Extratropical control of tropical climate, the atmospheric bridge and oceanic tunnel

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[1] A coupled ocean-atmosphere model study shows that the extratropical impact on tropical climate is as strong as the tropical impact on extratropical climate. A 2°C SST warming in the global extratropics increases equatorial ocean temperature by ~1°C in the surface and subsurface. The surface temperature change is caused by the atmospheric bridge of the Hadley circulation (70%) and the oceanic tunnel of thermocline subduction (30%), while the subsurface temperature change is forced predominantly through the oceanic tunnel. Furthermore, the dominant influence on the equator comes from the southern hemisphere atmosphere and ocean. *INDEX TERMS:* 1635 Global Change: Oceans (4203); 1620 Global Change: Climate dynamics (3309); 1610 Global Change: Atmosphere (0315, 0325). **Citation:** Liu, Z., and H. Yang, Extratropical control of tropical climate, the atmospheric bridge and oceanic tunnel, *Geophys. Res. Lett.*, *30*(5), 1230, doi:10.1029/2002GL016492, 2003.

1. Introduction

[2] The tropics has long been recognized as crucial for global climate because of its global impact through atmospheric teleconnections [e.g., *Lau*, 1997]. It, however, is still unclear how much the tropical climate itself is controlled by climate forcing from outside the tropics. In principle, the extratropics can influence the tropics through the atmospheric bridge of the Hadley circulation and the oceanic tunnel of thermocline subduction. The magnitude of this influence and the relative contributions of the atmospheric and oceanic tunnels, however, have remained uncertain. Previous work on extratropical-tropical interaction has been carried separately either in an atmosphere model that is decoupled from full ocean dynamics [*Lau*, 1997; *Barnett et al.*, 1999] or in an ocean model that is decoupled from full atmospheric dynamics [*Gu and Philander*, 1997; *Liu*, 1998]. These approaches, although useful for understanding the dynamics of each bridge, are inadequate for assessing the full extratropical impact on the tropics. Here, we present a first assessment of the extratropical impact on the tropics as well as the relative contribution of the atmospheric bridge and oceanic tunnel by using a coupled ocean-atmosphere model.

[3] We use the Fast Ocean Atmosphere Model (FOAM). Its atmosphere component (R15) is a parallel version of the NCAR-CCM2 and its ocean component (1.4° × 2.8° × 32-level) was developed following the GFDL-MOM. FOAM captures most major features of the observed climate [*Jacob*, 1997]. Without flux adjustment, the control simulation (CTRL) has been integrated for over 1000 years, showing no apparent climate drift. Experiments are performed to study the sensitivity of tropical climate to extratropical climate forcing, which is taken as a 2°C global SST warming. This idealized SST anomaly can be thought as a possible SST change similar to the scenarios of future global warming or past glacial cooling. All the experiments start from the 800th year of the CTRL and are integrated for 150-years, when the upper ocean has reached a quasi-equilibrium.

2. Extratropical Impact on Tropical Climate

[4] To assess the full impact of the extratropical forcing on tropical climate, we performed a ‘‘partial coupling’’ experiment (Atmosphere Bridge/Oceanic Tunnel: ABOT) in which a 2°C SST anomaly is ‘‘seen’’ by both the atmosphere and ocean in the global extratropics (>|30°| latitude) and is then ‘‘carried’’ equatorward by both the atmospheric bridge and oceanic tunnel. Specifically, the ocean and atmosphere in ABOT remain fully coupled within the global tropics (<|30°| latitude), but become only partially coupled in the extratropics. There, the atmosphere is forced by the heat flux that is calculated based on the prescribed SST seasonal cycle of the CTRL plus 2°C; the atmospheric variables are then used to calculate the fluxes of heat, freshwater and momentum at each time step (through the coupler with the model SST) to force the ocean, but the prescribed SST is still given to force the atmosphere. After the onset of the extratropical warming, equatorial SST increases rapidly by ~0.5°C in the first year and reaches a quasi-equilibrium after several decades (Figure 1a). The final SST warming is ~0.9°C (Figure 1a), distributing largely uniform in the tropics (Figure 2b1). In comparison, subsurface temperature increases gradually, especially in the first 50 years (Figure 1b). The final upper ocean temperature warms about the same as the SST (~0.9°C) (Figure 1b), reflecting a deep equatorial warming (Figure 2b2). Therefore, a warm SST in the extratropics forces a tropical SST warming of about half its magnitude, representing a significant extratropical control on tropical climate.

[5] The extratropical impact on tropical climate is as strong as the tropical impact on extratropical climate. This can be seen in a complementary experiment, T-ABOT, in which the regions of full coupling and partial coupling of ABOT are swapped such that the ocean and atmosphere remain fully coupled in the extratropics, but both ‘‘see’’ a 2°C SST warming in the global tropics. The extratropical SST is warmed finally by ~0.9°C in T-ABOT (Figure 1a

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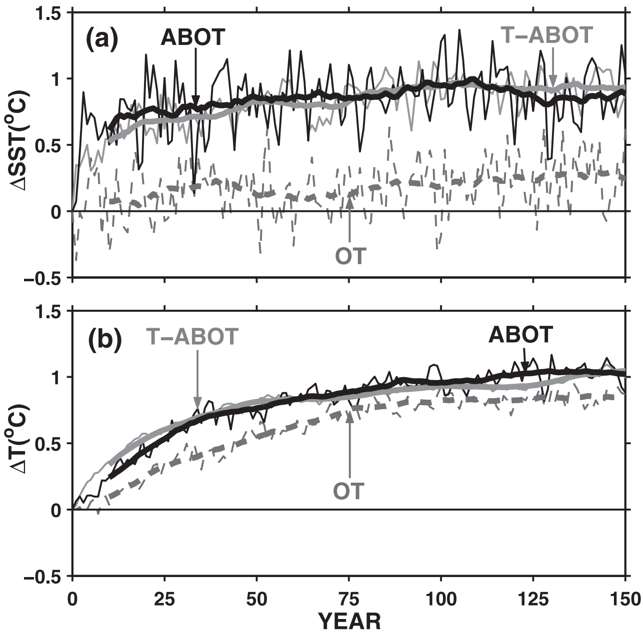

Figure 1. Evolution of anomalous annual mean (a) SST and (b) upper ocean (40–400 m average) temperature in ABOT (solid black), T-ABOT (solid grey) and OT (dash grey). The temperatures are averaged globally from latitude 0° to 30° for ABOT and OT, and 30° to 70° for T-ABOT. The 21-year running mean is also plotted for each curve as the heavy lines. The SST averaged in the last 50-year is increased ~0.9°C for ABOT and T-ABOT, and ~0.27°C for OT. (99% confidence level 0.09°C). The anomaly in each experiment is relative to its own control run, which has the identical setting as the respective partial coupling sensitivity experiment except for the absence of a SST anomaly on the prescribed seasonal cycle of CTRL.

and Figure 2c1), comparable with the tropical warming in ABOT.

3. Atmospheric Bridge and Oceanic Tunnel

[6] The extratropical impact on tropical SST in ABOT is accomplished by both the atmospheric bridge and oceanic tunnel. In the atmosphere, the increased extratropical SST reduces the latitudinal SST gradient, weakening the Hadley circulation [*Held and Hou*, 1980] (Figures 3a and 3b). The weaker Hadley circulation reduces the surface wind convergence towards the Intertropical Convergence Zone (ITCZ) and in turn the cloud cover, increasing shortwave radiation; it also weakens the equatorial trade wind and in turn the local upwelling. The Hadley circulation is weakened mainly in the southern branch (by 10%, Figures 3a and 3b), because of the hemispheric asymmetry of the tropical climate. The ITCZ is located north of the equator, which makes the changes in the southern Hadley circulation more effective in influencing the equatorial climate. In the ocean, the warm extratropical SST anomaly subducts equatorward (Figure 2b2), and eventually upwells on the equator [*Liu*, 1998]. The oceanic subduction occurs at decadal time scales, while the atmospheric adjustment at monthly time scales. This leads to the speculation from the SST evolution in ABOT (Figure 1a) that the rapid initial

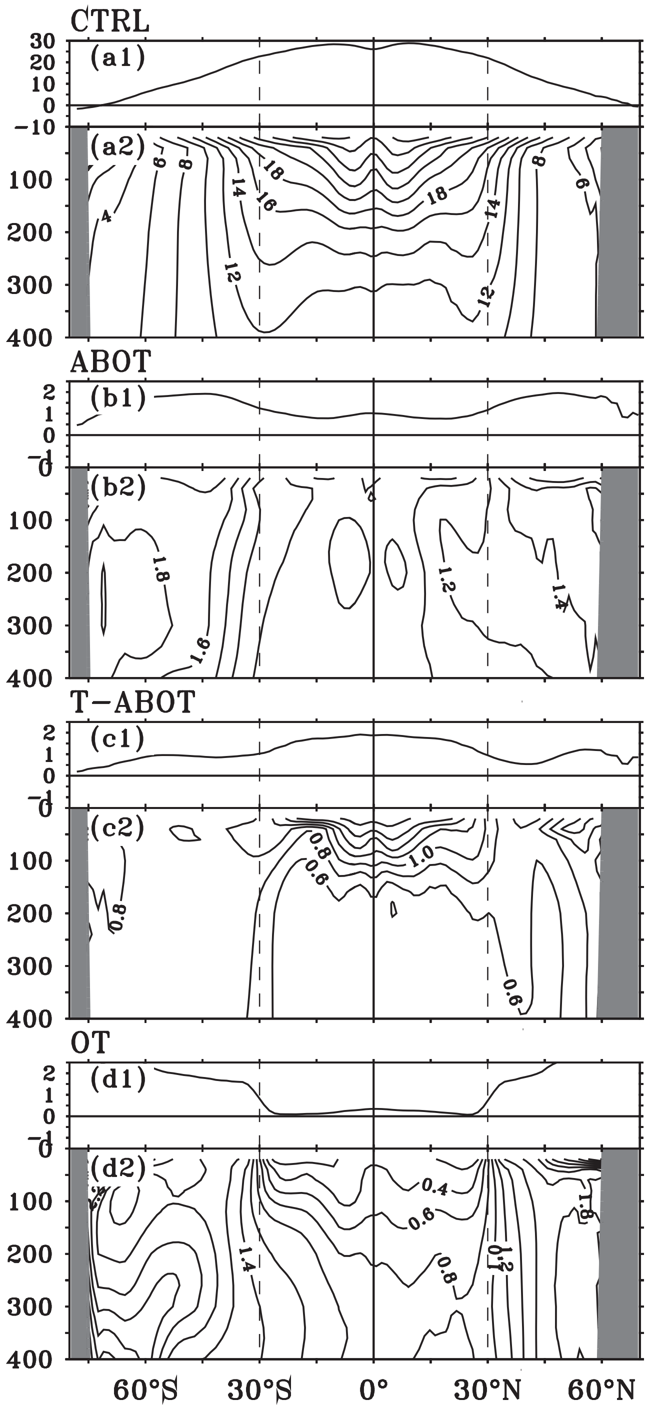

Figure 2. Zonal mean Pacific Ocean temperature averaged in year 100–150 for (b) ABOT simulation, (c) T-ABOT simulation and (d) OT simulation. For reference, the total temperature is also plotted for CTRL in (a). In each panel, the upper figure (a1, b1, c1, d1) shows the (a) total or (b–d) anomalous zonal mean SST (solid), while the lower figure (a2, b2, c2, d2) shows the meridional section of zonal mean ocean temperature. (Contour intervals are 2°C in (a) and 0.2°C in (b)–(d)). The equatorward subduction signal is clearly seen in OT, but less clearly in ABOT because of the surface atmosphere forcing. The poleward near-surface ocean temperature anomaly is confined to the mid-latitude in T-ABOT. The plot for the world ocean is similar to the Pacific here.

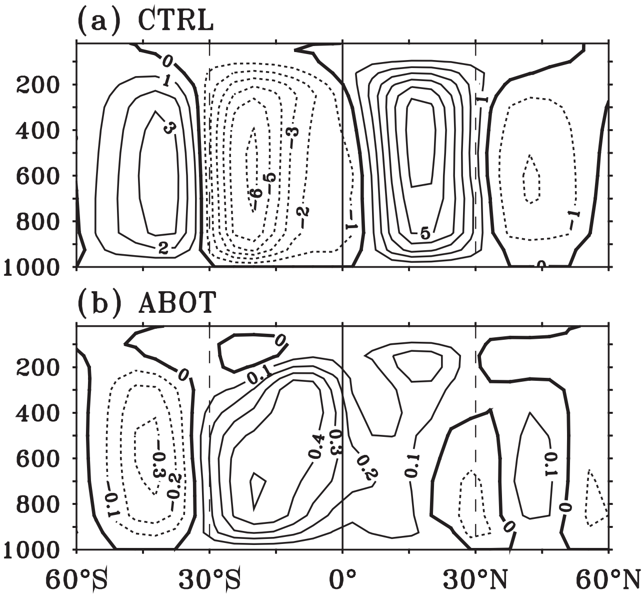

Figure 3. The meridional streamfunction of the atmosphere for (a) the CTRL and (b) the difference of ABOT and its control. The latter shows a reduction of the Hadley circulation by about 10% in the southern hemisphere. (Contour intervals are 1×10^{10} Kg/s in (a) and 0.1×10^{10} Kg/s in (b)).

warming (~0.5–0.6°C) is caused mainly by the atmospheric bridge while the gradual later warming (~0.3–0.4°C) by the oceanic tunnel.

[7] This effect of the oceanic tunnel is quantified with an additional experiment OT, which is the same as ABOT except for a modified partial coupling in the extratropics. There, the surface ocean is restored towards the prescribed SST seasonal cycle of CTRL plus 2°C, while the atmosphere is forced by the prescribed SST seasonal cycle of CTRL only. As such, only the ocean "sees" a 2°C SST warming and therefore contributes to the equatorward teleconnection of extratropical SST anomaly. Now, the equatorial SST increases gradually, becoming statistically significant (at 99% level) after 20–30 years (Figure 1a). The final equatorial SST warms ~0.27°C. This accounts for ~30% of the final SST warming in ABOT, implying a remaining 70% contribution from the atmospheric bridge.

[8] The effect of ocean subduction is seen in the final Pacific temperature change in ABOT (Figure 2b2), or more clearly in OT (Figure 2d2), which show a pair of subsurface warm tongues penetrating equatorward and upward, particularly clear from the south. The implied stronger oceanic contribution from the south is expected, because the northern influence is weakened by the ITCZ wind forcing [*Lu et al.*, 1998] and the Indonesia Throughflow [*Rodgers et al.*, 1999]. In the equatorial upper ocean, the temperature anomaly decreases upward towards the surface in OT (Figure 2d2), but decreases downward towards the subsurface in ABOT (Figure 2b2), because the SST is warmed from below through the oceanic tunnel in OT, but mainly from above by the atmospheric bridge in ABOT. The oceanic tunnel, although responsible for only a part of the equatorial SST warming, dominates the subsurface warming. Indeed, over 80% of the subsurface warming in ABOT can be accounted for by that in OB (Figure 1b), while the effect of surface atmospheric forcing is prohibited penetrating deep by the equatorial oceanic upwelling.

[9] In contrast to the important equatorward oceanic tunnel in ABOT and OT, the poleward oceanic teleconnection in T-ABOT is ineffective. Physically, this poleward teleconnection consists mainly of the surface Ekman flow, which tends to generate near-surface temperature anomaly tongues towards the mid-latitude, which, however, are easily damped by strong negative air-sea feedback, as seen in T-ABOT at about 30–35° (Figure 2c2). Instead, the poleward impact in T-ABOT is accomplished by the atmosphere which causes extratropical temperature changes in both the surface and subsurface (Figure 2c). Because of the deep oceanic mixed layer in the mid- and high- latitude (Figure 2a2), the atmospheric impact on the extratropical surface is mixed into the subsurface, delaying the surface warming, but increasing the subsurface warming. Thus, relative to the tropical warming in ABOT, the initial extratropical warming in T-ABOT is slower on the surface (Figure 1a) but faster in the subsurface (Figure 1b).

4. Summary and Implications

[10] Using a coupled climate model, we found that the extratropical control of tropical SST is as strong as the tropical control of extratropical SST, with the remote SST response being about half the magnitude of the imposed SST forcing. Furthermore, the extratropics affects equatorial SST through the atmospheric bridge by 70% and through the oceanic tunnel by 30%, and the extratropics control the subsurface temperature predominantly by the oceanic tunnel. This is in contrast to the tropical influence on the extratropics, which is accomplished mainly by the atmospheric bridge. These conclusions have important implications for the study of global climate changes.

[11] Our study suggests that the extratropics can exert a strong control on tropical climate, including even the climate of the western Pacific warm pool. Indeed, the tropical warming in ABOT and OT is almost uniform along the equator (not shown). Therefore, climate changes in the tropics should consider not only the feedbacks within the tropics [e.g., *Ramanathan and Collins*, 1991], but also those from the extratropics.

[12] Our simulation implies a stronger extratropical influence on the tropical climate from the southern hemisphere. This is consistent with recent glacial climate simulations in the NCAR CSM [*Liu et al.*, 2002]. In addition to the dynamic mechanisms discussed earlier, the larger area of ocean in the southern hemisphere also favors the stronger southern control. This stronger southern control may shed light on paleoclimate records that the tropical temperature evolves synchronously with the Antarctic air temperature and atmospheric CO_2, but leads the northern hemisphere continental ice volume and Greenland air temperature [*Shackleton*, 2000].

[13] The disparity of the time scales of the equatorward atmospheric bridge and oceanic tunnel also implies an extratropical control on the stratification of the equatorial thermocline, especially for extratropical climate forcing at interdecadal or longer time scales. This change of equatorial

thermocline gradient may modulate tropical climate variability such as ENSO.

[14] This work provides a first estimate of the extratropical influence on the tropics as well as a framework of quantifying atmospheric and oceanic processes in extratropical-tropical interactions in coupled models. The robustness of our estimate, however, needs to be tested with other models. Furthermore, more realistic anomalous SST forcings are needed to assess the role of the teleconnections for the observed climate change and climate variability.

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