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Influence of Meridional Overturning Circulation on Ocean Heat Storage Rate in an Idealised Climate Model

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Mathematics of Planet Earth

Abstract

To study the role of the Atlantic meridional overturning circulation (AMOC) in climate change, we perform an abrupt CO_2-doubling experiment using a coupled atmosphere-ocean-ice model with a simple geometry that separates the ocean into small and large basins. As in observations and high-end climate models, the small basin exhibits a MOC and warms at a faster rate than the large basin. In our set-up, this contrast in heat storage rates is 0.6 ± 0.1 W m^{-2}, and we argue that this is due to the small basin MOC. However, the MOC weakens significantly, yet this has little impact on the small basin's heat storage rate. We find this is due to the effects of both compensating warming patterns and interbasin heat transports. Thus, although the presence of a MOC is important for enhanced heat storage, MOC weakening is surprisingly unimportant.

1. Introduction

The vast majority (~ 93%) of the excess energy resulting from Earth's energy imbalance (EEI) manifests as an increase in ocean heat content (OHC)[1]. In observations and in CMIP5 models (Figure 1), the Atlantic warms at a faster rate and stores heat to greater depths relative to the Pacific. It is thought that this is due to the presence of the Atlantic's meridional overturning circulation (AMOC). The depth and strength of the AMOC positively correlates with the depth of global ocean heat storage (OHS) across CMIP5 models[2] and its multidecadal variability has been linked to periods of enhanced global surface warming and cooling[3]. Observations point to the AMOC having weakened since the mid-twentieth century, and it is unknown how this weakening response will affect ocean heat storage as the world continues to warm. To this end, we examine the abrupt CO_2-doubling response of a general circulation model with idealised geometry that separates the ocean into small and large basins. The small basin exhibits an overturning circulation akin to the AMOC, while the large basin does not. By focussing on small–large basin differences, we isolate the effect of the small basin MOC.

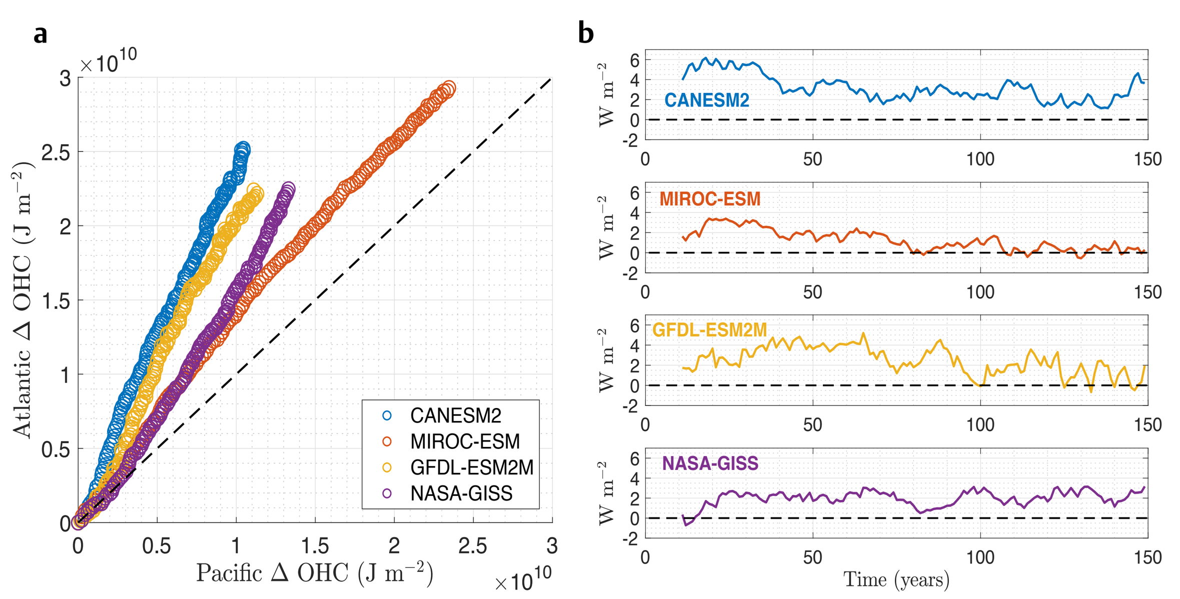

Figure 1. (a) Atlantic vs. Pacific top-3 km column-averaged annual OHC anomalies (in J m^{-2}) following an abrupt quadrupling of atmospheric CO_2 in four CMIP5 models. Atlantic and Pacific basins defined from 30°S to 65°N. The deviation from the identity line (black dashed) highlights the Atlantic's enhanced warming rate relative to the Pacific in these experiments. (b) Decadal running means of individual model Atlantic–Pacific heat storage contrasts $\partial/\partial t(\Delta OHC_{Atl} - \Delta OHC_{Pac})$ (in W m^{-2}).

2. Model set-up

- Coupled atmosphere-ocean-ice model using the MIT general circulation model code (MITgcm)[4] on a cubed-sphere grid
- Aquaplanet: flat-bottomed ocean of constant depth (3 km) split into 15 levels with increasing vertical resolution
- Meridional barriers extending from the North Pole to 35°S split the ocean into small and large basins
- System is perturbed by a step-function doubling of atmospheric CO_2 and run for 200 years

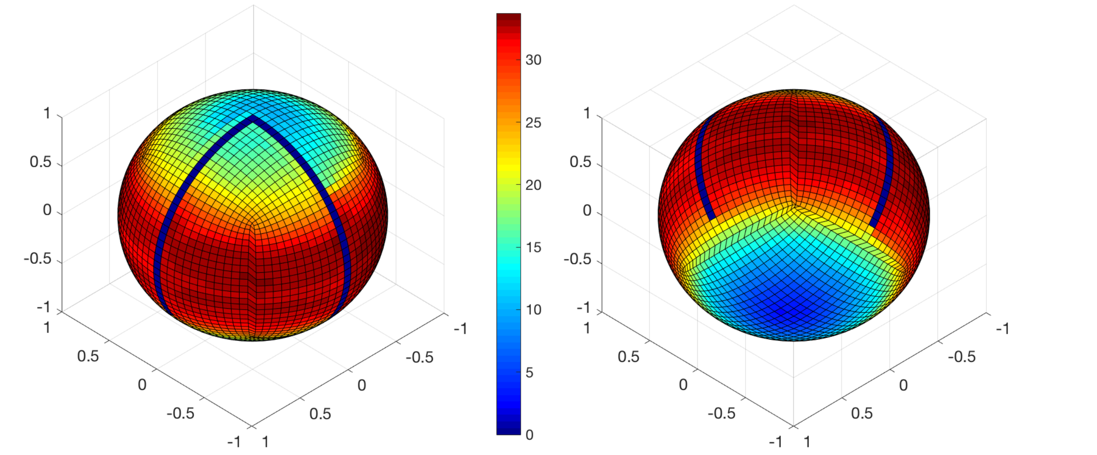

Figure 2. Model geometry showing the 'Double Drake' (DDrake) configuration[5], whereby two meridional barriers (dark blue) set 90° apart extend from the North Pole to 35°S, splitting the ocean up into small and large basins. Colour represents annual mean SST (°C) in the control equilibrium climate state.

3. Results

The small basin warms at a faster rate than the large basin (Figure 3a, b). Taking the difference between their heat storage rates gives us the heat storage contrast, which has a time-mean value of 0.6 ± 0.1 W m^{-2} (Figure 3c). The contrast shows no discernible trend over the 200 years. Furthermore, the small basin MOC strength rapidly weakens during the first 30 years (Figure 3d) having little, if any, impact on the heat storage contrast.

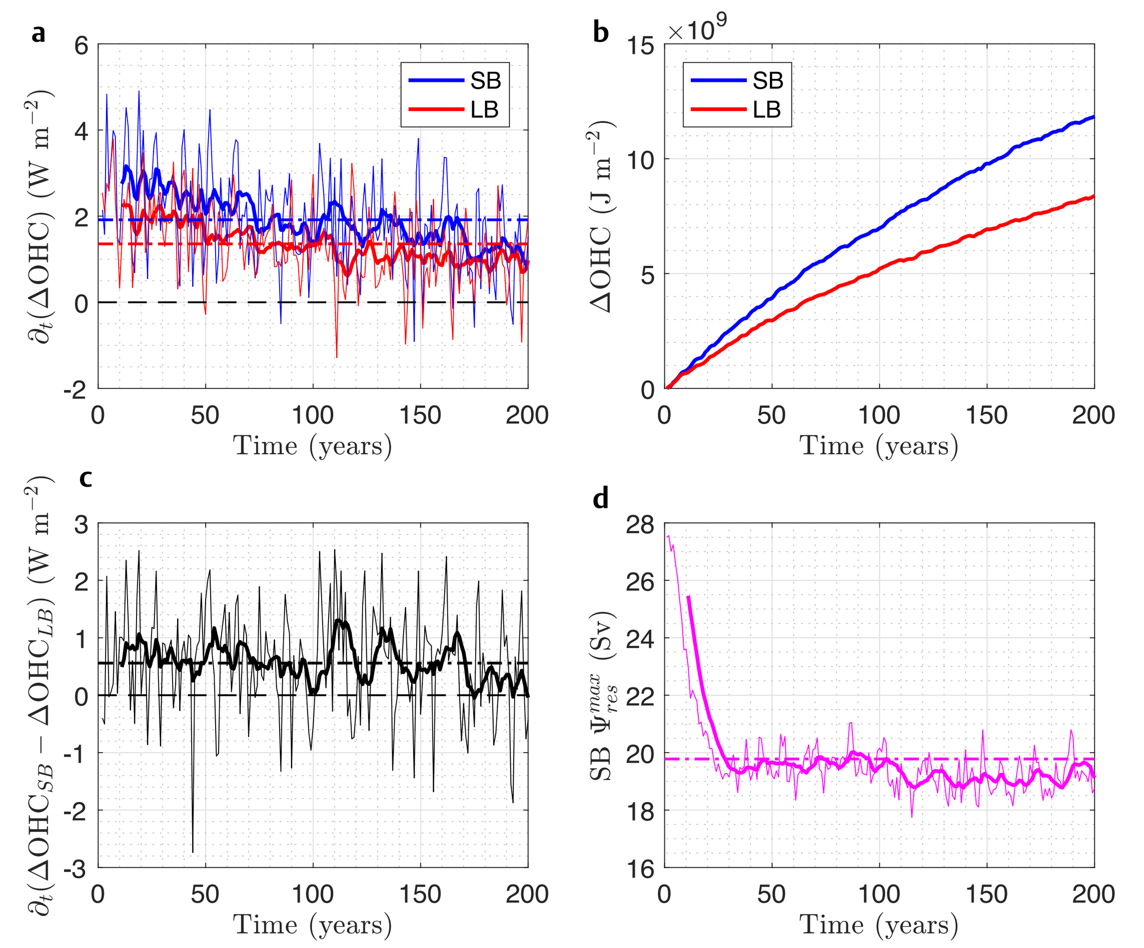

Figure 3. Time series of (a) Small basin (SB) and large basin (LB) heat storage rates; (b) OHC anomalies; (c) the difference in heat storage rates i.e. the heat storage contrast; and (d) SB MOC strength following an abrupt doubling of CO_2. Thick lines are decadal running means and horizontal dash-dot lines indicate time-mean values. The time-mean heat storage contrast is 0.6 ± 0.1 W m^{-2} (standard error).

3.1 Role of the small basin MOC

Looking at the vertically-averaged potential temperature response, we see that below 1 km depth, the temperature anomaly in the small basin flows along a deep western boundary current, coincident with the lower limb of the small basin's MOC (Figure 4b). Note there are no large temperature anomalies at depth in the large basin or southern ocean regions.

Plotting the control residual overturning over the zonally-averaged potential temperature response, we see a distinctive convective chimney at 60-80°N collocated with the downwelling branch of the MOC, and equatorward advection of temperature anomalies away from high latitudes (Figure 4c).

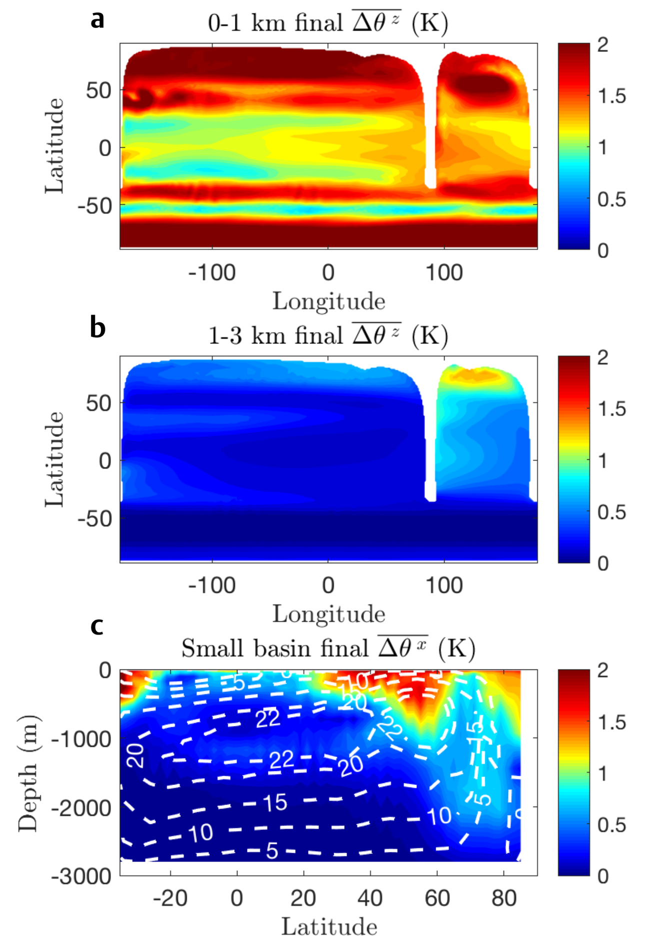

Figure 4. Vertically-averaged potential temperature response $\Delta\theta$ (in K) after 200 years following an abrupt doubling of atmospheric CO_2 in DDrake for the depth intervals (a) 0-1 km and (b) 1-3 km. The temperature anomaly at depth follows a deep western boundary current in the small basin. (c) Zonally-averaged $\Delta\theta$ (colour, in K) in the small basin after 200 years' warming, and streamlines (white dashed contours, in Sv) for the control residual overturning Ψ_{res}^{ctrl}.

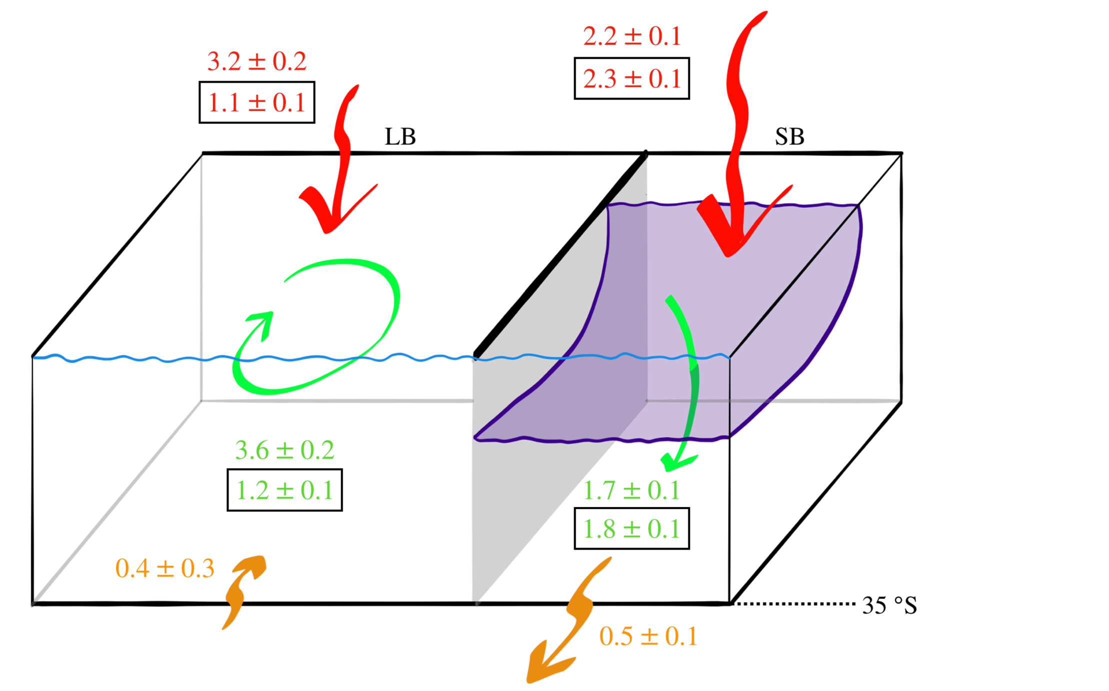

Figure 6. Schematic detailing the time-mean heat uptake rates (red), heat storage rates (green), and southern ocean exchanges (orange) for the small and large basins over 200 years following an abrupt doubling of atmospheric CO_2. Unboxed numbers are in units of 0.1 PW (10^{14} W), while boxed numbers are in units of W m^{-2} (with standard errors). The purple surface represents the base of the pycnocline in the SB, which outcrops at high latitudes, connecting the ocean surface to its interior. Heat readily enters the deep ocean in the SB, enabled by its MOC; whereas, in the LB, heat is confined to the upper ocean and recirculates (green arrows).

Conclusions

- A deep MOC connects the ocean surface to its interior and enhances heat storage rate under global warming
- The AMOC may give the Atlantic its enhanced heat storage rate relative to the Pacific in recent decades
- MOC weakening has little impact on ocean heat storage rate due to compensating physical processes

3.2 MOC weakening and compensation

The vertical heat flux associated with the SB MOC changes as the MOC weakens, approximated by $\Delta\mathcal{H}_{MOC} = \rho_0 c_p \Delta(\Psi_{res}\delta\theta)$ where $\delta\theta$ is the temperature difference across the downwelling and upwelling branches of the circulation. Let overlines represent time-mean quantities in the control climate and Δs represent changes due to the CO_2-doubling. Then, $\Delta\mathcal{H}_{MOC}/\rho_0 c_p$ is given by:

$$\Delta(\Psi_{res}\delta\theta) = \overline{\Psi_{res}}\Delta(\delta\theta) + \Delta\Psi_{res}\overline{\delta\theta} + \Delta\Psi_{res}\Delta(\delta\theta)$$

Plotting these terms in Figure 5a, we see that the control overturning dominates (blue line), while the 2nd and 3rd terms compensate each other (yellow and orange lines). Now, although the MOC heat flux *increases* as the MOC weakens, the heat storage contrast does not increase (Figure 3c). Considering the integrated air-sea heat flux (heat uptake) compared with the heat storage in the small basin, we find that the small basin *leaks heat* to the southern ocean region (Figure 5b). This leakage rate is matched by the increase in MOC heat flux, ensuring that the heat storage contrast remains stationary.

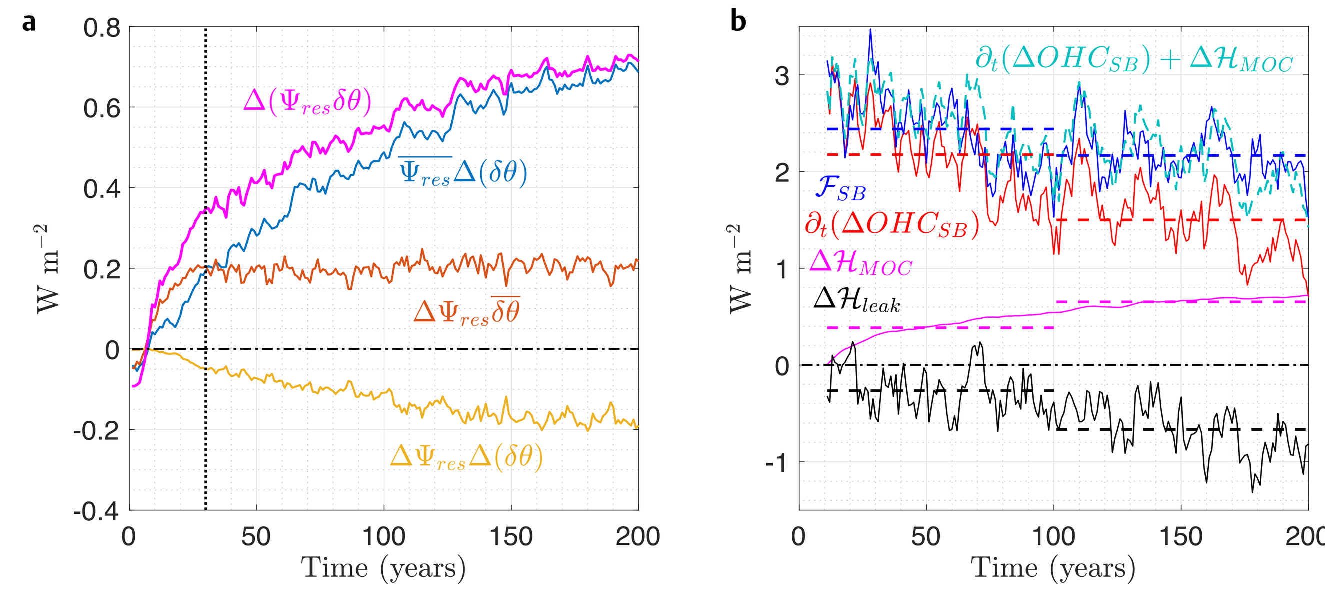

Figure 5. (a) Decomposition of the change in SB downward (positive) MOC heat flux ($\Delta(\Psi_{res}\delta\theta)$, magenta) into differential warming ($\overline{\Psi_{res}}\,\Delta(\delta\theta)$, blue), MOC weakening ($\Delta\Psi_{res}\overline{\delta\theta}$, orange), and nonlinear ($\Delta\Psi_{res}\Delta(\delta\theta)$, yellow) terms (in W m^{-2}). A vertical dotted line is plotted at 30 years to separate the weakening and non-weakening MOC regimes. (b) Decadal running means of the SB heat uptake rate ($\mathcal{F}_{SB}$, blue), heat storage rate ($\partial_t(\Delta OHC_{SB})$, red), MOC heat flux ($\Delta\mathcal{H}_{MOC}$, magenta), and leakage rate to the southern ocean ($\Delta\mathcal{H}_{leak} = \partial_t(\Delta OHC_{SB}) - \mathcal{F}_{SB}$, black) (in W m^{-2}). Note that the sum of the heat storage rate and MOC heat flux (light blue, dashed) almost matches the heat uptake rate. Horizontal dashed lines are centennial time-means.

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