The Control of Meridional Differential Surface Heating Over the Level of ENSO Activity: A Heat-Pump Hypothesis

De-Zheng Sun

NOAA-CIRES/Climate Diagnostics Center, Boulder, Colorado

Numerical experiments with a coupled model have been carried out to test the heat-pump hypothesis for ENSO. The hypothesis states that the level of ENSO activity is controlled by the meridional differential surface heating over the Pacific: either an enhanced surface heating over the equatorial region or an enhanced cooling over the subtropical/extratropical ocean may result in a regime with stronger ENSO events. Moreover, ENSO may be a mechanism that regulates the long-term stability of the coupled equatorial ocean-atmosphere system. The results from the numerical experiments are shown to be consistent with this hypothesis. A stronger tropical heating or a stronger subtropical/extratropical cooling tends to increase the contrast between the SST in the tropical western Pacific warm-pool and the temperature of the equatorial thermocline water and thereby destabilize the coupled equatorial ocean-atmosphere system. In response, a regime with stronger ENSO events sets in. The stronger ENSO events transport more heat downward and poleward, cooling the warm-pool SST and warming the equatorial thermocline water. In the presence of ENSO, the difference between the time-mean warm-pool SST and the time-mean temperature of the equatorial thermocline water is found to be insensitive to changes in the external forcing.

1. INTRODUCTION

The level of the ENSO activity has varied over the past [*Tudhope et al.,* 2001; *Cobb et al.,* 2003], suggesting it may vary in the future. What controls the level of ENSO activity, however, has not been well understood [*Wang and Picaut*, this volume]. For example, there is no consensus on the causes of the strengthening of the ENSO activity during the last 20 years relative to the previous two decades. At least three different explanations for this change in the level of ENSO activity have been put forward. *Wang and An* [2001] have suggested that the strengthening of ENSO activity during the last 20 years is due to a change in the background winds. *Jin et al.* [2003] attributes this strengthening of ENSO activity to nonlinear dynamic heating. *Sun* [2003] suggests that the strengthening of ENSO may be a consequence of an increase in the equatorial radiative heating or equivalently an increase in the tropical maximum SST. The understanding of the changes in the level of ENSO activity on the longer time-scales is not better. For example, there is also no agreement on the causes of the suppression of ENSO activity during the mid Holocene [*Rondel et al.,* 1999; *Sandweiss et al*., 1996]. *Sun* [2000] suggests that the warmer equatorial thermocline water could be a cause — the reduced difference between the tropical maximum SST and the temperature of the equatorial thermocline water makes the coupled system more stable. *Liu et al.* [2000] did find warmer equatorial thermocline water in their model simulation of the mid-Holocene, but suggests a role of the Asian summer monsoon. *Clement et al.* [2000] proposed another mechanism: orbitally driven changes in the seasonal cycle of solar radiation in the tropics. Because of the differences in the models used, whether these proposed mechanisms are really independent of each other or overlapping is not known.

The inadequacy in our understanding of what controls the level of ENSO activity is also reflected in the lack of consistency in the predictions by coupled GCMs. Some early models suggest that the level of ENSO activity may reduce in response to global warming [*Meehl et al.,* 1993; *Tett,* 1995; *Knutson et al.,* 1997]. The more recent experiments by *Timmerman et al.* [1999] suggest the opposite effect: the level of ENSO activity will increase in response to global warming. *Collins* [2001] even found different responses of ENSO to global warming in two different versions of the same model. The credibility of the predictions of the response to global warming by these coupled GCMs is also undermined by the lack of confidence in their simulation of cloud feedbacks [*Cess et al.,* 1989; *Sun et al*., 2003].

The rather scattered results concerning the causes of the variability in the level of ENSO highlight a need for a better delineation of the fundamental forces controlling the level of ENSO activity. The purpose of this article is to highlight recent progress in understanding the influence of surface heating over the level of ENSO activity, specifically, the heat-pump hypothesis [*Sun*, 2003; *Sun et al.,* 2004]. The hypothesis states that ENSO amplitude is proportional to the meridional differential surface heating over the Pacific: either an enhanced surface heating over the equatorial region or an enhanced cooling over the subtropical/extratropical ocean may result in a regime with stronger El Niño events. Moreover, El Niño may be a mechanism that regulates the stability of the time-mean state of the equatorial Pacific. This hypothesis, if proved to be true, could become a step stone to better understand why the level of ENSO activity has varied over the past and how it may change in the future as the CO_2 concentration in the atmosphere increases. The heat-pump hypothesis deals with the question of what controls the amplitude of ENSO. Therefore, it complements existing theories of ENSO as these theories mainly provide an explanation for the phase transition of ENSO.

The paper is organized as follows. The observational background for the conception of the heat-pump hypothesis is introduced in section 2. The numerical experiments that have been carried out to test this hypothesis are highlighted in section 3. The implications of the heat-pump hypothesis are discussed in section 4.

2. OBSERVATIONAL BACKGROUND

The distribution of the net surface heat flux over the Pacific is characterized by heating in the equatorial region and cooling in the higher latitudes (Fig. 1a). This implies that the ocean has to remove heat away from the equatorial Pacific to the higher latitudes. Extending previous calculations by *Wyrtki* [1985], *Meinen and McPhaden* [2000, 2001], *Sun and Trenberth* [1998], and *Sun* [2000], *Sun* [2003] calculated the poleward heat transport in the tropical Pacific over the last 20 years using a single ocean data set. The calculation showed that the required poleward heat removal is achieved episodically and those episodes correspond with the occurrence of El Niño events (see Fig. 5 in *Sun* [2003]). A basin-wide view of the anomalous heat transfer during El Niño is shown in Fig.1b. Shown is the divergent component of the heat transport vertically averaged over the upper ocean. As there is anomalous eastward heat transport to feed the El Niño warming, the poleward heat transport is enhanced across the equatorial Pacific. The center of the divergence in the transport occurs slightly west to the dateline while the surface heating is peaked in the far eastern Pacific. This indicates that the heat also has to be first transported westward, consistent with the observation that heat is transported to the subsurface ocean of the western Pacific during the quiescent periods — the La Niña events [*Wyrtki,* 1985; *Sun,* 2000; *Sun*, 2003]. Therefore, both phases of ENSO are fundamentally involved in the planetary heat transport in the tropical Pacific. The fact that El Niño corresponds to an elevated poleward heat transport has been noted earlier [*Wyrtki,* 1985; *Meinen and McPhaden*, 2000, 2001; *Sun* 2001]. *Jin* [1997ab] has suggested that this elevated poleward heat transport provides the negative feedback that terminates the anomalous surface warming. Therefore, the extended calculation by *Sun* [2003] may be viewed as evidence for the relevance of Jin's theory for the phase transition of ENSO. The key point in *Sun* [2003], however, is the connection between ENSO and the surface heating over the tropical Pacific and the implied long-term heat balance of the tropical Pacific.

Figure 1

Sun [2003] has also noted in his heat budget analysis that the two strongest El Niño events, the 1982-83 El Niño event and the 1997-98 El Niño event, are also accompanied by the strongest poleward heat transport. The peak value of the heat transport out of the equatorial Pacific (5^{o}S-5^{o}N) associated with the 1997-98 El Niño event almost doubles the mean peak value associated with the 4 weaker El Niño events (1986-87, 1991-92, 1993, and 1994-95). Fig. 2ab contrasts the heat transport during the two strongest El Niño events with a more moderate one, the 1991-92 El

Figure 2

Niño event. As there is more heat transport from the equatorial western Pacific to the equatorial eastern Pacific, the poleward heat transport is enhanced across the bulk of the tropical Pacific.

If all the El Niño events in the record were as strong as the 1997-98 El Niño event, we would have seen a stronger poleward heat transport in the time-mean. Conversely, if the time mean poleward heat transport is forced to increase for some reason, the mean level of ENSO activity may have to increase to maintain the time-mean heat balance. This consideration led to the conception that the meridional differential surface heating may act as a fundamental factor influencing the level of ENSO activity.

Admittedly, the above consideration only points to a possibility, not a necessity. For example, to achieve a higher poleward heat transport in the mean, the system could increase the poleward transport during the relative quiescent periods — the La Niña events. This scenario, however, is unlikely, because heat has to be pumped to the subsurface ocean for a substantial poleward ocean heat transport. Note that the tropical Pacific is stablely stratified in the vertical except the shallow surface mixed layer. It needs Ekman pumping to do the work to pump heat down to the subsurface ocean. The pattern of transport during El Niño shown in Fig. 2 also indicates that heat has to be transported from the eastern Pacific to the western Pacific. Pumping heat down to the subsurface ocean of the western Pacific appears to occur primarily during La Niña events [*Sun* 2001; *Sun* 2003]. To put these arguments and inferences from observations on a firmer ground, experiments with a coupled model have been carried out.

3. NUMERICAL RESULTS

3.1. The Model

The model is described in *Sun* [2003] and *Sun et al.* [2004]. The atmospheric model is an empirical one. The surface heat flux is parameterized in the same way as previous theoretical studies of ENSO: it is proportional to the difference between a prescribed radiative convective equilibrium SST (SST_p) and the actual SST predicted by the coupled model,

$$F_s(\lambda,\phi) = C_p \rho c H_m (SST_p(\phi) - SST(\lambda,\varphi)) \qquad (1)$$

where F_S is the net surface heat flux into the ocean, λ is the longitude, ϕ is the latitude, C_p is the specific heat, ρ is the density, c is the restoring coefficient, and H_m is the depth of the mixed layer (50 m). The SST_p in the equation is prescribed empirically such that the model ocean is heated in the equatorial region and cooled in the higher latitudes (see Eq. (5) in *Sun* [2003] for the exact form of the prescribed SST_p). The treatment of the coupling of winds is also in line with what has been done previously: the equatorial zonal wind stress is proportional to the equatorial zonal SST contrast,

$$\tau^x(\lambda,\phi) = \tau^x_{ref}(\lambda,\phi) - \mu(\phi)(\Delta T - \Delta T_{ref}) \qquad (2)$$

where τ^x is the zonal wind stress, τ^x_{ref} is the zonal wind stress that is used to spin up the ocean model to obtain a reference state. ΔT_{ref} is a measure of the equatorial zonal SST contrast of the reference state. It is defined as the area averaged SST difference between (5°S-5°N, 130°E-180°E) and (5°S-5°N, 230°E-280°E). ΔT is the same measure of the actual equatorial zonal SST contrast predicted by the model. μ measures the coupling strength and has a prescribed meridional profile.

The ocean component of the coupled model is the NCAR Pacific Basin model — the model of *Gent and Cane* [1989]. This ocean model, though less used so far for ENSO studies than the phenomenally successful model of *Zebiak and Cane* [1987], explicitly calculates the heat budget of the entire upper ocean. The ocean component of the model of *Zebiak and Cane* [1987], in contrast, has the mean temperature structure of the subsurface ocean fixed. For our present purpose, which is to examine how the coupled ENSO system responds to an increase in the radiative heating, it is crucially important to explicitly calculate the heat budget of the entire upper ocean. The NCAR Pacific basin model also features a fine spatial resolution in the equatorial waveguide (about 0.25°) and therefore ensures accurate simulation of the equatorial waves.

The model simulates the major observed characteristics of ENSO and the mean climate [*Sun,* 2003]. As in many other models, ENSO in this model is more regular than in the real world. With instantaneous coupling, the model does have some internal variability on multi-decadal time-scales apparently because of the presence of noise in the SST field and the resulting noisy winds. In the experiments we report in the present article, weekly mean SST is used to compute the winds in the coupling and this largely suppresses the internal variability of ENSO on multi-decadal time-scales. The lack of decadal variability in the amplitude of ENSO in the model helps to identify the effect of an external forcing, such as an increase in the tropical heating or subtropical cooling, on the amplitude of ENSO. The goal here is limited to isolating the mechanisms for further tests using observations or more sophisticated models.

3.2. Tropical Heating Experiments

A typical response of the Niño3 SST variability to an increase in the tropical heating is shown in Fig. 3. Fig. 3a

Figure 3

shows the Niño3 SST time series from a control run and a perturbed run. The increase in the tropical heating is introduced through an increase in the SST_p in that region. The exact form of the increase in the SST_p in the perturbed run is shown in Fig. 3b. (The heating in this particular case is confined to the equatorial region (5^{o}S-5^{o}N). Extending to a broader region (10^{o}S-10^{o}N) has essentially the same results). Fig. 3c shows the corresponding time series of the transport. The numerical results apparently support the hypothesis: ENSO becomes more energetic — the amplitude has become considerably larger — and the poleward heat transport becomes more episodical. The ENSO events are stronger and have a longer duration.

To understand the response of ENSO to the tropical heating, we have conducted experiments in which the equatorial coupling is turned off — setting the coupling strength parameter in Eq. (2) to zero — so that the tendency created by the imposed surface heating can be isolated. Fig. 4ab shows the response of the upper ocean temperature to an increase in the tropical heating from such experiments. There is a considerable increase in the warm-pool SST. but there is little change in the temperature of the equatorial thermocline water. The effect of the imposed surface heating is confined to the surface mixed layer. As we will see later, this confinement is due to the absence of the coupling between the atmosphere and the ocean. The increase in the SST in the eastern equatorial Pacific is less than in the western Pacific. This is because the thermocline in the eastern Pacific is shallower and consequently the upwelling has more influence over the SST in that region. As the temperature of the source water for the equatorial upwelling — the temperature of the equatorial thermocline water — remains unaffected by the imposed surface heating, the upwelling reduces the sensitivity of the SST in the eastern Pacific to the increase in the surface heating. The resulting increase in the zonal SST contrast, measured by ΔT in Eq. (2), is about 0.50^{o}C. It should be emphasized that such an increase in the zonal SST contrast is fundamentally linked to the increase in the contrast between the warm-pool SST and the temperature of the equatorial thermocline water that feeds the equatorial upwelling. The difference between the western Pacific warm-pool SST and the characteristic temperature of the equatorial thermocline water is a fundamental parameter in determining the stability of the coupled equatorial ocean-atmosphere [*Sun* 2000; *Sun*, 1997; *Jin,* 1996; *Sun,* 1996]. We use the mean SST over the region (5^{o}S-5^{o}N, 120^{o}E-160^{o}E) Tw to measure the warm-pool SST and the core temperature of the equatorial undercurrent Tc [*Sun et al*., 2004] to represent the characteristic temperature of the equatorial thermocline water. The perturbation from the enhanced tropical heating to the value of Tw-Tc without equatorial coupling is about 1.0^{o}C (Fig. 4a). Thus, the

Figure 4

imposed tropical heating tends to reduce the stability of the coupled equatorial ocean-atmosphere system.

In the presence of coupling, the perturbation to the zonal SST contrast by the increase in the difference between Tw and Tc is expected to be amplified by the Bjerknes feedback loop: stronger zonal SST contrast results in stronger winds and stronger upwelling which in turn enhances the zonal SST contrast. Moreover, because this perturbation depends on the equatorial upwelling, it has more effect during the La Niña phase; namely, this perturbation will result in stronger La Niña. Indeed, the zonal SST contrast during the cold phase of the coupled run with the enhanced tropical heating is much larger than the control run. Measured by ΔT in Eq. (2), the zonal SST contrast has increased by 2.0^{o}C during the cold phase (Fig. 5a).

Figure 5

Because of the effect of the enhanced upwelling and the enhanced zonal advection during the cold phase, the eastern equatorial Pacific is colder in the perturbed run than in the control run despite the increase in the surface heating (Fig. 5a). This regulatory effect has been noted before [*Clement et al*., 1996; *Sun and Liu*, 1996]. The SST in the far western Pacific does increase significantly during the cold phase. The stronger La Niña in the perturbed run results in a higher upper ocean heat content in the western Pacific apparently because of a stronger equatorial zonal wind and a stronger Ekman pumping in the off-equatorial region. This higher heat content further leads to stronger El Niño. *Sun* [2003] noted in the observations that stronger El Niño tends to be preceded by a higher heat content in the western Pacific. The stronger El Niño then transports the accumulated heat in the western Pacific subsurface ocean eastward and largely reverses the large increase in the zonal SST contrast during the cold-phase (Fig. 5b). During and immediately flowing this zonal redistribution of heat, more heat is also transported poleward (Fig. 3c).

Figure 6

Fig. 6ab further shows the time-mean upper ocean temperature differences between the coupled perturbed run and the coupled control run. By comparing Fig. 6 with Fig. 4, one sees the effect of the equatorial ocean-atmosphere coupling on the response of the equatorial upper ocean temperature to the enhanced surface heating. In the uncoupled case, the effect of heating is confined to the mixed layer. There is a significant increase in the warm-pool SST. In the coupled case, heat is transported downward all the way to the thermocline. The temperature of the thermocline water is increased considerably. The core temperature of the equatorial undercurrent Tc is increased by 0.80^{o}C. At the same time, the increase in Tw is reduced by 0.20^{o}C. The change in the value of Tw-Tc in the coupled case is thus negligibly small. Therefore allowing ocean-atmosphere to couple — allowing the presence of ENSO — reduces the sensitivity of the difference between Tw and Tc in the time-mean state to the increase in the surface heating, offering evidence for a stabilizing role of ENSO in maintaining the mean climate. Comparing Fig. 6b with Fig. 4b, it further reveals that heat is not only transported to a deeper depth, but also to higher latitudes in the coupled case than in the uncoupled case.

3.3. Subtropical Cooling Experiments

A typical response of ENSO to an increase in the subtropical cooling is shown in Fig. 7. There is a considerable delay in the response of the ENSO amplitude (about 15 years), but eventually a regime with stronger ENSO develops. In the regime with strong ENSO, the poleward heat transport is also more episodical. The duration of El Niño events appears to become longer also.

Figure 7

To understand the response of the amplitude of ENSO to subtropical surface cooling, we have also conducted runs in which the coupling between the surface winds and the zonal SST gradients is turned off so that the tendency created by the subtropical surface cooling can be isolated. Fig. 8 shows the effect of the subtropical surface cooling on the equatorial upper ocean temperature. Shown are differences in the upper ocean temperature between a control run and a perturbed run. The perturbed run is subject to the cooling shown in Fig. 7b. The temperature of the equatorial thermocline water is considerably colder (The core temperature of the equatorial undercurrent Tc is about 0.75^{o}C colder). The cooling of the equatorial thermocline is through the subtropical cell or the "ocean tunnel" [*Sun et al*., 2004]. The cooling is largely confined to the thermocline water. The change in the warm-pool SST Tw is small (about -0.13^{o}C). Therefore, the subtropical cooling increases the difference between Tw and Tc and has the same effect on the stability of the coupled equatorial ocean atmosphere as the tropical heating. The subsequent upwelling of the colder thermocline water perturbs the zonal SST contrast and triggers stronger coupled instability — ENSO. Fig. 9ab shows respectively the equatorial upper ocean temperature differences during the cold phase and the warm phase. Again, the zonal SST contrast is much enhanced during the cold phase — ΔT is increased by about 2.1^{o}C. The cold phase in the perturbed run is also accompanied with greater upper ocean heat content in the western Pacific, which is responsible for stronger El Niño events.

Figure 8

Figure 9

Fig. 10 further shows the time-mean upper ocean temperature differences between the coupled perturbed run and the coupled control run. By comparing Fig. 10 with Fig. 8, one sees the effect of equatorial ocean-atmosphere coupling — the presence of ENSO — on the response of the upper ocean temperature to the enhanced subtropical cooling. In the uncoupled case, the effect of cooling to the equatorial upper ocean is confined to the thermocline. There is little change in the warm-pool SST. In the coupled

Figure 10

case, however, the cooling effect is commuted upward all the way to the surface. Consequently, there is a significant decrease in the warm-pool SST. (The value of Tw is lowered by about 0.67^{o}C). The cooling to the temperature of the equatorial thermocline water is at the same time reduced (the cooling to Tc is reduced from about 0.75^{o}C to 0.45^{o}C). Therefore, the equatorial ocean-atmosphere coupling or the presence of ENSO reduces the sensitivity of the difference between Tw and Tc to an external forcing. Therefore in response to either an increase in the equatorial surface heating or an increase in the subtropical surface cooling, the onset of the coupled instability — ENSO — plays as a negative feedback mechanism, preventing increases in the value of Tw-Tc in the time-mean state. Comparing Fig. 10b with Fig. 8b, it further reveals that the subsurface cooling in the off-equatorial region is also significant reduced by the coupling.

4. DISCUSSION

We have presented numerical evidence supporting the heat-pump hypothesis. Due to limited space, we only reported two cases. We have done more experiments and found that the results do not qualitatively depend on the details of the heating profile used. ENSO become stronger so long as the heating or cooling increases the contrast between the warm-pool SST and the temperature of the equatorial thermocline water. Conversely, we have also found that a decrease in the equatorial heating or a decrease in the subtropical cooling reduces the amplitude of ENSO.

This article is motivated to further delineate the role of surface heating in controlling the level of ENSO activity. It is also motivated to highlight some potential inaccuracies in some popular notions about ENSO. For example, ENSO has been largely regarded as an adiabatic phenomenon — it results from an adiabatic redistribution of warm water in the ocean (see review by *Neelin et al.,* 1998). In light of the present results, this notion about an adiabatic ENSO only has ground in a model with a prescribed mean climate. The present results suggest that ENSO is in fact fundamentally diabatic: it is a coupled instability in response to the destabilizing effect of the meridional differential surface heating.

The present results also challenges describing ENSO as an oscillator about an independent mean climate. We see evidence from the numerical experiments for a regulatory role of ENSO in determining the long-term stability of the coupled equatorial ocean-atmosphere, specifically, the difference between the warm-pool SST and the temperature of the water feeding the equatorial undercurrent (the value of Tw-Tc).

The present results have significant implications for the response of ENSO to global warming. Since the heating in the higher latitudes may have the opposite effect on the level of ENSO activity from the effect of a local heating over the equatorial ocean, the response of the level of ENSO activity to global warming could be complicated, but should depend strongly on the effect of global warming on the meridional differential surface heating over the Pacific ocean. In the same vein, in understanding why different coupled GCMs give different predictions of the response of ENSO activity to global warming, one may need to pay attention to the change in the meridional differential surface heating over the Pacific due to global warming in the models. Because the surface heating distribution is greatly affected by clouds that are a major uncertainty in the GCMs [*Cess et al.,* 1989], the response in the meridional differential surface heating to global warming may be significantly different in the GCMs, causing different response of ENSO to global warming in different models.

It has to be mentioned that the coupled model used for the numerical experiments presented in this article is still very idealized. The parameterization of the surface heating and the wind-SST coupling particularly need improvement. Therefore, the results presented in this article are only suggestive at present. Further experiments are needed to further substantiate them. In particular, future experiments need to take into account the feedback from the Hadley circulation in the atmosphere as its strength also depends strongly on the meridional differential heating. The focus of the present analysis is also limited — it is on the changes in the amplitude of ENSO. More analysis is also needed to understand the changes in the period of ENSO in response to changes in the meridional differential heating. In both the tropical heating and subtropical cooling experiments, we find that the period of ENSO increases.

The ultimate test of the heat-pump hypothesis has to come from observations. In this connection, it may be worth noting the recent data from *Cobb et al.* [2003]. Their coral records appear to suggest that ENSO during the little ice age was stronger than in the medieval warm period. They have also noted in the same record that the equatorial time-mean climate has little change from periods with strong ENSO activity to periods with weak ENSO activity.

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D.-Z. Sun, NOAA-CIRES/Climate Diagnostics Center, R/CDC1, 325, Broadway, Boulder, CO 80305. (E-mail: Dezheng.Sun@noaa.gov)

FIGURE CAPTIONS

Figure 1. (a) Distribution of annual mean surface heating over the Pacific Ocean (from Sun 2003). (b) A basin-wide view of the anomalous heat transport during El Niño. Shown are the average differences in the divergent component of the ocean transport in the upper ocean between El Niño and non-El Niño periods. The divergent component of the ocean transport in the upper ocean is obtained by solving a Laplace equation using the heat divergence data (D_o) calculated by Sun (2003) (see Eq. (1) in that paper). Realistic topography is used for the lateral boundary conditions. The meridional domain is from 35 ^{o}S to 45 ^{o}N. The model outside the analysis model domain is fixed to the climatology over the 1980-98 period. The definition of El Niño and La Niña periods follows Trenberth (1997).

Figure 2. A basin-wide view of the anomalous heat transport during the two exceptionally strong El Niño events: the 1997-98

(a) and the 1982-83 (b) events. Shown are the divergent component of the mean upper ocean heat transport during these two events relative to that during the 1991-92 El Niño event (the 97-98 event minus the 91-92 event and the 82-83 event minus the 91-92 event respectively). The 1991-92 El Niño event has a similar life cycle to the two strongest El Niño events.

Figure 3. (a) Response of ENSO in the coupled model to an increase in the tropical heating. Shown are time series of Niño3 SST from a control run (solid line) and a perturbed run (dashed line). (b) The differences in the radiative convective equlibrium SST between the perturbed run and the control run (the perturbed run minus the control run). (c) Response in the poleward heat transport out of the equatorial region (5^{o}S-5^{o}N) to an increase in the tropical heating. The solid line is for the control run; the dashed line is for the perturbed run.

Figure 4. The equilibrium response in the upper ocean temperature to an increase in the tropical heating in the absence of ENSO. Shown are the differences between a control run and a perturbed run in which there is no equatorial ocean-atmosphere coupling. The perturbed run is subject to the same tropical heating as the coupled perturbed run (Fig. 3b). Both the control run and the perturbed run are 27 years long. Shown are the mean differences over the last 3 years. The dashed lines are the mean isentropes of the control run. (a) A zonal section for the equatorial Pacific (averaged over 5^{o}S-5^{o}N). (b): A meridional section for the central Pacific (averaged over 160^{o}E-210^{o}E).

Figure 5. Response during the cold phase (a) and the warm phase (b) in the equatorial upper ocean temperature (5^{o}S-5^{o}N) to an increase in the tropical heating when the equatorial ocean atmosphere is allowed to produce ENSO. The definition of the cold and warm phase of the ENSO in the model is the same as in Sun (2003). Shown are the differences of the phase-averaged temperature between the control run and the perturbed run whose Niño3 SST time series are shown in Fig. 3a. The last 4 cycles of ENSO in the time series are used for the calculation.

Figure 6. The response in the time-mean upper ocean temperature to an increase in the tropical heating in the presence of ENSO. Shown are the time-mean differences between the control run and the perturbed run whose Niño3 SST time series are shown in Fig. 3a. The entire run (27 years) is used for computing the time-mean. The dashed lines are the mean isentropes of the control run. (a) A zonal section for the equatorial Pacific (averaged over 5^{o}S-5^{o}N). (b): A meridional section for the central Pacific (averaged over 160^{o}E-210^{o}E).

Figure 7. (a) Response of ENSO in the coupled model to an increase in the subtropical cooling. Shown are time series of Niño3 SST from a control run (solid line) and a perturbed run (dashed line). (b) The differences in the radiative convective equilibrium SST between the perturbed run and the control run (the perturbed run minus the control run). (c) Response in the poleward heat transport out of the equatorial region (5^{o}S-5^{o}N). The solid line is for the control run; the dashed line is for the perturbed run.

Figure 8. The equilibrium response in the upper ocean temperature to an increase in the subtropical cooling in the absence of ENSO. Shown are the differences between a control run and a perturbed run in which there is no equatorial ocean-atmosphere coupling. The perturbed run is subject to the same subtropical cooling as the coupled perturbed run (Fig. 7b). Both the control run and the perturbed run are 27 years long. Show are the mean differences over the last 3 years. The dashed lines are the mean isentopes of the control run. (a) A zonal section for the equatorial Pacific (averaged over 5^oS-5^oN). (b): A meridional section for the central Pacific (averaged over 160^oE-210^oE).

Figure 9. Response during the cold phase (a) and the warm phase (b) in the equatorial upper ocean temperature (5^oS-5^oN) to an increase in the subtropical cooling when the equatorial ocean-atmosphere is allowed to couple to produce ENSO. Shown are the differences of the phase-averaged temperature between the control run and the perturbed run whose Niño3 SST time series are shown in Fig. 7a. The last 4 cycles of ENSO in time series are used for the calculation.

Figure 10. The response in the time-mean upper ocean temperature to an increase in the subtropical cooling in the presence of ENSO. Shown are the time-mean differences between the control run and the perturbed run whose Niño3 SST time series are shown in Fig. 7a. The last 20 years of the 32 year long run are used to compute the time mean. The dashed lines are the mean isentropes of the control run. (a) A zonal section for the equatorial Pacific (averaged over 5^oS-5^oN). (b): A meridional section for the central Pacific (averaged over 160^oE-210^oE).

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