Atlantic pycnocline theory scrutinized using a coupled climate model

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Simulations with changed Southern Ocean wind-stress, oceanic vertical mixing, surface freshwater forcing and global warming confirm the basic equations of the *Gnanadesikan* [1999] theory: one vertical scale, the pycnocline depth D, contributes inversely proportional to low-latitudinal upwelling and linearly to Southern Ocean eddy transport. The maximum Atlantic overturning is confirmed to be quadratic in D but is also shown to be linear in a meridional density difference $\Delta\rho$. Our simulations strongly suggest that the theory needs to be complemented by a dynamical equation for $\Delta\rho$ since changes in both D and $\Delta\rho$ are significant and mutually independent. While, under global warming D varies strongly and $\Delta\rho$ is practically constant, the situation is reversed for altered surface freshwater fluxes. Similarily, variations in the meridional length scale of Southern Ocean outcropping require a dynamical equation in order to capture the fundamental behaviour of the Atlantic meridional overturning circulation.

1. Introduction

The Atlantic meridional overturning circulation (AMOC) plays a fundamental role for global climate [*Vellinga and Wood*, 2002, 2007]. In its conceptual understanding, two qualitatively different approaches have been undertaken. On the one hand, *Stommel* [1961] stresses the importance of an oceanic meridional density difference $\Delta\rho$, that controls the North Atlantic Deep Water (NADW) formation and thereby the AMOC strength. In this context, *Rahmstorf* [1996] finds a linear relation between NADW formation and the meridional density difference in a global ocean circulation model. A scaling of this sinking process [*Bryan*, 1987] indicates that such a linear flow law would only hold, if the rate of northern sinking was independent of a vertical scale depth D, the pycnocline. Other simulations with ocean general circualtion models (OGCM) confirm this linearity (eg. *Hughes and Weaver* [1994]; *Griesel and Morales-Maqueda* [2006]; *Schewe and Levermann* [2009]) and therefore reinforce the view of a stable pycnocline depth. On the other hand, focussing on processes in the Southern Ocean (SO), *Gnanadesikan* [1999](G99 hereafter) presented a framework, which directly links the strength of the overturning rate to the pycnocline depth D. This idealized model, which has been used as a paradigm for the meridional overturning circulation [*Kamenkovich and Sarachik*, 2004; *Marzeion and Drange*, 2006; *Johnson et al.*, 2007], solely allowed for variations in the universal pycnocline depth D, but kept the meridional density difference $\Delta\rho$ as an external parameter. Each of the two approaches emphasizes a different oceanic property whose variations are assumed to control the overturning strength. Here we investigate variations of both the density difference $\Delta\rho$ and the pycnocline depth D by use of a variety of experimental set-ups. We find that the idealized model of G99 is an appropriate description for the large-scale oceanic circulation, but has to be extended by the dynamics of $\Delta\rho$.

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G99 identifies four essential mechanisms controlling the magnitude of the overturning circulation. These processes are described through a vertical scale D, identified as the oceanic pycnocline depth. The upwelling in the SO m_W has its origin in predominant westerly winds and the zonal ocean band at the latitude of the Drake Passage. A scaling of this Drake Passage effect shows no direct dependence on stratification in the SO and is therefore parameterized to be independent of D.

Several approaches exist which estimate the amount of northward volume transport m_N, either employing boundary layer theory [*Gnanadesikan*, 1999] or geostrophic balance [*Bryan*, 1987; *Marotzke*, 1997; *Johnson and Marshall*, 2002] to describe the sinking rate or maximum overturning, which are indentified in this conceptual framework. In principle, these different studies agree on the obtained scaling for the overturning strength

$$m_N = C_N \cdot \Delta\rho \cdot D^2 . \quad (1)$$

In G99, C_N is a constant which comprises geometry and boundary layer structure, and $\Delta\rho$ is a meridional density difference. The quadratic dependency of the northward flow on D arises from vertical integration and the representation of the meridional pressure difference as $D \cdot \Delta\rho$.

The third process inherent in G99 is upwelling in low latitudes m_U described by a vertical advection-diffusion balance [*Munk and Wunsch*, 1998] which yields

$$m_U = C_U \cdot \frac{\kappa}{D} . \quad (2)$$

The constant C_U is associated with the effective upwelling area and κ denotes the average vertical diffusivity. Eddies contribute to the large scale advection of tracers and a parameterization from *Gent and McWilliams* [1990](GM90) provides an additional eddy-induced tracer transport m_E linear in D

$$m_E = C_E \cdot \frac{D}{L_y} . \quad (3)$$

The proportionality constant C_E comprises geometry and a thickness diffusion coefficient. Potential energy for eddy the induced transport is provided by outcropping isopycnals in the SO whose slope D/L_y is determined by its meridional extent L_y.

2. Model and Experiments

In order to investigate the processes included in the G99 model, experiments were carried out with changed SO wind stress, vertical diffusivity, anomalous surface freshwater fluxes and global warming scenarios. All results are based on simulation with the model of intermediate complexity CLIMBER-3α [*Montoya et al.*, 2005]. The oceanic component (based on the MOM-3 GFDL code) has a horizontal resolution of $3.75^\circ \times 3.75^\circ$ and 24 variably spaced vertical levels. The influence of baroclinic eddies on tracer transport is included via the parameterization of GM90 with a constant thickness diffusivity of $250\, m^2/s$.

The first group of experiments (denoted 'CO_2') comprises five equilibrium simulations with $1, 2, 4, 8$ and 16 times the preindustrial CO_2 concentration of 280ppm (described in *Levermann et al.* [2007]). Another set of steady state experiments ('fwf') investigates the influence of anomalous freshwater fluxes to the North Atlantic between $30^\circ N - 50^\circ N$, analoguous to *Levermann and Griesel* [2004]. Experiments with equivalent freshwater fluxes of 0.1, 0.2, 0.3 and $0,35\,Sv$ were carried out. The third set of experiments ('tau') varied the zonal wind stress in the SO by multiplication with a factor $\alpha = 0.5, 1.0, 1.5$ and 2 in the latitudinal band between $30^\circ\,S$ and $71.25^\circ\,S$ as first suggested by *Toggweiler and Samuels* [1995] and used to investigate the relation between density differences and Drake Passage effect in CLIMBER-3α by *Schewe and Levermann* [2009]. For the last set of equilibrium runs ('diff'), the vertical background diffusivity κ is varied from 0.3, 0.4 to $1.0 \cdot 10^{-4} m^2/s$ [*Mignot et al.*, 2006].

Most experiments are closely linked to one of the transport mechanisms in G99. Changing κ has an immediate effect on low-latitudinal upwelling m_U, while the fwf-experiments alter the meridional density gradient in the North Atlantic. The tau-experiments change the magnitude of the Ekman transport in the SO, which also influences the local eddy activity [*Hallberg and Gnanadesikan*, 2006]. In contrast to these experiments, the CO_2-experiments cause a global warming which affects the ocean in many aspects. Thus, they are suitable to study the theory in a comprehensive way.

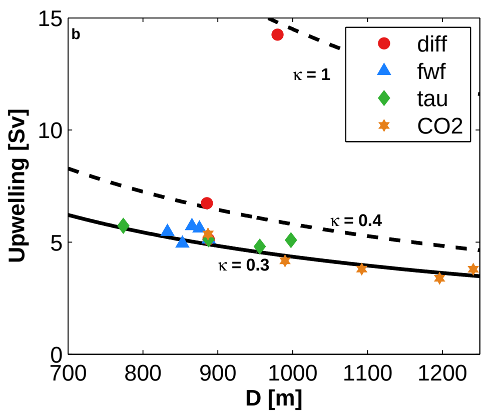

Figure 1. Low-latitudinal upwelling m_U is inversely proportional to D. The symbols define different experiment groups with CLIMBER-3α, showing large variations in D. The experiments with the standard vertical diffusivity of $0.3 \cdot 10^{-4} m^2/s$ follow the theoretic prediction. Variation in vertical diffusion coefficent κ (red dots) confirm the theoretical scaling (dashed lines).

3. Low-latitudinal upwelling and SO eddy flux

According to G99, low-latitudinal upwelling m_U is inversely proportional and eddy-induced transport m_E directly proportional the pycnocline depth D. Following the definition in *Gnanadesikan et al.* [2007] (with horizontal integration between $80^\circ W - 0^\circ$ and $20^\circ S - 20^\circ N$), the performed experiments with CLIMBER-3α span an interval of $D \in$ [750m, 1250m] (fig. 1). At this depth the vertical resolution of the model is about $200\,m$, which means that three model layers are covered. Since D is determined from the e-fold depth of an exponential fit to the vertical density profile, we obtain continuous values of D which are influenced by the whole column. For this reason the variations in the pycnocline depth D are significant in the considered experiments, despite the model's coarse resolution.

The low latitudinal upwelling m_U is obtained as the difference between the maximum of the Atlantic stream function in the North Atlantic ($20^\circ N - 70^\circ N$ and $400 - 5\,000\,m$) and the SO outflow (maximum of stream function at $30^\circ S$). The experiments with changes in surface freshwater flux, in SO wind stress and global warming have a constant vertical diffusivity of $0.3 \cdot 10^{-4} m^2/s$ and confirm the inverse proportionality between m_U and D (fig. 1). The theoretical curve (solid line) is obtained with a constant effectiv horizontal upwelling area of $1.45 \cdot 10^8 km^2$ which completely determines equation (2). By applying the same area variations in κ are equally well captured by the theory (dashed curves). The fact that the effective area exceeds the surface area of the Atlantic Ocean is likely due to spurious upwelling along the continental boundaries, which is a model artefact observed in coarse resolution models [*Yang*, 2003].

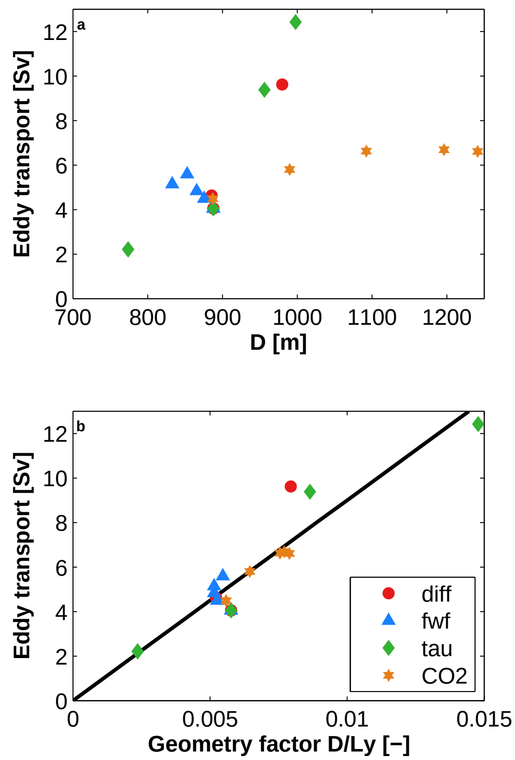

Figure 2. The eddy-induced transport m_E from GM90 approximation as a function of D does not show linearity (a). Considering the meridional extent of the outcropping region L_y (b) the theoretic approach is confirmed in CLIMBER-3α.

The eddy-induced return flow m_E defined here as the maximum of the negative eddy stream function in the SO ($70^\circ S - 0^\circ$, $200 - 2\,000\,m$) does not exhibit the linear behaviour in D (fig. 2a) as could be expected from equation (3) for constant L_y and C_E. The largest discrepancy appears in the warming and SO wind experiments. This is due to variations in the meridional length scale for outcropping L_y. The experiments collapse onto a straight line (fig. 2b), when the meridional extent of the outcropping region L_y is taken into account. In order to define L_y, we determine the density at $35^\circ S$ at the depth D. This position is chosen to be just north of the outcropping region but close enough to assure that the corresponding isopycnal does indeed outcrop in the SO. L_y is then defined as the meridional distance between the crossing of the specific isopycnal at $450\,m$ and $80\,m$. Values for L_y group around $1.6 \cdot 10^5$m with small deviations, except for the wind and warming experiments. For example, a doubling of SO wind stress halvens L_y, which can be explained by an increased Ekman tranpsort from the south compressing the outcropping isopycnals [*Schewe and Levermann*, 2009].

4. Northern Sinking

The scaling for the northern sinking m_N (equation (1)) depends on variations in D and $\Delta\rho$. The meridional density difference $\Delta\rho$ is computed between regions along the Western Boundary of the American coast; $(70^\circ W - 50^\circ W, 35^\circ N - 45^\circ N)$ and $(45^\circ W - 20^\circ E, 35^\circ S - 35^\circ N)$ at a depth of $800\,m$. Figure 3 shows that both quantities are relevant for the volume transport. The CO_2 experiments, for example, result in strong variations in D, while the meridional density difference is relatively constant. The situation is reversed in the freshwater experiments, which exhibit almost no change in D, but strong variations in $\Delta\rho$. SO wind experiments yield variations in both quantities. Thus, the experiment type is decisive for the respective role of D or $\Delta\rho$ and neither can be neglected.

Defining northern sinking m_N as the maximum of the Atlantic stream function in the same region as above, reveals a clear scaling with $\Delta\rho \cdot D^2$ (fig. 4) for all experiments. Slight discrepancies can be attributed to possible variations in the coefficient C_N that comprises, for example, the geometry of the volume transport. We find a small m_N-offset of about 5 Sv. This is partly due to a recirculation in the Mediterranean (~2-3Sv, not shown) which is not controlled by the described processes and spurious upwelling at the boundary and over rough topography [*Yang*, 2003; *Mignot et al.*, 2006]. Figure 4 is robust to changes in definition of $\Delta\rho$.

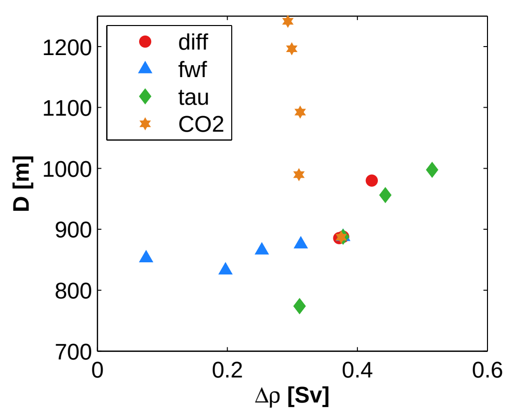

Figure 3. Scatter plot of D and $\Delta\rho$ for all experiments conducted with CLIMBER-3α. There are experiment sets which only show variations in D (CO_2) or in $\Delta\rho$ (fwf). The wind experiments (tau) in turn exhibit variations in both variables.

5. Conclusion and Discussion

We investigate the applicability of the simple predictive theory of the oceanic pycnocline depth [*Gnanadesikan*, 1999] in a coupled climate model with comprehensive but coarse oceanic component. A variety of model experiments confirm the universal role of the pycnocline depth D as defined in *Gnanadesikan et al.* [2007]. The G99 expressions for low-latitudinal upwelling and northern sinking are applicable under variations of SO wind stress, vertical diffusivity and atmospheric CO_2 concentrations. As shown earlier [*Levermann and Griesel*, 2004] some variations in the Atlantic overturning are not captured by changes in D. Simulations with varying surface freshwater forcing only change the meridional density gradient keeping D constant.

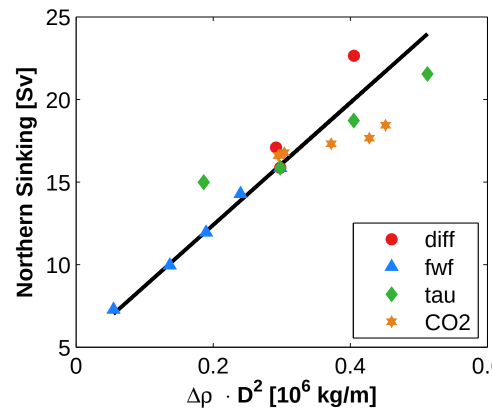

Figure 4. The northern sinking m_N is depicted as a function of the combined expression $\Delta\rho \cdot D^2$. Various equilibrium experiments in CLIMBER-3α confirm a linear dependency, which is predicted by theory.

Our simulations thus suggest that the seemingly contradictory approaches of a dominant influence of the meridional density difference *Stommel* [1961]; *Rahmstorf* [1996] as opposed to the vertical density structure *Gnanadesikan* [1999] can be consolidated by implication of a dynamical equation for the meridional density difference in the North Atlantic as suggested by *Johnson et al.* [2007]. Note however the special role of the eddy return flow. While SO eddies have been reported to transport large amounts of heat and salinity [*Naveira-Garabato et al.*, 2007] it is not clear whether surface wind-driven upwelling, i.e. actual large scale water volume transport, can be compensated by a net eddy-induced downwelling. The applicability of the G99 theory to a situation without Atlantic overturning ("off-state") is therefore questionable.

Our simulations show furthermore that the behaviour of the eddy return flow can only be consolidated with the simple parameterization when taking changes in the horizontal scale for the SO outcropping L_y into account. Its variations require a dynamical equation. One possibility could be the introduction of a meridional density difference in the SO $\Delta\rho_{SO}$. The eddy-induced tracer transport m_E could then be parameterized as

$$m_E \propto D \cdot \Delta\rho_{SO} \tag{4}$$

This equation is compatible with heat and salinity advection as in [*Johnson et al.*, 2007] and represents the baroclinic instability in a similar fashion as **?**.

In summary, our simulations confirm the approach by *Gnanadesikan* [1999], but suggest a generalization by two additional dynamical equations for $\Delta\rho$ and L_y.

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