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Atlantic deep circulation controlled by freshening in the Southern Ocean

Oleg A. Saenko and Andrew J. Weaver
School of Earth and Ocean Sciences, University of Victoria, Victoria, Canada

Andreas Schmittner
Institut für Geowissenschaften, Universität Kiel, Kiel, Germany

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[1] Numerical simulations with a climate model of intermediate complexity are used to illustrate the effect of meridional moisture transport in the Southern Hemisphere mid-latitudes on the meridional overturning circulation (MOC) and heat transport in the Atlantic. A novel feature of the model is a diapycnal mixing scheme in the ocean, which ensures low values of diffusivity (about 10^{-5} m^{2}s^{-1}) in the pycnocline. It is shown that the Atlantic MOC, northward oceanic heat transport and the associated air-sea heat flux anomalies are all proportional to the southward moisture transport from subtropical to subpolar regions in the Southern Hemisphere. The effect of the intensified ocean circulation on sea surface temperature and salinity is also illustrated. *INDEX TERMS:* 4532 Oceanography: Physical: General circulation; 4516 Oceanography: Physical: Eastern boundary currents; 4283 Oceanography: General: Water masses. **Citation:** Saenko, O. A., A. J. Weaver, and A. Schmittner, Atlantic deep circulation controlled by freshening in the Southern Ocean, *Geophys. Res. Lett.*, *30*(14), 1754, doi:10.1029/2003GL017681, 2003.

1. Introduction

[2] A number of factors controlling the strength of large-scale meridional overturning circulation (MOC) in the ocean have been proposed. Among others, these include diapycnal mixing [*Munk*, 1966; *Bryan*, 1987] and the associated sources of mechanical energy required to support the mixing against gravity [*Munk and Wunsch*, 1998; *Huang*, 1999]; Southern Ocean winds [*Toggweiler and Samuels*, 1995; *Toggweiler and Samuels*, 1998] and the associated heating in the Southern Ocean [*Hasumi and Suginohara*, 1999]; geothermal heating [*Huang*, 1999]; the inter-basin salinity contrasts [*Broecker et al.*, 1990; *Stocker et al.*, 1992; *Rahmstorf*, 1996; *Seidov and Haupt*, 2003].

[3] Here we seek to illustrate the effect of meridional moisture transport at mid-latitudes of the Southern Hemisphere on the overturning circulation and heat transport in the Atlantic, using a coupled model. We show, in particular, that the heating in the Southern Ocean proposed by *Hasumi and Suginohara* [1999] as a control of Atlantic deep circulation can, in part, be a passive response to the strengthening of the deep circulation itself. In the experiments presented here, the heat gain anomaly in the south and heat loss anomaly in the north are implicitly a result of the enhanced southward moisture transport from subtropical to subpolar regions in the Southern Hemisphere. The latter has a potential to intensify the MOC and northward heat transport, causing an efficient heat transfer to the deep ocean north of 60°S without the need for stronger zonal winds in the Southern Ocean.

[4] An important difference here from most of the forementioned studies is that we employ a model (see below) which both consumes a realistic amount of energy to support diapycnal mixing in the ocean and does not use restoring boundary conditions for sea surface temperature (SST) and salinity (SSS). The latter ensures that the SST and SSS in the model can respond to the changes in the ocean circulation.

2. The Model

[5] The model we use is a climate model of intermediate complexity described in *Weaver et al.* [2001]. This is a coupled model which comprises an ocean general circulation model (GCM), a dynamic-thermodynamic sea ice model and an energy-moisture balance atmosphere model. All model components have the same horizontal resolution of 3.6° × 1.8° in longitude and latitude, respectively. The ocean model uses isopycnal mixing after *Gent and McWilliams* [1990] with the coefficients of thickness diffusivity and isopycnal diffusivity set to 1.0×10^3 m^{2}s^{-1} and 2.0×10^3 m^{2}s^{-1}, respectively.

[6] A novel feature of the oceanic component of the model is a parameterization of vertical mixing. Here we use a mixing scheme described in *St. Laurent et al.* [2002] and adopted for a use in GCMs by *Simmons et al.* [2003]. It accounts for the energy ε coming from dissipation of internal tides in the regions of rough oceanic topography. A prescribed part of this energy $\Gamma = 1/5$ goes to support turbulent mixing in the ocean against gravity, out of which a fraction of $q = 1/3$ goes to enhance local vertical mixing [*St. Laurent et al.*, 2002]. A coefficient of vertical diffusivity k_v is then given by [*St. Laurent et al.*, 2002; *Simmons et al.*, 2003]: $k_v = k_b + q\Gamma\varepsilon/(\rho N^2)$, where $N^2 = -(g/\rho)\rho_z$ and $k_b = 0.1 \times 10^{-4}$ m^{2}s^{-1} is the background diffusivity due to non-local sources of mixing. The vertical structure of ε (in W m^{-3}) ensures its exponential intensification toward the ocean bottom [*St. Laurent et al.*, 2002; *Simmons et al.*, 2003], with near zero values within the pycnocline. The latter has an effect of producing very low values of diffusivity (mostly due only to k_b) in the oceanic interior within the upper 2000 m. We note that it is within the oceanic pycnocline where vertical diffusivity has the potential to affect overturning circulation.

[7] The atmospheric model computes surface fluxes of heat and freshwater, as well as the atmospheric transport of

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sensible heat and moisture. The latter is given by [*Weaver et al.*, 2001]: $\rho_a H\{q_t + \gamma\nabla(\mathbf{u}q) - \nabla\mu\nabla q\} = \rho_o(E - P)$ where q is the surface specific humidity, μ is an eddy moisture diffusivity (see next section), $\mathbf{u}$ is the surface wind, H = 1.8 km is a scale height for specific humidity, γ = 0.4 is an empirical parameter, which relates the vertically-averaged advective moisture transport to the surface advective moisture transport, E and P are the model-predicted evaporation and precipitation.

[8] The SST and SSS evolve in a response to changes in the ocean circulation and climate. However, wind and wind stress are prescribed in this model version from monthly NCEP reanalysis and do not vary in the experiments described below.

3. Results

[9] We present results from two sensitivity experiments. These illustrate the effect of mid-latitude atmospheric eddies on the ocean MOC and heat transport through their ability to transport large amount of water vapor from the subtropical to subpolar regions in the Southern Hemisphere. In the first experiment (E1), southward atmospheric moisture transport produces northward oceanic freshwater transport which closely resembles the optimal 4D VAR data assimilation solution of *Wenzel et al.* [2001], particularly in the Southern Hemisphere (Figure 1). This was achieved by setting moisture eddy diffusivity to $\mu = \mu_b + 3\sin(2y) \times 10^6$ (m^2s^{-1}) in the Southern Hemisphere and to $\mu_b = 10^6\ m^2s^{-1}$ in the Northern Hemisphere. In the second experiment (E2), we set $\mu = \mu_b$ in both hemispheres, which considerably reduces the southward (northward) moisture (freshwater) transport at mid-latitudes of the Southern Hemisphere (Figure 1). The experiments were run for 3000 years, starting from an idealized zonal distribution of ocean temperature and uniform salinity.

[10] Figures 2a and 2b show the effect of the changed meridional moisture transport on the Atlantic MOC. It can be seen that, even though both experiments have almost the same shape of freshwater transport in the Northern Hemisphere (Figure 1), they have quite different strength of MOC. In experiment E2, the maximum overturning is only 6 Sv (1 Sv = $10^6\ m^3s^{-1}$), whereas in E1 it reaches 15 Sv. The increase of water sinking in the north is compensated in the south (Figure 2c) by both an increase of deep water upwelling and by a decrease of bottom water production. The introduction of additional buoyancy in the Southern Ocean in E1 intensifies the transformation of relatively dense Circumpolar Deep Water (CDW) into relatively light Antarctic Intermediate Water (AAIW) by about 9 Sv, as can be inferred from the surface buoyancy fluxes (e.g., see *Speer et al.* [2000]). The circulation of Antarctic Bottom Water (AABW) weakens from 11 Sv in E2 to 5 Sv in E1.

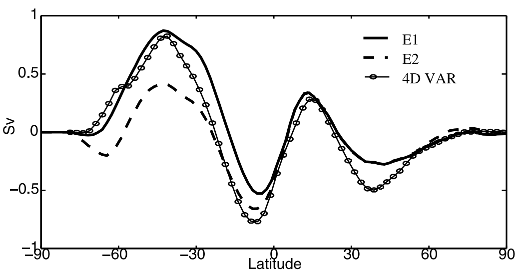

Figure 1. Northward meridional freshwater transport in the ocean in experiments E1 (solid) and E2 (dashed). Also shown is the optimal 4D VAR data assimilation solution (FIN) of *Wenzel et al.* [2001].

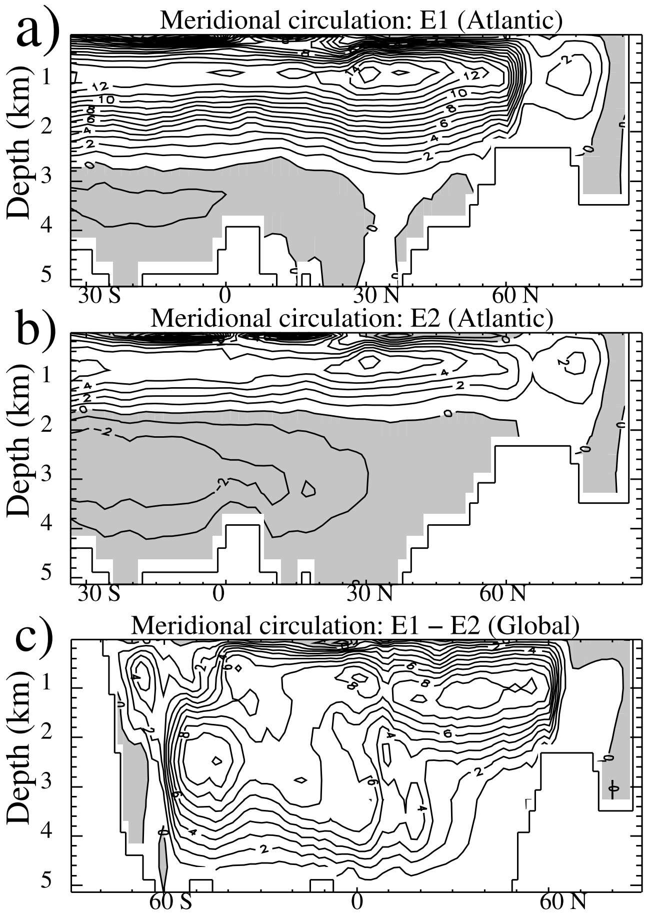

Figure 2. Meridional overturning streamfunction in the Atlantic in experiment E1 (a), in the Atlantic in experiment E2 (b), and global difference E1−E2 (c). Contour interval is 1 Sv. Negative values are shaded.

[11] The intensification of Atlantic MOC can be viewed in terms of the north-south density contrast and the depth of the pycnocline in the Atlantic [e.g., *Gnanadesikan*, 1999]. The mean density contrast ($\Delta\sigma$) between 60–65°N and 55–40°S in the Atlantic and the depth of the pycnocline (D) within 40°S–40°N and 30°W–65°W both increase, respectively, from 0.43 kg/m^3 and 463 m in experiment E2 to 1.25 kg/m^3 and 526 m in experiment E1. Assuming that the strength of MOC scales as $\Delta\sigma D^2$ [e.g., *Gnanadesikan*, 1999], the deepening of the pycnocline and the increase of the density contrast would intensify the MOC by a factor of 1.3 and 2.9, respectively. It is thus the increase of the density contrast, representing essentially a density difference between North Atlantic Deep Water (NADW) and AAIW, which is a dominant factor in balancing the intensified MOC. It is worth noting that in a coupled system with interactive surface fluxes, a considerable fraction of this density contrast can be set by the ocean circulation itself (e.g., *Speer et al.* [2000]; see also Figure 5).

[12] As a result of the more intense MOC, about 0.3 PW more heat is transport northward in the Atlantic in E1 compared to E2 (Figure 3a). Globally, more heat is transported from the south to the north in the ocean (Figure 3b), which must be balanced by more heat loss in the north and by more heat gain in the south, north of about 60°S (Figure 4). Hence, the heat gain in the Southern Ocean is mostly a passive response to the intensified MOC and to the associated intensification of northward heat transport in the ocean. This is in contrast to *Hasumi and Suginohara* [1999], who argue that the Atlantic deep circulation is controlled by heating in the Southern Ocean. In experiments with stronger Southern Ocean winds, such as presented in *Hasumi and Suginohara* [1999], the MOC can be intensified by the effect of wind stress on the deepening of the thermocline north of the Antarctic Circumpolar Current (ACC) [*Gnanadesikan and Hallberg*, 2000].

[13] It should be noted that even with the enhanced southward moisture transport in the Southern Hemisphere, the heat transport in the Northern Hemisphere is about two times less than the observational estimates [*Ganachaud and Wunsch*, 2003]. This reflects the coarseness of the model resolution, which is particularly important within western boundary currents. Nonetheless, an important result is that the increase of southward moisture transport at around 45°S by a factor of two (Figure 1), increases the rate of deep water formation in the North Atlantic and its outflow by more than a factor of two (Figure 2), with the associated considerable increase of northward heat transport (Figure 3).

[14] This result holds as long as the diapycnal mixing is realistically low away from rough topographic features in the upper 2000 m of the ocean. To show this, two additional experiments were performed. These are identical to E1 and E2, except k_v was increased to about 0.8×10^{-4} m^{2}s^{-1} in the upper 2000 m. In the experiment similar to E1, the maximum overturning in the North Atlantic reached 21.8 Sv (not shown). However, in the experiment similar to E2, the overturning also remained at a rather high level, with a maximum of 18.5 Sv. The increase of diapycnal mixing makes the MOC more mixing-controlled and, accordingly, the northward heat transport in the ocean becomes much less sensitive to the southward moisture transport (Figure 3).

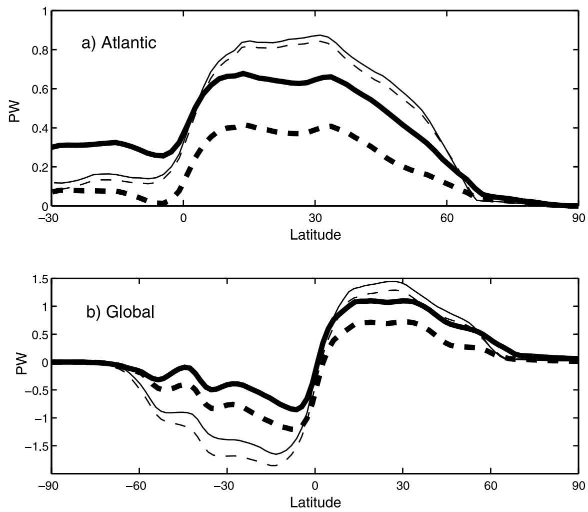

Figure 3. Meridional oceanic heat transport in experiments E1 (heavy solid) and E2 (heavy dashed): (a) in the Atlantic and (b) global. Thin lines show the transports in the experiments identical to E1 (solid) and E2 (dashed), but with larger diapycnal mixing (see the text). Units are PW (1 PW = 10^{15} W).

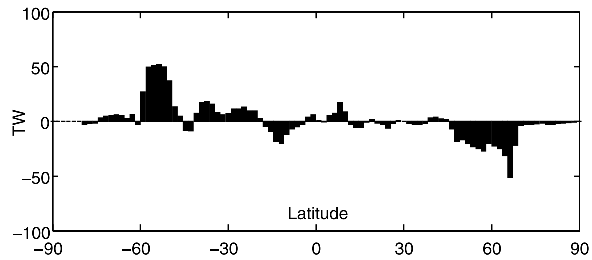

Figure 4. Annual-mean heat flux difference between E1 and E2. Units are TW (1 TW = 10^{12} W).

[15] The response of SST and SSS to the intensified MOC (and, here, to the moisture transport in the south) is shown in Figure 5. This gives an idea of what kind of suppression one can expect in sensitivity experiments with strong restoring to prescribed SST and SSS. For example, the North Atlantic SST in experiment E1 is up to 7°C larger compared to E2. The increase of SST in the Southern Ocean is mainly a result of the latent heat flux as the transported moisture condenses and warms up the air. Another important feature to note is a positive salinity anomaly in the North Atlantic in the response to the intensified MOC. This suggests that the inter-basin salinity contrasts not only can drive the MOC [e.g., *Seidov and Haupt*, 2003], but also can be *driven* by the MOC through a positive feedback between the circulation and salinity in the Atlantic [*Stommel*, 1961]. Thus, in an ocean model with both SST/SSS and diapycnal mixing prescribed, there can be an internal inconsistency between the strength of the MOC dictated by the boundary conditions and that dictated by the mixing.

4. Discussion and Conclusions

[16] Mechanisms controlling deep water formation in the North Atlantic remain controversial. A number of mechanisms appear to be important. Among others is diapycnal mixing, proposed long ago [*Munk*, 1966]. The importance of mixing, however, has been disputed by *Toggweiler and Samuels* [1998] and by *Webb and Suginohara* [2001]. A weak point of the Toggweiler and Samuels arguments is that they employed an ocean GCM with restoring to prescribed SST and SSS. As we illustrate, the latter could themselves be functions of ocean circulation. Still, in both experiments discussed here, vertical mixing is quite small in the upper 2000 m. Further, both steady state oceans consume almost equal and perhaps reasonable amount of energy to support the diapycnal mixing (about 0.9 TW). Yet, they produce quite different rates of deep water formation in the North Atlantic.

[17] Since the early work of *Gill and Bryan* [1971], it is understood that the very existence of Drake Passage affects the structure of the ocean pycnocline. Essentially, a deepening of the pycnocline to the north of the ACC is required to maintain a geostrophic balance. Such a deepening of the

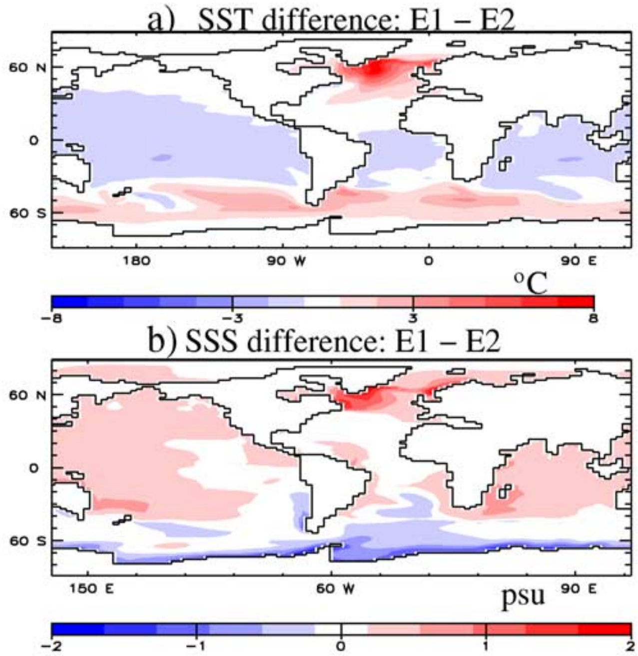

Figure 5. Difference of annual-mean sea surface (a) temperature and (b) salinity between experiments E1 and E2.

pycnocline can intensify the MOC in the north [*Cox*, 1989]. An increase of zonal wind stress in the Southern Ocean has an additional positive effect on the deepening of pycnocline north of the ACC and on its shallowing south of the ACC [e.g., *Cox*, 1989; *Gnanadesikan and Hallberg*, 2000], increasing the available potential energy in the ocean and intensifying the rate of deep water formation in the North Atlantic [*Toggweiler and Samuels*, 1998].

[18] The key result here is that the meridional water vapor transport in the Southern Hemisphere could be at least as important for the MOC as the zonal wind stress. Essentially, we show that in the case of realistically low diapycnal mixing away from the regions of rough topography, the northward oceanic heat transport in the Atlantic is proportional to the southward water vapor transport in the Southern Hemisphere. The increase of meridional heat transport is balanced by the heat loss in the north and heat gain in the Southern Ocean. When diapycnal mixing is increased to less realistic values in the upper ocean, the MOC and the meridional heat transport become more mixing-dependent and less sensitive to the freshening in the south.

[19] Our results are in line with results of *Stocker et al.* [1992] and more recent results of *Seidov and Haupt* [2003] on the effect of salinity contrast between the North Atlantic and the Southern Ocean on the Atlantic MOC. As we show, however, the magnitude of this salinity contrast can, in turn, be controlled by the ocean circulation itself through a positive feedback between the circulation and salinity.

[20] Our results may have implications for understanding the response of the Atlantic MOC in global warming scenarios. It has often been pointed out that in a warmer climate, an intensified hydrological cycle would weaken the MOC by transporting more moisture northward. Our results suggest that the intensified hydrological cycle could also tend to stabilize the MOC by transporting more moisture southward.

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O. A. Saenko, School of Earth and Ocean Sciences, University Victoria, P. O. Box 3055, Victoria V8W 3P6, Canada. (oleg@ocean.seos.uvic.ca)