12.5 The Effect of Subtropical/Extratropical Cooling On ENSO: A Numerical Study

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1. INTRODUCTION

Theoretical, observational, and modeling studies have suggested the existence of an "ocean tunnel" –the water constituting the equatorial undercurrent and therefore the upwelling water in the equatorial Pacific comes from the subtropical/extratropical region (Pedlosky 1987, Liu et al. 1994, McCreary and Lu 1994). Gu and Philander (1998) even hypothesized that such a "tunnel" may be an underlying cause for the Pacific decadal variability. Zhang et al. (1998) provided further observational support for this hypothesis. Although it is found later that the processes in the real ocean appears to be more complex than what Gu and Philander (1998) originally envisioned (Lu et al. 1998, Schneider et al. 1999), the finding remains robust that the water feeding the equatorial undercurrent comes from the higher latitudes. Using two ocean GCMs, Shin and Liu (2001) demonstrated that a change in the subtropical/extratropical SST can induce a significant change in the temperature of the equatorial thermocline. Unfortunately, in their perturbation experiments, the equatorial winds are not coupled to the SST, effectively eliminating a necessary mechanism supporting ENSO. Nonetheless, their results add weight to the possibility of a significant subtropical/extratropical impact on ENSO through the aforementioned "ocean-tunnel". It has been known since the pioneering study of Zebiak and Cane (1989) that El Niño results from instability of the coupled tropical ocean-atmosphere (see also the review by Neelin et al. 1998). A change in the equatorial thermocline temperature is an effective way to perturb the stability of the equatorial ocean. The recent theory of Jin (1996) also hints a role of the influence on ENSO from the off-equatorial region. While the recent studies on the implications of the 'ocean-tunnel" are encouraging and enticing for its role on ENSO, it remains to be demonstrated within a single model context, whether and how a temperature change in the subtropical or extratropical ocean affects the amplitude of ENSO.

The need to examine the response of the ENSO to a subtropical/extra-tropical cooling is further highlighted by the "heat-pump" hypothesis for ENSO (Sun 2003). Based on an analysis of the heat balance in the equatorial Pacific, Sun suggested that the amplitude of ENSO may be linked to the poleward heat transport out of the equatorial ocean and therefore by extension to the meridional differential heating over the Pacific ocean. In the paper of Sun (2003), he only reported numerical experiments demonstrating that an increase in the equatorial surface heating (or equivalently an increase in the tropical maximum SST) results in more energetic El Niños.

2. METHODOLOGY

This study directly extends the study of Sun (2003). The same numerical model used in that study will be used to investigate the effect of a cooling over the subtropical/extra-tropical Pacific on the amplitude of ENSO. The atmospheric component of the coupled model of Sun (2003) is an empirical atmospheric model. The surface heat flux into the ocean is assumed to be proportional to the difference between the radiative-convective equilibrium SST (SST_p) and the actual SST. The ocean component is the NCAR Pacific basin model (Gent and Cane

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1989, Gent 1991). The ocean model is a primitive equation model and therefore explicitly calculates the heat budget of the entire upper ocean. Enhanced cooling in the subtropical/extra-tropical ocean is introduced by reducing SST_p in that region. The dynamical coupling between the atmosphere and ocean in the coupled model is limited to the equatorial region. Coupling between the winds and the SST in the equatorial region is a necessary mechanism supporting ENSO (Zebiak and Cane 1989, Jin 1996, Neelin et. 1998). The goal here is to investigate whether a cooling in the subtropical/ extratropical surface ocean can affect the amplitude of ENSO through the "ocean tunnel" that connects the surface ocean in the subtropical/ extratropical region with the subsurface ocean in the equatorial region (Pedlosky 1987, Liu et al. 1994, McCreary and Lu 1994).

3. RESULTS

Fig.1a shows the time series of Niño3 SST from a control run and a perturbed run. The perturbed run has an enhanced cooling in the subtropical/extratropical ocean. The exact difference between the SST_p in the control run and the perturbed run is shown in Fig.1b. To be in line with the heating experiment reported in Sun (2003), the enhanced cooling starts from the off-equatorial region and assumed to increase with the latitude. The results reported in this note are qualitatively independent of the exact form of cooling imposed. The two runs shown in Fig.1a start from the same initial condition.

After some years of delay (about 8 years in this particular case), stronger ENSO develops. Note that La Niña becomes colder and the El Niño events become warmer. Comparing with the amount of cooling introduced outside of the equatorial region, the change in the amplitude of ENSO is large. Again, the zonal gradients of SST in the time-mean remain essentially unchanged (Fig. 2a). The enhanced subtropical/extratropical cooling apparently mainly cools the cold phase of ENSO in the equatorial region east of the dateline (Fig. 2b).

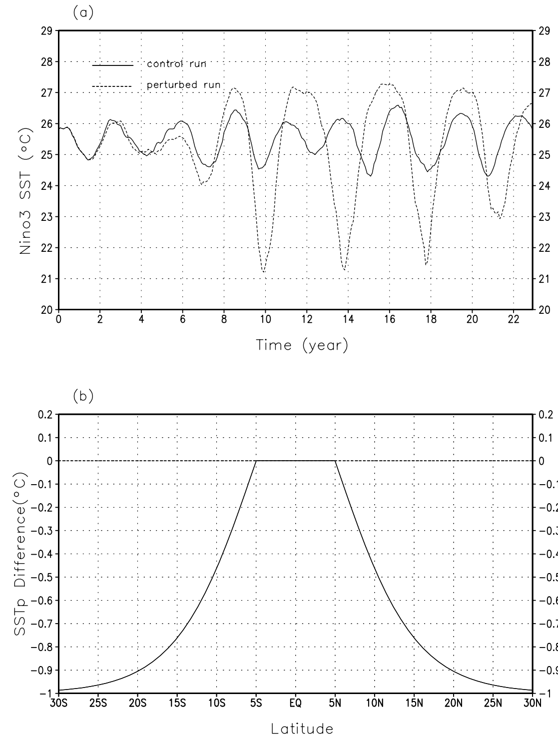

Figure 1: (a) Time series of Nino3 SST from the control run (solid line) and the perturbed run (dashed line). The two runs starts from the same initial condition. The perturbed run is subjected to a reduction in SST_p in the form shown in (b).

But then El Niño events are stronger, which largely reverse the cooling effect during the cold phase. Clearly, the response of ENSO to a subtropical/ extratropical cooling is very similar to its response to an equatorial heating reported in Sun (2003).

Fig. 3 further shows the time series of the temperature of the equatorial undercurrent (Tc) for the control run and the perturbed run. Comparing with Fig.1a reveals that Tc first feels the cooling. A significant difference between the Tc in the perturbed run and the Tc in the control run started to occur at about 44 months, while a significant difference between the Niño3 SST in the perturbed run and the control run did not occur about 18 months later which happens to be in a growth phase of El Niño. This El Niño is damped, but the subsequent La Niña is also colder. After this stronger La Niña, El

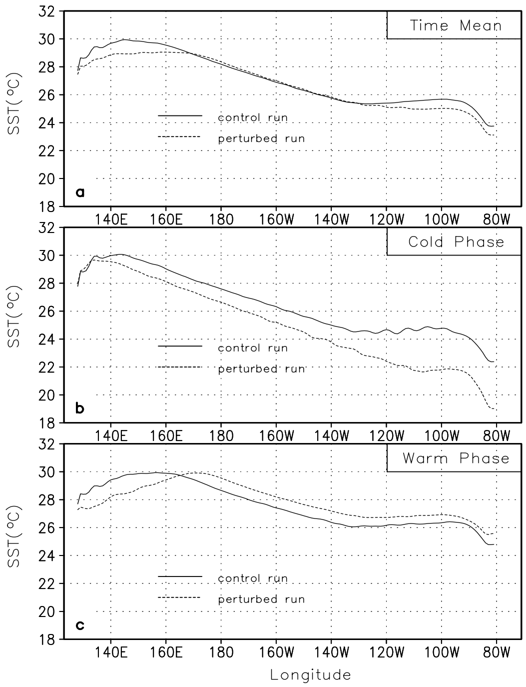

Figure 2: Zonal distribution of equatorial SST for the control run (solid line) and the perturbed run (dashed line) in the time mean (a), the cold phase (b), and the warm-phase (c).

Niño becomes warmer and a regime with stronger ENSO develops. In both the control run and the perturbed run, Tc generally leads the Niño3 SST though the leads varies (2--8 months). Tc is anomalously warm prior to the onset of the warm events and anomalously cold prior to the onset of the cold events.

To confirm the impression that the perturbation to the equatorial dynamics by the subtropical cooling is through its cooling effect on the equatorial thermocline water, we have run the same experiments shown in Fig. 2, but without equatorial coupling between the equatorial surface winds and the zonal SST gradients. Fig. 4a shows the value of Tc from the experiment with a subtropical/extratropical cooling start to diverge from the control run significantly at approximately the same time as in the coupled runs. Fig. 4b-c further show that across sections in the central (160^{o}E-210^{o}E) and eastern Pacific (210^{o}E-270^{o}E) of the upper ocean tempera-

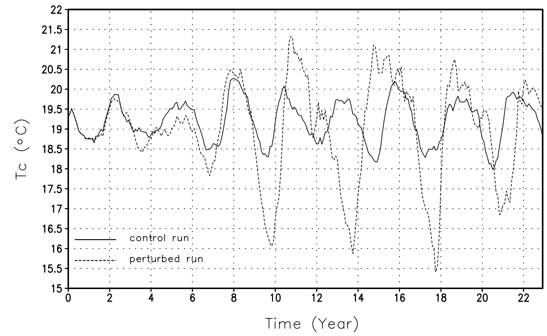

Figure 3: Time series of the temperature of the equatorial undercurrent (Tc) from the control run (solid line) and the perturbed run (dashed line). Tc is the zonal mean equatorial ocean temperature at the depth where the zonal velocity has its maximum U_{max}. Longitudes at which the U_{max} is less than 60 cm/s were not included in the calculation.

ture differences between the control and perturbation run. The surface cooling in the subtropical ocean clearly sinks into the equatorial thermocline. Interestingly, the cooling in the equatorial thermocline is even stronger than the surface cooling imposed in the subtropical/extratropical region.

As expected, in the enhanced subtropical/extratropical cooling case, more heat is transported out of the equatorial Pacific to the higher latitudes and the transport becomes more episodic (Fig. 5).

We have further verified that the delay of the response in ENSO to a subtropical/extratropical cooling become progressively longer as we move the cooling progressively to the higher latitudes. An example is shown in Fig. 6. Now the response of ENSO did not occur until almost 12 years later.

4. CONCLUSION

Numerical experiments have been conducted to show that a cooling in the subtropical Pacific ocean can indeed force stronger El Niños. It appears that the effect of a surface cooling in the subtropical ocean perturbs the stability and the heat balance of the coupled equatorial Pacific through cooling the equatorial undercurrent and the associated equato-

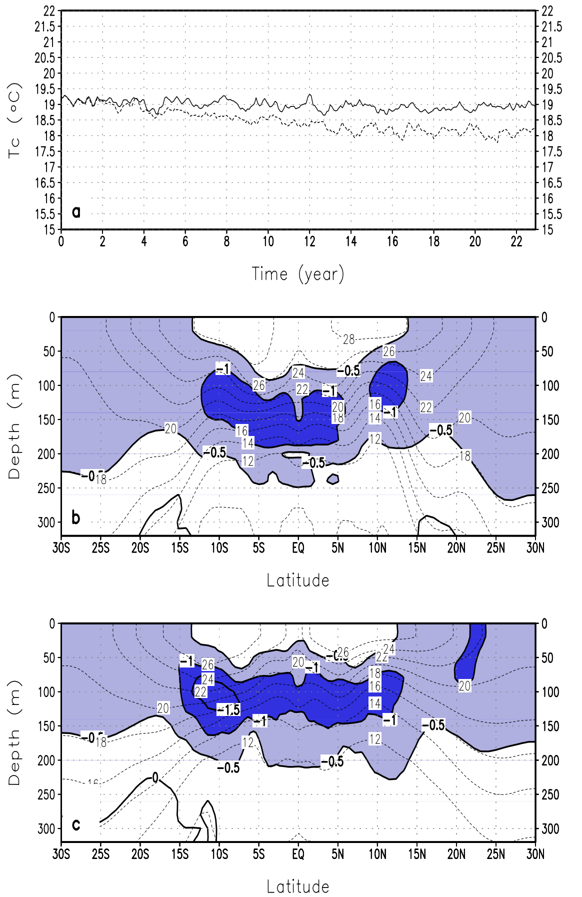

Figure 4: (a) Time series of the temperature equato
undercurrent (Tc) from two uncoupled runs. The sc
line corresponds to the control run in fig. 3 while th
dashed line corresponds to the perturbed run in fig.
(b) &(c): Across section of the upper ocean temper
ture difference in the central and eastern Pacific dur
the last three years of the run.

rial upwelling water. This further leads to a cooling in the central and eastern equatorial Pacific SST. When this cooling is sufficiently strong and coincides with an ongoing La Niña, the equatorial zonal winds are enhanced which further depress the thermocline in the western Pacific. The equatorial ocean then becomes more unstable and a stronger El Niño develops. The stronger El Niño cools the equatorial western Pacific and warms the equatorial eastern Pacific and thereby largely reverses the perturbation from the subsurface to the equatorial zonal SST contrast during the La Niña phase. The time-mean equatorial SST contrast again appears to be strongly regulated. The findings here

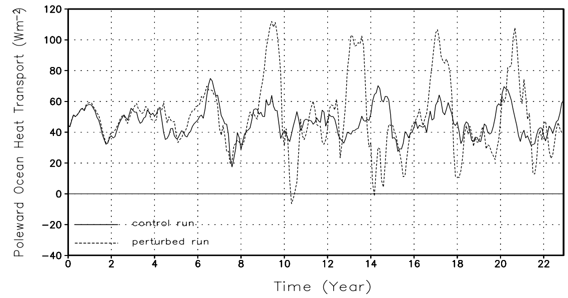

Figure 5: Time series of the poleward heat transport out of the equatorial Pacific from the control run (side line) and the perturbed run (dashed line).

are consistent with the argument presented in Sun (2003). More importantly, the present findings appear to substantiate the argument of Gu and Philander (1998) and Zhang et al. (1998) that the "ocean tunnel" may be an important mechanism for decadal variability.

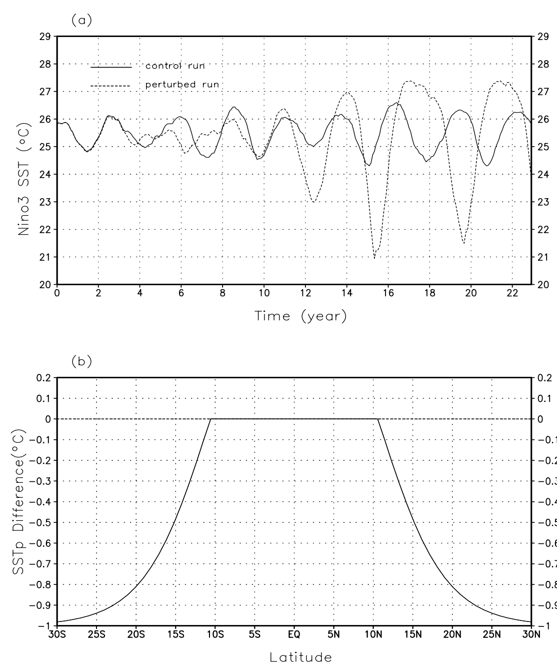

Figure 6: (a) Time series of Niño3 SST from the control run (solid line) and a perturbed run (dashed line). The two runs starts from the same initial condition. The perturbed run is subjected to a reduction in SST_p in the form shown in (b). Note that with cooling starting from higher latitude, there is prolonged delay in the response of the Niño3 SST.

To ensure understanding, the experiments reported here are highly idealized. The winds and SST are only coupled in the equatorial region. Presumably, as the subtropical/extratropical ocean cools, the Hadley circulation may become stronger and the subtropical/extratropical surface winds may change correspondingly. These changes may in turn influence the equatorial SST response. Additional experiments with a global ocean model are also needed. A global ocean model allows us to examine the response of ENSO to enhanced cooling in the region poleward of 30^{o}N and 30^{o}S including cooling in other basins. All these details may potentially modify the mechanism suggested here by which subtropical/extratropical cooling affects ENSO. The ultimate test of this mechanism and the "heat pump" hypothesis in general, however, has to come from paleo climate data. In this connection, it may be worth noting a recent finding by Cobb (2002). Based on coral records, she found that ENSO during the little ice-age was stronger than in the present climate.

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