Stability of the Atlantic meridional overturning circulation: the effects of wind stress, freshwater fluxes and diapycnal mixing in a 2D ocean model

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Change in Atlantic THC [$10^6$ m$^3$/s]

IPCC 2001

IPCC 2007
Hosing experiments in a coupled and ocean-only GCMs (GFDL models)

Barreiro, Fedorov et al 2008
A schematic picture of the AMOC

Barreiro, Fedorov and co-authors 2008
Important parameters: 

- $\tau$ – wind stress in the Southern ocean
- $k_D$ – diapycnal diffusivity
- $\mathcal{F}$ – surface freshwater fluxes
2D (zonally-averaged) Ocean Models:

- Marotzke, Welander, and Willebrand 1988
- Wright and Stocker 1991
- Stocker and Wright 1991
- Wright and Stocker 1992
- Stocker, Wright and Broecker 1992
- Sakai and Peltier 1995
- Wright, Stocker and Mercer 1998
- Drbohlav and Jin 1998
- Marchal et al 2007

Wright and Stocker 1992 -> wind stress ->
“Sensitivities of a Zonally Averaged Global Ocean Circulation Model”
The basin for the 2D (zonally-integrated) ocean model
Prognostic equations:

\[ \partial_t T = -J(\psi, T) + \partial_s (K_I \partial_s) + \partial_n (K_D \partial_n T) \]

\[ \partial_t S = -J(\psi, S) + \partial_s (K_I \partial_s S) + \partial_n (K_D \partial_n S) \]

\( J \) – Jacobian, \( \psi \) – streamfunction,
\( K_I \) – isopycnal diffusivity, \( K_D \) – diapycnal diffusivity

Temperature and salinity forcing (mixed boundary conditions):
\( F_T \) - heat fluxes (restoring to a prescribed Temperature)
\( F_S \) - salt fluxes
Prognostic equations:

\[ \partial_t T = -J(\psi, T) + \partial_s (K_I \partial_s) + \partial_n (K_D \partial_n T) + F_T \]

\[ \partial_t S = -J(\psi, S) + \partial_s (K_I \partial_s S) + \partial_n (K_D \partial_n S) + F_S \]

Diagnostic equations:

Meridional velocity \( v \):

\[ v = -\frac{1}{\kappa \rho_0} \partial_y P + v_{\text{Wind}} + v_{\text{G&M}} \]

Density gradient

Hydrostatic:

\[ \partial_z P = -\rho g \]

Density:

\[ \rho = \rho_0 [1 - \alpha(T - T_0) + \beta(S - S_0)] \]

Non-divergence:

\[ \partial_y v + \partial_z w = 0 \]

Baroclinicity condition:

\[ \int_{-H}^{0} v \, dz = 0 \]

1/\(k\) = 8.7 \times 10^{-4} \, s; \quad \text{but } 1/\(k\) = 0 \text{ in the channel}
Gent & McWilliams:

\[ \nu_{G&M} = -\partial_z \left( -\frac{\partial y \rho}{\partial z \rho} K_I \right), \quad w_{G&M} = \partial_y \left( -\frac{\partial y \rho}{\partial z \rho} K_I \right) \]

Wind Effects (Ekman + return flow):

\[ \nu_{\text{Wind}}(\text{surf}) = M_{\text{Ek}}(\tau_x)/h_{\text{Ek}} \]

\[ \nu_{\text{Wind}}(z) = -\nu_{\text{Wind}}(\text{surf}) \ast \exp(-z/H_{\text{Wind}}) \]

Following Vallis (2006):

\[ H_{\text{Wind}} = \left( \frac{w_{\text{Ek}} f^3}{\beta^2 N^2} \right)^{1/3} \]

In the ACC:

\[ H_{\text{Wind}} = H_0 \quad \sim 2500 \text{m} \]
2D model:
(a) $H_o=2500\text{m}$

(b) $H_o=800\text{m}$
Transport streamfunction

Eulerian streamfunction

Marshall and Radko 2003: Residual-mean circulation
The AMOC collapse: the 2D model and GFDL’s ocean model

Zonally-averaged (2D) ocean model:

Forcing: freshwater flux in the North Atlantic

GFDL’s ocean GCM (OM2):
AMOC intensity as a function of freshwater anomaly

\[ k_d = 2 \text{ cm}^2/\text{s} \]
AMOC intensity as a function of freshwater anomaly – hysteresis

$k_d = 2 \text{cm}^2/\text{s}$
AMOC intensity as a function of freshwater anomaly for different diffusivities
AMOC intensity as a function of the SO wind stress for different diffusivities \( k_D \)

\[ k_d = \{5, 2, 1, 0.2\} \text{cm}^2/\text{s} \]

± 50% SO wind changes

AMOC intensity as a function of the SO wind stress for different diffusivities \( k_D \)
Stability maps for the AMOC

The AMOC strength (in Sv) as a function of freshwater forcing in the Northern Hemisphere and wind stress anomaly in the Southern Ocean.
AMOC intensity as a function of diapycnal diffusivity $k_d$

$\tau_a = 0.75 \text{ N/m}^2$

$\tau_a = 0.2 \text{ N/m}^2$

$\tau_a = 0$

$\tau_a = -0.2 \text{ N/m}^2$

$\sim k_d^{2/3}$

MOC intensity, Sv

Diapycnal diffusivity, cm$^2$/s

$k_d$
Summary:

- We have formulated a 2D model of the AMOC that includes explicit effects of the wind. The overturning strength in the model depends on freshwater fluxes in the Northern Atlantic ($F$), diapycnal mixing ($k_D$) and the wind stress intensity in the Southern Ocean ($\tau$).

- The amount of freshwater forcing needed for a shut-down of the AMOC depends on the value of diapycnal diffusivity only weakly, but stronger on the SO wind stress.

- The SO westerly wind stress stabilizes the circulation and increases its intensity, but there is a clear saturation – large increases in the wind stress lead to a slight increase in the overturning.

- For low to medium values of diapycnal diffusivity and realistic SO winds, the overturning strength is relatively insensitive to changes in diapycnal diffusion.
Stability maps for the AMOC for different diapycnal diffusivities $K_D$ (cm$^2$/s)

- $K_D = 0.5$ cm$^2$/s
- $K_D = 0.2$ cm$^2$/s
- $K_D = 2$ cm$^2$/s

Wind stress anomaly, N/m$^2$
Stability maps for the AMOC

The AMOC strength (in Sv) as a function of freshwater forcing in the Northern Hemisphere and wind stress anomaly in the Southern Ocean.
AMOC intensity as a function of the SO wind stress for different diffusivities $k_D$
AMOC intensity as a function of the SO wind stress - hysteresis
Ocean GCM (OPA):
AMOC intensity as a function of freshwater anomaly for different diffusivities
A cartoon of the global thermohaline circulation (the ‘conveyor belt’, originally by Broecker, After Rahmstorf).
What controls the structure and stability of the ocean meridional overturning circulation: implications for abrupt climate change

PI: Alexey Fedorov, Yale University

**GFDL’s ocean GCM (OM2):**

![GFDL’s ocean GCM](image1)

**2D ocean model:**

![2D ocean model](image2)

**Lagrangian Ocean model:**

![Lagrangian Ocean model](image3)
The collapse of the ocean meridional overturning in GFDL’s ocean model forced by a freshwater forcing in the Northern Atlantic
Salinity changes in the Atlantic over half-a-century

$\Delta S$

After Curry et al 2003
Protactinium/Thorium ratio (Pa/Th)

Residence time in the water column:
- Protactinium: 100-200 years
- Thorium: 20-40 years

McManus et al. 2004
Protactinium/Thorium ratio (Pa/Th)

Residence time in the water column:

Protactinium: 100-200 years
Thorium: 20-40 years
Fig. 1.22 (after Cubasch et al. 2001): Simulations of the Atlantic THC strength under CO₂ increase, relative to the means of the years 1961-1990.
IPCC 2007
Stommel (1961):

Mixed boundary condition:
- Restoring for temperature
- Flux for salinity
Two solutions of the bi-stable regime

Zonally-averaged (2D) ocean model:

Forcing: freshwater flux in the North Atlantic
$k_d = 1 \text{cm}^2/\text{s}$
Zonal-averaged wind stress (N/m$^2$) over the ocean from different datasets:
- COADS (blue; da Silva et al. 1994; Woodruff et al. 1987)
- ECMWF reanalysis (red; Gibson et al. 1997)
- the ERS satellite scatterometer (green; CERSATIFREMER 2002)
- AM2–LM2 (black).
Mean zonal-averaged wind stress (Pa) over the ocean from different datasets

The sign convention is such that a positive stress indicates an easterly stress on the atmosphere and a westerly stress on the ocean.

Westerlies
2D model:

**TEMPERATURE (°C)**

**SALINITY (psu)**

**OVERTURNING (Sv)**
Circulation change due to SO winds

De Boer et al., 2008, JPO
Barreiro, Fedorov and co-authors 2008
The effect of the AMOC collapse on SSTs in coupled and ocean-only GCMs

Barreiro, Fedorov and co-authors 2008