The effect of Denmark Strait overflow on the Atlantic Meridional Overturning Circulation

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[1] Hydraulic constraints on the Denmark Strait overflow (DSO) are used as a parameterisation to improve the overflow representation in a global climate model. The parameterisation increases deep water formation in the Nordic Seas and strengthens the Norwegian Atlantic Current. Associated higher northward heat transport leads to a northward shift of the sea-ice edge and warming by 2.5°C in the eastern Nordic Seas despite a small effect on the Atlantic Meridional Overturning Circulation (AMO). This emphasises the impact of the DSO on climate even though the response in overturning due to the DSO representation in this model is less than expected from previous studies using ocean only models. In contrast to previous studies almost no stabilising effect of the overflow on the AMO is found to freshwater perturbations. **Citation:** Kösters, F., R. H. Käse, A. Schmittner, and P. Herrmann (2005), The effect of Denmark Strait overflow on the Atlantic Meridional Overturning Circulation, *Geophys. Res. Lett.*, *32*, L04602, doi:10.1029/2004GL022112.

1. Introduction

[2] The Denmark Strait (DS) forms together with the Faroe Bank Channel (FBC) the two main gateways for dense water from the Nordic Seas into the North Atlantic. Thus, the DSO constitutes an important part of the thermohaline circulation in present-day climate. It has been suggested that the facilitating downslope flow of dense water has a strong stabilising effect on the AMO [*Lohmann*, 1998]. Overflow dynamics act on Rossby radius length scale (10 km) in the horizontal plane which cannot be resolved by present-day climate models (resolution ~100 km). Even in high-resolution *z*-level models the representation of overflows using a step-like topography, especially through DS, is still an unresolved issue [*Ezer and Mellor*, 2004]. The sensitivity of *z*-level ocean models to bathymetry variations is well known [*Roberts and Wood*, 1997] and in coarse-resolution climate models one hardly obtains realistic transport rates for the DSO without subjective tuning of the model bathymetry [*Gerdes*, 1993]. The lack of a physical basis for the bathymetry tuning provides the rationale for an overflow parameterisation based on hydraulic transport estimates. Hydraulic theory suggests that the volume transport is set by the relative density contrast between the water masses north and south of the DS and the height of dense water above sill level [*Whitehead et al.*, 1974; *Käse and Oschlies*, 2000]. The idea is to diagnose the hydraulic transport from the large-scale conditions and then impose this value on the exchange across the sill in a coarse-resolution model. Thus the main objectives of this study are to test the parameterisation in a coupled climate model for long-term integrations, to identify changes in the large-scale circulation due to the changed overflow representation, and to determine the influence thereof on the stability of the AMO.

2. Evaluation of the Parameterisation

[3] It has been previously proposed to employ hydraulic constraints as an overflow parameterisation for DS [*Kösters*, 2004]. This has been implemented here in the global coupled UVic Earth System Climate Model [*Weaver et al.*, 2001]. Technically, the parameterisation was included as a momentum source term during the computation of the internal mode velocities. This was done by replacing the advective and diffusive fluxes with the diagnosed hydraulic transport in the bottom cell at the sill (510–690 m depth). The maximum hydraulic transport estimate Q_{WLK} diagnosed from the large-scale environmental density field is based on the integral form of *Whitehead et al.* [1974] as

$$Q_{\mathrm{WLK}} = \frac{g}{f\,\rho_0}\int_{\mathrm{h}}^{0} \left(\rho_{\mathrm{N}}(z) - \rho_{\mathrm{S}}(z)\right) z\,dz. \qquad (1)$$

The integral is evaluated from sill depth $z = h$ to surface $z = 0$, with ρ_{N} and ρ_{S} being the laterally averaged but depth dependent potential densities north and south of the sill (Figure 1). g is the gravitational acceleration, f is the Coriolis parameter and ρ_0 is the mean density. When applying equation (1) over a two-layer ocean one yields the familiar expression for hydraulic transport of *Whitehead et al.* [1974] as $Q_{\mathrm{WLK}} = \frac{1}{2}\frac{g'}{f}H^2$, with $g' = g \cdot \frac{\Delta\rho}{\rho_0}$ being reduced gravity and H the height of dense water above sill level. The hydraulic transport diagnosed from equation (1) is then imposed on the bottom cell's velocity. In order to account for unresolved entrainment downstream of the sill and the poor representation of the descending plume the prescribed transport was taken to be the maximum hydraulic transport.

[4] In three long-term (2000 years) equilibrium experiments different representations of the DSO were evaluated. Since the topography cannot be adequately resolved in coarse-resolution models the effects are commonly incorporated by other means. Experiment (DEEP) applies the approach of previous studies [e.g., *Weaver et al.*, 2001] to deepen large parts of the Greenland-Scotland Ridge (GSR) artificially to 2000 m and to remove Iceland. In the reference experiment (REF) realistic topography of the GSR is used with a sill depth of 600 m for the DS and 1012 m for the Faroe-Shetland Channel. These experiments

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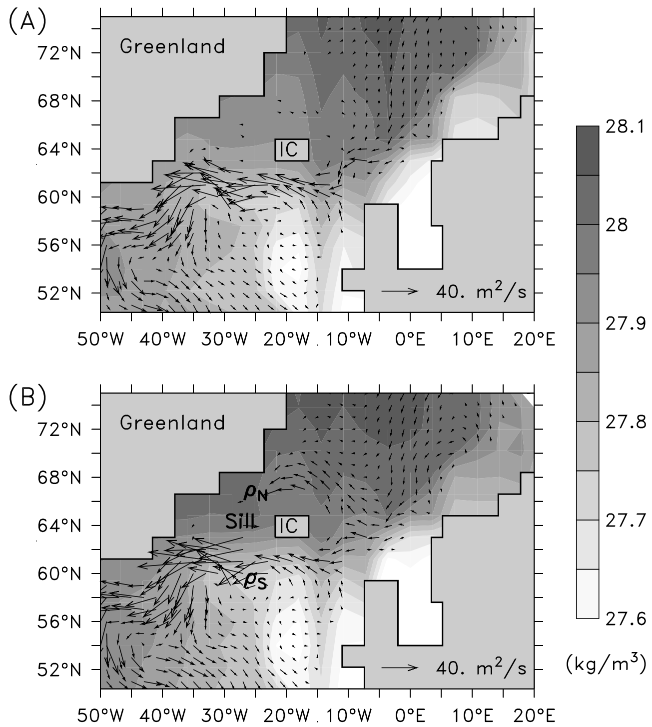

Figure 1. Water mass properties at the GSR region of outflowing dense water. The average potential density σ_θ (kg/m^3) of south-westward flowing water is shaded for experiment REF (A) and HYD (B). Note the increased density of water masses south of DS if the overflow is parameterised. The transport vectors of vertically integrated velocity (m^2/s) illustrate the upstream circulation of dense water upstream north of the GSR and overflow water south of it.

are then compared to experiment HYD with parameterised DSO using realistic topography.

[5] In experiment REF deep water is formed by cooling of warm and saline water of the North Atlantic Drift south of the GSR (Figure 2). The mixed layer depth indicates that convection mainly takes place west of Scotland and in the Irminger and Labrador Seas. Thus an important feature of observations [e.g., *de Boyer Montégut et al.*, 2004] showing MLD maxima in deep water formation regions in the Nordic Seas is absent. This also leads to a too weak Norwegian Atlantic Current causing a well known cold bias in the Nordic Seas [*Weaver et al.*, 2001]. In the parameterised version (HYD) the location of convection sites in the model is closer to observations. Additional convection occurs in the Iceland Sea down to a depth of 500 m and further north in the Norwegian Sea reaching down to 900 m. In turn, convection areas in the Irminger Sea are reduced. Although this improves the model performance deep water formation north of the GSR is still underestimated.

[6] The DSO transport (defined from $\sigma_\theta \geq 27.8$) in REF has a rate of 0.7 Sv, directed to the north. When the hydraulic parameterisation is applied (HYD) the flow is directed southward and strongly enhanced to 6 Sv. This is about two times the observed dense water transport [*Dickson and Brown*, 1994]. Part of this dense outflow causes an unrealistic recirculation directly at the sill but the density of the overflow plume increases and more dense water is exported from the Nordic Seas through DS (Figure 1). Note the changes in the upstream circulation north of the GSR where due to the parameterisation a realistic advection path in direction of the DS is obtained. The additional export of cold water causes a compensating flow of warm water east of Iceland into the Nordic Seas thus increasing the northward heat transport to more realistic values. The barotropic circulation in HYD shows a strengthening of the subpolar gyre by 2 Sv and of the subtropical gyre by 1 Sv compared to REF similar to previous findings by *Döscher et al.* [1994]. As a result of increased DSO and more extensive deep water formation in the Nordic Seas the North Atlantic Drift and the Norwegian Atlantic Current are intensified leading to increased northward heat transport in the North Atlantic by a maximum of 80 TW at the GSR and 20 TW at low latitudes. This causes warmer sea surface temperatures (SSTs) by 2.5°C averaged over the eastern Nordic Seas (10°E–20°W, 62°N–72°N) and slightly higher surface air temperatures in the Norwegian Sea (Figure 2). Moreover, the sea-ice edge is displaced northwards improving the agreement with observations.

[7] The effect on the AMO is rather small with an increase by 6% from 19 Sv to 20 Sv (Figure 3) but the unrealistic disconnection of Nordic Seas and subpolar North Atlantic is overcome. The changes in AMO due to the parameterisation are less than expected from previous

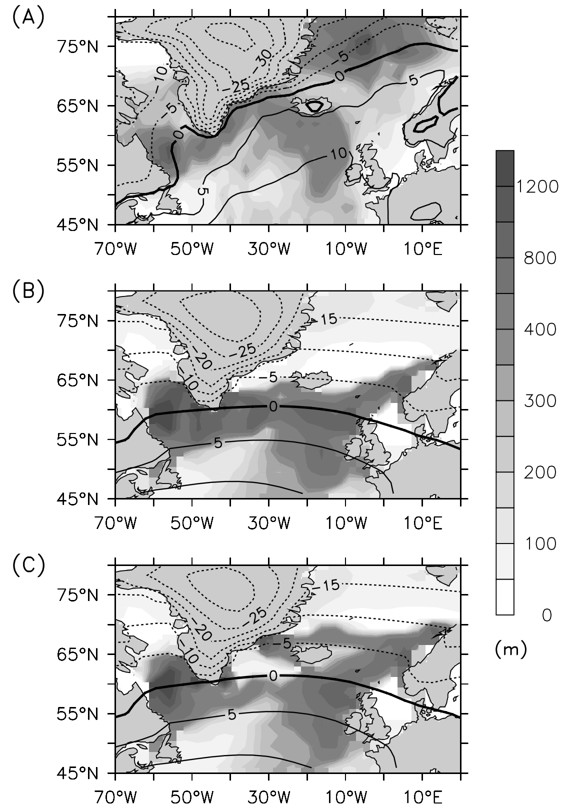

Figure 2. Maximum mixed layer depth (shading) as found in observations [*de Boyer Montégut et al.*, 2004] (A), experiments REF (B), and HYD (C). Contour lines represent the annual mean near surface air temperature (in °C), observations (A) are from *Gibson et al.* [1997]. The mixed layer depth was calculated based on the difference of potential density at depth from the near-surface (10 m) using a threshold value of 0.03 kg/m^3 following *de Boyer Montégut et al.* [2004].

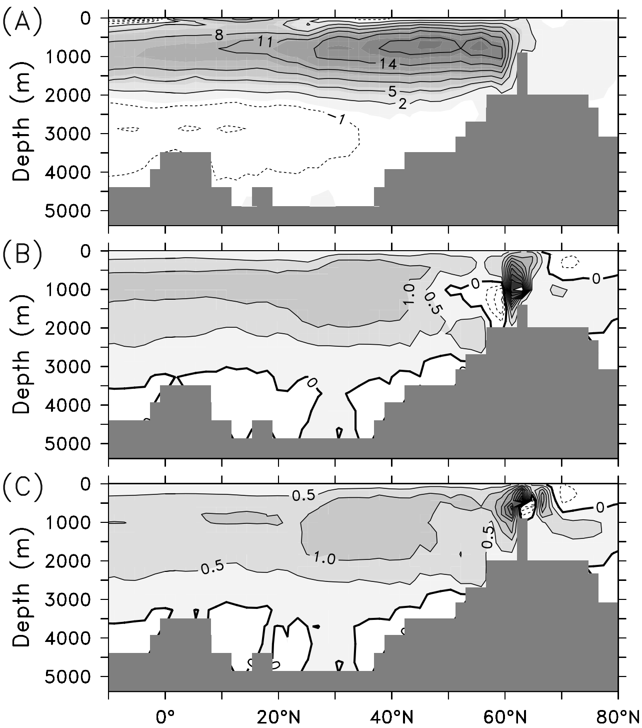

Figure 3. Atlantic Eulerian meridional overturning streamfunction (annual mean over years 1900 to 2000) for experiment REF (A) and the differences DEEP-REF (B) and HYD-REF (C). The contour interval is 3 Sv in A and 0.5 Sv in B and C.

studies with ocean only models using surface restoring boundary conditions [e.g., *Döscher et al.*, 1994; *Döscher and Redler*, 1997]. *Döscher and Redler* [1997], using a regional North Atlantic model with prescribed densities of the overflows at the closed northern boundaries at 65°N, found a strong dependence of the overturning on overflow density. The experiments presented here suggest that the export of Denmark Strait Overflow Water can be strongly increased (6 Sv) with little effect on the AMO (1 Sv). Even though the density structure at the GSR is locally significantly changed, remote effects are rather small. Artificially deepening the GSR has a similar effect on the overturning (small increase) as the parameterisation of the overflow (Figure 3). However, the circulation across the GSR is less realistic in DEEP-REF. Due to the changes in topography there is no longer a distinction between the overflows through DS and FBC. *Roberts and Wood* [1997], on the contrary, find a much stronger increase of the AMO when deep gateways are included in the GSR crudely representing Faroe Bank Channel. This result is questioned in a subsequent study with the same model but on a global scale and coupled to an atmosphere model, which found that the large-scale circulation is broadly insensitive to changes of mixing parameterisation and downstream bathymetry (sill depth remaining the same) at the DS [*Thorpe et al.*, 2004]. The models showing a strong impact of the GSR overflows are regional, ocean only North Atlantic models, whereas the influence in coupled models seems to be much reduced. One possible explanation of this discrepancy can be inferred from changes in surface air temperature. An increased overflow transport results in increased surface air temperatures thus providing a negative feedback on dense water production. Employing restoring conditions using cold temperatures from observations will thus cause an artificially high buoyancy forcing leading to the exaggerated importance of the DSO in regional ocean models. Nevertheless, coarse-resolution models in general have problems to simulate realistic deep water formation. If the reference state of the UVic experiments would have more pronounced deep water formation in the Nordic Seas the impact of a better overflow representation on the AMO might have been stronger. Therefore, these results need to be verified using other global coupled models. One has to keep in mind that the technical development for realistic overflow transport rates presented here does not necessarily yield a better representation of the overflow plume downstream. However, the combination of the hydraulic parameterisation of the overflow and a bottom boundary layer (BBL) scheme as discussed in the next section did not change the results significantly.

3. Influence on the Stability of the Thermohaline Circulation

[8] A collapse of the Atlantic thermohaline circulation has a severe global climatic impact [*Vellinga and Wood*, 2002] leading to colder and drier conditions in the Northern Hemisphere. Therefore, it is important that dense overflows might have a stabilising effect on the thermohaline circulation [*Lohmann*, 1998]. This view might be supported by hydraulic considerations as the Nordic Seas can be seen as a reservoir of dense water, which cannot be rapidly flushed. It is evaluated below if this mechanism can provide a negative feedback for the AMO, leading to a stabilisation by employing the DS parameterisation in experiments with a perturbed freshwater balance of the North Atlantic. The experiments follow a hysteresis loop of slow and linearly varying freshwater flux (Figure 4) as by *Schmittner et al.* [2002]. Two stable circulation patterns exist in the model for present-day conditions (Figure 4) similar to previous studies [e.g., *Rahmstorf*, 1996]. Starting from a state with active deep

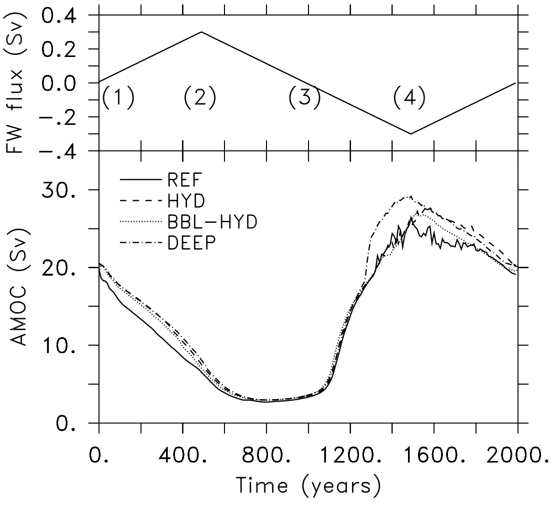

Figure 4. Temporal evolution and magnitude of freshwater (FW) flux perturbation experiments (upper panel) and hysteresis curves evaluating the effect of the parameterisation (lower panel). The perturbed area extends from 74°W–47°W, 49°N–65°N.

water formation (on-state, 1) the AMO gradually reduces with increasing freshwater flux until deep water formation is stopped (off-state, 2). Reducing the freshwater input, the system stays in the off-state (3) until a threshold is passed and a rapid resumption of the circulation occurs (transition from (3) to (4)). In the following the focus will be on the differences between the individual hysteresis loops for experiments REF, HYD, DEEP and an additional experiment (HYD-BBL) with a BBL included [*Campin and Goosse*, 1999] but otherwise as HYD. The difference at the starting point (1) is due to the slightly higher overturning in HYD, HYD-BBL and DEEP as compared to REF. With onset of the positive freshwater flux the AMO reduces in all experiments. Between (1) and (2) the perturbation in REF had a larger impact on the AMO and the parameterisation had a small stabilising effect (2.5 Sv). When further increasing the fresh water flux (2) the same low level is reached for all experiments during the off-state. When the freshwater flux changes sign (3), the AMO recovers at a similar rate in all experiments but with parameterisation a higher maximum for the maximum negative freshwater flux (4) is reached.

[9] Overall, the effect that can be attributed to the parameterisation during the anomalous freshwater input is an increased overturning by about 2 Sv. In the starting phase of the freshwater anomaly there are indications for a potential stabilising feedback of the parameterisation but this effect is of small amplitude only. Note that freshwater perturbations at this area can lead to oscillatory behaviour for large negative anomaly when cold and salty water is flushed periodically from the shallow parts of the Labrador Sea to depth as visible between years 1400 and 1700 in experiment REF.

[10] *Lohmann* [1998], using a highly idealised BBL scheme, suggested that facilitating overflow has a strong stabilising effect on the AMO. Our results using a more realistic representation of the BBL and a representation of the DSO, however, indicate the contrary. That is, neither including the BBL scheme nor a parameterisation of the overflows changes the stability of the AMO much. Even though the BBL scheme employed here is considered to improve the representation of entrainment in the model it is still too high downstream of the DS. Strong entrainment rates in the Irminger basin cause a dilution of DSO water mass properties and possibly limit the effect of the parameterisation.

4. Summary

[11] An overflow parameterisation based on hydraulic constraints has been evaluated in a global climate model. The overflow representation was significantly improved using the parameterisation. In the UVic model the parameterisation has a significant but small effect on the meridional overturning circulation and closely linked quantities such as the surface air temperature in the northern North Atlantic. Sea-ice cover in the Nordic Seas is reduced and the deep water formation north of the GSR is enhanced. The dense signal can be traced downstream of the DS eventually strengthening the DWBC. The effect of these changes in a long-term integration using a coupled model is smaller than expected from previous studies based on ocean only, regional North Atlantic models [*Döscher et al.*, 1994; *Böning et al.*, 1996; *Redler and Böning*, 1997]. This stresses the fact that additional experiments with global coupled models are necessary to corroborate our findings. However, a strong stabilising effect on the thermohaline circulation could not be found. Changes in the overflow properties do have sizeable remote impact emphasising that there is no need for very pronounced changes in the overturning to yield a noticeable impact on Europe's climate.

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