Stratification-dependent Mixing Decreases the Stability of the Atlantic Overturning in a Coupled Climate Model

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Abstract

The Atlantic Meridional Overturning Circulation (AMOC) is contributing considerably to the mild climate of north-western Europe by transporting heat from the low latitudes northward. On long timescales, the AMOC is limited by the amount of potential energy that is put into the ocean by vertical mixing.

By assuming a constant rate of mixing, most state-of-the-art climate models do not represent the effect of vertical mixing well, since theoretical arguments and measurements indicate that the vertical mixing strongly depends on local physical parameters – above all, on stratification.

We implemented stratification-dependent mixing into a coupled climate model, and found the sensitivity of the AMOC to freshwater forcing to depend critically on the coupling between stratification and mixing. Weak coupling reproduces results from previous studies that assume constant vertical mixing. Stronger (and more realistic) coupling however allows for a positive feedback in the high northern latitudes which creates a strongly stratified layer. This layer is not penetrated by winter deep convection. Thus, the overturning north of the Greenland-Scotland Ridge is stopped.

1 Model Description

The model CLIMBER-3α is a coupled climate model of intermediate complexity. It combines a 3-d, 24 layer ocean general circulation model based on the GFDL MOM3 code with a statistical-dynamical atmosphere (POTSDAM-2) and a dynamic and thermodynamic sea-ice module. The horizontal resolution of the ocean is $3.75° \times 3.75°$, while the atmosphere uses a coarse resolution of $7.5° \times 22.5°$, assuming a universial vertical structure of temperature and humidity.

Mixing Parameterization

The background vertical diffusivity of the ocean κ is calculated depending on the buoyancy frequency N as

$$\kappa = \kappa_0 \left(\frac{N}{N_0} \right)^{-\alpha}$$

where N_0 is chosen to represent the typical value of N in the pycnocline to assure compatibility between the different experiments. The parameter α controls the coupling strength between the stratification and vertical mixing (see fig. 1).

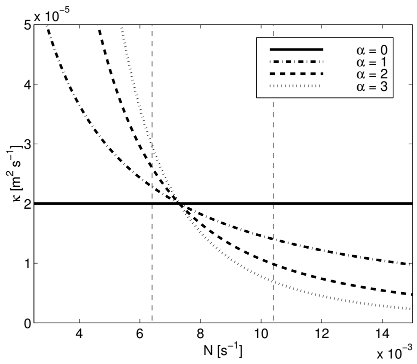

Figure 1: Background diffusivity κ depending on buoyancy frequncy N for values of α between $\alpha = 0$ ($\kappa = \mathrm{const.}$) and $\alpha = 3$ (steepest curve). $N_0 = 0.0073\ \mathrm{s}^{-1}$, $\kappa_0 = 0.2\ \mathrm{cm}^2\mathrm{s}^{-1}$. The vertical dashed lines indicate the range of N found in the unperturbed experiments around pycnocline depth (i.e. between 450 and 800 m) in the global ocean.

2 Experiments

First, the model is run for ~2500 years until it has reached equilibirum, using different values of α corresponding to the range found in open ocean measurements. Then, in two groups of experiments, an anomalous freshwater forcing of 0.1 Sv (sflx01 runs) and 0.2 Sv (sflx02 runs) is started in the Atlantic between 20°N and 50°N. The model is run for another ~2000 years with continued anomalous freshwater forcing.

3 Results

Response of the Overturning

The equilibrium of the unperturbed runs is very similar for all values of α. As the anomalous freshwater forcing is started, the overturning is weakened. The amplitude of the weakening depends critically on the value of α.

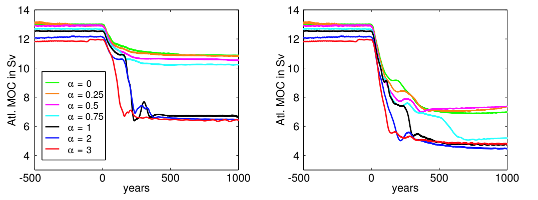

Figure 2: The maximum of the Atlantic Meridional Overturning. Left: sflx01 runs, right: sflx02 runs. The anomalous freshwater forcing is started at $t = 0$. In both the sflx01 and sflx02 runs, there are two distinct groups of experiments, seperated by a critical value α_{cr}.

Changes in Surface Air Temperature

Since the AMOC is contributing to the northward oceanic heat transport, there is a strong connection between the strength of the AMOC and temperatures in the North Atlantic region. The weakening of the AMOC caused by the anomalous freshwater forcing thus leads to a cooling of the North Atlantic (see figure 3).

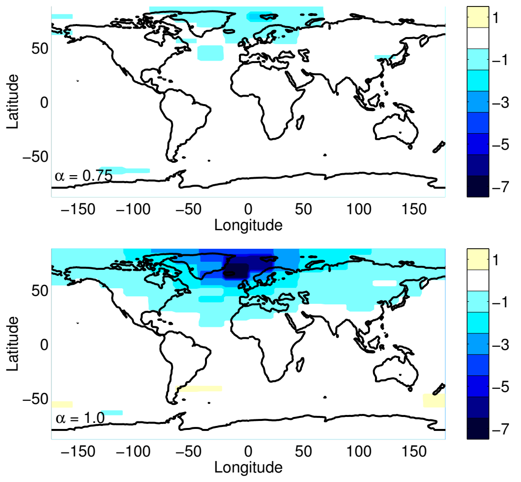

Figure 3: Surface air temperature anomalies in K caused by 0.1 Sv of anomalous freshwater forcing. Upper panel: $\alpha = 0.75$ (subcritical), lower panel: $\alpha = 1.0$ (supercritical).

In the supercritical runs ($\alpha > \alpha_{\mathrm{cr}}$), the effect of freshwater forcing on surface air temperature is tripled compared to the subcritical runs ($\alpha < \alpha_{\mathrm{cr}}$).

4 The Mechanism

Initially, the negative salt anomaly created by the anomalous freshwater forcing is mixed into the high latitudes deep ocean by winter deep convection in both the subcritical and supercritical case (figure 4).

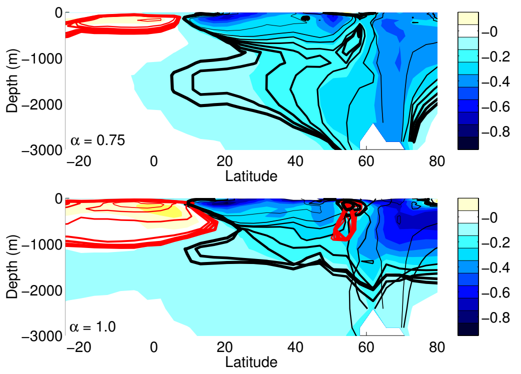

Figure 4: Temporal evolution of the zonally averaged temperature and salinity anomalies. Upper panel: $\alpha = 0.75$, lower panel: $\alpha = 1$. Background shading: Salinity anomaly in PSU after 300 years of 0.1 Sv anomalous freshwater flux. Black lines: Position of the zonally averaged -0.2 PSU salinity anomaly, starting at t = 100 years with the thinnest line, line thickness increasing with 50 years time steps. Thickest line shows the position at t = 450 years. Red lines: the same as black, but for the zonally averaged 0.7 K temperature anomaly. The values of the contours were chosen such that they represent approximately the same change in density.

However, if $\alpha > \alpha_{\mathrm{cr}}$, a positive feedback between stratification and vertical mixing is activated: The fresh anomaly at the surface creates stratification, which decreases mixing. The decreased mixing in turn leads to an increased stratification. A stratified layer is formed in the high latitudes, which cannot be penetrated by winter deep convection. This further limits the freshwater anomaly to the surface, and the overturning north of the Greenland-Scotland Ridge is stopped (figure 5).

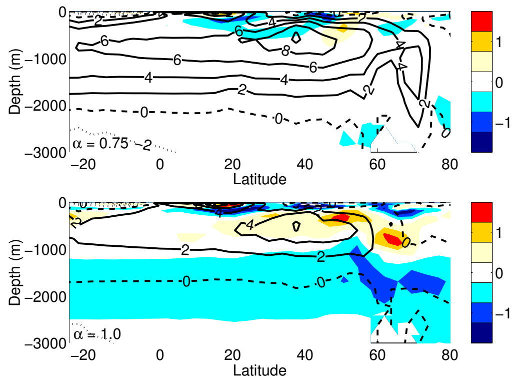

Figure 5: Changes in mixing and overturning after 800 years of 0.1 Sv freshwater flux. Shading: zonally averaged anomalies of the background diffusivity κ in $10^{-6}\ \mathrm{m}^2\mathrm{s}^{-1}$. Contours: overturning streamfunction in Sv. Upper panel: $\alpha = 0.75$, lower panel: $\alpha = 1$. A barrier layer of low diffusivity is formed by the freshwater anomaly in the supercritical case (lower panel), which inhibits penetration by deep convection. Since the freshwater is more evenly distributed in the subcritical case (upper panel), diffusivity remains unchanged.

5 Discussion

Previous studies with box models and idealized ocean-only models found an increase of the AMOC as a response to freshwater forcing for supercritical values of α. The reason was deep advection of the fresh anomaly with the return flow of the AMOC, decreasing the stratification in low latitudes, thus increasing low latitudes mixing. The advection of the freshwater is evident also in our model, but it is balanced by a surface warming in the low latitudes, which is caused by the reduced northward heat transport (figure 6).

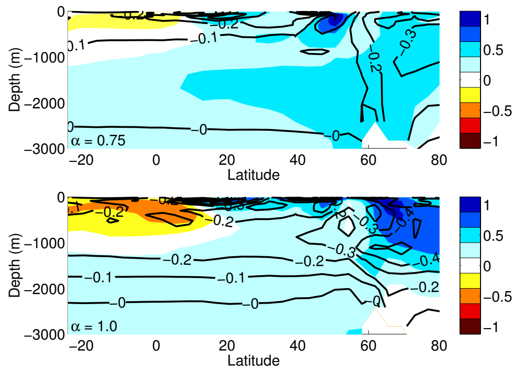

Figure 6: Relative contributions of temperature and salinity anomalies to the density anomlies. Upper panel: $\alpha = 0.75$, lower panel: $\alpha = 1$. Shading: $\Delta\rho_T - \Delta\rho_S$ in $\mathrm{kg/m}^3$ after 800 years of 0.1 Sv freshwater flux, where $\Delta\rho_T$ is the density anomaly calculated using the salinity of the unperturbed run, and $\Delta\rho_S$ is the density anomaly calculated using the temperature of the unperturbed run. Contour lines: full density anomaly. Red color indicates that temperature is dominating the density anomaly, white color indicates regions where temperature and salinity contribute equally, and blue color indicates salinity-dominated density changes.

References

Marzeion, B., A. Levermann, and J. Mignot, 2006: The Role of Stratification-dependent Mixing for the Stability of the Atlantic Overturning in a Global Climate Model, submitted to *Journal of Physical Oceanography*, downloadable at `www.marzeion.info`.

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