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Supporting Information for

Connecting Tropical Climate Change with Southern Ocean Heat Uptake

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Introduction

This supporting information includes supplementary Text S1 and Figures S1 to S2. Text S1 describes the derivation of SST diagnostic equation (Eq.2 in the main text), using mixed layer energy budget analysis and the bulk formula for evaporation. Figure S1 shows the changes in surface flux in the idealized slab ocean experiments and the CMIP5 fully coupled models. Figure S2 demonstrates the time series of zonal mean SST after quadrupling CO_2.

Text S1.
SST diagnostic equation derivation

In order to understand the cause of the east-west asymmetry, we perform an energy budget analysis of the mixed layer ocean. As described in the main text, the mixed layer energy budget can be written as

$$\rho C_p H \frac{\partial T}{\partial t} = Q'_{sw} + Q'_{lw} + Q'_{lh} + Q'_{sh} + O' \qquad \text{(Eq.S1)}$$

(Xie et al. 2010; Deser et al. 2010). The term on the left hand side is the storage term (or the tendency term), which is very close to zero in the quasi-equilibrium tropics. ρ is density, C_p is the specific heat of seawater, H is mixed layer depth, and $\frac{\partial T}{\partial t}$ is temperature tendency. The right hand side includes all of the factors that would affect the mixed layer energy budget: net longwave radiation (Q_{lw}), net shortwave radiation (Q_{sw}), latent heat flux (Q_{lh}), sensible heat flux (Q_{sh}), and the contribution from ocean dynamics (O), including advection, diffusion, and vertical mixing. Downward fluxes are defined as positive, which heat the mixed layer ocean. In the slab ocean setting, the changes of oceanic heat advection, the last term O, is zero. The prime symbol (') refers to changes between the two quasi-equilibrium states: the average over years 10-19 after quadrupling CO_2 minus the 50-year climatology.

The changes of net longwave radiation (Q'_{lw}) and sensible heat flux (Q'_{sh}) are small. We can further decompose the two main terms:

$$Q'_{sw} = Q'_{sw,clr} + Q'_{sw,cld}, \qquad \text{(Eq.S2)}$$

where $Q'_{sw,clr}$ is the changes of shortwave radiation at the surface in clear sky and $Q'_{sw,cld}$ is changes of shortwave cloud radiative forcing at the surface.

In the tropics, latent heat flux is mostly due to evaporation. Following the standard bulk formula for evaporation,

$$Q'_E = L_v C_E \rho_a W(q_s - q_a) = L_v C_E \rho_a W[q_s(T) - RH \bullet q_s(T+\Delta T)], \qquad \text{(Eq.S3)}$$

we decompose the changes of latent heat flux Q'_{lh} as (see Jia and Wu 2012):

$$Q'_{lh} \cong -Q'_E = -\frac{\partial Q_E}{\partial T}T' - \frac{\partial Q_E}{\partial W}W' - \frac{\partial Q_E}{\partial RH}RH' - \frac{\partial Q_E}{\partial \Delta T}\Delta T', \qquad \text{(Eq.S4)}$$

where Q_E is evaporation, L_v is the latent heat of evaporation, C_E is the transfer coefficient, ρ_a is the surface air density, T is sea surface temperature, W is the surface wind speed, RH is the surface humidity, and $\Delta T = T_a - T$, T_a is the surface air temperature. The four terms on the right hand side are changes in latent heat flux related with Newtonian cooling, changes in wind, changes in humidity, and changes in stability, respectively. The more detailed expressions are as follow:

$$Q'_{E,SST} = \frac{\partial Q_E}{\partial T}T' = \alpha \overline{Q}_E T',$$

$$Q'_{E,W} = \frac{\partial Q_E}{\partial W}W' = \frac{\overline{Q}_E}{\overline{W}}W',$$

$$Q'_{E,RH} = \frac{\partial Q_E}{\partial RH}RH' = \frac{-\overline{Q}_E}{e^{-\alpha\overline{\Delta T}} - \overline{RH}}RH',$$

$$Q'_{E,\Delta T} = \frac{\partial Q_E}{\partial \Delta T}\Delta T' = \frac{-\alpha\overline{Q_E RH}}{e^{-\alpha\overline{\Delta T}} - \overline{RH}}\Delta T', \qquad \text{(Eq.S5)}$$

where $\alpha = L_v/(R_v T^2)$ is assumed to be a constant 0.06 K^{-1}, with R_v being the gas constant for moist air. Note that the changes and the climatological values of each month are considered separately.

We can substitute Eq.S5 to Eq.S1:

$$Q'_{sw,cld} + Q'_{sw,clr} + Q'_{lw} - \alpha\overline{Q_E}T' - Q'_{E,W} - Q'_{E,RH} - Q'_{E,\Delta T} + Q'_{sh} = 0, \quad \text{(Eq.S6)}$$

and obtain a diagnostic equation for changes in SST:

$$T' = \frac{Q'_{sw,cld} + Q'_{sw,clr} + Q'_{lw} - Q'_{E,W} - Q'_{E,RH} - Q'_{E,\Delta T} + Q'_{sh}}{\alpha\overline{Q_E}} \quad \text{(Eq.S7)}$$

This diagnostic equation interprets the SST pattern as a forced response problem. In our quasi-steady slab ocean analysis, the numerators can be understood as atmospheric forcings, including changes in shortwave cloud radiative forcing, changes in shortwave in clear sky, changes in longwave radiation, changes in evaporation due to variations in wind, relative humidity, or near surface stability, and changes in sensible heat flux. The denominator is the Newtonion cooling coefficient, $\alpha\overline{Q_E}$, which captures the ocean's ability to limit SST warming by evaporation. The climatological evaporation is the same between the *deepSO* and the *control* experiments and contributes very little to the east-west SST gradient. Thus, we demonstrate the results in the following form:

$$\begin{aligned} T' &= \frac{Q'_{sw,cld}}{\alpha\overline{Q_E}} + \frac{Q'_{sw,clr}}{\alpha\overline{Q_E}} + \frac{Q'_{lw}}{\alpha\overline{Q_E}} + \frac{-Q'_{E,w}}{\alpha\overline{Q_E}} + \frac{-Q'_{E,RH}}{\alpha\overline{Q_E}} + \frac{-Q'_{E,\Delta T}}{\alpha\overline{Q_E}} + \frac{Q'_{sh}}{\alpha\overline{Q_E}} \\ &= T'_{sw,cld} + T'_{sw,clr} + T'_{lw} + T'_{lh,w} + T'_{lh,RH} + T'_{lh,\Delta T} + T'_{sh}\,. \end{aligned} \quad \text{(Eq.S8)}$$

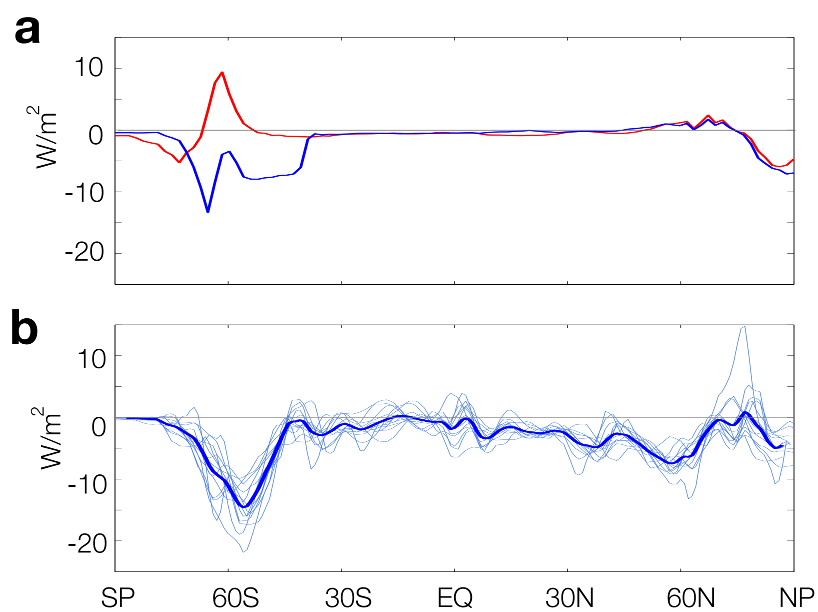

Figure S1. Surface flux changes. Zonal mean upward surface flux changes (year 10~19 after quadrupling CO_2 minus the 20-year average pre-industrial climatological condition before increasing CO_2) in *control* (red) and *deepSO* (blue) experiments **(a)** and *abrupt4xCO*$_2$ experiments in CMIP5 **(b)**. Each line is one model and multi-model means are in bold. Note this plot is qualitatively similar to Figure A1(a) in Rose et al. 2014.

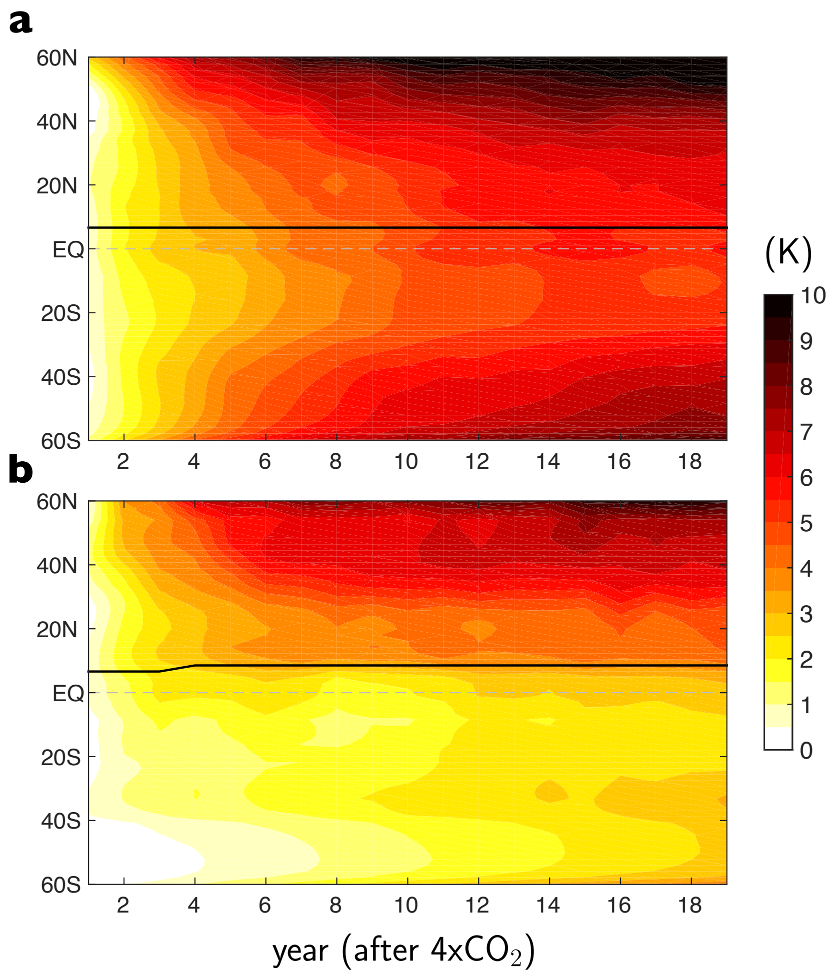

Figure S2. Zonal mean SST response (K) as a function of latitude and time after instantaneously quadrupling CO_2. Anomalous zonal mean SST relative to the 20-year average before quadrupling CO_2 in *control* **(a)** and *deepSO* **(b)** experiments. Black lines mark the latitudes of maximum annual mean precipitation.