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ENSO Amplitude Change in Observation and Coupled Models

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ABSTRACT

Observations show that the tropical El Niño-Southern Oscillation (ENSO) variability, after removing both the long term trend and decadal change of the background climate, has been enhanced by as much as 60% during the past 50 years. This shift in ENSO amplitude can be related to mean state changes in global climate. Past global warming has caused a weakening of the Walker circulation over the equatorial Indo-Pacific oceans, as well as a weakening of the trade winds and a reduction in the equatorial upwelling. These changes in tropical climatology play as stabilizing factors of the tropical coupling system. However, the shallower and strengthening thermocline in the equatorial Pacific increases the SST sensitivity to thermocline and wind stress variabilities and tend to destabilize the tropical coupling system. Observations suggest that the destabilizing factors, such as the strengthening thermocline, may have overwhelmed the stabilizing effects of the atmosphere, and played a deterministic role in the enhanced ENSO variability, at least during the past half century. This is different from the recent assessment of IPCC-AR4 coupled models.

Key words: ENSO variability, global warming, thermocline, Equatorial Pacific

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1. Introduction

El Niño-Southern Oscillation (ENSO) is the most important climate phenomenon in the tropical Pacific that can significantly affect the global climate. The ENSO properties have undergone significant climate shifts in the paleoclimatic timescale (Cole, 2001; Tudhope et al., 2001). It is changing in the current climate (e.g., Trenberth and Hoar, 1996) and is likely to shift substantially in a future, warmer climate. One of largest debates is whether the ENSO properties are related to the changes in background climate. Some studies on the high resolution fossil-coral record suggest a poor relationship between ENSO activity and the mean climate during the last millennium, and the ENSO behaviour has a board range that may arise from dynamics internal to the ENSO system itself (Cobb et al., 2003).

Studies on the past century's observations suggest that judging whether the ENSO is shifting or not depends on how we view the background climate. The tendency for more El Niño and less La Niña events is clear since the late 1970s if the background climate is viewed as constant (Trenberth and Hoar, 1996). When considering the decadal change of the tropical Pacific background climate, the El Niño and La Niña still occur alternatively and their amplitudes are comparable (Fedorov and Philander, 2000). These raise concerns on the uncertainty of assessing ENSO changes in a future climate.

Recently, ENSO behaviours in an enhanced greenhouse gas (GHG) scenario of the IPCC-AR4 coupled models have been examined (eg., Philip and van Oldenborgh, 2006; Guilyardi, 2006; Merryfield, 2006; van Oldenborgh et al., 2005; Meehl et al., 2006). A large study suggests, however, that it would cause significant changes in the global mean climate, and that future global warming has little impact on the ENSO properties (Philip and van Oldenborgh, 2006; Guilyardi, 2006; van Oldenborgh et al., 2005; Zelle et al.,

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2005), because the destabilizing and stabilizing factors of the atmosphere and ocean compensate for each other. Some studies show that the significance of the ENSO amplitude reduction in CO_2 increasing experiments depends on the extent of the change in the mean state or the strength of the external forcing (Meehl et al., 2006). A validity check on future climate simulations via past observations is still needed.

Consistent with the persistent increase of atmosphere greenhouse gases (GHGs), the earth climate has warmed in the past century (e.g., Levitus et al., 2005). In this study we re-examine the observed ENSO amplitude in the warming background and compare this with some IPCC-AR4 coupled model results. Observations show that the shift (increase) in ENSO amplitude is significant, especially in the past 50 years. We conclude that the impact of global warming on ENSO properties can not be neglected. The mean state change in the ocean may play a more important role in determining the long-term change in ENSO behaviours.

2. Data and models

Observational ocean datasets used in this study include (1) the Met Office Hadley Centre's monthly sea ice and sea surface temperature (SST) dataset (HadISST) spanning the period from January 1870 to June 2006 (Rayner et al., 2003); (2) the monthly upper ocean temperature dataset from the Joint Environmental Data Analysis Center (JEDAC-XBT), the Scripps Institute of Oceanography spanning the period 1955–2003; and (3) the yearly ocean temperature dataset (0–700 m) from the National Oceanographic Data Center (NODC) spanning the period 1955–2003 (Levitus et al., 2005).

The model datasets used here are from the IPCC-AR4 coupled models GFDL-CM2.1 and NCAR-CCSM3.0. The modelled present-day climate is from the GFDL-CM2.1 "Climate of twentieth century" (20c3m) ensemble experiments (run1–run5). For the future climate we use "1% increase per year to doubling" (1pctto2x) experiments from GFDL-CM2.1 and NCAR-CCSM3.0, for which the control runs are the pre-industrial control (picntrl) and present-day (1990) control, respectively.

The temperature anomaly discussed in this study is obtained as follows. First, the mean seasonal cycle of each dataset is removed. Second, the secular linear trend is subtracted. Third, a band-pass filter of 5–85 months (for monthly data) or 1–7 years (for annual data) is further applied so that the resultant variabilities only contain ENSO timescale information. Both the high-frequency variability and the decadal fluctuation of the background state have been excluded. For model datasets, the ensemble mean is first obtained before the calculation of the anomalies and standard deviations.

3. Observed changes in ENSO amplitude and mean states

The temporal evolution of SST anomaly over the Niño-3 region shows an amplifying variability in the past 50 years (Fig. 1a). The standard deviation of Niño-3 SST reaches the minimum (0.6°C–0.7°C) during the 1940s, while it increases to around 0.9°C–1.0°C during the past two decades, showing a nearly 50%–60% increase in the ENSO variability (Fig. 1b). This increase passes the student t-test of 95% significant level, although the change in the standard deviation does not appear as a smooth increase and exhibits some decadal variability. The rising trend is robust and consistent in different datasets (Fig. 1b). Besides the surface, the standard deviation of the subsurface temperature anomaly also shows a robust rising trend.

It is worth noting that the temperature variability studied here has been applied with a band-pass filter, which excludes both the long-term trend and the decadal variation of the background. Without this kind of filter, the tropical variability clearly shows a more and stronger (less and weaker) El Niño (La Niña) situation in the past two decades (Trenberth and Hoar, 1996). The decadal variation of the tropical climate has considerable positive contribution to the ENSO variability as shown in Fedorov and Philander (2000). Here we show that even when this positive contribution is removed, the amplitude of the ENSO variability still exhibits a robust rising trend. This is not explicitly pointed out in previous studies.

Should the enhanced ENSO variability be attributed to the dynamics internal to the ENSO system itself (Cobb et al., 2003) or the mean global climate change? It is unlikely to provide a deterministic answer merely based on the past short observations. However, the combined observational and modelling studies do show that the global climate change, for example the weakening Walker circulation and the trade winds, can be only attributed to anthropogenic forcing, instead of natural variabilities (Vecchi et al., 2006). Here, we are inclined to relate the enhanced ENSO variability to mean climate change.

The enhancing ENSO in the present climate is consistent with the strengthening thermocline along the equator (Fig. 2b). During the past 50 years, the warming rate of SST is generally over 1°C $(100\ \mathrm{yr})^{-1}$ in the tropics; it reaches 1.5°C $(100\ \mathrm{yr})^{-1}$ in the eastern equatorial Pacific. This big surface warming, however,

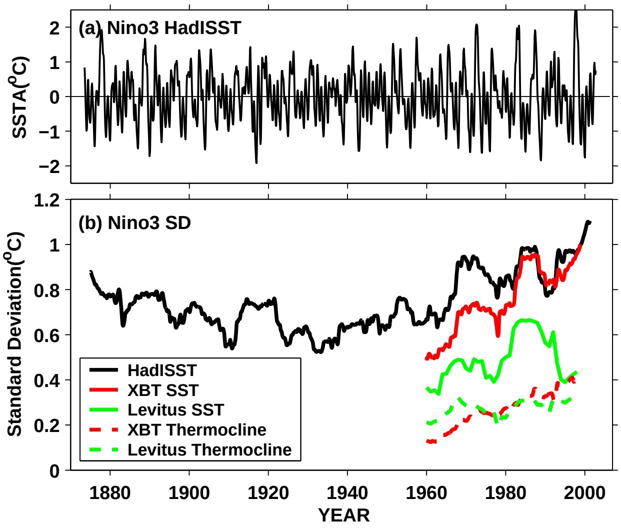

Fig. 1. Time series of (a) SST anomaly from HadISST2 (1870–2006) averaged over Niño-3 region (5°S–5°N, 150°W–90°W), and (b) Standard deviations of Niño-3 SST anomalies from HadISST (black), JEDAC-XBT (red, 1955–2003) and Levitus (green, 1955–2003), and standard deviations of Niño-3 temperature anomalies averaged between 40–400 m from JEDAC-XBT (red dashed) and Levitus (green dashed). The temperature anomalies have been detrended and band-pass filtered. The standard deviations are calculated from temperature anomalies by applying a low-pass filter with a sliding window of 10 years wide.

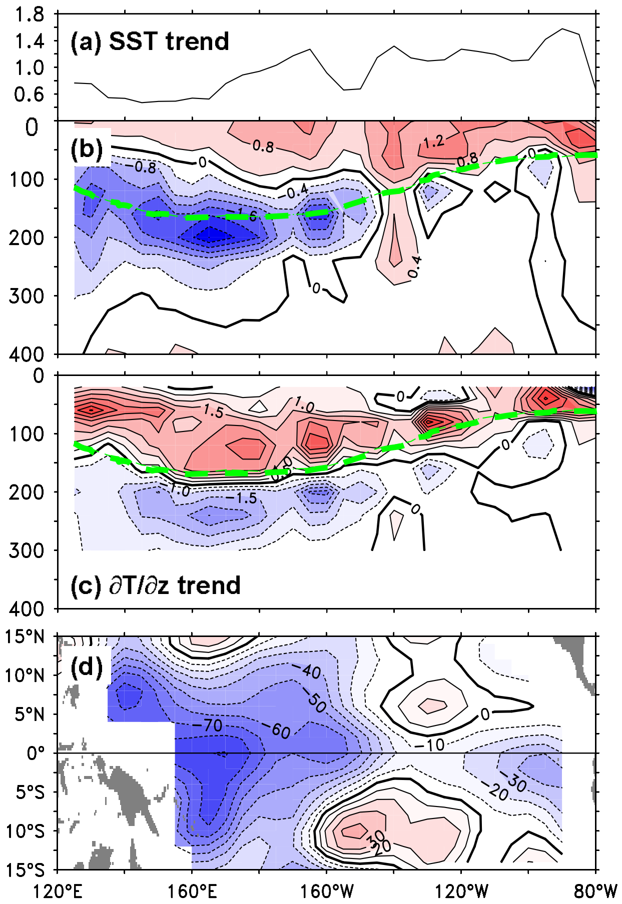

Fig. 2. Linear trends of (a) SST [°C $(100\ \mathrm{yr})^{-1}$], (b) the upper ocean temperature [°C$(100\ \mathrm{yr})^{-1}$], (c) the vertical temperature gradient $\partial T/\partial z$ [°C$(100\ \mathrm{m})^{-1}(100\ \mathrm{yr})^{-1}$] averaged between 5°S–5°N, and (d) the equatorial thermocline depth anomaly Z_{tc}[m $(100\ \mathrm{yr})^{-1}$] from JEDAC-XBT, over the period 1955–2003. Z_{tc} is calculated as the location of the maximum vertical temperature gradient. The dashed thick green line in (b) and (c) represents the mean thermocline depth.

does not appear to penetrate downward into the thermocline, where a cooling trend occurs. The cooling rate in the western Pacific reaches as much as −2°C $(100\ \mathrm{yr})^{-1}$. Although the cooling rate in the eastern thermocline is not as significant as that in the west, the overall vertical temperature gradient is enhanced substantially during the past 50 years (Fig. 2c). Many coupled models have indicated a general increase of interannual variability with enhanced thermocline strength, or an increased vertical temperature contrast ΔT across the thermocline (e.g., Meehl et al., 2001; Collins, 2000; Timmermann et al., 1999). The argument is that for a large ΔT, even relatively small perturbations in the system can change the temperature of the entrained water much more efficiently (Munnich et al., 1991). It appears that there is an increase in the sensitivity of SST to the thermocline strength.

The cooling trend in the western thermocline may result from both the equatorial and off-equatorial processes. The weakened trade winds cause the flattening of the east-west thermocline slope (we will return to this later), resulting in an upward movement of the deeper colder water. This may involve equatorial wave processes that span the width of the basin. The off-equatorial cold Rossby waves could also propagate westward and southward along the mean potential vorticity contours cooling the western equatorial thermocline (Yang et al., 2005). The less cooling trend in the eastern thermocline may result from two opposite effects. The weakened trade winds favor a warming of the eastern thermocline because of a weakened cold water upwelling, while the cooling in the west could propagate eastward along the thermocline and result in cooling there. In general, the discussion above is highly speculative and a detailed check on the mechanisms through numerical models is needed. Coupled models forced by increasing GHGs have simulated the cooling thermocline in the equator (Timmermann et al., 1999). Some IPCC-AR4 simulations also show the cooling thermocline (see next section).

Note that the SST trend along the equator in the past 50 years shows an El Niño-like pattern (Fig. 2a). Controversies exist for the trend pattern of the historical SST observations, which could differ substantially among different datasets and for different time periods (Liu et al., 2005). This El Niño-like pattern is robust for all observations over the past 50 years. The importance of the east-west SST contrast along the equator shows that it could affect the ENSO variability. Some studies show that the enhanced zonal SST contrast (i.e., the La Niña-like pattern) acts as a destabilizing effect on the coupling, and favors a stronger ENSO (Sun et al., 2004), while the weakened SST contrast (i.e., the El Niño-like pattern) acts as a stabilizing effect and favors a weaker ENSO. However, sensitivity experiments using fully coupled models suggest that the relationship between the zonal SST contrast and ENSO amplitude is not necessarily straightforward (Meehl et al., 2001), because different radiative forcings can affect the zonal SST contrast without notable changes in ENSO amplitude (Meehl et al., 1993).

The weakened trade winds mentioned above are evident in reconstructed observations and coupled models. They are due to the weakening Walker circulation (see details in Vecchi et al., 2006; Vecchi and Soden, 2007). On one hand, a slowdown of Walker circulation would result in a more stable equatorial atmosphere and stabilize the tropical atmosphere-ocean coupling system (Vecchi et al., 2006; Meehl et al., 2001; Neelin et al., 1992), which would result in the suppression of the ENSO variability. This has been confirmed by sensitivity studies of linear and coupled models (Fedorov and Philander, 2001; Meehl et al., 2001). On the other hand, consistent with the change in trade winds, the ocean exhibits a substantial shoaling trend in the western equatorial Pacific thermocline depth ($Z_{\rm tc}$) in the last 50 years (Fig. 2d). The shoaling trend of $Z_{\rm tc}$ is moderate in the eastern Pacific. Figure 2d clearly shows the reductions in both the east-west tilt of the equatorial Pacific thermocline and its mean depth, which implies an increase in SST sensitivity to the thermocline, especially in the Niño-3 region. This can be understood as follows. The shoaling trend of $Z_{\rm tc}$ in the equatorial Pacific suggests that the local mode or SST mode, resulting from local SST-wind interaction in the central-east Pacific, may play a relatively important role in generating ENSO variability (Fedorov and Philander, 2001; Guilyardi, 2006). This local mode corresponds to the anomalous upwelling of the mean temperature gradient ($-w'\overline{T}_z$) in the SST equation. A shallower $Z_{\rm tc}$ means the thermocline water would be easier to affect the SST through the anomalous upwelling (w'). A stronger thermocline ($\overline{T}_z$) means a bigger impact on SST. Here, the w' is closely related to the local wind variability and bridges the mean thermocline with the SST variability. The observations show that the mean SST increases the most in Niño-3 region (Fig. 2a), where an increased wind response to SST variability is expected (Philip and van Oldenborgh, 2006). Therefore, the shallower and stronger thermocline could result in an enhanced ENSO variability, because of the positive feedback among the wind variability, anomalous upwelling and SST variability in the central-east Pacific. In general, the observational facts suggest that the destabilizing factor of the enhanced equatorial thermocline overwhelms the stabilizing factor of weakened trade winds and thus leads to an elevated ENSO variability in the past 50 years.

4. Modelled changes in ENSO amplitude and mean states

The coupled model simulations of 20th century climate show a mild increase in ENSO amplitude since the 1940s (Fig. 3a). Here we examine the "20c3m" ensemble experiments (run1-run5) from GFDL-CM2.1. The standard deviation of Niño-3 SST anomaly during the period of 1970–2000 is about 1.2°C, nearly 20% larger than that (1.0°C) during 1920–1950 (Fig. 3a). This increase is less significant than that in observations (Fig. 1b). However, the linear trend of the equatorial thermocline is quite similar to the observations (Fig. 3d). An enhancing thermocline is reproduced in the model: the SST has a warming trend while the thermocline temperature has a cooling trend. This favors a stronger ENSO. The destabilizing effect of the enhanced thermocline does not seem to be completely compensated for by some stabilizing effect of the atmosphere as discussed in Philip and van Oldenborgh (2006).

The coupled model simulations on a future warming climate also show a weak increase in ENSO amplitude. The standard deviations of the Niño-3 SST anomaly in 1pctto2x runs of GFDL-CM2.1 and CCSM3.0 are 1.2°C and 0.8°C, respectively, while the corresponding values in their control runs are 0.9°C and 0.7°C (Figs. 3b and 3c). These small changes in ENSO amplitude are not significant. Here we use the data from year 1 to 70 of the 1pctto2x runs to derive the mean standard deviation in the transient period, and the data from year 300 to 500 of GFDL-CM2.1 control and year 400 to 600 of CCSM3.0 control to derive the reference standard deviation.

The future change in ENSO amplitude is also con-

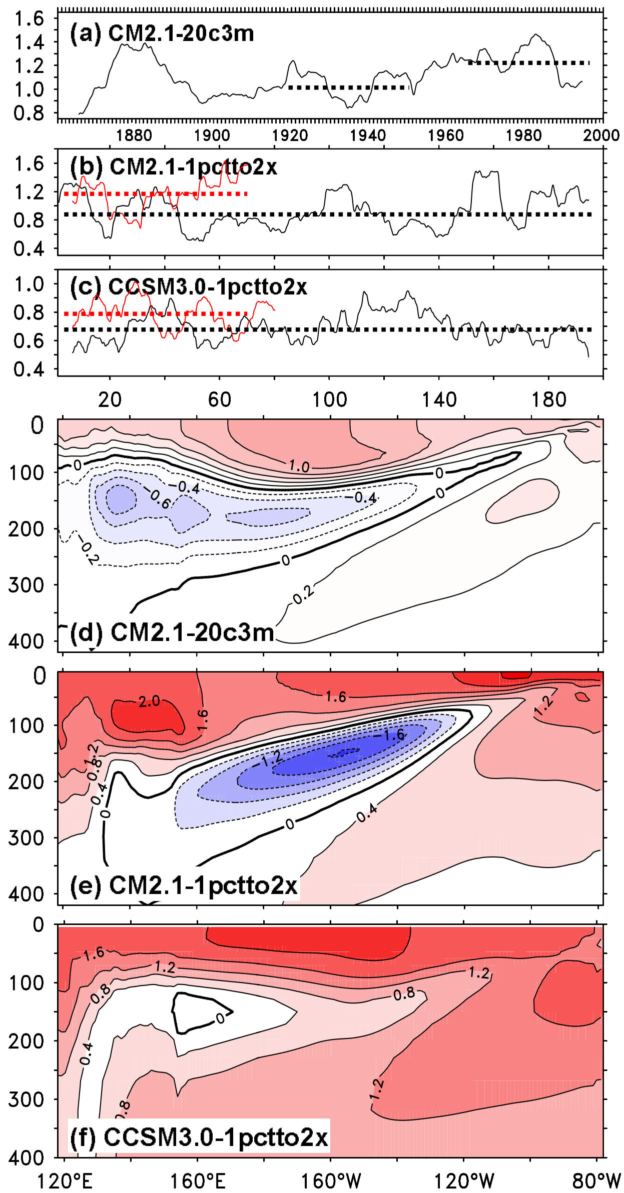

Fig. 3. Time series of standard deviations (°C) of Niño-3 SST anomaly for (a) GFDL-CM2.1 "20c3m" ensemble experiments, (b) GFDL-CM2.1 and (c) NCAR-CCSM3.0 control runs (black) and "1pctto2x" runs (red). Linear trends [°C $(100\ \text{yr})^{-1}$] of the upper ocean temperature averaged between 5°S–5°N for (d) GFDL-CM2.1 "20c3m" ensemble experiments over 1940–2000, and for (e) GFDL-CM2.1 and (f) NCAR-CCSM3.0 "1pctto2x" runs over year 1–70. The dashed lines in (a) represent the mean standard deviation for period 1920–1950 and 1970–2000, respectively. The dashed lines in (b) and (c) represent the mean standard deviation for the period considered.

sistent with background thermocline change in the equator. An enhanced thermocline is evident in both models (Figs. 3e and 3f). There are also some differences in the temperature trend between models. The maximum SST trend in GFDL-CM2.1 is located in the eastern Pacific while that in CCSM3.0 is in the central Pacific. Compared with CCSM3.0 (Fig. 3f), the GFDL-CM2.1 has a much stronger cooling trend in the thermocline (Fig. 3e), which is responsible for the larger ENSO change in the GFDL-CM2.1 than in the CCSM3.0. It appears that the enhancing thermocline plays an important role in determining the ENSO properties in these experiments.

5. Summary and discussion

The amplitude of ENSO variability has increased by as much as 60% in the past 50 years. This can be attributed to the enhanced thermocline in the equatorial Pacific, which plays as a destabilizing effect on the tropical coupling system. The comparison between the observations and coupled model simulations indicate that the selected models in this study are capable of providing a reasonable simulation of the ENSO property shift in the past and future climate. However, due to the difficulty in downloading the huge amount of IPCC-AR4 datasets through the internet, we are unable to check the ENSO behaviours in other coupled models. Many recent studies on IPCC-AR4 data have concluded that global warming has little impact on ENSO (e.g., van Oldenborgh et al., 2005; Merryfield, 2006; Guilyardi, 2006). The observations suggest we should be very prudent on the model. It might be necessary to reassess the capability of coupled models in modelling the ENSO behaviours in a future climate.

This study is not necessarily in contradiction with the prediction of a weaker ENSO in a future warmed climate (e.g., Meehl et al., 2006). Due to the large thermal inertia of ocean, the tropical SST always warms much faster than the subsurface ocean. This will result in a strengthening equatorial thermocline, and thus an amplified ENSO variability during the transient period of global warming. However, for the equilibrium response to global warming, the subsurface ocean will finally warm up, which could in turn reduce the vertical temperature gradient and result in a weakening of ENSO variability. The atmospheric processes may always have a stabilizing effect on the ENSO variability during the whole warming period due to their fast responses to external forcings. The ocean, therefore, appears to play as a deterministic role in the long term changes of ENSO variability.

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