A Regulatory Effect of ENSO on the Time-Mean Thermal Stratification of the Equatorial Upper Ocean

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Abstract

To investigate the role of ENSO in regulating the time-mean thermal stratification of the equatorial Pacific, perturbation experiments are conducted in pairs with a coupled model. In one experiment, ENSO is turned off while in the other experiment ENSO is kept on. Perturbations are introduced through either enhancing tropical heating or increasing subtropical cooling. In the absence of ENSO, the time-mean difference between the warm-pool SST (Tw) and the characteristic temperature of the equatorial thermocline (Tc) responds sensitively to either enhanced tropical heating or enhanced subtropical cooling. In the presence of ENSO, such a sensitivity to destabilizing forcing disappears. The lack of sensitivity in the response of Tw-Tc is linked to a stronger ENSO in response to the destabilizing forcing. ENSO in the model acts as a basin-scale heat "mixer" that enables surface heat to be transported to the depths of the equatorial thermocline. The study raises the question whether models with poor simulations of ENSO can give reliable predictions of the response of the time-mean climate to global warming.

1. Introduction

The dependence of ENSO on the stability of the time-mean state of the coupled tropical Pacific ocean-atmosphere has been extensively studied (Neelin et al. 1998). Whether ENSO in turn contributes to the maintenance of the stability of the time-mean climate is less well understood. In this connection, a question of particular interest is the effect of ENSO on the time-mean upper ocean thermal stratification of the equatorial Pacific, namely, the time-mean difference between the warm-pool SST (Tw) and the characteristic temperature of the equatorial undercurrent (Tc). The difference between Tw-Tc is a key parameter that measures the stability of the coupled tropical Pacific ocean-atmosphere(Jin 1996, Sun 1997). Note that through upwelling, this difference controls the zonal SST contrast and therefore the strength of the zonal winds. It has been suggested that the time-mean climate state of the coupled tropical Pacific ocean-atmosphere hovers closely around its neutral point (Penland and Sardeshmukh 1995, Penland et al. 2000). What prevents the time-mean coupled system from becoming substantially unstable? Could it be ENSO?

A role of ENSO in regulating the stability of the time-mean state of the coupled system has been suggested by recent analysis of the role of ENSO in the heat balance of the tropical Pacific (Sun 2000, Sun 2003, Sun et al. 2004). What destabilizes the coupled tropical ocean-atmosphere system is the meridional differential heating. Tropical heating tends to increase the SST of the warm-pool

(Tw). Subtropical cooling tends to reduce the temperature of the equatorial thermocline (Tc) as the cooling can be extended to the equatorial subsurface through subduction (Shin and Liu 2000, Sun et al. 2004). If ENSO corresponds to a mechanism of downward and poleward heat transport, there is a good chance that ENSO may play a role in stabilizing the time-mean state of the coupled tropical Pacific ocean-atmosphere system. The reasoning here is similar to the reasoning that has led to the hypothesis that the neutrality of the time-mean thermal structure of the tropical troposphere to moist convection is due to moist convection (Xu and Emanuel 1989). (As radiative heating of the surface and cooling of the interior of the atmosphere destabilize the atmosphere, moist convection takes place to deliver heat from the surface to the free troposphere. Consequently, the mean lapse rate is strongly regulated).

Whether the analogy with the relationship between moist convection and the lapse rate of the tropical troposphere is entirely pertinent to the relationship between ENSO and the value of Tw-Tc, it appears to be appealing enough to test this hypothesis that ENSO may play a fundamental role in regulating the stability of the time-mean state of the coupled tropical Pacific ocean-atmosphere, the long-term mean value of Tw-Tc in particular. The purpose of this paper is to report the results from a group of numerical experiments that were especially designed to test this hypothesis. A hallmark of ENSO is the zonal “sloshing” of water in the equatorial upper Pacific (Philander 1990). So from a pure phenomenological perspective, it is of interest to investigate the effect of the recurrent occurrence of ENSO on the time-mean upper ocean temperature structure.

This paper is organized as follows. First, the methodology is briefly described in section 2. Section 3 presents the results. Summary and discussion are provided in section 4.

2. Methodology

Our method to test this hypothesis is through conducting numerical experiments in pairs with a coupled model. In one experiment, ENSO is turned off. We turn off ENSO in the model by setting the coupling coefficients between the SST and surface winds in the equatorial region to zero. In the other experiment, ENSO is kept on. We then contrast the differences in the response in the time-mean climate, the difference between Tw and Tc in particular as it determines the stability of the time-mean climate.

The perturbation takes the form of either increased radiative heating over the tropics or increased radiative cooling over the subtropics. For reasons mentioned in the introduction, changes like these tend to increase the difference between Tw and Tc and thereby tend to destabilize the coupled climate system.

The model is the one used in Sun (2003) and Sun et al. (2004). The model has the NCAR Pacific basin model (Gent and Cane 1989) as its ocean component. Thus the model calculates the upper ocean temperatures based on the first principles. This feature is in contrast with the intermediate ocean models used in the pioneering studies of ENSO (Neelin et al. 1998). (Intermediate ocean models do not have a heat budget for the subsurface ocean). The parameterizations of the net surface heat flux and zonal wind stress in the present model are in line with those used in previous theoretical studies of ENSO and tropical climatology (Neelin et al. 1998). Specifically, the net surface heat flux into the ocean is proportional to the difference between the radiative convective equilibrium SST and the actual SST, and the anomalous equatorial zonal wind-stress is proportional to the anomalous equatorial zonal SST gradients (see Eq. (1) and Eq. (2) in Sun et al. 2004). These parameterizations are supported by observations (Neelin et al. 1998, Sun and Trenberth 1998). The model simulates well the observed characteristics of ENSO (Sun 2003).

3. Results

Table 1 shows the response in Tw, Tc and Tw-Tc in three pairs of enhanced tropical heating experiments. The three pairs presented in the table differ in the meridional width of the region where an enhanced tropical heating--an increase in *the radiative convective equilibrium SST*--is applied. In all these pairs, the response in Tw-Tc in the presence of ENSO is much reduced than in the absence of ENSO. Take pair II as an example, change in Tw-Tc in the absence of ENSO is about 1.3^{o}C. With ENSO this change is reduced to 0.0^{o}C, following a reduction in the increase in Tw (from 1. 4^{o}C to 0.92^{o}C) and an increase in Tc (from 0.08^{o}C to 0.94^{o}C). Apparently, the presence of ENSO reduces the warming to the surface western Pacific and increase the warming in the subsurface.

Fig.1a and Fig.1b provide a more detailed look of the response in the time-mean temperature in the equatorial upper ocean. These two figures show respectively the equatorial temperature differences (5^{o}S--5^{o}N) between the control run and the perturbed run for the case without ENSO (Fig.1a) and for the case with ENSO (Fig. 1b). Without ENSO, the warming of the tropical ocean is essentially confined in the surface layer with the response in the western Pacific being slightly deeper than in the eastern Pacific. With ENSO, the response extends to the themocline. While the thermocline water is much warmer in the case with ENSO, the response at the surface western Pacific is reduced. (The presence of ENSO also warms slightly the surface ocean of the central Pacific (180^{o}-240^{o}E) and cools the surface ocean near the eastern boundary).

A typical response in the time-mean temperature of the equatorial upper ocean (5^{o}S--5^{o}N) to an enhanced subtropical cooling is shown in Fig.2a for the case without ENSO and in Fig.2b for the case with ENSO. Without ENSO, the equatorial thermocline water (Tc) is cooled by about 1^{o}C by the imposed cooling over the subtropical surface ocean. The cooling of the equatorial ocean is largely confined to the subsurface--the cooling of the western Pacific SST (Tw) is negligible. With ENSO, the cooling of the thermocline water is reduced down to about 0.5^{o}C while the cooling of the surface western Pacific is enhanced by about the same amount. Again, the presence of ENSO warms the thermocline water and cools the surface ocean of the western Pacific and thereby reduces the sensitivity of the time-mean response of Tw-Tc to the destabilizing forcing. (A close look of Fig.2 also reveals a slightly warming effect of ENSO on the surface ocean of the central Pacific and a cooling effect on the surface ocean near the eastern boundary, consistent with what we see from Fig.1).

In response to either the enhanced tropical heating or enhanced subtropical cooling, ENSO becomes much stronger. In the three enhanced tropical heating cases, the variance of Niño3 SST has increased from the control case to the perturbed case by 0.94^{o}C, 1.40^{o}C, and 1.28^{o}C respectively. The increase in the variance of the Niño3 SST for the subtropical cooling case shown here is 0.89^{o}C based on the same period of data used for Fig.2b. With stronger La Niña, more heat is pumped to the subsurface of the western Pacific (Fig. 3a). A stronger El Niño then redistributes the heat zonally across the depth of the equatorial upper ocean (Fig. 3b). An effective basin-scale vertical "mixing" is achieved in the time-mean through this "sloshing" process. Note the asymmetry between changes in the upper ocean temperature during the La Niña phase (Fig.3a) and the El Niño phase (Fig.3b).

Fig.4a and Fig.4b show respectively the time-mean upper ocean temperature differences between the two control runs and the two perturbed runs listed in Pair II in Table 1. Recall that the two control runs have identical thermal forcing—the same radiative convective equilibrium SST, but one has ENSO and the other does not. The same is true for the two perturbed runs. Fig.4a and Fig.4b both show that the presence of ENSO warms the thermocline water and cools the surface ocean of the western Pacific. Fig. 4b shows a more pronounced ENSO effect than Fig. 4a because the coupled perturbed run has a stronger ENSO than in the coupled control run. Fig. 4 confirms that a higher level of ENSO activity generally warms the thermocline water and cools the surface western Pacific. Fig.4 also suggests a slightly warming effect of the presence of ENSO on the surface ocean of the central Pacific and cooling effect on the surface ocean near the eastern boundary, consistent with our earlier inference from Fig.1 and Fig.2. Corresponding calculations from the subtropical cooling experiments lead to the same results. The gross features shown in Fig.4 are similar to those in Fig. 11 of Schopf and Burgman (2005).

4. Summary and Conclusion

Numerical experiments have been carried out to investigate the role of ENSO in regulating the stability of the time-mean state of coupled tropical Pacific ocean-atmosphere system. The results suggest that ENSO acts as a basin-scale heat mixer that prevents any significant increase from occurring in the time-mean difference between the warm-pool SST (Tw) and the temperature of the thermocline water (Tc). A positive perturbation to the value of Tw-Tc results in a higher level of ENSO activity, which damps out this perturbation. The finding that a higher level of ENSO activity tends to cool the western Pacific warm-pool and warm the subsurface thermocline water is consistent with the results from Schopf and Burgman (2005).

Given the regulating effect of ENSO on the time-mean state of the equatorial upper ocean, one naturally wonders about the reliability of prediction of global warming made by climate models that do not have good simulations of ENSO. Moreover, if ENSO regulates the stability of the time-mean climate, using changes in the time-mean climate to predict changes in the level of ENSO activity could be problematic. Therefore, the present results echo the concern raised by Schopf and Burgman (2005). The results also lend support to the suggestion by Rodger et al (2004) and Yeh and Kirtman (2004) that the tropical Pacific decadal variability may be more a consequence of the decadal variations in the level of ENSO activity than a cause of them. In the same vein, some outstanding biases in the coupled GCM simulations of the time-mean tropical Pacific SST, such as the excessive cold-tongue (Sun et al. 2005), may not just be a cause of errors in the simulated ENSO—it could well be a consequence of the poor simulation of ENSO as well.

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Table Legends

Table 1: Response of Tw, Tc, and Tw-Tc to an enhanced tropical heating with and without ENSO. The definitions of Tw and Tc are the same as in Sun et al. (2004). The values for the restoring coefficient *c* and the coupling strength at the equator $\mu(0)$ are also the same as in that study (5.8×10^{-8} s^{-1} and 6.0×10^{-3} $Nm^{-2}K^{-1}$ respectively). (This value of *c* corresponds to an increase in the net surface heat flux of about 12.2 Wm^{-2} for a *1 K* increase in the difference between the radiative convective equilibrium SST (SST_p) and the actual SST). The three pairs presented here differ in the meridional extent of the regions where an enhanced tropical heating—an increase in SST_p—is applied. The increase in SST_p is confined to 5^oS-5^oN for Pair I, 10^oS-10^oN for Pair II, and 15^oS-15^oN for Pair III. In all three cases, the increases in SST_p have a maximum value of 2^oC at the equator and then decrease with latitude following a cosine profile to zero at the specified latitudes (i.e., 5^o, 10^o, and 15^o respectively for the three cases). The last 3 years of a pair of 27-year-long runs are used in the calculation for the case without ENSO, and the last 23 years of a pair of 27-year-long runs are used in the calculation for the case with ENSO.

Figure Legends

Fig.1: Time-mean equatorial upper ocean temperature response to an enhanced tropical heating for the case without ENSO (a) and the case with ENSO (b). Shown are the results from experiments of Pair II listed in Table 1. Data used for the calculations here are the same as those used for obtaining changes in Tw and Tc in Table 1. The thin dashed contours in the two figures are the mean isotherms of the respective control run.

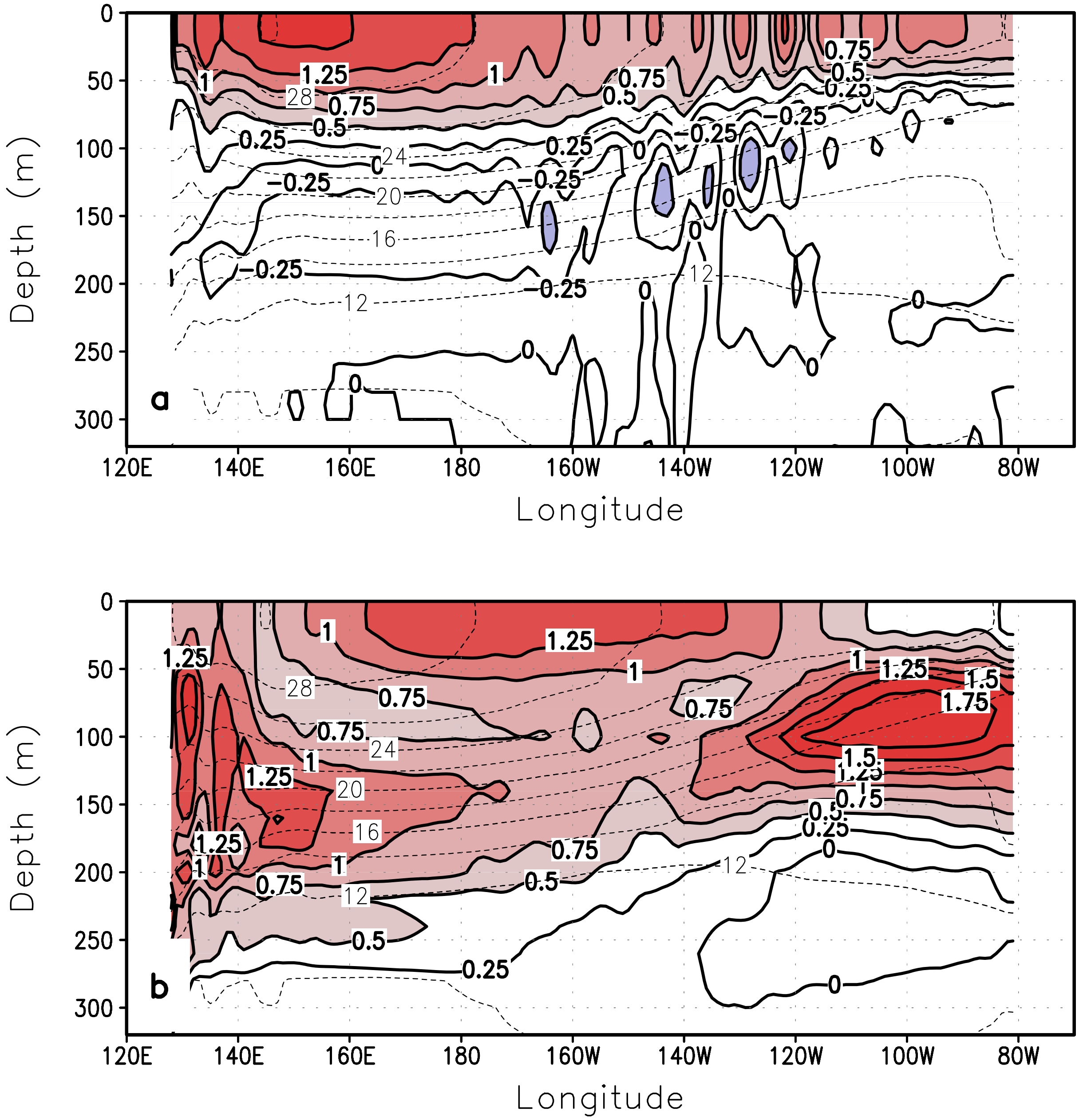
Fig. 2: Time-mean equatorial upper ocean temperature response to an enhanced subtropical cooling for the case without ENSO (a) and the case with ENSO (b). The anomalous subtropical cooling—a reduction in the radiative convective equilibrium SST—starts at 10^{o} S(N) for this case and increases monotonically with latitude to a fixed value 1^{o}C at 30^{o}S(N). The last 3 years of a pair of 27-yr-long runs are used in the calculation for the case without ENSO. For the case with ENSO, the last 23 years of a pair of 40-year long runs are used. Not like the almost instantaneous response of ENSO to an increase in the tropical heating, there is a delay for the onset of the regime with stronger ENSO in response to an increase in subtropical cooling. Consequently there is a need for a longer run to obtain a time series of Niño3 SST that is representative of the regime. The thin dashed contours in the two figures are the mean isotherms of the respective control run.

Fig. 3: Equatorial upper ocean temperature response to an enhanced tropical heating during the La Niña phase (a) and during the El Niño phase (b). The control run and the perturbed run used for this figure are those two runs with ENSO listed in pair II in Table 1. The last 6 cycles of ENSO in the two runs are used for obtaining their respective mean temperatures during the two phases. The definitions of the El Niño phase and the La Niña phase are the same as in Sun (2003). The thin dashed contours in the figures are the mean isotherms of the control run.

Fig. 4: Time-mean differences in the equatorial upper ocean temperature between the two control runs in Pair II in Table 1 (a), and between the two perturbed runs in Pair II in Table 1 (b). Data used for the calculations here are the same as those used for obtaining Fig. 1.

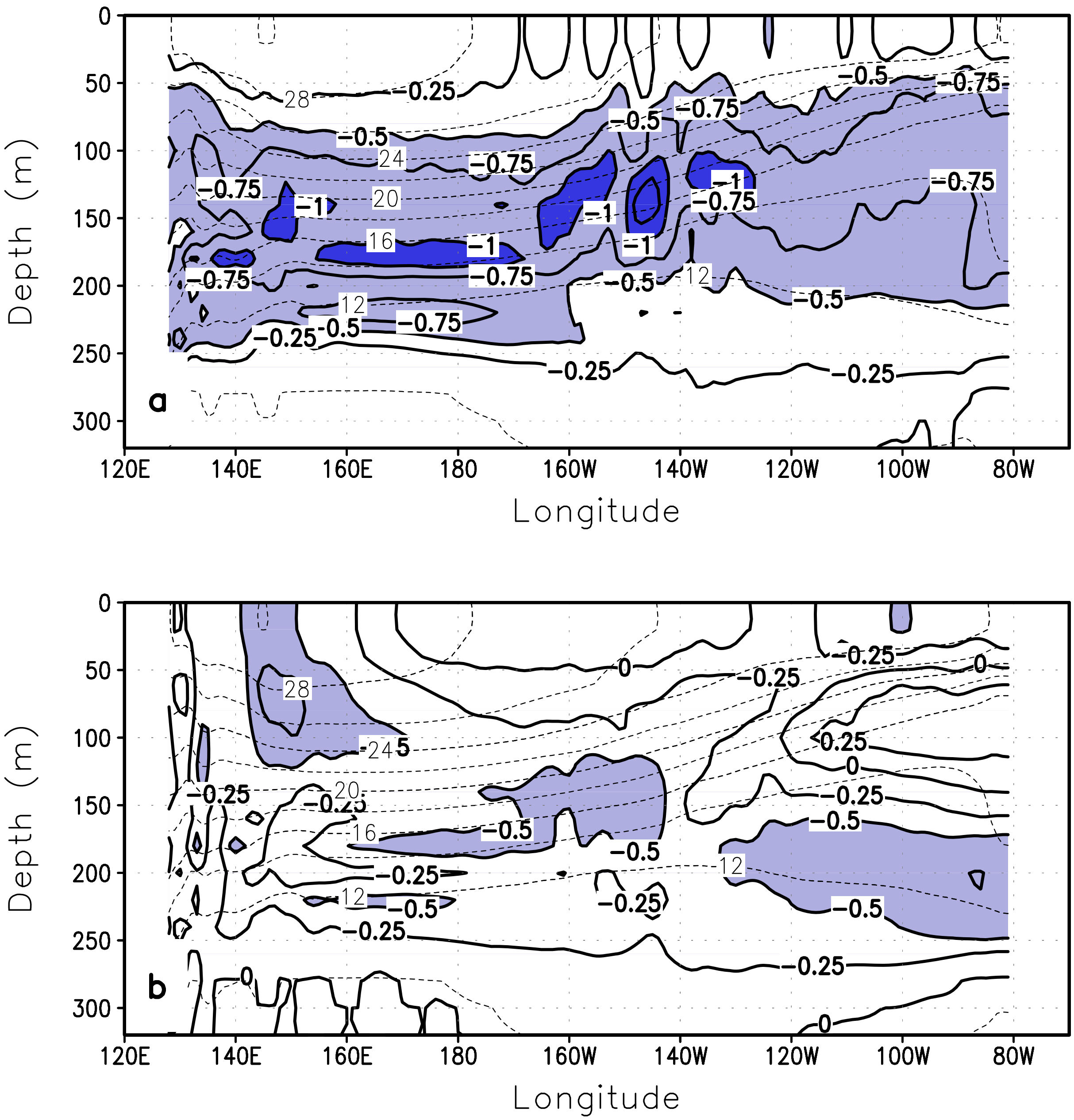
perturbation type	experiment type	change of Tw (°c)	change of Tc (°c)	change of Tw-Tc (°c)
Pair I (5^oS-5^oN)	No ENSO	1.03	0.0050	1.02
	With ENSO	0.82	0.86	-0.040
Pair II (10^oS-10^oN)	No ENSO	1.40	0.082	1.32
	With ENSO	0.92	0.94	-0.020
Pair III (15^oS-15^oN)	No ENSO	1.73	0.25	1.48
	With ENSO	1.28	1.15	0.13

Table 1



Depth (m)
Longitude
a
b
120E
140E
160E
180
160W
140W
120W
100W
80W

Fig.1


a
b
Depth (m)
Longitude
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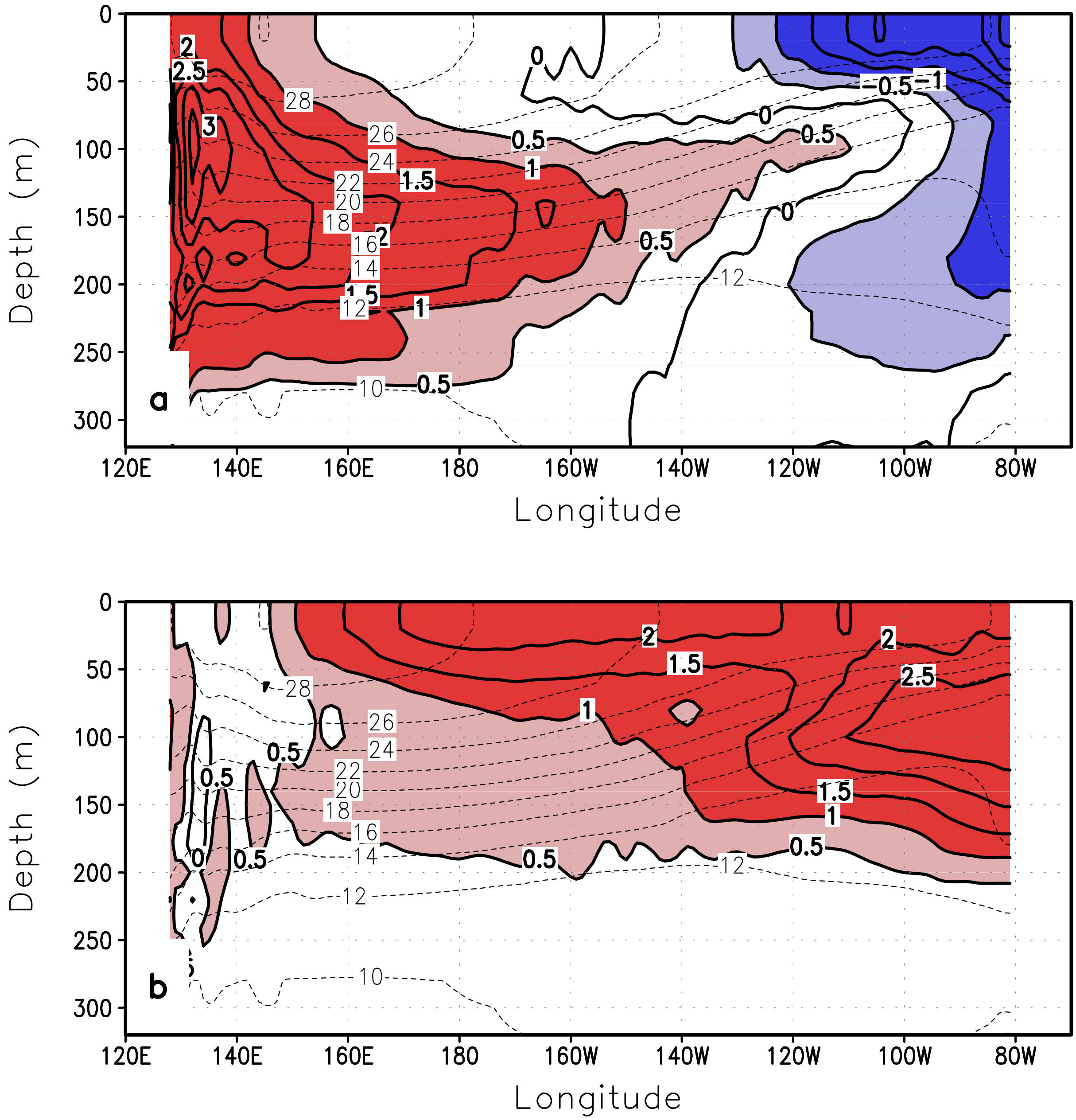
50
100
150
200
250
300
120E
140E
160E
180
160W
140W
120W
100W
80W

Fig.2


a
b
Depth (m)
Longitude
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100
150
200
250
300
120E
140E
160E
180
160W
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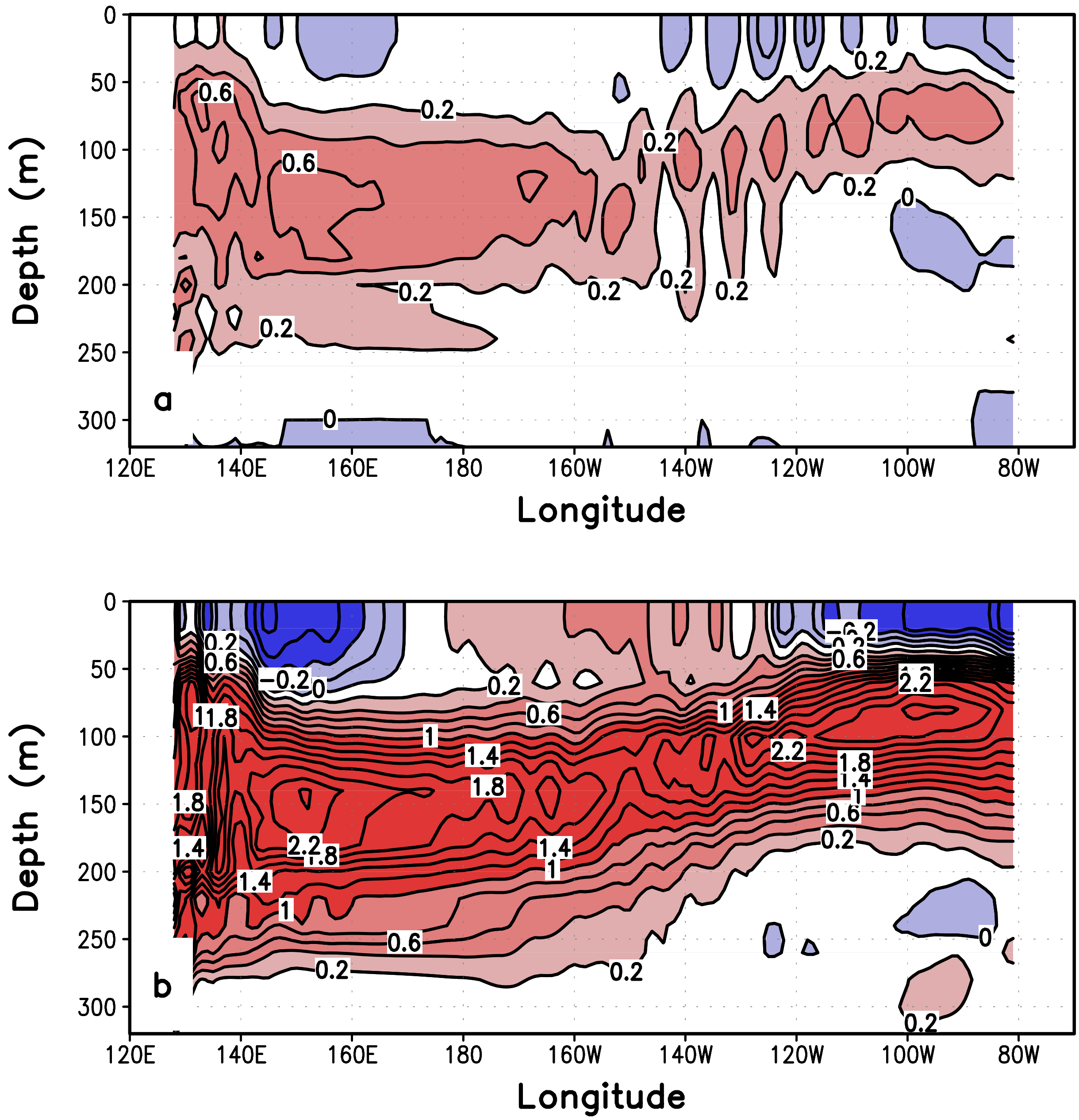
120W
100W
80W

Fig.3



a
b
Depth (m)
Longitude
120E
140E
160E
180
160W
140W
120W
100W
80W

Fig.4