Atmospheric Compensation of Variations in Tropical Ocean Heat Transport: Understanding Mechanisms and Implications on Tectonic Timescales

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Motivation

- The poleward transport of energy is a key aspect of the climate system, with surface ocean currents presently dominating the transport out of deep tropics and atmospheric eddies dominating in mid-latitudes.
- A classic study by Stone (1978) proposed that the total heat transport is determined by astronomical parameters and is highly insensitive to the detailed atmosphere-ocean dynamics.
- On the other hand, previous modeling work has shown that past continental configurations could have produced substantially different tropical ocean heat transport (OHT) (Enderton and Marshall, 2009).
- This implies that for past continental configurations, variations in tropical OHT must result in a compensating change in the atmospheric poleward heat transport (AHT).

How thoroughly does the atmosphere compensate for changes in ocean transport, what are the relevant mechanisms, and what are the consequences for the climate?

Model Description

- We use the 1.2 CESM atmospheric GCM with the CAM4 physics package coupled to an aquaplanet slab ocean with a prescribed source/sink term representing the local convergence of OHT.
- A control climate state is initialized with an axial tilt of 0° coupled to a 10-m mixed layer ocean depth with no prescribed OHT.
- Ice formation has been turned off to keep the model simple.

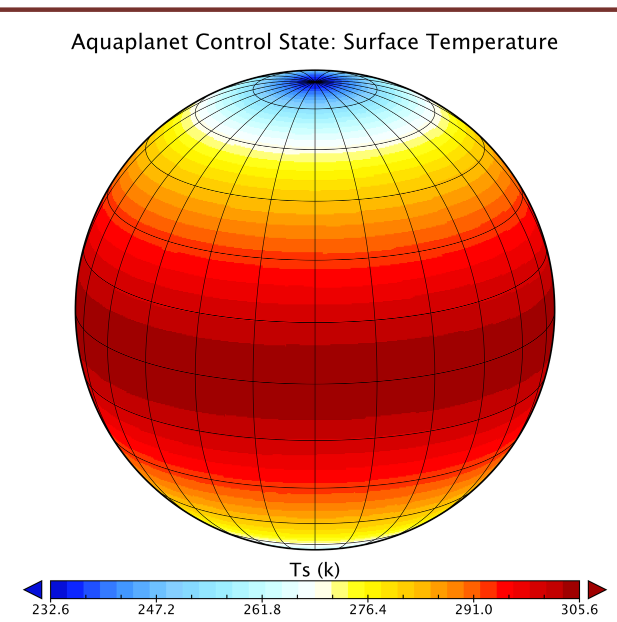

Figure 1. Surface Temperature of initial control climate state.

Prescribed Ocean Heat Transport: $OHT = \Psi \sin(\phi) \cos(\phi)^{2N}$

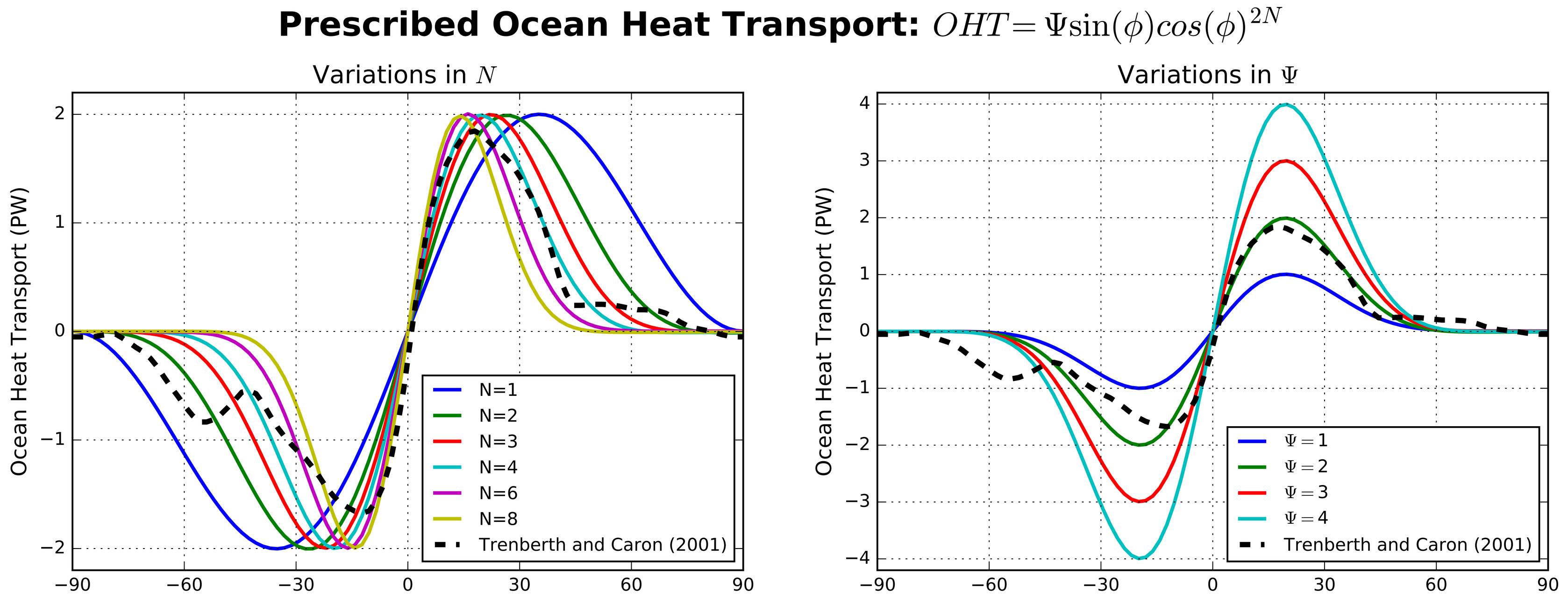

Figure 2. Range of the poleward extent of the prescribed simple analytical form of OHT analyzed as compared to present day estimate of OHT from Trenberth and Caron (2001) (left panel). Range of OHT magnitudes analyzed as compared to the same estimate (right panel). Poleward extent of OHT increase as N decreases. OHT magnitude increases as Ψ increases.

Prescribed OHT

- We analyze the effects of variations in the spatial structure and magnitude of OHT through the application of a simple analytical equation from Rose and Ferreira (2013) (shown above).
- Here, OHT is calculated for N=1, 2, 3, 4, 6, and 8, and Ψ is scaled such that the peak energy transport ranges from 1 to 4 PW.
- Models are run out to equilibrium and the last 20 years are averaged to reduce variability.

Atmospheric Compensation

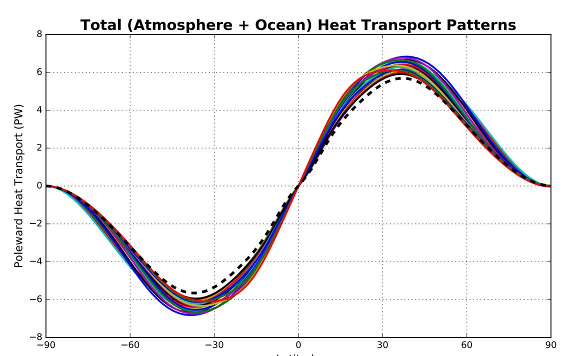

Figure 3. Total poleward energy transport (PW) for all OHT patterns compared to control run (dashed line).

- We find substantial, but incomplete compensation in the total poleward energy transport (mainly due to variations in cloud cover).
- The decrease in AHT out of the tropics can be attributed to a decrease in the energy transport associate with the Hadley Cell (HC).

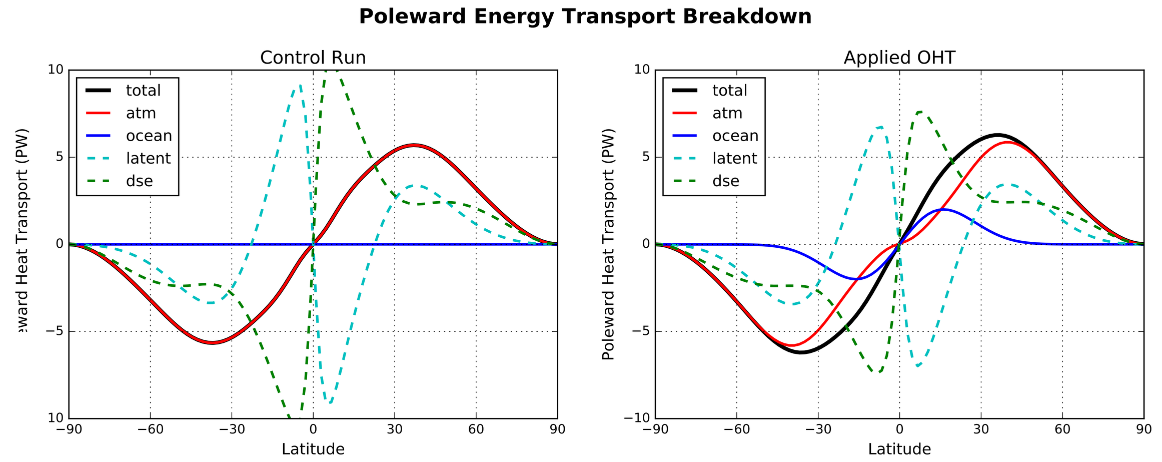

Figure 4. Poleward Energy transport breakdown for a control climate state (left) and an applied OHT (right). Total Energy transport is broken into atmospheric and oceanic components, and AHT is further broken down into the poleward transport of dry static energy and latent heat.

Climate Effects

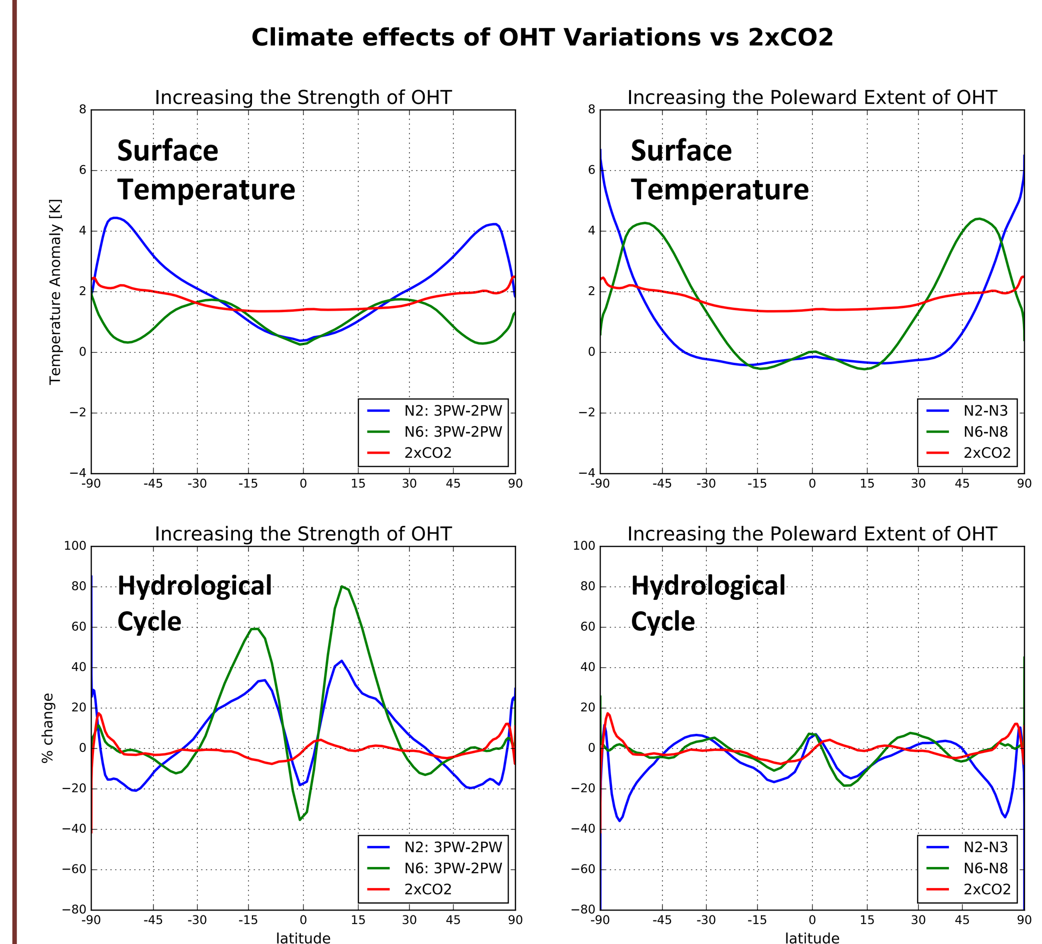

Figure 7. Surface Temperature anomalies (upper panels) and normalized precipitation minus evaporation anomalies (lower panels) for an increase in the magnitude of OHT at N = 2, 6 (left panels) and an increase in the OHT spatial patterns poleward for with a constant magnitude (rights panels) compared to a 2xCO2 warming scenario.

Relevant Mechanisms

- We decompose the energy transport via the HC ($F_{HC}(\phi)$) into its dynamical and thermodynamical components, the rate of mass circulation ($\Psi_{max}(\phi)$) and the transport efficiency ($\Delta_{HC}(\phi)$) respectively, and find that the application of an OHT results in both a reduction of the circulation and an increase in the transport efficiency.
- $F_{HC}(\phi) = \Delta_{HC}(\phi)\Psi_{max}(\phi) \Rightarrow \dfrac{\delta F_{HC}(\phi)}{F_{HC}(\phi)} \approx \dfrac{\delta\Delta_{HC}(\phi)}{\Delta_{HC}(\phi)} + \dfrac{\delta\Psi_{max}(\phi)}{\Psi_{max}(\phi)}$

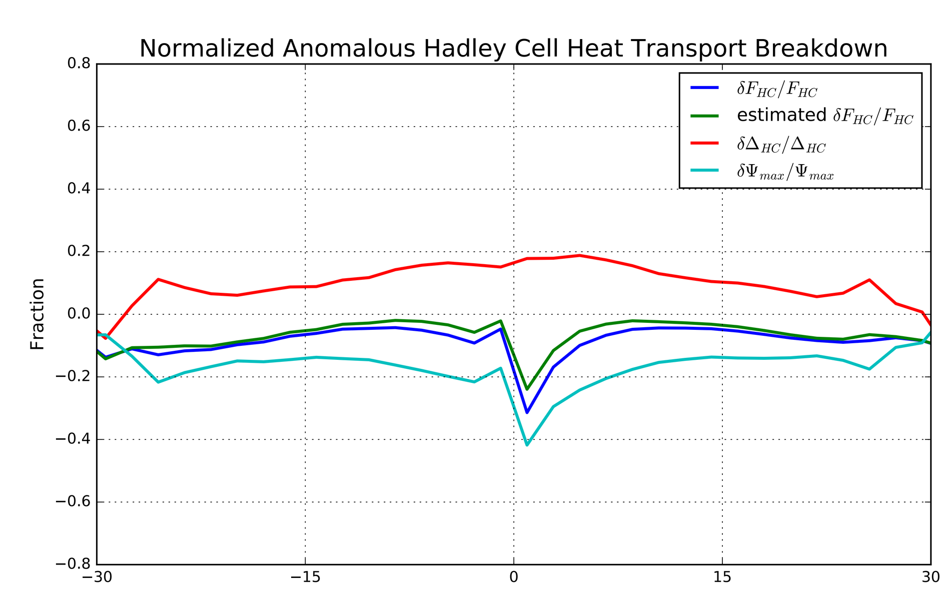

Figure 5. The approximated, normalized anomalous HC heat transport breakdown into the fractional change of the mass flux and efficiency for the addition of an OHT.

- Following Schneider and Bordoni (2008), the decrease of the mass circulation is analyzed by decomposing the streamfunction into its eddy driven and mean momentum components.

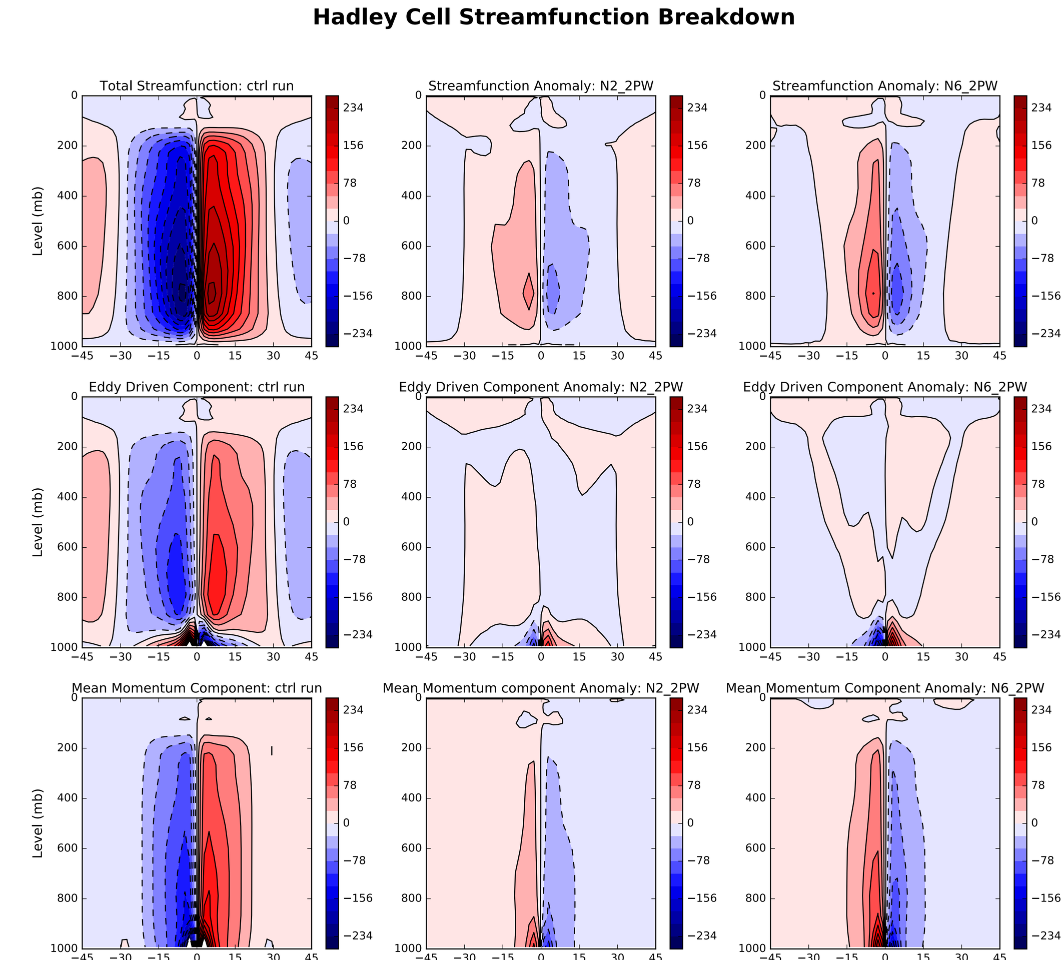

Figure 6. The HC streamfunction broken down into its eddy driven and mean momentum components for the control run (left panels) and the associated anomies for N = 2, 2 PW (middle panels) and N = 6, 2 PW (right panels)

Discussion

- We find substantial, but incomplete compensation in the atmospheric component of poleward heat transport for variations in OHT.
- In the tropics, this compensation is achieved via a decrease in the energy transport associated with the Hadley Cell.
- This energy decrease is characterized by a decrease in the mass flux (a slowdown of the cell) and an increase in the transport efficiency.
- While the atmospheric eddies are crucial to setting the strength of the HC, the majority of the slowdown can be attributed to a decrease in the mean momentum component. This change is greater for OHT fluxes limited to the tropics.
- Increasing either the magnitude or the poleward extent of the OHT leads to climate variations different than those exhibited by a 2xCO2 warming scenario.
- The hydrological cycle is most sensitive to changes in the strength of the OHT due to its effects on the HC. Surface temperature is most sensitive to changes in the poleward extent of the OHT.
- We ran the same experiment using a warm initial climate state with an axial tilt of 23.5° and encountered no major deviations from the results presented.

Future work

- What sets the changes in the efficiency and the momentum driven component of the HC, and how do the 2 parameters influence each other as the climate reacts to OHT variations?
- This model presented represents an extremely simplified version of the Earth's surface. How does this compensation work for models of increased complexity (including the addition of sea-ice, land surface features, non-static oceans, etc.)?

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