Spin-up and adjustment of the Antarctic Circumpolar Current and global pycnocline

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Summary

The Antarctic Circumpolar Current (ACC) is a dominant feature of the global ocean circulation, providing a physical connection between the three major ocean basins. Long-term variations in its strength have the potential to influence the rate at which heat and carbon are exchanged between the atmosphere and ocean. Here we present a theory for the adjustment of the baroclinic ACC and global pycnocline to a sustained change in wind forcing. We find that:

- **The adjustment timescale is multidecadal to centennial, implying that long observational time series will be required to detect dynamic change in the ACC due to anthropogenic forcing.**
- **The timescale is controlled by Southern Ocean eddy activity and deep water formation in the North Atlantic.**

For more information, see Allison et al (2011), in press for J. Mar. Res.

1. Background information

- Southern Ocean isopycnals are tilted steeply upwards towards Antarctica, and the baroclinic transport of the Antarctic Circumpolar Current (ACC) is linked to this meridional isopycnal slope.
- Variations in the Southern Ocean wind stress drive ACC transport variability on interannual timescales, through the effect of Ekman pumping on the isopycnal slope (e.g., Hall and Visbeck, 2002)
- The Southern Ocean's response to wind stress changes on longer timescales is unknown, but is important for understanding the response of the global ocean to anthropogenic forcing, in terms of the oceanic uptake of carbon and the global ocean heat content.
- Here we aim to understand the long-term adjustment of the ACC though its connection to the global pycnocline.

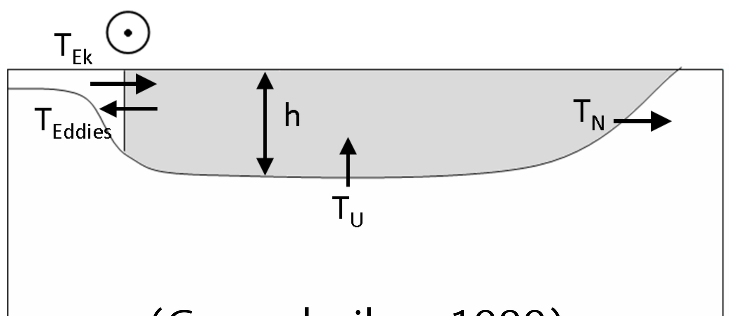
2. Theory

- The baroclinic ACC transport can be related through geostrophic balance to the global pycnocline depth:

$$T_{ACC} \approx \frac{-g'}{2f}(h^2 - h_S^2)$$

- The pycnocline depth, h, in a basin of area A, is set by Southern Ocean winds and eddies (T_{Ek} and T_{Eddies}), diapycnal mixing (T_U) and northern sinking (T_N).

$$\frac{\partial h}{\partial t} A = T_{Ek} - T_{Eddies} - T_N + T_U$$



(Gnanadesikan, 1999)

$$T_{Eddies} \approx \frac{\kappa_{GM} L_x}{L_y} h = Gh$$

(Gent & McWilliams, 1990)

$$T_U \approx \frac{\kappa_v A}{h}$$

(Munk, 1966)

$$T_N \approx \frac{\gamma g' h^2}{f_N}$$

(see Fürst & Levermann, 2011)

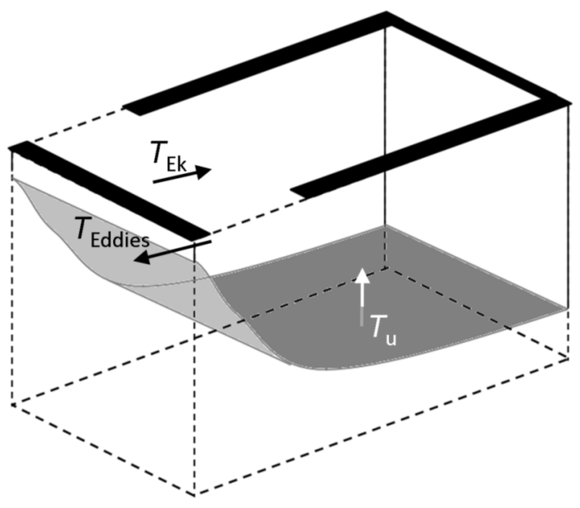
- Following Allison et. al. (2010), T_{Ek} is evaluated using the wind stress over the region of circumpolar streamlines.
- Approximation to time-dependent solution:

(with linearised T_N term)

$$\Delta h = |h_{eq} - h(t)|$$
$$\Delta h_0 = \Delta h(t=0)$$

$$\Delta h \approx \Delta h_0 \exp \frac{-2\left(G + \left.\frac{\partial T_N}{\partial h}\right|_{h=h_{eq}}\right)t}{A}$$

3. Simple numerical model



- 2D reduced-gravity ocean model, 1° resolution. Single sector basin with circumpolar channel.
- Active surface layer above motionless abyssal layer; the layer interface represents the global pycnocline.
- The model has no deep water formation in the north: the experiments test the theory in the limit of T_N=0.
- The layer interface is pinned close to the surface at the southern boundary, to represent surface buoyancy loss and bottom water formation near Antarctica.
- Forced by an idealized zonal wind jet near the circumpolar channel, with parameterized eddies (Gent & McWilliams ,1990) and diapycnal mixing.
- Experiments begin from an initial state with a flat shallow surface layer and no ACC.

References

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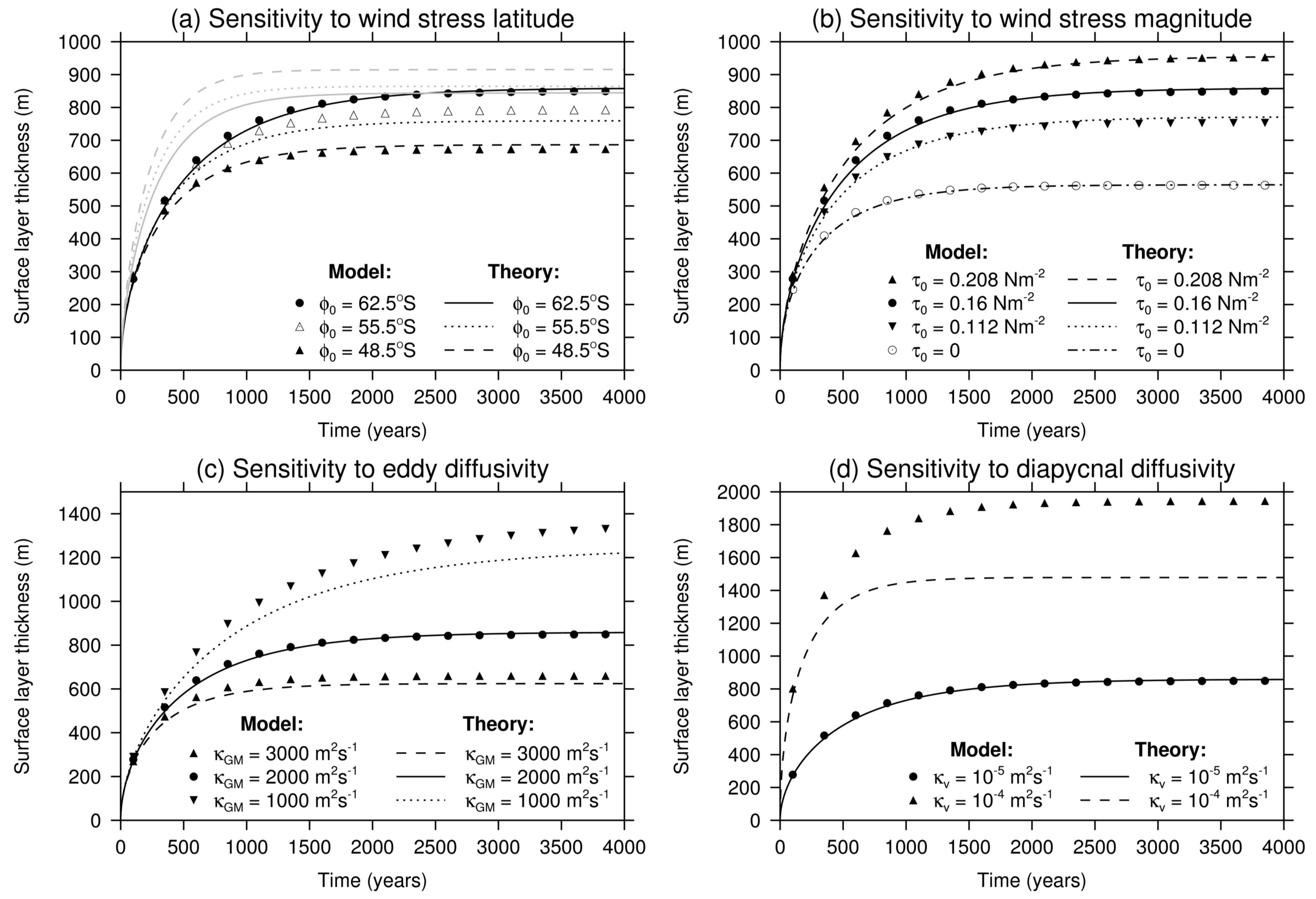
4. Theory and model comparison

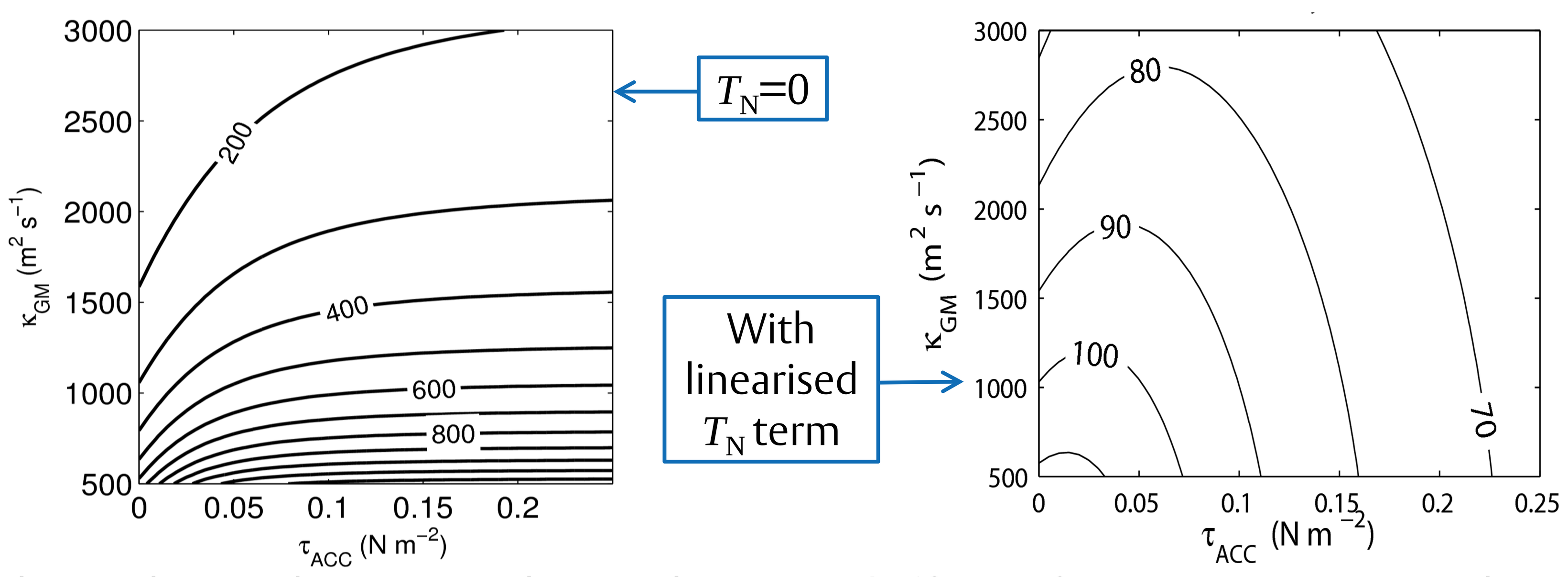
(Without T_N)



- The above figures show the evolution of surface layer thickness (closely related to circumpolar transport) in the numerical model and theory, for varying: (a) wind stress jet latitude, (b) wind stress magnitude, (c) eddy diffusivity, and (d) diapycnal diffusivity. The corresponding theoretical estimates are generally in good agreement with the numerical results.
- The adjustment timescale (several centuries) is strongly influenced by the magnitude of the eddy diffusivity parameter.
- With zero wind forcing (panel b), a circumpolar current still exists, driven by diapycnal mixing (see also Munday et al, 2011).
- The grey lines in panel (a) show the theoretical estimate in which T_{Ek} is evaluated using the peak wind stress in the jet, rather than the mean wind stress over the circumpolar streamlines as suggested by Allison et al (2010). This leads to a reversal of the variation of the equilibrium pycnocline depth with wind stress latitude and an underestimate of the adjustment timescale.

5. The role of northern sinking

- The northern sinking term can be linearised and incorporated into the analytical solution
- The figures below show the theoretical adjustment timescale (in years) as a function of Southern Ocean winds and eddy diffusivity, without T_N, and with the linearised T_N term.



- The northern sinking acts to shorten the timescale (from a few centuries to just under a century), and reduces its sensitivity to the Southern Ocean eddies.
- However, the simple h^2 scaling for T_N does not take into account the thermohaline feedbacks that are central to the dynamics of the Atlantic overturning.

6. Conclusions

- The long-term adjustment of the ACC and global pycnocline is controlled by Southern Ocean eddies and deep water formation in the North Atlantic, but their relative importance cannot be determined here, due to the inadequacies of the commonly-used scalings.
- The potential importance of Southern Ocean eddy activity has implications for climate model studies, as most eddy parameterizations underestimate the sensitivity of eddy fluxes to changes in the mean strength of the ACC, so the timescale is likely to be overestimated.
- The adjustment timescale is multidecadal to centennial, implying that long observational records would be required to detect dynamic change in the ACC due to anthropogenic forcing (see also Böning et al, 2008).
- The dependence of the adjustment timescale on the basin area means that the global ocean needs to be considered to capture long-term ACC adjustment (implications for channel models with a limited meridional extent).

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