Wind-Forced Variability of the Remote Meridional Overturning Circulation

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Abstract

The mechanisms by which time-dependent wind stress anomalies at mid-latitudes can force variability in the meridional overturning circulation at low latitudes are explored. It is shown that winds are effective at forcing remote variability in the overturning circulation when forcing periods are near the mid-latitude baroclinic Rossby wave basin-crossing timescale. Remote overturning is required by an imbalance in the mid-latitude mass storage and release resulting from the dependence of the Rossby wave phase speed on latitude. A heuristic theory is developed that predicts the strength and frequency-dependence of the remote overturning well when compared to a two-layer numerical model. The theory indicates that the variable overturning strength, relative to the anomalous Ekman transport, depends primarily on the ratio of the meridional spatial scale of the anomalous wind stress to its latitude. For strongly forced systems, a mean deep western boundary current can also significantly enhance the overturning variability at all latitudes. For sufficiently large thermocline displacements, the deep western boundary current alternates between interior and near-boundary pathways in response to fluctuations in the wind, leading to large anomalies in the volume of North Atlantic Deep Water stored at mid-latitudes and in the downstream deep western boundary current transport.

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1. Introduction

Wind-forcing is known to be an important driver of AMOC variability and upper ocean heat content, especially on interannual to decadal time scales.

Most analysis relies on comprehensive numerical models or hydrography but a simple theory connecting wind and AMOC or heat content is lacking.

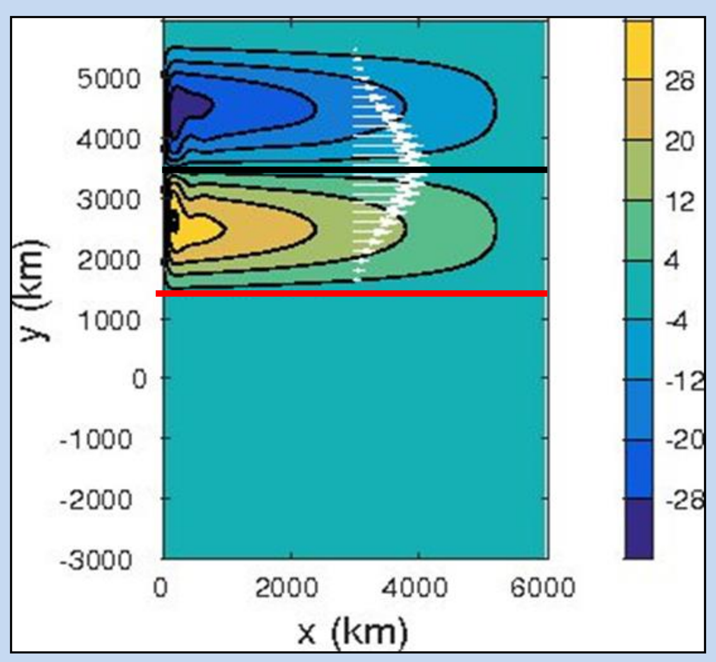
Present approach combines an idealized two-layer numerical model with a simple theory to understand how wind-forcing drives remote AMOC variability

2. Two layer shallow water model

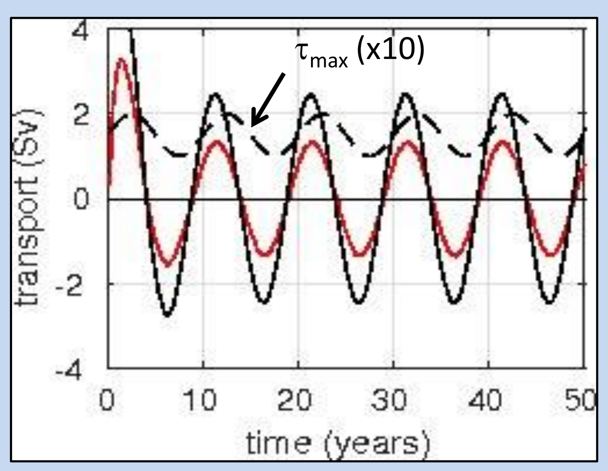
Zonal winds force mid-latitude subtropical and subpolar gyres with Ψ_{sv} = 35 Sv transport

Wind strength τ_0 oscillates with period P and amplitude $\alpha\tau_0$ as

$$\tau(y) = 0.5\tau_0(1+\cos \pi(y-y_0)/L_y)(1+\alpha \sin 2\pi t/P)$$



Mean streamfunction and wind stress pattern



Black line: MOC at gyre boundary
Red line : MOC at edge of subtropical gyre

1. The MOC at the gyre boundary (black line) oscillates with amplitude 2.5 Sv, close to that required to balance the meridional Ekman transport
2. However, at the southern limit of the subtropical gyre the MOC oscillates with amplitude 1.4 Sv even though there is no Ekman transport at this latitude
3. Indicates that MOC is not just a simple local response that opposes the Ekman transport

What determines the strength of this remote wind-forced component of the MOC ?

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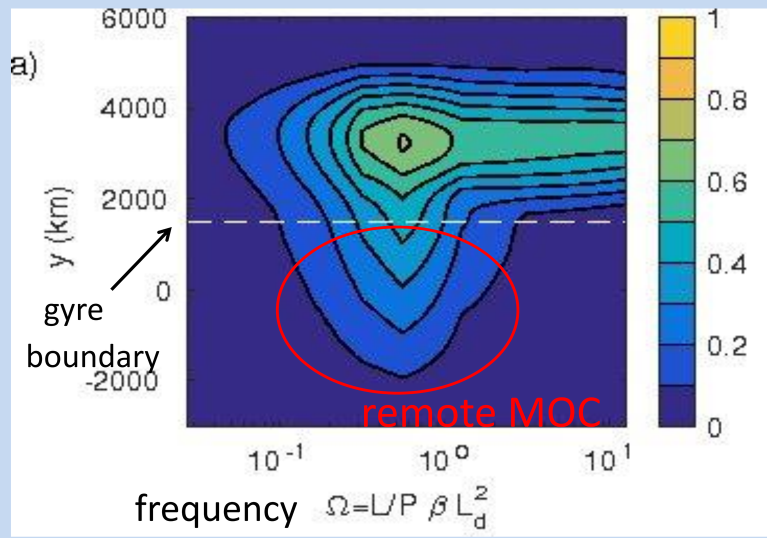
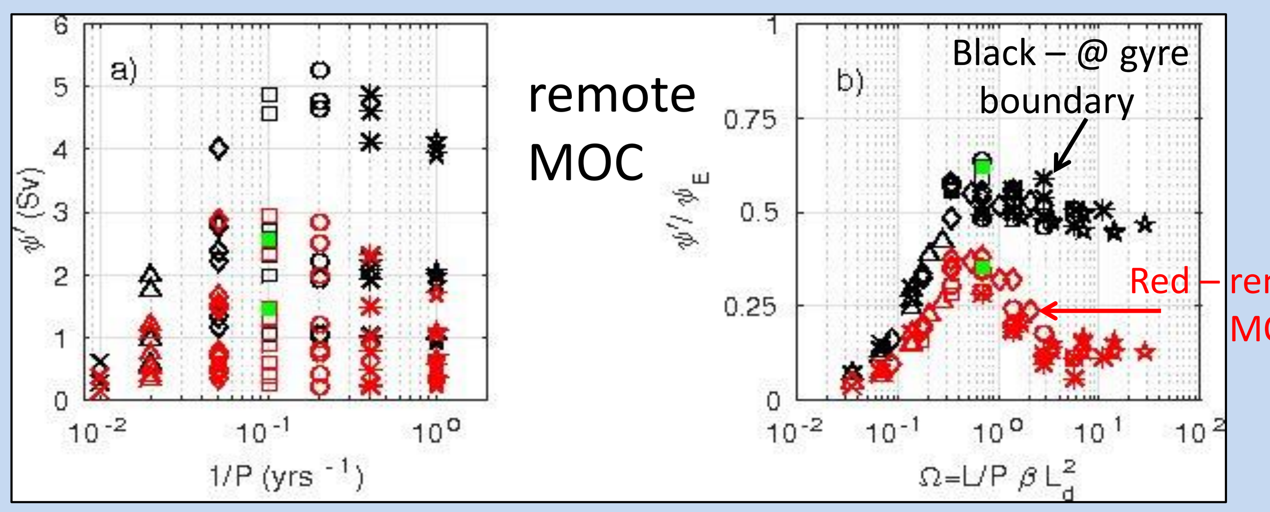
3. Mechanism of remote forcing



Amplitude of MOC variability vs latitude and forcing frequency

Forcing period is scaled by the mid-latitude Rossby wave basin-crossing time scale
MOC is scaled by the variability in Ekman transport

1. High frequency variability is confined to mid-latitudes and scales with ½ the Ekman transport
2. Low frequency MOC is weak at all latitudes
3. Strong remote MOC is found for forcing periods close to the basin-crossing time scale

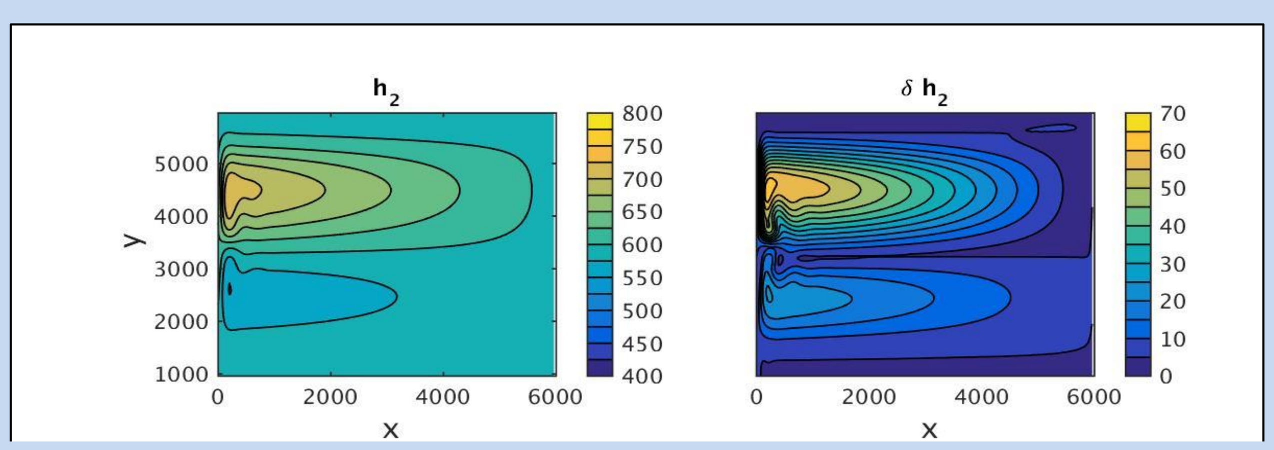


dimensional — non-dimensional

Ran a series of model calculations with various values for reduced gravity, beta, forcing period.

1. Dimensional MOC variability shows no pattern with forcing period
2. Non-dimensional MOC shows peak when forcing period is twice the mid-latitude basin-crossing time scale

So what is going on?



mean thickness layer 2 — change in h_2 over forcing period

1. The thermocline displacement in the subpolar gyre is much larger than that in the subtropical gyre when subject to the same change in wind stress curl (due to larger *f*).
2. Thus, oscillating winds cause the volume of the subpolar gyre to fluctuate much more than that in the subtropical gyre.
3. The difference in the change of volume between the two gyres is imported/exported from lower latitudes.
4. This is the basic mechanism for the remotely-forced MOC

4. An Analytic Model

$$h(x,y) = (h_{1e}^2 + \Psi_{sv}\beta y/g')^{1/2} \approx h_{1e} + 0.5\Psi_{sv}\beta y/g'h_{1e}$$

Layer 1 thickness required to support Sverdrup transport

$$\delta V = \iint_{(\max \tau)} h^+ dxdy - \iint_{(\min \tau)} h^- dxdy \approx \frac{\alpha\tau_0 L_y L_x^2}{\rho_0 g' h_{1e}}$$

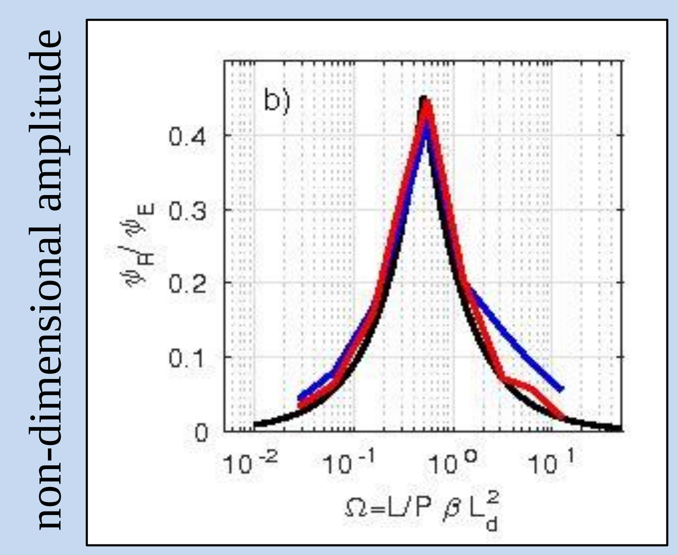
Change in volume integrated over both gyres due to changing winds. At low frequencies this change occurs over ½ period P

This gives a maximum MOC variability of $\frac{\pi}{2}\frac{\delta V}{.5P} = \frac{\pi}{P}\frac{\alpha\tau_0 L_y L_x^2}{\rho_0 g' h_{1e}}$

At periods shorter than the basin crossing time scale the change in volume is reduced in proportion to the forcing period.
The amplitude of the remote MOC may then be written as:

$$\Psi_R = \frac{\pi}{2}\frac{\min(0.5P/T_{RW},1)}{\max(.5P, T_{RW})}\frac{\alpha\tau_0 L_y L_x^2}{\rho_0 g' h_{1e}} \qquad (1)$$

Comparison between model and theory



non-dimensional forcing frequency

strength of remote MOC variability
theory, (non-dim eqn (1))
model with no DWBC
model with mean DWBC

1. Model and theory compare closely over all forcing periods
2. Remote MOC is weak at high and low frequencies, maximum at ½ the basin-crossing frequency
3. The amplitude of the remote MOC can be the same order of magnitude as the anomalous Ekman transport

5. SUMMARY

1. Variability in mid-latitude winds can force variability in the MOC far from the forcing region
2. The basic mechanism arises as a result of the geostrophic circulation in the thermocline and its adjustment to changing winds via Rossby wave propagation
3. A simple heuristic theory formalizes this adjustment process and accurately predicts the amplitude of the remotely-forced AMOC in a shallow water model
4. Addition of a mean MOC can enhance variability at all latitudes in strongly-forced systems due to a diversion of DWBC water into the basin interior (not shown)

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