Supplementary information for "Control of land-ocean temperature contrast by ocean heat uptake"

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1 Description of the energy balance model

The two-box Energy Balance Model (EBM) used in this paper simulates the response of global ocean and land temperatures to anomalous tropopause radiative fluxes caused by climate forcings. One box represents global ocean and the atmosphere above; the other box represents global land and the atmosphere above. Each box has a temperature anomaly with respect to unperturbed conditions, ΔT, a heat capacity, c, and a climate sensitivity parameter, λ, that determines the strength of upward climate response radiative fluxes as a linear function of temperature. We use the subscripts O and L to represent ocean and land values respectively. ΔA represents the anomalous flow of heat from land to ocean, and is proportional to the temperature difference between them. The land-ocean heat exchange term, $\Delta A = \beta(\Delta T_L - \Delta T_O)$, is based on those used by *Murphy*, [1995] and *Rowntree*, [1998]. A schematic diagram of the EBM is presented in Figure S1.

ΔT_O is given by

$$\Delta Q - \frac{\Delta T_O}{\lambda_O} + \frac{\beta}{1-f}(\Delta T_L - \Delta T_O) = c_O \frac{dT_O}{dt}, \tag{1}$$

where ΔQ is the radiative forcing due to external factors, $\frac{\beta}{1-f}(\Delta T_L - \Delta T_O)$ is the anomalous atmospheric land-ocean heat transport, f is the land fraction and $c_O \frac{dT_O}{dt}$ is the ocean heat uptake. ΔT_L is given by

$$\Delta Q - \frac{\Delta T_L}{\lambda_L} - \frac{\beta}{f}(\Delta T_L - \Delta T_O) = c_L \frac{dT_L}{dt}, \tag{2}$$

where $c_L \frac{dT_L}{dt}$ is the land heat uptake. For simplicity, we assume that ΔQ is the same over both land and ocean, and that atmospheric heat capacity is negligible on annual and longer timescales. Multiplying equation 1 by the ocean fraction, $(1 - f)$, multiplying equation 2 by the land fraction, f, and adding, the land-ocean heat flux terms cancel and we find an equation for global energy balance.

2 Set up of energy balance model experiments

We integrate equations 1 and 2 forward in time from 1955-2003 numerically, taking values of ΔQ calculated by the GISS model. We run the model for a wide range of parameter values. Because we do not have observed estimates of possible λ_O and λ_L, we calculate ranges from our observed estimate of ϕ and the global climate sensitivity parameter, λ, estimate of *Forster and Gregory*, [2006]. The null hypothesis is that ϕ is not maintained constant, but remains close to its equilibrium value as a consequence of ΔQ, λ_O, λ_L, ΔU_O and ΔU_L. Subtracting equation 2 from 1 and dividing by ΔT_O, we derive an expression relating β, λ_O and λ_L:

$$\beta = \frac{f(1-f)}{(\phi - 1)}\left(\frac{1}{\lambda_O} - \frac{\phi}{\lambda_L}\right). \tag{3}$$

λ_L and λ_O are related to λ via $\frac{1}{\lambda} = (1-f)\frac{1}{\lambda_O} + f\frac{1}{\lambda_L}$. Specifying β from GCM data, we determine λ_O and λ_L using our estimates of ϕ and Forster and Gregory's estimates of λ. Hence, we use observed ϕ to estimate parameter values of equations 1 and 2 consistent with the real world, but do not hold ϕ constant while running the EBM.

3 Global land-ocean temperature contrast

Table S1 in the main paper shows values of ϕ, ϕ', r and r_5 for observations and GCMs, where the GCM data are masked so that only values for which there are equivalent observations are considered. Here, we present GCM results for full global coverage, Table S1.

ϕ and ϕ' are closer to unity and slightly less uncertain than for masked data. Values of r are generally less than for masked data, but values of r_5 are similar.

4 Effective ocean heat capacity

It is difficult to rule out a role for an adaptive ocean heat capacity, c_O, in maintaining constant ϕ. (If c_O is smaller on shorter timescales, then the ocean could respond rapidly to rapid changes in forcing.) Modeling ocean heat uptake as $\Delta U_O = \gamma \Delta T_O + c_O \frac{dT}{dt}$, we regress values of ΔU_O against ΔT_O and $\frac{dT}{dt}$ filtered on various timescales in four models. Estimates of γ and c_O on below 5-year, 5-10 year and 10-20 year timescales are presented in Table S2 for model ensemble means for 1901-97. A summary of c_O values is also shown in Figure S2.

As stated in the main text, estimates of c_O on below 5-year timescales are lower than on 5-10 year timescales. However, 5-10 year values are consistent with 10-20 year values. This does not mean that changes in c_O do not assist in the maintenance of constant ϕ. However, such changes are not readily detectable using a simple regression method, because the ocean heat uptake time series contain significant variations unrelated to temperature change.

5 References

Forster, P.M. de F. and J.M. Gregory, The Climate Sensitivity and Its Components Diagnosed from Earth Radiation Budget Data, *J. Clim., 19*, 39–52, 2006.

Murphy, J.M., Transient Response of the Hadley Centre Coupled Ocean-Atmosphere Model to Increasing Carbon Dioxide. Part III: Analysis of Global-Mean Response Using Simple Models, *J. Clim, 8*, 496–514, 1995.

Rowntree, P., Global average climate forcing and temperature response since 1750, *Int. J. Climatol., 18*, 355–377, 1998.