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Estimating the nonlinear response of tropical ocean to extratropical forcing in a coupled climate model

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[1] The nonlinear response of the tropical ocean to the extratropical forcing is quantitatively estimated using a coupled climate model. Preliminary results based on sensitivity experiments show that the tropical response attributed to nonlinear processes is less than 10% of the linear response for annual mean climatology. This occurs mainly because the ocean circulations, especially the meridional overturning circulation, tend to change proportionally with external forcings. This work provides a practical estimate of oceanic nonlinear response to global climate change in a complex model system, which in turn may allow the assessment of future climate change from the linear extrapolation of current climate. **Citation:** Yang, H., and L. Wang (2008), Estimating the nonlinear response of tropical ocean to extratropical forcing in a coupled climate model, *Geophys. Res. Lett.*, *35*, L15705, doi:10.1029/2008GL034256.

1. Introduction

[2] The climate system is a highly nonlinear system. Previous studies have tried to understand the patterns, magnitude, frequency and mechanisms of nonlinear responses in global climate change [e.g., *Palmer*, 1999; *Christiansen*, 2003; *Dewar*, 2003]. It is extremely complicated to fully identify the nonlinear response of the climate system to external forcings. There are many studies of nonlinear responses in the atmosphere using atmospheric general circulation models, with focuses on the responses to ENSO strength [*Hoerling et al.*, 2001] or phase [*Hannachi*, 2001; *Lin et al.*, 2007], greenhouse gas and aerosol [*Feichter et al.*, 2004], specific regional forcings [*Sutton and Hodson*, 2007] and so on.

[3] The role of oceanic nonlinearity in the oceanic response to global climate change and the contribution of nonlinear response to the total oceanic changes remains unclear. Nonlinearity in the ocean is important in some regions with strong horizontal or vertical moments [e.g., *Dewar*, 2003; *Kessler et al.*, 2003; *Kuhlbrodt and Monahan*, 2003], while it plays a minor role in the ocean interior. The nonlinear response is yet to be quantified. In this work the nonlinear response of tropical oceans to extratropical forcing is assessed using a fully coupled climate model. It should be borne in mind that this preliminary estimate obtained from our model relies largely on the model features, such like model physics, resolution [*Palmer*, 1999], sensitivity to external forcings and characteristics of the imposed forcings and so on.

[4] We use the Fast Ocean-Atmosphere Model (FOAM) [*Jacob*, 1997]. FOAM is computational efficient and has been used to simulate the global climate in the past, present and future (see *Yang and Liu* [2005] and *Wu and Li* [2007] for details). Using the same modelling technique as in the work by *Liu and Yang* [2003], we perform three pairs of "partial coupling" (PC) experiments to quantify the relative contributions of linear and nonlinear processes in the extratropical impact of the tropical climate. All experiments start from a stable control run (CTRL) and are integrated for 200 years. Specifically, the paired PC experiments are performed in which a homogenous ±2°C (±4°C, ±8°C) SST warming is "seen" by both the atmosphere and ocean in the extratropics (>|30°| latitude) and is then "carried" equatorward through both the atmospheric and oceanic bridges. The ocean and atmosphere is fully coupled within the tropics (<|30°| latitude), but partially coupled in the extratropics where the atmosphere is forced by mean seasonal cycle of heat flux from the CTRL plus a heat flux anomaly generated by the ±2°C (±4, ±8°C) SST anomaly. The CTRL run for these experiments is performed, in which the PC is also applied in the extratropics but without the anomalous SST forcing. With the PC technique, the tropical coupled variability cannot feed back to the extratropics, and in turn be affected by the contaminated extratropical forcings. Thus the tropical response can be thought as "purely passive" response. In general, our results show that the nonlinear response contributes less than 10% to the total forced response in the tropics, and it is also insensitive to the changes in external forcings' strength.

2. Tropical Response

[5] Extratropical climate change can affect the tropical climate significantly [*Liu and Yang*, 2003]. A warm (cold) SST in the extratropics can forces a upper ocean temperature warming (cooling) of about half its magnitude in the tropics (Figures 1a and 1b). The strong and deep equatorial response occurs because the extratropical impact on tropical climate is accomplished by both the atmospheric bridge of the Hadley cell and oceanic tunnel of the meridional overturning circulation.

[6] The tropical change related to the nonlinear processes can be estimated from the positive/negative pair experiments. Here we use P2, P4, P8 to represent the experiments forced by +2, +4, +8°C SST anomalies, and M2, M4, M8 to represent the −2, −4, −8°C cooling experiments, respectively. The residual of the sum [(P+M)/2] is thought to be associated with nonlinearity, while the difference between the warming and cooling experiments [(P−M)/2] is viewed

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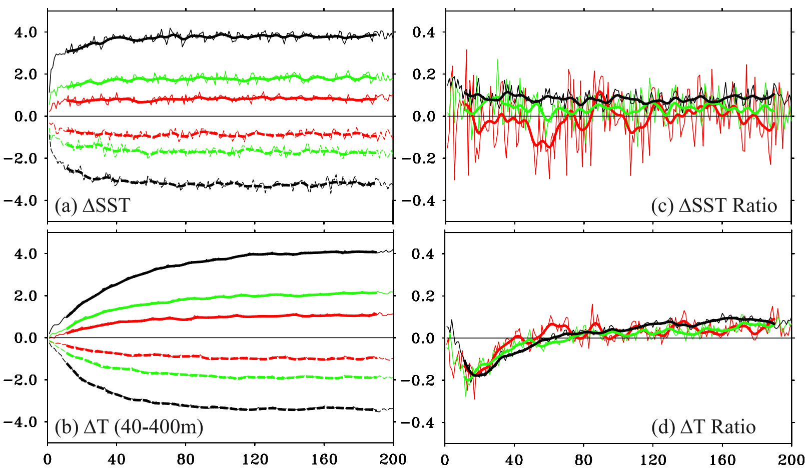

Figure 1. Evolution of the anomalous annual mean (a) SST, (b) upper ocean temperature (40–400m averaged), and the ratio of nonlinear to linear responses in (c) SST and (d) upper ocean temperature. The anomalies are obtained by removing the CTRL. The temperature is averaged globally within10°S–10°N. The black, green and red lines are for ±8, ±4, ±2°C experiments, respectively, in which the solid (dashed) lines are for warming (cooling) experiments. In Figures 1c and 1d, the ratio is obtained by dividing the nonlinear response with the linear part. The 21-year running mean are also plotted as thick lines.

as the linear response. Here it is assumed that (P+M) should be exactly zero if the ocean response to external forcings were totally linear. This is not a strict mathematical definition, though. It is a convenient way to quantify the nonlinear and linear responses in our simulations. The specific nonlinear processes are not our focuses in this work.

[7] The nonlinear response in the tropical temperature changes is less than 10% in general. This percentage contribution is obtained by dividing (P+M) by (P−M). For the tropical SST (Figure 1c), the time mean nonlinear response is nearly zero for P2 experiment. It is slightly increased to about 5–10% in P4 and P8 experiments. For the tropical subsurface temperature (Figure 1d), the nonlinear response is also generally within the range of 10%. It is not obvious that the nonlinear response would increase with enhanced external forcing, particularly for the subsurface ocean. It appears that the nonlinear response of the tropical oceanic temperature could be ignored in the long term large scale climate change based on our model.

[8] The response patterns in the tropical sea surface temperature exhibit a proportional increase in the magnitude with the enhanced extratropical forcing (Figure 2). The patterns also show an enhanced equatorial response in the Pacific and Atlantic, which is caused by the enhanced surface heat flux and suppression of equatorial upwelling [*Liu et al.*, 2005] as well as the reduced meridional advection. Figures 2a–2c represent the linear responses of the tropical SST to extratropical forcing. Similar to Figure 1c, the nonlinear response is very weak (Figure 2d–2f). For the 2°C forcing, the nonlinear response is about 5% of the linear part (Figure 2d). For the 4°C and 8°C forcings, the nonlinear response is slightly increased to 10–15% (Figures 2e and 2f). It is worth noting that the nonlinear response is zonally nonuniform in the tropics. It is larger in the western tropical Pacific, which may be related to the stronger horizontal oceanic current and the recirculation of equatorial overturning cells in the upper ocean there [*Liu et al.*, 1994].

[9] For the upper tropical oceans in general, the nonlinear response is less than 10% (Figure 3c). The zonal averaged temperature anomaly shows nearly symmetrical structures for P4 and M4 experiments (Figures 3a and 3b). This is also true for P2/M2 and P8/M8 experiments. The nonlinear response is smallest in the tropics but increasing at the higher latitudes. Despite being weak, the nonlinear response is worth investigating since it may disclose some subtle but important differences between the climate responses to global warming or cooling. The positive (negative) values in Figure 3c indicate that the ocean has a stronger response to the global warming (cooling). Intuitionally, a cooling in the ocean surface would increase the water density and thus should penetrate downward deeper, and eventually result in a bigger response in the ocean interior when compared to the situation forced by a surface warming. However, this cannot be taken for granted because the change in temperature also alters the three dimensional ocean circulation at the same time. Figure 3c shows that, for the Southern Hemisphere (SH) the extratropical cooling does induce bigger response in the ocean interior. However, for the Northern Hemisphere (NH) extratropics, the surface warming has bigger impact instead.

3. Mechanisms: Linear Versus Nonlinear

[10] Both the linear and nonlinear responses can be understood when taking into account the associated changes in the ocean circulation. An efficient way is to examine the oceanic meridional overturning circulation, for instance, the Pacific subtropical cells (STCs). The strength of annual mean STCs is weakened (enhanced) by about 20% in P4 (M4) experiment (Figures 4b and 4c), showing a nearly opposite change in STCs in response to the extratropical warming and cooling. This is also true in 2°C and 8°C experiments (figure not shown). The symmetric changes in STCs are particularly clear in the local equatorial cells within 10° of equator. The local tight cells form because

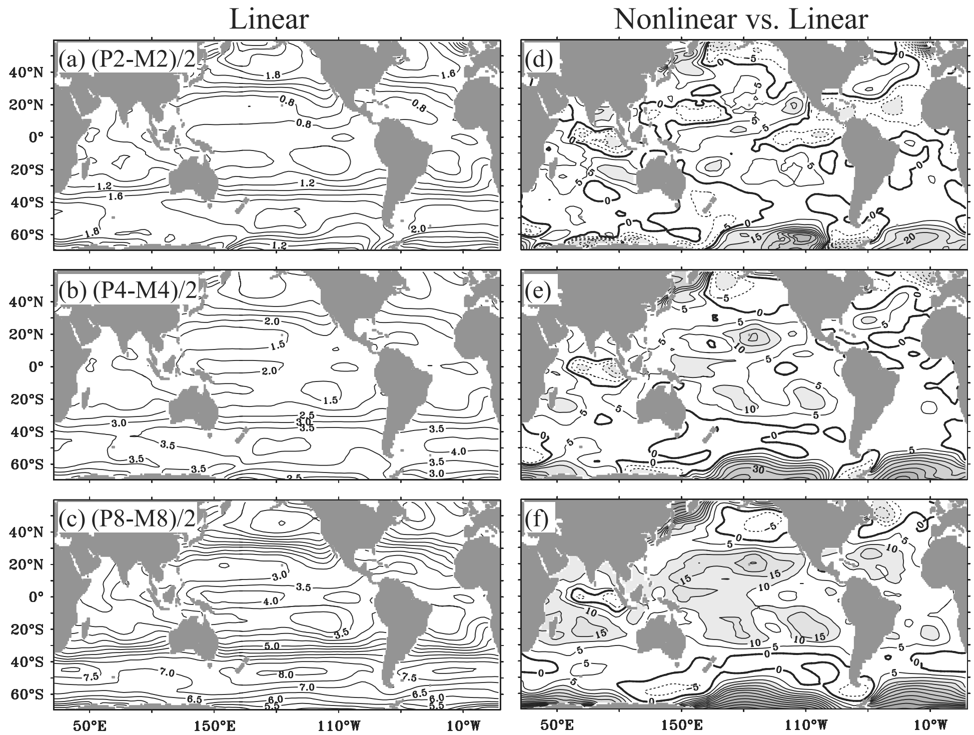

Figure 2. Linear response in SST (°C) for (a) ±2°C, (b) ±4°C and (c) ±8°C experiments. The SST is averaged in year 150–200 and that from CTRL is removed. Also shown are the ratio of nonlinear vs. linear for (d) ±2°C, (e) ±4°C and (f) ±8°C experiments (unit in %).

the equatorial subsurface cold water upwells and diverges poleward by means of Ekman drift under easterlies, and then descends near 10° due to the Ekman convergence. They recirculate in the upper 200 m of the equator and spiral on a depth-latitude plane in the zonal direction [*Liu et al.*, 1994], which play important roles in the dynamical control of the tropical temperature. The changes in STCs are closely related to the changes in the atmospheric Hadley cells, because the strength of the former depends closely on the wind stress in the subtropics [*McCreary and Lu*, 1994]. The Hadley cells are slowed down in the warming experiments, and so are the subtropical westerlies and the equatorial trade winds [*Yang and Liu*, 2005].

[11] In our experiments the tropical temperature change is typically controlled by the ocean dynamics as suggested by *Yang and Liu* [2005]. The surface heat flux forcing is important to drive the temperature change only in the transient stage of the externally forced change. In the equilibrium stage of climate change, the most direct factor maintaining the tropical temperature change arises mainly from the change in the ocean circulation, while the surface heat flux (only for SST) acts as a damping factor. This dynamical control of the tropical temperature is closely related to the STCs because, on the one hand, the extratropical surface anomaly can be transported equatorward through the STCs and causes changes in the tropical oceanic climate. On the other hand, the extratropics can also affect the tropics by changing the strength of the STCs without any anomalous water reaching the equator. The former is usually referred as the mean advection mechanism ($-vT'_y$) [e.g., *Gu and Philander*, 1997] while the latter is usually referred as the perturbation advection mechanism ($-v'T_y$) [*Kleeman et al.*, 1999; *Nonaka et al.*, 2002].

[12] The smallness of the nonlinearity in the tropical temperature changes is inferred from the fact that the linear components of the anomalous advection terms tend to be the same magnitude with opposite signs in the warming and cooling experiments. Due to the opposite changes of the STCs, the perturbation advections ($-v'T_y$, $-w'T_z$) are always opposite in sign in the warming and cooling experiments. Due to the opposite signs of the forcings in the source region, the mean advection ($-vT'_y$, $-wT'_z$) are also opposite in sign. Therefore, the residual of their sum is nearly zero. More specifically, for the NH tropical surface ocean, the v' and w' are negative (positive) in the warming (cooling) experiments due to the slowdown (speedup) of the STCs (Figures 4b and 4c). For the subsurface ocean, v' is positive (negative) and w' is negative (positive) in the warming (cooling) experiments. The temperature gradient T'_y and T'_z also have opposite signs in the warming and cooling experiments (Figures 3b and 3c). To quantify the contributions of the advection terms, we have analyzed the heat budget by calculating the terms in temperature anomaly equation following the approach of *Yang and Liu* [2005]. For each experiment, the anomalous advection is obtained by subtracting the corresponding term in CTRL. Then the time average of the final fifty years' results is analyzed.

[13] The small nonlinear response exists due to the nonlinear components of the anomalous advection ($-v'T'_y$, $-w'T'_z$). For the NH tropical surface, the meridional nonlinear advection $-v'T'_y$ tends to favor the cooling of the ocean in both the warming and cooling experiments, because both the v' and T'_y are negative (positive) in warming

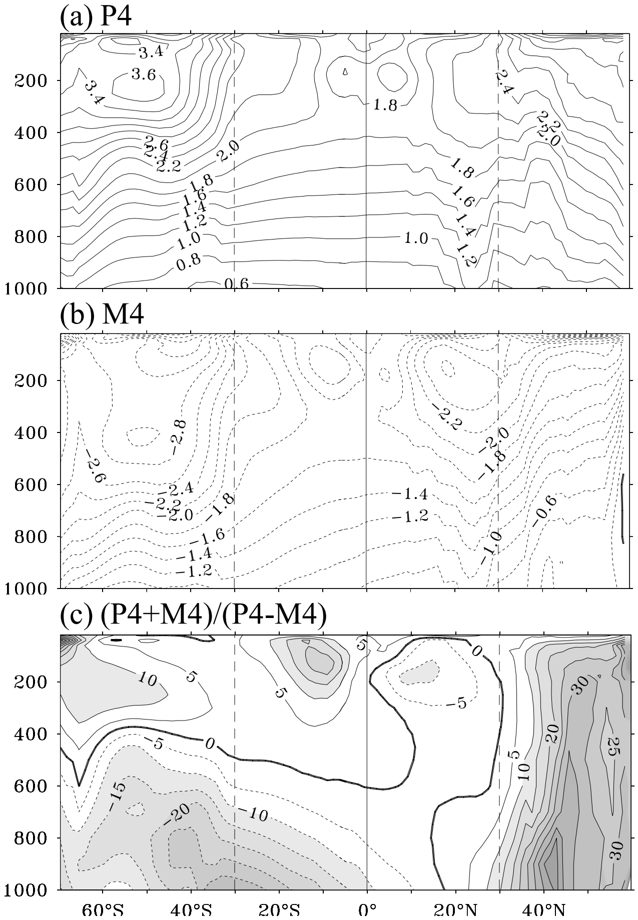

Figure 3. Zonal mean Pacific Ocean temperature for (a) +4°C, (b) −4°C experiments, and (c) the ratio of nonlinear vs. linear responses (unit in %). The temperature is averaged in year 150–200 and that from CTRL is removed.

(cooling) experiments. However, the vertical nonlinear advection $-w'T'_z$ is always in favor of the ocean warming because of the suppressed equatorial upwelling ($w' < 0$) and the enhanced vertical temperature gradient ($T'_z > 0$) in the warming experiments, and the exact contraries in the cooling experiments. The meridional nonlinear cooling can be compensated by the vertical nonlinear warming to some extent, but there is no guarantee that they will exactly cancel with each other. This situation is also true for the tropical subsurface ocean.

4. Summary and Discussion

[14] The tropical oceanic nonlinear response to extratropical forcing is explicitly pinpointed using a coupled climate model. The nonlinearity is widely thought to be important in many parts of ocean. But practically there is still lack of a quantitative estimate of the nonlinear response to the global climate change. Our experiments show that the nonlinear response in the tropical ocean is less than 10% of the extratropical forced tropical change. This is also confirmed by our global warming (cooling) experiments in which no PC technique is used and the model is forced only by increased (decreased) atmospheric CO_2 concentration. We analyze the heat budget in the double/half and quadruple/quarter CO_2 pair experiments. The nonlinear response in the tropical ocean is always very small and, furthermore, insensitive to the changing external forcings. It turns out to be a robust conclusion that in our coupled model the nonlinearity can be ignored in the tropical-extratropical climate interaction even all feedback processes are included as suggested in CO_2 experiments.

[15] The smallness of the tropical nonlinear response is mainly derived from the fact that the ocean circulation tends to change proportionally with the external forcings. The tropical ocean may be ‘‘less nonlinear’’ than the extratropical ocean in the sense of the lack of deep oceanic convection due to the stable vertical stratification. The nonlinear response exists because of the nonlinear anomalous advection, shallow convection and other processes. The tropical surface coupled wind-evaporation-SST feedback may also play a role [*Wu and Li*, 2007]. The nonlinear response to climate change can be substantial (about 20–30% of the linear part) in some regions, for example, the western boundary current region in the North Pacific, the Antarctic Circumpolar Current region along the coast of Antarctica (Figure 2f), and the intermediate and deep water in the mid- and high latitudes (Figure 3c). This occurs

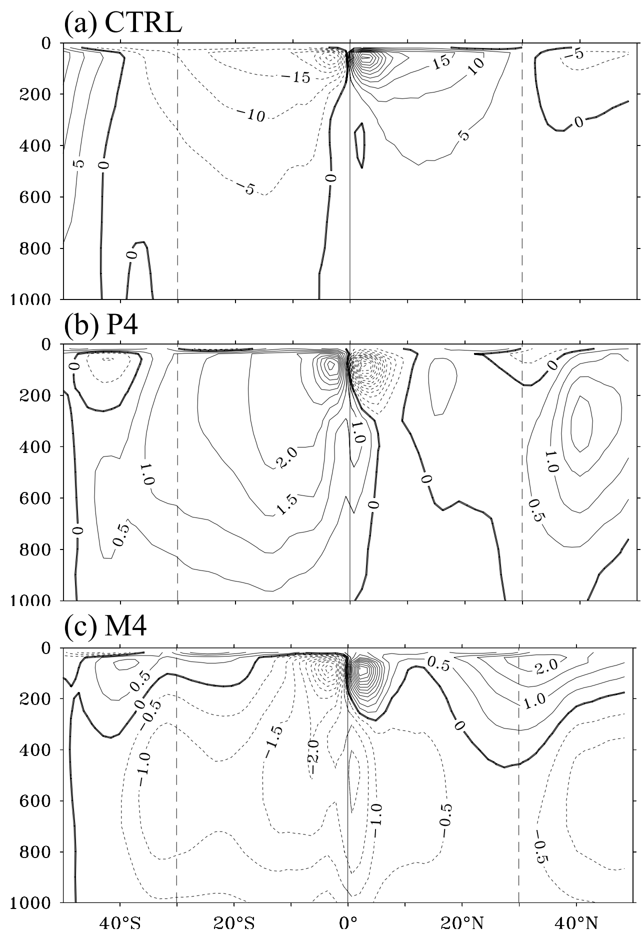

Figure 4. The mean meridional overturning circulation of the Pacific for (a) the CTRL and the changes in (b) +4°C and (c) −4°C experiments averaged in year 150–200 (unit in Sv, 1 Sv = $10^6 m^3/s$).

because of either strong horizontal currents or substantial change in the vertical ocean stability. The latter may be closely related to the changes in the open-ocean deep convection [*Kuhlbrodt and Monahan*, 2003] caused by strong anomalous surface heat flux. It is interesting to notice the anti-symmetrical responses in the extratropics below 400 m (Figure 3c), which exhibit a stronger response to surface cooling (warming) in the SH (NH) and imply a nonlinear sensitivity to the signs of the forcings [*Sutton and Hodson*, 2007]. A detail study on this is under the way.

[16] The quantitative estimate of nonlinearity in this work is only based on our coupled model. The nonlinear response could be substantially different in other climate models, since climate response or sensitivity could be very different in different models or in the same model with different resolutions. It also may depend on the climate regime or threshold of response [*Palmer*, 1999; *Yeh and Kirtman*, 2007]. However the estimate in this work may be practically useful in the global change research. For instance, it implies that the future mean oceanic climate change might be roughly assessable from a linear extrapolation of current climate.

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