Tipping Points in Overturning Circulation Mediated By Ocean Mixing and the Configuration and Magnitude of the Hydrological Cycle: A Simple Model

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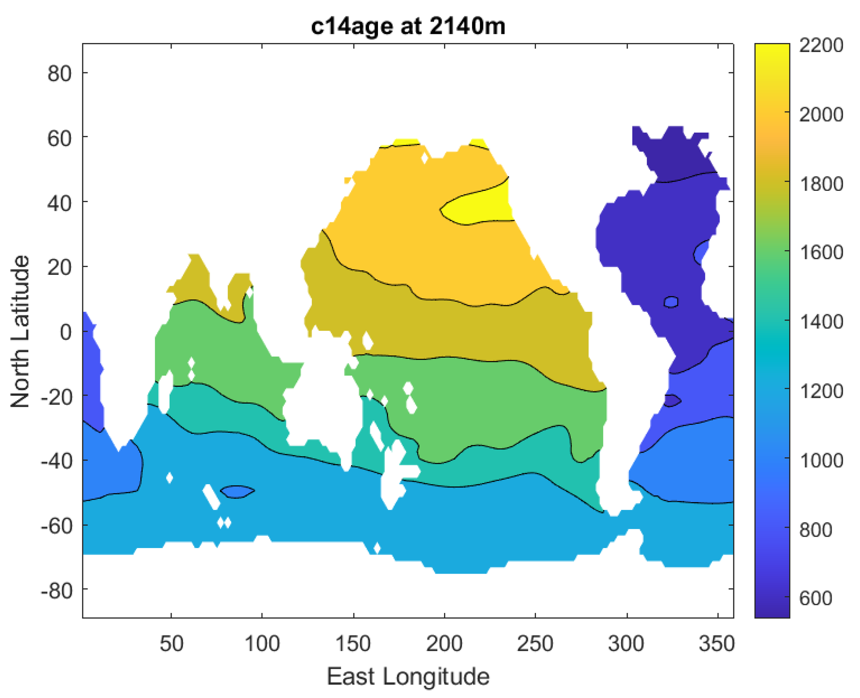
Motivation



Age of ocean water in deep ocean is low in Atlantic, high in North Pacific.

Reflects fact that transformation of young, well-equilibrated surface water to dense, deep water is concentrated in North Atlantic.

Why is this the case?

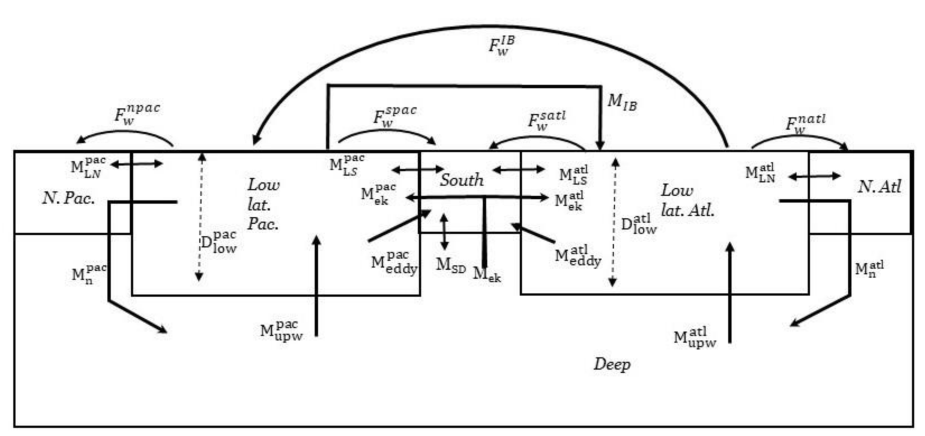
Standard explanations focus on configuration of hydrological cycle-which imports freshwater into the Pacific and Southern Ocean. Once circulation s set up, it reinforces this configuration.

Might it have changed in the past? .Evidence for deep water formation in the Pacific under both colder and warmer climates suggest this story is incomplete.

Climate models often have some deep water formation under modern conditions.

Strategy

Configure a box model that separates three water mass formation regions, includes interbasin exchange.



Temperatures, salinities allowed to vary in each box.

Allow depths of low-latitude boxes $D_{low}^{atl,pac}$ to vary.

Compute closure for advective/mixing fluxes following previous work (Gnanadesikan, 1999; Gnanadesikan et al., 2018). Of particular importance is

$$M_n^{atl,pac} = g\left(1 - \frac{\rho_{latl,lpac}}{\rho_{natl,npac}}\right) * \frac{{D_{low}^{atl,pac}}^2}{\epsilon_{atl,pac}}$$

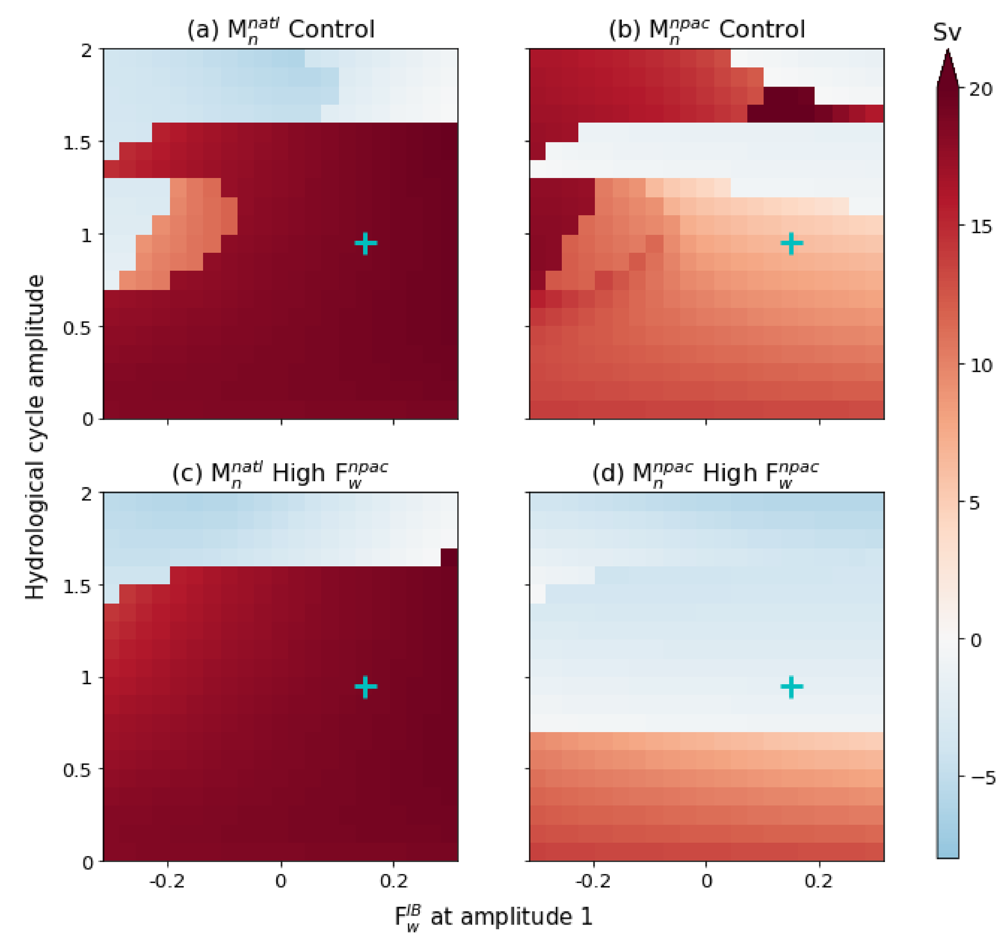
Key new addition… resistance to overturning $\epsilon_{atl,pac}$ depends on gradient between northern and *Antarctic* surface boxes. If Antarctic is lighter, AAIW provides kick to sinking (low resistance). If it is denser it does not (high resistance).

Change is necessary to explain why observed ϵ appears to be about twice as large in North Pacific (currently lighter than AAIW). Also supported with runs from coupled climate models (Pradal and Gnanadesikan, 2014)

Backing out freshwater fluxes from observations, we find 0.45 Sv in the North Atlantic, 0.34 Sv in North Pacific, 1.1 Sv in Southern Ocean, 0.15 Sv interbasin.

Allows us to consider counterfactual case where North Pacific Flux is larger than Atlantic (0.6Sv), as is the case in idealized models, reflecting a wider basin.

Results



Initialized with present day conditions. Instantaneously changed configuration and amplitude of hydrological cycle, ran for 2000 yrs.

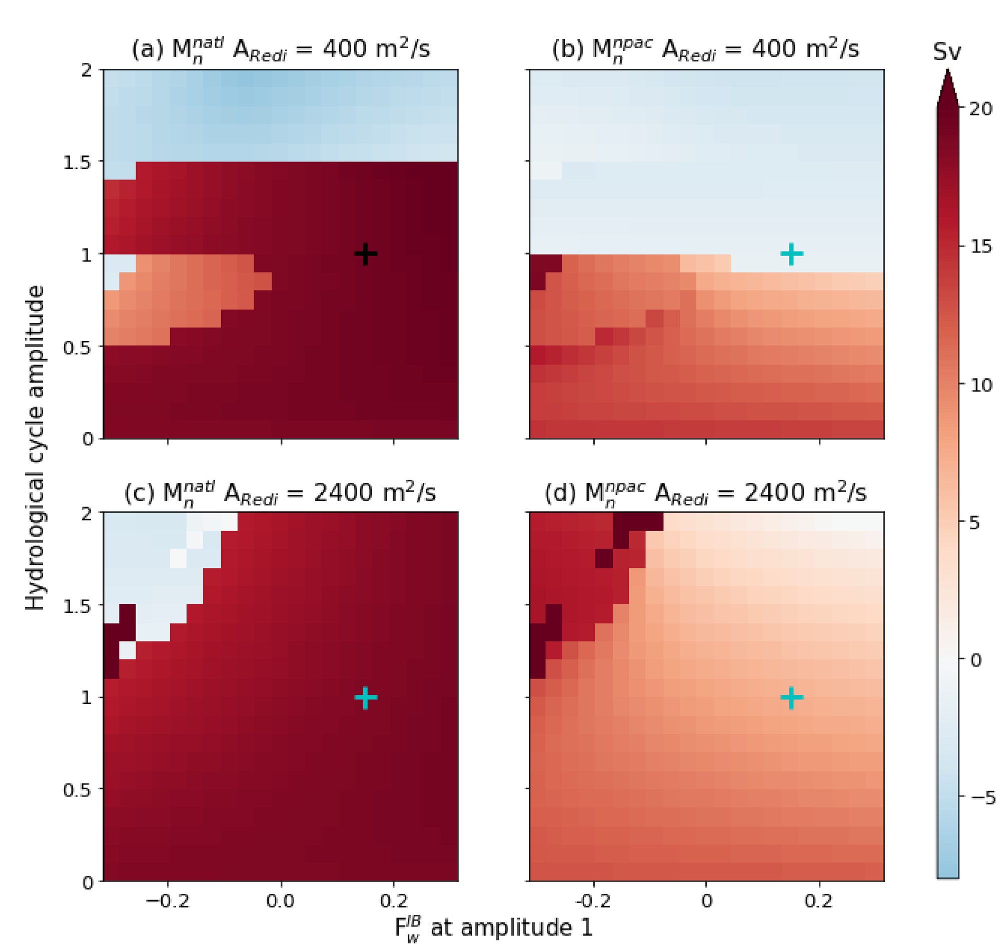
Horizontal axis above shows value of interbasin flux at initial amplitude of hydrological cycle.

Vertical axis shows scaling of hydrological cycle. Factor of 2 is roughly 10 degrees of warming/cooling.

Overturning in North Atlantic (left-hand column) and North Pacific (right-hand column).

With modern configuration of overturning (top row) we can get stronger overturning in North Pacific by increasing hydrological cycle amplitude (turning off overturning in Atlantic allows it to re-establish in the Pacific), decreasing the hydrological cycle, or changing the direction of the interbasin flux.

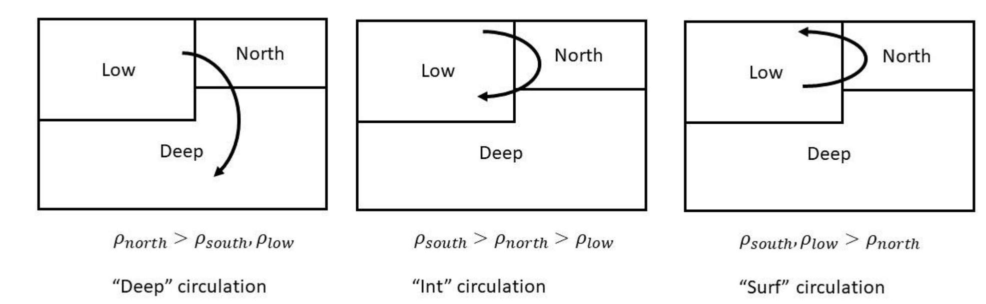
With counterfactual configuration (bottom row), behavior is much less rich. Increasing hydrological cycle amplitude turns off overturning, first in Pacific then in the Atlantic.



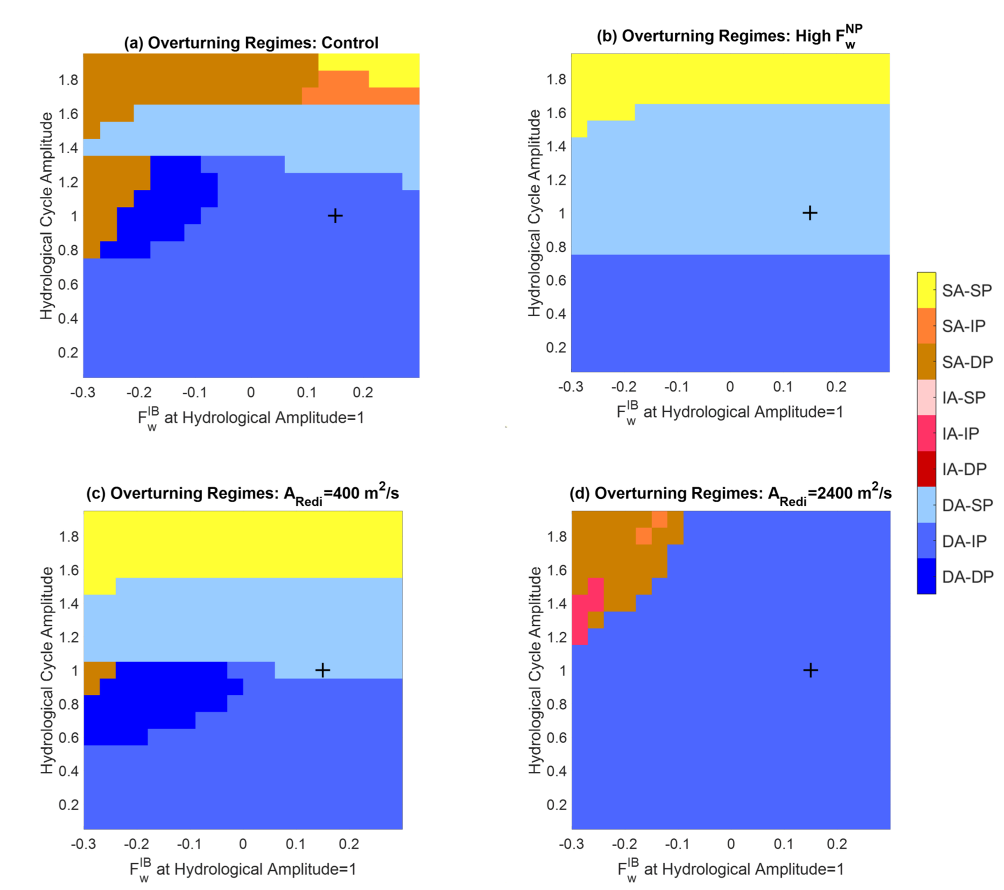
Results are highly dependent on subgridscale lateral mixing, which varies substantially across modern climate models (Abernathey et al., 2022 finds range of <400 -2000 m²s⁻² in CMIP6 models).

Lower values (top row) show less stability, overturning that is initially "off" In pacific.

Higher value (bottom row) shows more stability, over range shown need to reverse interbasin flux to get overturning to reverse.



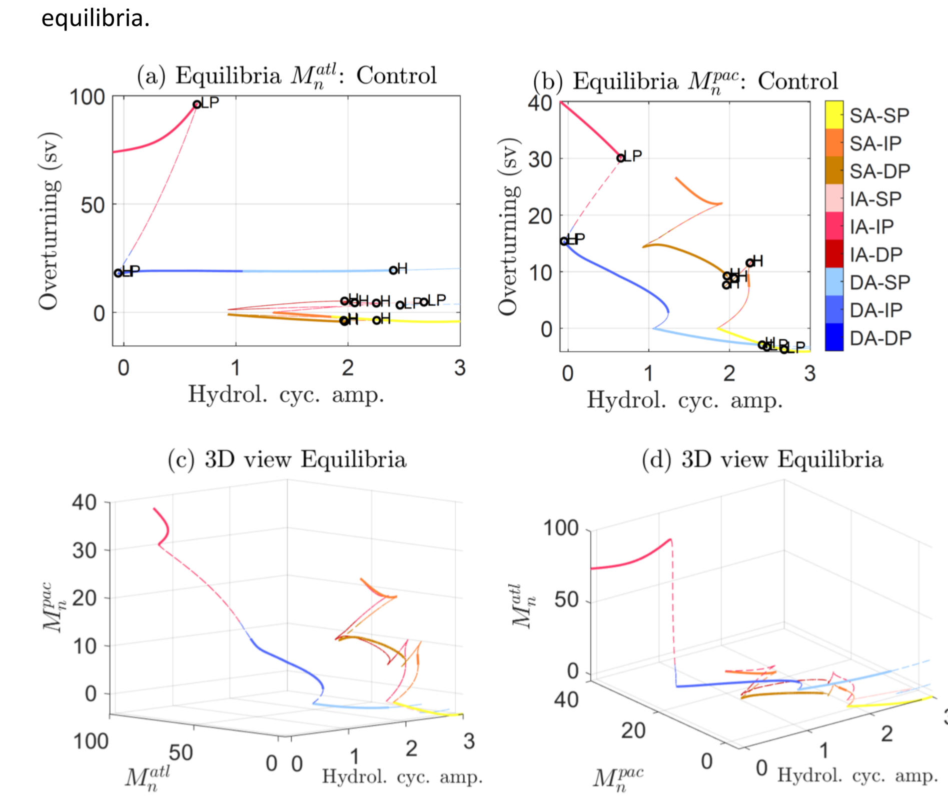
Can characterize overturning circulation in terms of whether it results in the formation of deep water (current North Atlantic). Intermediate water (density close to AAIW), similar to current North Pacific or a reverse circulation (classic "off" state in Stommel box model,found in some ESMs).



Code configuration of overturning. Color palette shows Atlantic (blue is deep in Atlantic, reddish is intermediate, brown-yellow is shallow), intensity shows Pacific.

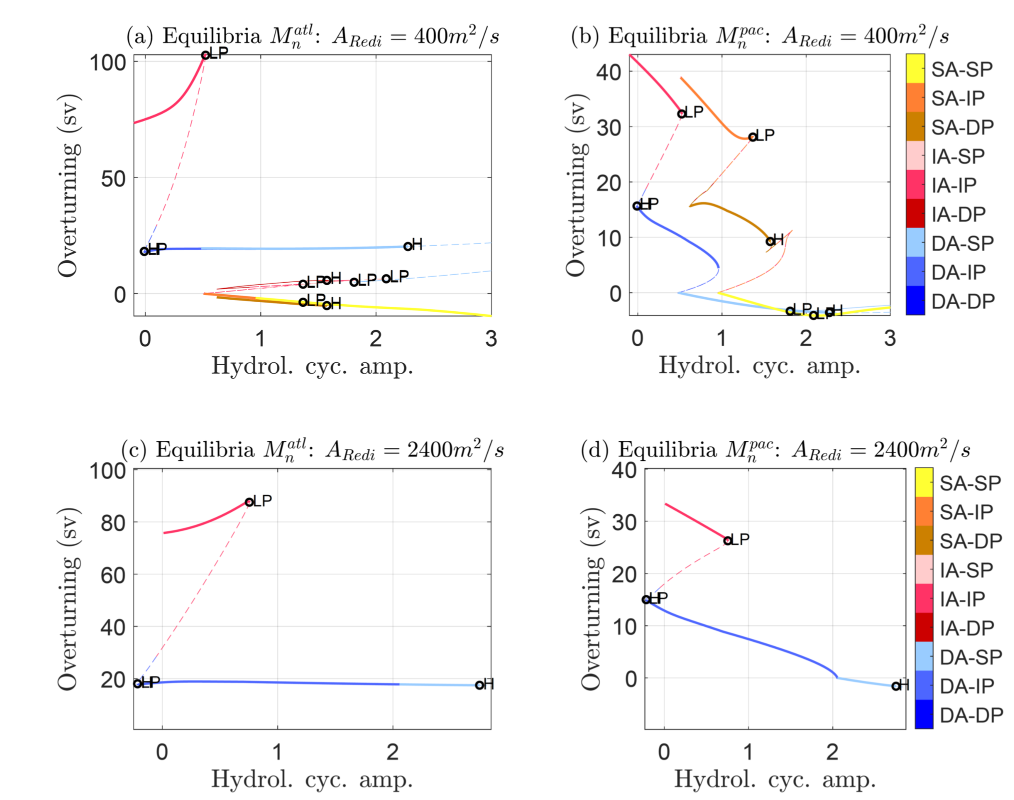
Note that starting from current ocean, we can access seven different configurations.

What if we also vary initial conditions? This allows us to find a wide range of equilibria.



Multiple configurations possible at a given hydrological cycle amplitude. Changing amplitude allows for a wide range of "tipping points" between states, involving Hopf and limit point bifurcations.

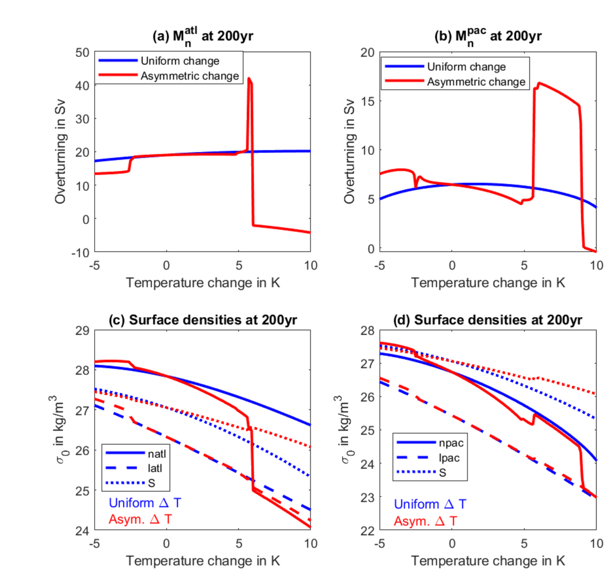
Suggests wider exploration of phase space of possible states.



Possible states depend strongly on lateral mixing.

Upper panel above shows low mixing. States generally shift to the left (collapses occur at lower values of hydrological cycle amplitude.

Lower panel shows high mixing states. Off states generally not found. High amplitude cases become time-dependent.



Final suprising result- changing temperatures and hydrological cycle consistently (7%/C), does not produce collapse in overturning if temperature change is uniform (blue lines at left).

Asymmetric change in temperature (NH>SH) does produce a collapse for baseline conditions driven by NH becoming lighter than SH.

Conclusions

We have developed a new box model of the global overturning that combines multiple insights from previous models (role of Southern Ocean, interbasin transport).

The new model reveals the possibility of many possible steady-states.

Lateral mixing in the ocean is an important modulator of which states occur.

Calibrating the model reveals that while interbasin atmospheric water vapor transport localizes sinking to North Atlantic, intrabasin freshwater transport fights this.

More work needed using idealized/realistic coupled models.

Important to focus on interhemispheric density differences.

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