001). The dynamics of the model are governed by the primitive equations under hydrostatics and the Boussinesq approximation in σ-coordinates with a free surface. The model domain is confined within the tropical Pacific region (30°S–30°N, 121°E–69°W), with realistic land-sea boundaries and a flat bottom. There are 14 vertical levels with a 20 m resolution in the upper 60 m, and a 30 m resolution between 60 m and 240 m depth. To improve its performance, the model has been refined from $1^\circ \times 2^\circ$ to $0.5^\circ \times 0.5^\circ$ (Fu et al., 2005), which can properly resolve the equatorial wave activity. In this paper, the fine resolution version is used. Detailed descriptions of the OGCM can be found in Zhang and Endoh (1992) and Fu et al. (2005).

2.2 *Observational data*

Various observational data are used for driving the ocean model and verifying the results. The momentum forcing is a combination of climatological wind stress from Hellerman and Rosenstein (1983) and the ERA40 wind stress anomalies (Gibson et al., 1997). The surface heat flux is calculated based on the bulk formula, in which the climatologies from SMD94 (da Silva et al., 1994) and anomalies from ERA40 (Gibson et al., 1997), such as shortwave radiation, 2 m air temperature, 1000 hPa specific humidity, wind speed, sea level pressure, and cloud cover, are used. The freshwater flux is taken as a restoring boundary condition by which the model top-level salinity is restored to the WOA01 seasonally varying climatology (Conkright et al., 2002) with a relaxation time of 60 days.

The simulated results are further compared with those taken from a satellite-derived SST monthly product (Smith et al., 1996).

2.3 *Experimental design*

The OGCM, initiated from the WOA01 temperature and salinity fields, is spun up for 50 years with climatological forcing fields to achieve a near-equilibrium seasonal cycle. The subsequent inter-annual experiments are initiated from this climatological run.

To study the role of meridional wind stress anomalies and heat flux in the tropical Pacific inter-annual simulations, four comparative experiments have been conducted, as shown in Table 1. Experiment 1 will be considered as the control run, which includes the impact from both wind stress and heat flux variability. Expteriment 2 was conducted to examine the role of meridional wind stress in the tropical Pacific on the inter-annual timescale by changing the sign of meridional wind stress anomalies. Expteriment 3 was carried out to check the impact of heat flux on El Niño simulation. In this experiment, heat flux was estimated by climatological atmosphere fields and simulated SST, just as in the control run. Another experiment (Expt. 4) was carried out with only zonal wind stress anomalies being realistic (Table 1).

The model was integrated from October 1957 to July 2002 in the four experiments, but only the results from January 1971 to December 2000 are analyzed, and the modeled climatologies are calculated based on the same time period.

3. Results

In this section, we will analyze the modeled results and compare the sensitive experiments with the control run to explore the role of meridional wind stress anomalies and heat flux. Our analysis will focus mainly on SST anomalies.

3.1 *OGCM performance*

Figure 1a shows the simulated Niño-3 index from the control run. The main cold and warm events are

Table 1. Experiments descriptions.

	Zonal wind stress (T_x)	Meridional wind stress (T_y)	Heat flux (heat)
Expt. 1 (Control run)	T_x	T_y	heat
Expt. 2	T_x	$-T_y$	heat
Expt. 3	T_x	T_y	no heat
Expt. 4	T_x	$-T_y$	no heat

captured well by the model, including some unusual cases, such as events during 1991–1995. The correlation and root-mean-square (RMS) error between the control run and observation are 0.935 and 0.371°C, respectively, for the period January 1971 to December 2000.

The point-to-point anomaly correlation and RMS error during 1971–2000 are shown in Figs. 2a and 3a, respectively, showing the overall performance of the OGCM. Note that no filtering has been carried out on the monthly time series before the calculations. Compared to other OGCMs with no impact of heat flux (Miller et al., 1993; Zhang and Zebiak, 2004), our model performs quite well. High correlations ($\geqslant$0.8) are seen over a broad area in the central and eastern Pacific, with large RMS errors ($\geqslant$0.8°C) confined to a much smaller region. These large errors appear in the far eastern equatorial Pacific and along the South American coast, which is common in other OGCM results (Miller et al., 1993; Zhang and Zebiak, 2004). In fact, many OGCMs and coupled models, including our model, simulate lower SST variability in the far eastern Pacific and along the South American coast compared with observations (Fig. 4b vs. Fig. 4a). These biases have been partly ascribed to the model deficiencies in parameterization of entrainment and vertical mixing processes which underestimate the effect of the thermocline on surface temperatures (Syu and Neelin, 2000; Meehl et al., 2001; Zhang and Zebiak, 2004).

3.2 *The role of meridional wind stress anomalies*

The role of meridional wind stress anomalies in ENSO can be seen mainly through comparing Expt. 2 with the control run. Figure 1b shows the Niño-3 index from Expt. 2. Compared to the control run, there seems to be no significant difference. Expteriment 2 captures each warm and cold event, and the correlation and RMS error of the Niño-3 index between Expt. 2 and the observed results are 0.929 and 0.378°C, respectively, which seem only a little lower and larger than those of Expt. 1 (control run). Figures 2b and 3b show the point-to-point anomaly correlations and RMS errors. Compared to the control run, the "unrealistic" treatment of the direction of meridional wind stress anomalies did not degrade the simulation skill too much, except in a narrow region in the far eastern equatorial Pacific where the simulation of Expt. 2 seems just a little worse than the control run. However, in view of the current simulation skill of OGCMs, this difference is insignificant. The case analysis of a strong El Niño event in January 1998 for which the wind stress anomalies were larger supports this conclusion too (Fig. 4b vs. Fig. 4c).

In order to examine the extreme "unrealistic" treatment of meridional wind stress anomalies, another additional three sensitivity experiments were conducted in which the meridional wind stress anomalies were multiplied by 1.5, 2.5 and 5.0, respectively. However, due to the limitation of available computational resources, these three additional experiments were run for 11 years from January 1988 to December 1999. Among these experiments, only the 5.0-run shows a slight difference from the control run. The RMS difference of the Niño-3 index between them is only 0.369°C (Fig. 5). Considering the "unrealistic" large magnification ($\sim$5.0) and the current simulation skill (RMS error for the control run was 0.371°C), the magnitude of meridional wind stress anomaly has little effect on ENSO simulations. In addition, we ran the 5.0-experiment for the period of January 1964 to December 1974 prior to the decadal shift occurring in the late 1970s, and found the results showed no sensitivity to decadal variability (not shown).

When atmospheric inter-annual variability is omitted from the estimation of heat flux absorbed by the ocean, the results regarding the effect of meridional wind stress anomalies on ENSO simulation are unchanged (Fig. 1c vs. Fig. 1d; Fig. 2c vs. Fig. 2d; Fig. 3c vs. Fig. 3d; and Fig. 4d vs. Fig. 4e).

From the above experiments and analyses, the contribution of meridional wind stress anomalies seems negligible in the current model simulation. On the other hand, though some dynamical analyses show that meridional wind stress anomalies have some influence on the occurrence of El Niño (Zhang and Zhao, 2001), comparative analyses indicate that unstable air-sea interactions are dominated by the zonal component of wind stress, and ignoring meridional wind stress is generally legitimate when studying tropical unstable air-sea interactions. However, observational data analyses show that convergent meridional wind stress

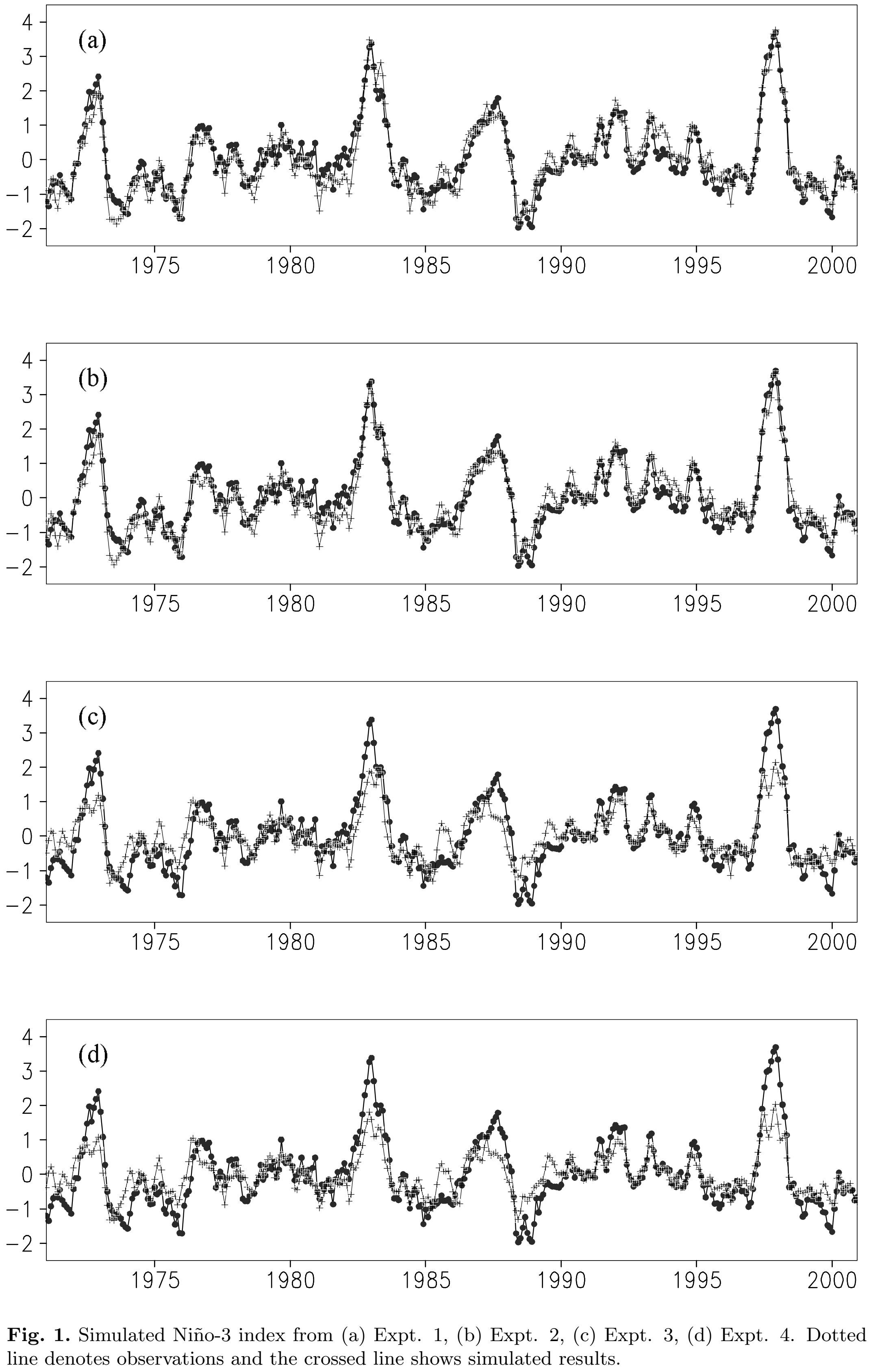

Fig. 1. Simulated Niño-3 index from (a) Expt. 1, (b) Expt. 2, (c) Expt. 3, (d) Expt. 4. Dotted line denotes observations and the crossed line shows simulated results.

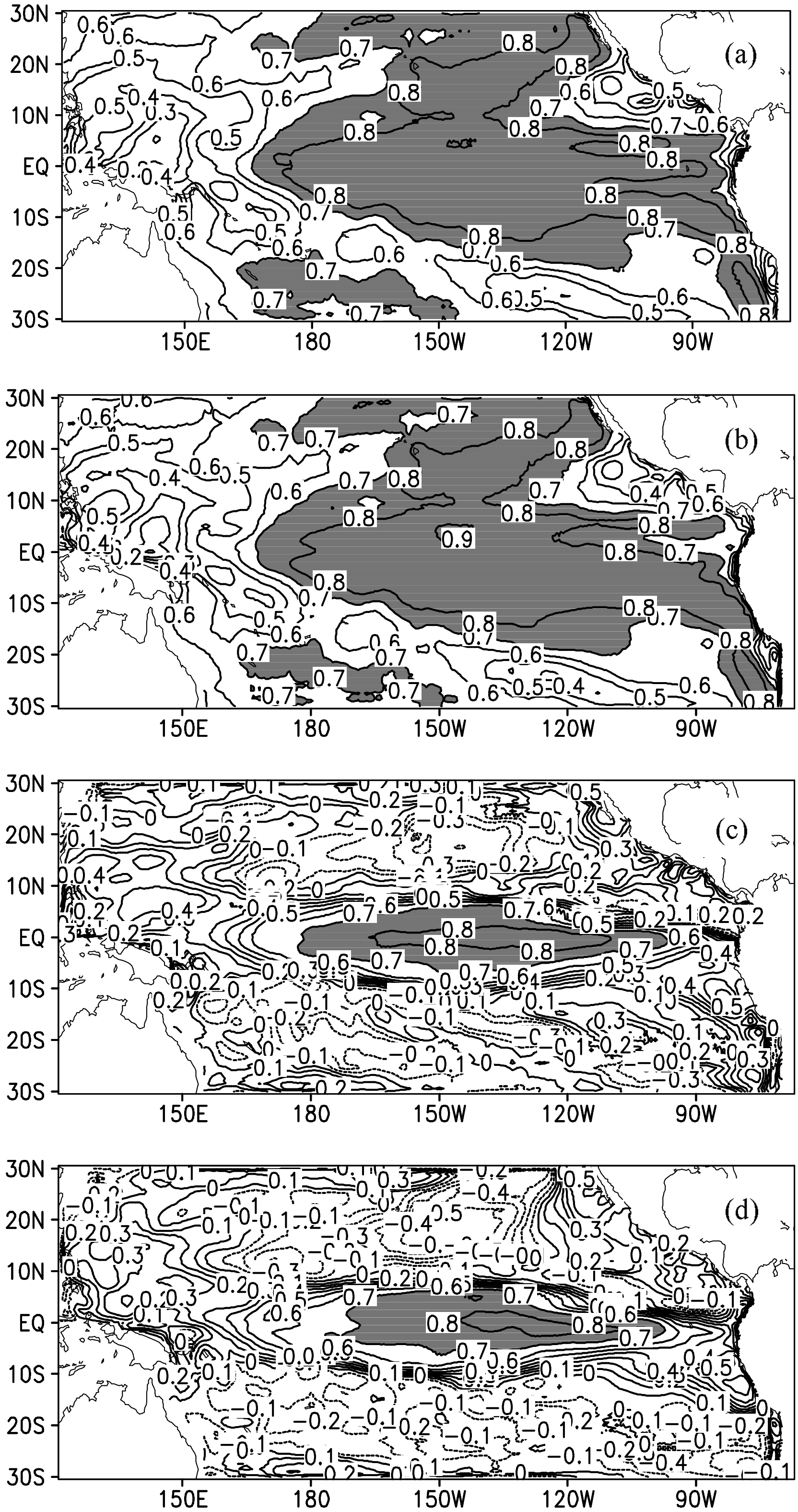

Fig. 2. Correlation for the period 1971–2000 between SST anomalies, observed and simulated, by (a) Expt. 1, (b) Expt. 2, (c) Expt. 3, (d) Expt. 4. The contour interval is 0.1.

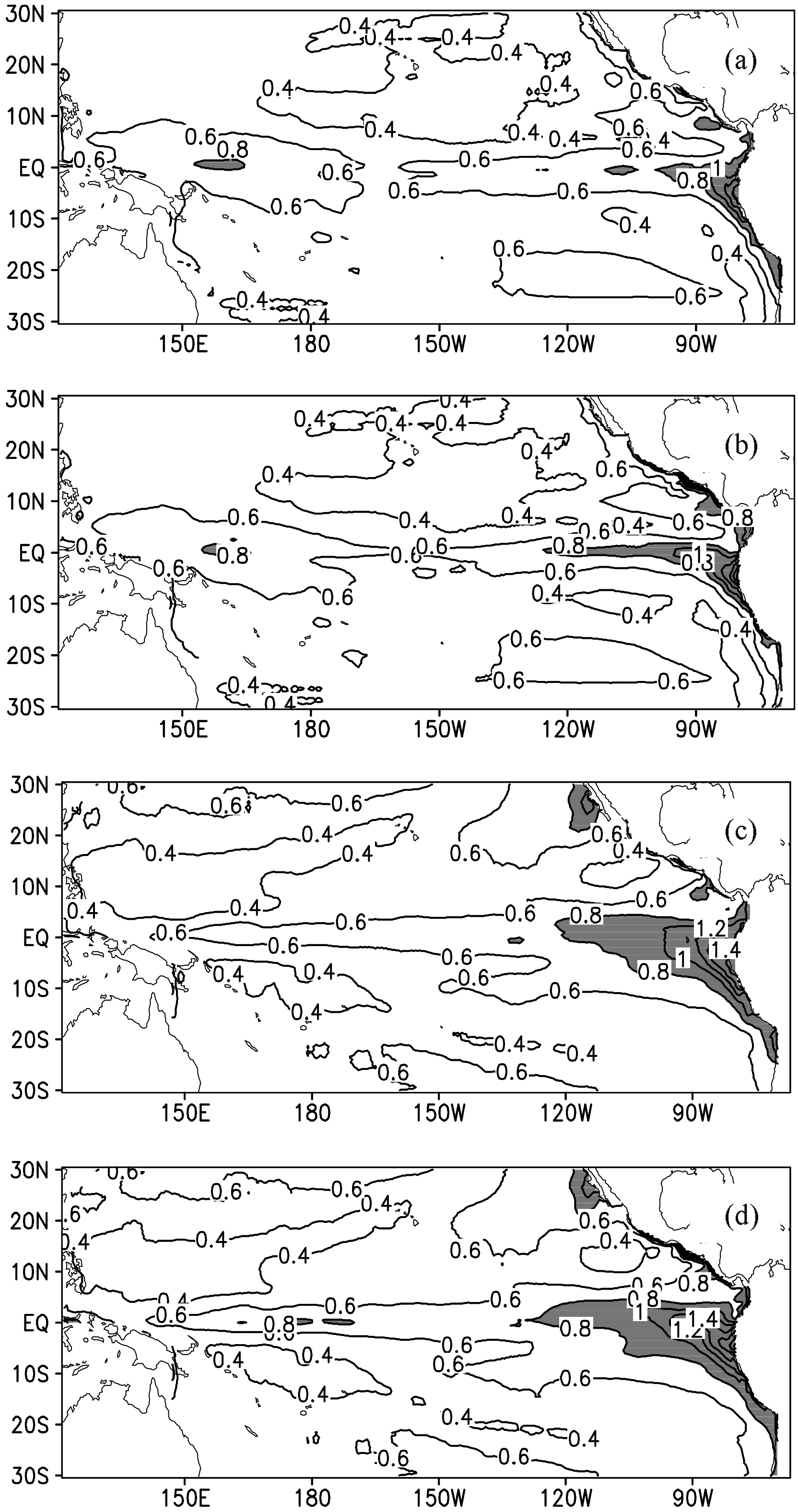

Fig. 3. As in Fig. 2, but for RMS error. The contour interval is 0.2°C.

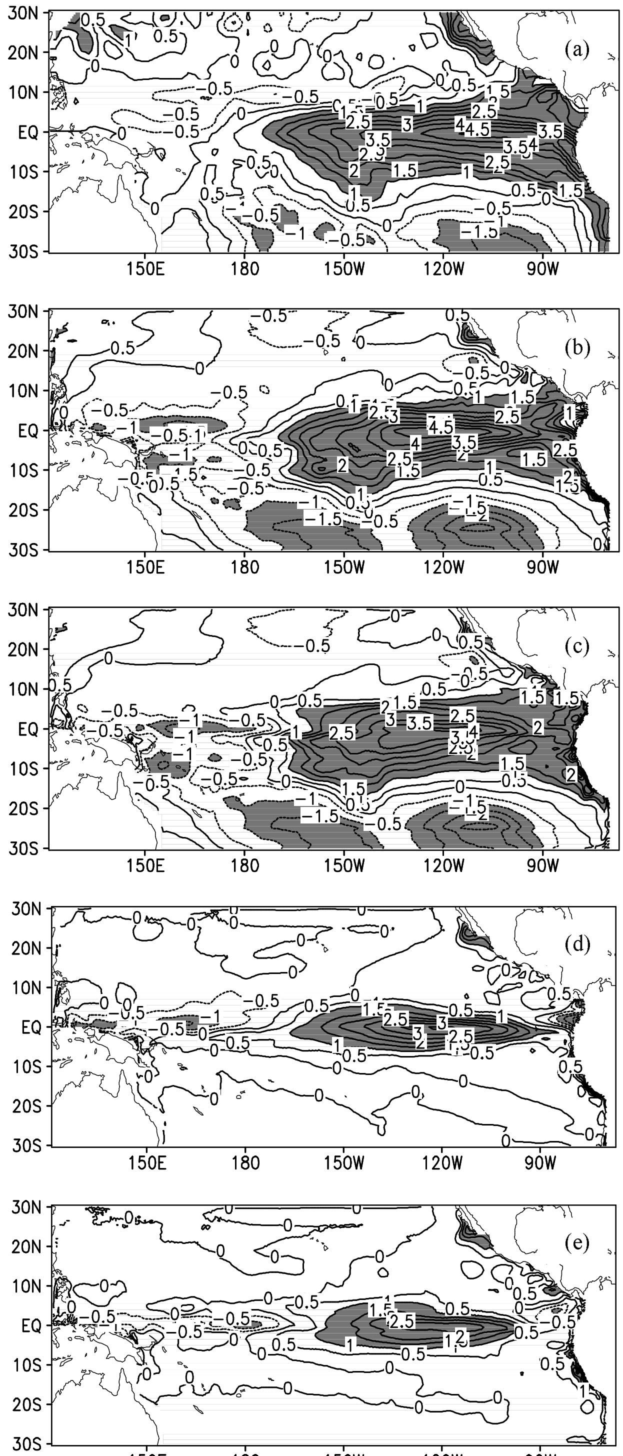

Fig. 4. Horizontal distribution of SST anomalies for January 1998 from (a) observations, and simulations of (b) Expt. 1, (c) Expt. 2, (d) Expt. 3, (e) Expt. 4. The contour interval is 0.5°C.

anomalies in the central and eastern equatorial Pacific are significantly correlated with the El Niño events (Zhang et al., 2001). All these results demonstrate that convergent meridional wind stress anomalies may just be a response to zonal wind stress variability, and thus cannot contribute to the occurrence of El Niño. In a word, the meridional wind stress anomalies may play only a "tail" role in ENSO.

3.3 *The role of heat flux*

In this section, we provide an analysis of the role of heat flux in ENSO simulations by comparing Expt. 3 with Expt. 1. As mentioned in Section 1 (Introduction), most simulations of ENSO used to omit the role of heat flux, which is partly due to the unavailability of credible long-term flux data and the notion that El Niño is the dynamical response to surface wind stress (Stockdale et al., 1998). Now, some reanalysis datasets (e.g., ERA40) give us a chance to check the role of heat flux in ENSO simulations.

Figure 1c shows the simulated Niño-3 index from Expt. 3. It is clear that most warm/cold events can be simulated by the model even when driven only by surface wind stress anomalies. However, it is also quite striking that there are obvious differences between the simulated results of Expt. 3 and Expt. 1 (control run). Compared to the control run, the Niño-3 index from Expt. 3 shows less variability. The magnitudes of SSTA are ~1.0°C lower than in the control run at the peak of strong events, e.g., 1972/73, 1982/83 and 1997/98 El Niños, and the 1988/89 La Niña. Correlation between simulated and observed results decreased to 0.852 and RMS error increased to 0.573°C.

From the point-to-point anomaly correlation and RMS error figures (Figs. 2c and 3c), this model performs better than, or at least comparable to, other OGCMs if the heat flux effect is not fully included (Miller et al., 1993; Zhang and Zebiak, 2004). Compared to Expt. 1 (control run), the simulation skills decrease dramatically off the equatorial waveguide region, where the correlation turns negative, which indicates that the dynamical processes are dominant in SST variability only within the equatorial waveguide of the central and eastern Pacific, and the heat flux variability plays a vital role off the Equator. The simulation skills are also degraded even over the waveguide region, although it is not as significant as off the Equator: the correlation value decreased by about 0.1, and RMS error over the far eastern Pacific increased by about 0.2°C.

The above analysis can also be revealed by the case of a mature, intense El Niño in January 1998 (Fig. 4d). The SST variability in the southern subtropical Pacific disappeared and the SSTA in the eastern Pacific was weaker than the observations (Fig. 4a) and the control

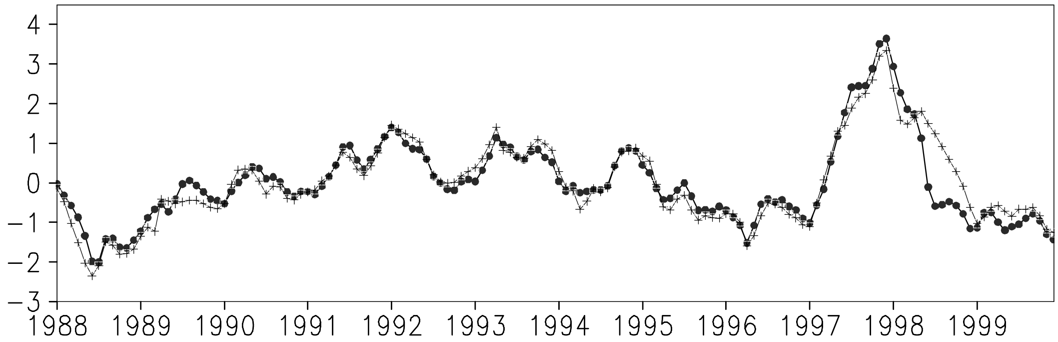

Fig. 5. Simulated Niño-3 index from the control run (dotted line) and the sensitive experiment (crossed line) in which the meridional wind stress anomalies are multiplied by 5.0.

run (Fig. 4b) by about 1.0°C.

4. Conclusions and remarks

In this paper, we have examined the role of the meridional wind stress anomalies and heat flux variability in ENSO simulations using a high-resolution OGCM. Four comparative experiments were carried out for the period of October 1957 to July 2002 and the results from January 1971 to December 2000 were analyzed.

The comparisons have shown that meridional wind stress anomalies seem to play a minor role in ENSO. When the direction of meridional wind stress anomalies was reversed, there was no significant difference from the control run. Furthermore, we carried out another three experiments to check the magnitude of meridional wind stress anomalies in ENSO simulations in which the meridional wind stress anomalies were multiplied by 1.5, 2.5 and 5.0, respectively. These experiments indicated that the magnitude of meridional wind stress anomalies also had little effect on ENSO simulations, unless it reached "unrealistically large" (>5.0). In fact, some results regarding the importance of meridional wind stress anomalies on ENSO seem too sensitive to the model's specified parameters. For example, Périgaud et al. (1997) pointed out in their paper that the key role of meridional wind stress anomalies in ENSO oscillations is only found in the Zebiak-Cane model with its standard parameterization, and a small change of some parameters, e.g. with a drag coefficient 20% stronger or with thermodynamic damping decreased from 125 d^{-1} to 250 d^{-1}, would reconstruct an oscillatory regime.

Heat flux, on the other hand, through comparative experiments, showed an overwhelming importance in SST variability off the equatorial waveguide. The correlations of long-term simulation turned to negative from above 0.6 poleward of 10°N(S) when atmospheric inter-annual variability was omitted in the heat flux computation. Even over the equatorial waveguide, the heat flux variability also showed an impact on SST variability to a certain extent. When heat flux variability was not fully under consideration, the simulated Niño-3 index was lower by ~ 1.0°C at the peaks of intense events, and its correlation/RMS error for long-term simulation decreased/increased from 0.935/0.371°C to 0.852/0.573°C.

When only zonal wind stress anomalies were adopted as driving, the model captured the main warm/cold events, similar to the result of fully considering the momentum forcing, but the high skills are just within the equatorial waveguide in the central and eastern Pacific.

From the viewpoint of the ocean, ENSO is described as the dynamical response of the upper ocean, including the thermocline, to atmospheric forcing. Therefore, zonal wind stress anomalies are of first-order importance since they can excite the oceanic Kelvin and Rossby waves which control the anomalous signals' propagations in the tropical Pacific (Schopf and Suarez, 1988). Near the surface, however, SST variability is controlled not only by oceanic dynamics, but also by heat exchanges between atmosphere and ocean influencing the heat storage of the upper ocean. Thus heat flux can also play an important role in SST anomalies, especially in regions where dynamical processes are relative weak, e.g. off the equatorial waveguide. It is interesting that the impact of meridional wind stress anomalies seems insignificant from the experiments in this paper. This is consistent with some theoretical results, but disagrees with some other studies (Zhang et al., 2001; Zhang and Zhao, 2001). Nevertheless, it needs to be mentioned that this conclusion is obtained from uncoupled OGCM simulations with wind stress anomalies being specified. Thus the interaction between ocean and atmosphere might not be properly described. Further investigations are certainly warranted, including examining the sensitivity and dependence of models, exploring the relationship between zonal and meridional wind anomalies etc.

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