What drives heat transport in the Atlantic: Sensitivity to mechanical energy supply and buoyancy forcing in the Southern Ocean

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[1] Climate model simulations are used to demonstrate that there is not a simple link between the mechanical energy supply and heat transport in the Atlantic. Setting the flux of momentum into the ocean to zero between 35–60°S reduces the net mechanical energy input by more than a factor of two without much effect on the heat transport in the Atlantic. The strong westerly winds in the Southern Ocean are found to be more important for the circulation of bottom water and for localizing the upwelling of deep water around Antarctica. Furthermore, it is illustrated that the hydrological cycle plays a significant role in maintaining the global ocean circulation and the associated heat transport in the Atlantic, given sufficient mechanical energy to support the diapycnal mixing. A reduction of the meridional moisture transport to the Southern Ocean by a factor of two reduces heat transport in the Atlantic by about the same factor. *INDEX TERMS:* 4532 Oceanography: Physical: General circulation; 4512 Oceanography: Physical: Currents; 4255 Oceanography: General: Numerical modeling. **Citation:** Saenko, O. A., and A. J. Weaver (2004), What drives heat transport in the Atlantic: Sensitivity to mechanical energy supply and buoyancy forcing in the Southern Ocean, *Geophys. Res. Lett.*, *31*, L20305, doi:10.1029/2004GL020671.

1. Introduction

[2] One of the reasons why the global ocean circulation is important for climate is its role in net poleward heat transport. Observational estimates suggest that about 0.3 PW (1 PW = 10^{15} W) enters the Atlantic Ocean at 30°S and about 0.6–0.7 PW is directed northward at 40–60°N towards the subpolar North Atlantic and Arctic [e.g., *Talley*, 2003]. These same observational estimates suggest that essentially no heat is transported in the Pacific across about 45°N. Since in the present climate deep water forms in the Atlantic but not in the Pacific, it seems reasonable to believe that at least a fraction of the heat entering the Atlantic at 30°S and leaving it towards high northern latitudes is due to the formation and circulation of North Atlantic Deep Water (NADW).

[3] Perhaps the most simplified schematic view of the large-scale ocean circulation in the meridional plane (i.e., the meridional overturning circulation or MOC) is to assume that it consists of two cells (Figure 1). One of them, the mid-depth cell originating in the North Atlantic, is normally associated with the circulation of NADW, whereas the bottom cell originating around Antarctica is associated with the flow of Antarctic Bottom Water (AABW). In his review of the deep ocean circulation *Warren* [1981] notes that the global air-sea heat transfer, and hence the heat transport in the ocean, is really a passive response to a circulation which is forced some other way. What forces this circulation, and particularly the mid-depth cell and the associated heat transport in the Atlantic, remains unclear. *Munk and Wunsch* [1998] argue that the transport of heat in the ocean due to the MOC would not be possible without an external supply of mechanical energy to support diapycnal mixing, with main sources of such energy being due to tidal stirring and the wind field. On the other hand, *Toggweiler and Samuels* [1998] illustrate that their ocean model could produce strong overturning in the Atlantic in the limit of very low diapycnal mixing, given strong enough zonal wind stress in the Southern Ocean.

[4] Although some amount of mechanical energy is undoubtedly needed to drive heat transport in the ocean, the estimates vary substantially. For example, *Webb and Suginohara* [2001] estimate that the required mechanical energy input is less than 0.6 TW (1 TW = 10^{12} W); A. Gnanadesikan et al. (The energetics of ocean heat transport, submitted to *Journal of Climate*, 2004, hereinafter referred to as Gnanadesikan et al., submitted manuscript, 2004) estimate it to be 0.15 TW. Both these estimates are substantially smaller than the value of 2.1 TW found by *Munk and Wunsch* [1998] (in reality, the supply of mechanical energy to the oceanic interior may be even larger than the latter value [*Wang and Huang*, 2004]). However, Gnanadesikan et al. (submitted manuscript, 2004) argue that there is not necessarily a connection between the mechanical energy supply and the heat transport in the ocean.

[5] This latter point is also illustrated here, using coupled model experiments. In this study we focus on the processes in the Southern Ocean and show that, as long as enough moisture is supplied to that basin, setting wind stress (and hence the mechanical energy supply) to zero between 35–60°S (the region of strongest winds) has little effect on heat transport in the Atlantic. This holds even for the case considered here of low (as observed) values of diapycnal diffusivity (about 10^{-5} $m^2 s^{-1}$) away from the regions of rough ocean bottom topography. A (somewhat surprising) result is that the strong westerly winds in the Southern Ocean play a greater part in the circulation of AABW, and hence should have small direct impact on heat transport in the Atlantic. Another important result is that the strong rate

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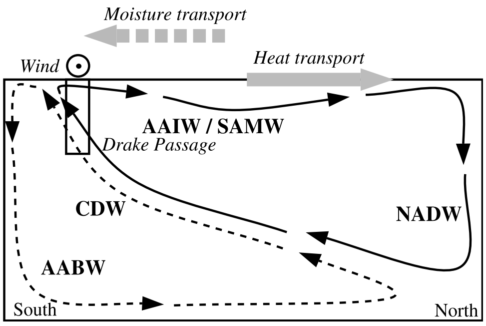

Figure 1. A schematic illustration of two major cells of the global overturning circulation in the ocean. The mid-depth cell originating in the north (dark solid arrows) is associated with the circulation of North Atlantic Deep Water (NADW), whereas the bottom cell originating in the south (dark dashed arrows) is associated with the circulation of Antarctic Bottom Water (AABW). The cells are closed by the upwelling of Circumpolar Deep Water (CDW) and by subduction of Antarctic Intermediate Water (AAIW) and Subantarctic Mode Water (SAMW) in the Southern Ocean. Heavy gray arrows show a component of oceanic heat transport in the Northern Hemisphere associated with the NADW cell (solid) which is "driven" by the atmospheric vapor transport in the Southern Hemisphere (dashed).

of deep water formation in the North Atlantic and its associated heat transport appear to be more sensitive to the buoyancy, rather than to the momentum forcing in the Southern Ocean.

2. The Model

[6] 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 developed at the GFDL (Modular Ocean Model, version 2, see *Pacanowski* [1995]; the original ocean model, including the conservation properties of its finite difference equations, is outlined in *Bryan* [1969]), a dynamic-thermodynamic sea ice model and an energy-moisture balance atmosphere model. All model components have the same horizontal resolution of $3.6° \times 1.8°$ in longitude and latitude, respectively. The ocean model uses isopycnal mixing after *Gent and McWilliams* [1990]. There are 19 vertical levels in the ocean model that vary smoothly in thickness from 50 m at the surface to 518 m at the deepest level of 5200 m.

[7] A new 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 recently for a use in GCMs by *Simmons et al.* [2004]. 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] and *Simmons et al.* [2004]: $k_v = k_b + q\Gamma\varepsilon/(\rho N^2)$, where $N^2 = -(g/\rho)\rho_z$ and $k_b = \times 10^{-5}\ \mathrm{m^2 s^{-1}}$ is the background diffusivity due to non-local sources of mixing. The vertical structure of ε (in W $\mathrm{m^{-3}}$) ensures its exponential decay from the ocean bottom toward the surface [*St. Laurent et al.*, 2002; *Simmons et al.*, 2004]. This has an effect of producing very low values of diffusivity (mostly due only to k_b) in the oceanic interior away from rough topography. The averaged diapycnal diffusivity at the base of the thermocline ($\sim$1500 m) is close to $0.3 \times 10^{-4}\ \mathrm{m^2 s^{-1}}$, i.e., enough to upwell up to 10 Sv of deep water; the value averaged over the ocean volume is close to $10^{-4}\ \mathrm{m^2 s^{-1}}$.

[8] The atmospheric model computes surface fluxes of heat and freshwater, as well as the atmospheric transport of sensible heat and moisture. The SST and SSS evolve in a response to changes in the ocean circulation and climate. However, the wind and hence wind stress are prescribed in this model version from monthly NCEP reanalysis. Further details on the model can be found in *Weaver et al.* [2001].

3. Results

[9] We present three model experiments, where we try to illustrate the effects of mechanical energy supply and moisture supply to the Southern Ocean on the global ocean circulation and heat transport. In the first experiment (E1), the model was integrated for 5000 years to produce a control large-scale ocean circulation and climate. The second experiment (E2) is identical to E1, except the zonal momentum flux into the ocean was set to zero between 35–60°S (Figures 2a and 2b). Finally, the third experiment (E3) is the same as E2 (i.e., no zonal wind stress between 35–60°S), except we reduced moisture transport from subtropical to subpolar regions in the Southern Ocean in a manner similar to that described in *Saenko et al.* [2003]. Freshwater transport in the control ocean of E1 (which is very similar to that in E2 due to weak feedback between the oceanic circulation and the hydrological cycle [see *Hughes and Weaver*, 1996]), and the effect of the reduction of southward moisture transport in the atmosphere on the freshwater transport in the E3 ocean are shown in Figures 2c and 2d, respectively.

[10] Both circulation cells, i.e., the one associated with the flow of NADW and that associated with AABW, can be seen in the control climate (Figure 3a). The mid-depth cell is characterized by sinking of water in the North Atlantic. This

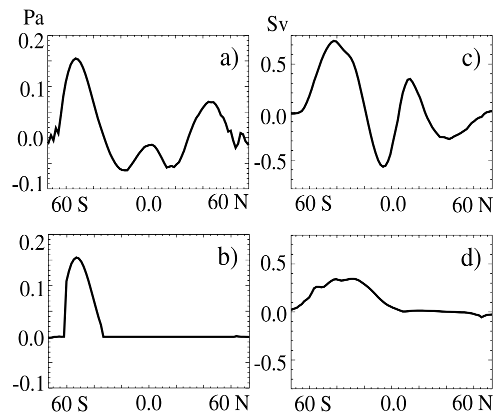

Figure 2. Annual-mean eastward momentum flux into the ocean: in experiment E1 (a) and the difference between E1 and E2 (b). Annual-mean northward transport of freshwater in the ocean (or southward transport of water vapor in the atmosphere): in experiment E1 (c) and the difference between E1 and E3 (d).

water then makes its way to the Southern Ocean where it joins the deep flow of Antarctic Circumpolar Current (ACC). The bottom cell in turn is fed by dense water formed south of the ACC.

[11] By setting the zonal momentum flux to zero between 35–60°S, the rate of NADW formation reduces, but not dramatically (Figure 3b), in general agreement with *Rahmstorf and England* [1997], but contrary to *Toggweiler and Samuels* [1998]. *Rahmstorf and England* [1997] showed that allowing the ocean-atmosphere thermal feedback to operate reduces the sensitivity of NADW flow to the wind forcing in the Southern Ocean with respect to models employing restoring boundary conditions such as that of *Toggweiler and Samuels* [1998]. This likely explains the difference between our results and those of *Toggweiler and Samuels* [1998]. About 9.0 Sv (1 Sv = 10^6 $m^3 s^{-1}$) of deep water still outflows from the Atlantic at 30°S, which is only 2.5 Sv less than in the control experiment (not shown). This deep water then broadly upwells (Figure 3b), resembling the closed basin overturning circulation in experiments of *Bryan* [1986]. This suggests that the direct effect of westerly winds in the Southern Ocean is more important for making the upwelling of deep water more localized to the Southern Ocean, rather than for driving the flow of NADW in the

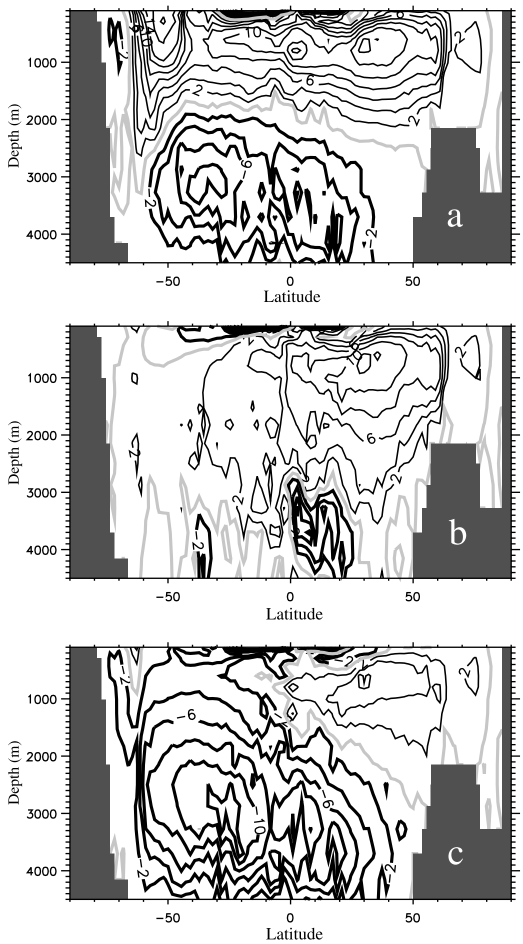

Figure 3. Global meridional overturning stream function in experiment E1 (a), in experiment E2 (b), and in experiment E3 (c). Contour interval is 2 Sv. Negative values are shown as heavy contours; zero contour is light.

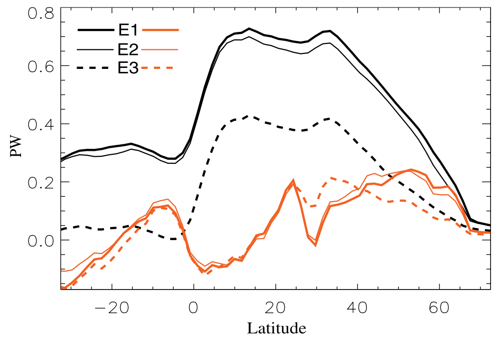

Figure 4. Total meridional heat transport in the Atlantic Ocean (black) and its "gyre" component (red) in the three experiments. The gyre component is given by $H_G = c \int \int v'T'$ $dxdz$, where v' and T' are the deviations of meridional velocity and temperature from their zonal averages; c is the volumetric heat capacity. Units are PW (1 PW = 10^{15} W).

Atlantic (the indirect effect of these winds, as a possible source of mixing energy in the ocean, is not considered here; in reality, a reduction of winds could result in a reduction of diffusivity). On the other hand, the absence of westerly winds around Antarctica has a more dramatic effect on the strength of the bottom circulation cell associated with AABW (Figure 3b). Without these winds, the transport of ACC weakens (by more than a factor of three) and the surface ocean south of ACC becomes warmer. This extra buoyancy around Antarctica effectively suppresses the formation of sea-ice and bottom water in the region.

[12] By reducing moisture supply to the Southern Ocean by about a factor of two in experiment E3 (Figures 2c and 2d), the mean density contrast in the pycnocline between the North Atlantic and the South Atlantic reduces by roughly a factor of two. As a result, the strength of NADW flow reduces by more than a factor of two (Figure 3c). Now, only 4.4 Sv of deep/intermediate water outflows from the Atlantic (not shown). The total heat transport in the Atlantic considerably decreases in E3 compared to both E1 and E2 (Figure 4). This is mostly due to the changes in the heat transport component associated with the overturning circulation, whereas the so-called "gyre" component does not differ much between the three experiments (Figure 4). Also note that the transport of heat is less than observed even in E1 due to the coarse model resolution of the western boundary currents [*Fanning and Weaver*, 1997]. Nonetheless, Figures 3 and 4 illustrate the importance of moisture transport in the Southern Hemisphere for maintaining the enhanced rates of heat transport and deep water formation in the Northern Hemisphere, as sketched in Figure 1. Another effect of the reduction of moisture supply to the Southern Ocean is that it reduces surface buoyancy there and intensifies circulation of bottom water (Figure 3c). However, this does not have much effect on the heat transport in the Atlantic.

[13] It is important to note that the mechanical energy supply due to the work done by the winds on the large-scale ocean circulation (as measured by $\int (\boldsymbol{\tau} \cdot \mathbf{u}) dA$, where $\boldsymbol{\tau}$ is the wind stress vector and $\mathbf{u}$ is the velocity vector in the model's first layer, and dA is the element of ocean area) is considerably different between E1 and E2 due to the absence of westerly winds around Antarctica in E2. This

energy is equal to 0.65 TW in E1, whereas it is only 0.28 TW in E2. However, the heat transport in the Atlantic is about the same in these two experiments (Figure 4). On the other hand, the mechanical energy input due to the wind stress is essentially the same between E2 and E3 (0.28 TW in E2 versus 0.25 TW in E3), whereas we find that the heat transport is considerably different between these two experiments (Figure 4). Finally, the energy consumption due to the diapycnal mixing (as given by *Osborn*'s [1980] relation, i.e., $\Gamma^{-1} \int \rho k_v N^2 dV$, where dV is the element of ocean volume) is similar in all three experiments (between 0.86–0.91 TW). Yet, the heat transport in experiments E1 and E2 is quite different from that in E3 (Figure 4). This suggests that there is not a simple link between the mechanical energy supply and heat transport in the ocean. Instead, surface buoyancy flux, although being inefficient by itself in "driving" the overturning [*Sandström*, 1908; *Huang*, 1999], becomes one of the key factors in maintaining the overturning circulation and the associated heat transport in the Atlantic Ocean if sufficient mechanical energy is supplied.

4. Discussion and Conclusions

[14] Recently, arguments were put forward suggesting that mechanical energy supply is the key factor in driving the global ocean overturning circulation and its associated transport of heat [*Munk and Wunsch*, 1998; *Huang*, 1999]. If true, this may require a very accurate representation of the mechanical energy sources in climate models in order to obtain an accurate simulation of heat transport due to MOC. On the other hand, a secondary importance has been assigned to the hydrological cycle [*Wunsch*, 2002]. To test this hypothesis, we performed a set of experiments with a coupled model. Our findings can be summarized as follows.

[15] 1. There is not a simple link between the mechanical energy supply and heat transport in the ocean. Having considerably different mechanical energy inputs into the ocean does not guarantee having different heat transports. Moreover, the same mechanical energy inputs can result in considerably different heat transports. This is in general agreement with the arguments presented by Gnanadesikan et al. (submitted manuscript, 2004), in that not all mechanical energy inputs have equivalent impact on heat transport in the ocean. Furthermore, we find that the westerly winds in the Southern Ocean, and the mechanical energy they provide, appear to play a greater part in driving the circulation cell associated with the formation of bottom water around Antarctica, rather than in driving the deep water flow and heat transport in the North Atlantic. These winds are more important for localizing the upwelling of deep water to the Southern Ocean.

[16] 2. The hydrological cycle plays a significant role in maintaining the global ocean circulation and the associated heat transport in the Atlantic, given sufficient mechanical energy to support the diapycnal mixing in the pycnocline. While it has been shown in a number of studies that a supply of freshwater to the North Atlantic would tend to reduce deep water formation and heat transport in the Atlantic, we further illustrate that the supply of moisture to the Southern Ocean tends to enhance deep water formation and heat transport in the Atlantic [see also *Saenko et al.*, 2003].

[17] In conclusion, some amount of mechanical energy is certainly required to mix the ocean against gravity. In addition, winds are particularly important for driving heat transport in low-latitude oceans. However, an accurate representation of mechanical energy is less important for that part of the heat transport which is associated with the global overturning circulation. For the latter, it is more important to have an accurate simulation of the buoyancy flux in climate models.

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References

Bryan, F. (1986), High-latitude salinity effects and interhemispheric thermohaline circulations, *Nature*, *323*, 301–304.
Bryan, K. (1969), A numerical model for the study of the circulation of the world ocean, *J. Comput. Phys.*, *4*, 347–376.
Fanning, A. F., and A. J. Weaver (1997), A horizontal resolution and parameter sensitivity study of heat transport in an idealized coupled climate model, *J. Clim.*, *10*, 2469–2478.
Gent, P. R., and J. C. McWilliams (1990), Isopycnal mixing in ocean general circulation models, *J. Phys. Oceanogr.*, *20*, 150–155.
Huang, R. X. (1999), Mixing and energetics of the oceanic thermohaline circulation, *J. Phys. Oceanogr.*, *29*, 727–746.
Hughes, T. M. C., and A. J. Weaver (1996), Sea surface temperature—Evaporation feedback and the ocean's thermohaline circulation, *J. Phys. Oceanogr.*, *26*, 644–654.
Munk, W. H., and C. Wunsch (1998), Abyssal recipes II: Energetics of tidal and wind mixing, *Deep Sea Res.*, *45*, 1977–2010.
Osborn, T. R. (1980), Estimates of the local rate of vertical diffusion from dissipation measurements, *J. Phys. Oceanogr.*, *10*, 83–89.
Pacanowski, R. C. (1995), MOM2 documentation, user's guide and reference manual, *GFDL Ocean Group Tech. Rep. 3*, GFDL/NOAA, Princeton Univ., Princeton, N. J.
Rahmstorf, S., and M. H. England (1997), The influence of Southern Hemisphere winds on North Atlantic deep water flow, *J. Phys. Oceanogr.*, *27*, 2040–2054.
Saenko, O. A., A. J. Weaver, and A. Schmittner (2003), Atlantic deep circulation controlled by freshening in the Southern Ocean, *Geophys. Res. Lett.*, *30*(14), 1754, doi:10.1029/2003GL017681.
Sandström, J. W. (1908), Dynamische Versuche mit Meerwasser, *Ann. Hydrog. Mar. Meteorol.*, *36*, 6–23.
Simmons, H. L., S. R. Jayne, L. C. St. Laurent, and A. J. Weaver (2004), Tidally driven mixing in a numerical model of the ocean general circulation, *Ocean Model.*, *6*, 245–263.
St. Laurent, L. C., H. L. Simmons, and S. R. Jayne (2002), Estimating tidally driven mixing in the deep ocean, *Geophys. Res. Lett.*, *29*(23), 2106, doi:10.1029/2002GL015633.
Talley, L. D. (2003), Shallow, intermediate, and deep overturning components of the global heat budget, *J. Phys. Oceanogr.*, *33*, 530–560.
Toggweiler, J. R., and B. Samuels (1998), On the ocean's large-scale circulation near the limit of no vertical mixing, *J. Phys. Oceanogr.*, *28*, 1832–1852.
Wang, W., and R. X. Huang (2004), Wind energy input to the Ekman layer, *J. Phys. Oceanogr.*, *34*, 1267–1275.
Warren, B. A. (1981), Deep circulation of the world ocean, in *Evolution of Physical Oceanography, Scientific Surveys in Honor of Henry Stommel*, edited by B. A. Warren and C. Wunsch, pp. 6–41, MIT Press, Cambridge, Mass.
Weaver, A. J., et al. (2001), The UVic Earth System Climate Model: Model description, climatology and application to past, present and future climates, *Atmos. Ocean*, *39*, 361–428.
Webb, D. J., and N. Suginohara (2001), Vertical mixing in the ocean, *Nature*, *409*, 37.
Wunsch, C. (2002), What is the thermohaline circulation?, *Science*, *298*, 1179–1181.

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