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Effects of different closures for thickness diffusivity

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ABSTRACT

The effects of spatial variations of the thickness diffusivity (K) appropriate to the parameterisation of [Gent, P.R. and McWilliams, J.C., 1990. Isopycnal mixing in ocean circulation models. J. Phys. Oceanogr., 20, 150–155.] are assessed in a coarse resolution global ocean general circulation model. Simulations using three closures yielding different lateral and/or vertical variations in K are compared with a simulation using a constant value. Although the effects of changing K are in general small and all simulations remain biased compared to observations, we find systematic local sensitivities of the simulated circulation on K. In particular, increasing K near the surface in the tropical ocean lifts the depth of the equatorial thermocline, the strength of the Antarctic Circumpolar Current decreases while the subpolar and subtropical gyre transports in the North Atlantic increase by increasing K locally. We also find that the lateral and vertical structure of K given by a recently proposed closure reduces the negative temperature biases in the western North Atlantic by adjusting the pathways of the Gulf Stream and the North Atlantic Current to a more realistic position.

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1. Introduction

In many state-of-the-art, non-eddy-resolving ocean models the so-called thickness diffusivity K appropriate to the Gent and McWilliams (1990) (GM) parameterisation is used. This lateral diffusivity is meant to account for the advective effects of the turbulent lateral mixing by meso-scale eddies. In the GM parameterisation, the value of K has to be specified and was chosen in the past as a constant value of $\mathcal{O}(1000\ \mathrm{m}^2/\mathrm{s})$. Modern ocean models. however, are beginning to incorporate spatially varying thickness diffusivities (Griffies et al., 2005; Danabasoglu and Marshall, 2007). It is the aim of this study to compare a representative selection of such closures for K in a global ocean model and to document their impacts on the simulated circulation and watermass characteristics. In particular, we consider four different choices for the thickness diffusivity:

- $K = 800\ \mathrm{m}^2/\mathrm{s}$, i.e. a constant value (experiment CONST);
- $K(x,y,t)$ as suggested by Visbeck et al. (1997), i.e. $K = \alpha L^2 \bar{\sigma}$ where $\bar{\sigma}$ is the Eady growth rate averaged over the main thermocline, L an eddy length scale and α a tuning parameter (experiment VMHS);
- $K(x,y,z,t)$ as suggested by Danabasoglu and Marshall (2007) dependent on the local stability frequency (N), i.e. $K = K_0 N^2 N_{\mathrm{ref}}^{-2}$ with the parameters K_0 and N_{ref} as specified below (experiment NSQR);
- $K(x,y,z,t)$ dependent on an eddy length scale and time scale as suggested by Eden and Greatbatch (2008b), i.e. $K = cL^2\sigma$ where σ is the local Eady growth rate and L the minimum of Rossby radius and Rhines scale (experiment EG).

In CONST, the thickness diffusivity K shows no spatial or temporal variation (except for a tapering procedure) and can be considered as the zeroth order choice. This choice is often used due to the lack of knowledge about a physically meaningful spatial dependency of K. In a first step beyond a constant value, Visbeck et al. (1997) suggested to use a mixing length approach, first proposed for geophysical applications by Green (1970) and Stone (1972). Visbeck et al. (1997) chose the inverse Eady growth rate (σ) as a time scale and the maximum of the local Rossby radius, grid spacing or the width of the baroclinic zone (of the region of interest) as the eddy length scale. They also assumed a vertically constant K.

On the other hand, it is often proposed that K should also have a vertically varying structure. Danabasoglu and McWilliams (1995) and Jochum (1997) proposed prescribed exponentially varying vertical profiles for K. Ferreira et al. (2005) estimated the optimal value of K in a non-eddy-resolving model simulation using an adjoint technique, while Eden et al. (2007) and Eden (2006) diagnosed K directly from results of high-resolution models. In these studies significant horizontal and also vertical variations of K were found, with magnitudes ranging from zero to more than $5000\ \mathrm{m}^2/\mathrm{s}$, consistent with previous estimates of eddy diffusivity from observations and models (Rix and Willebrand, 1996; Ledwell et al., 1998; Stammer, 1998; Bryan et al., 1999; Treguier, 1999; Nakamura and Chao, 2000; Roberts and Marshall, 2000; Drijfhout

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and Hazeleger, 2001; Solovev et al., 2002; Zhurbas and Oh, 2004; Marshall et al., in press). In general all these studies, and in particular Ferreira et al. (2005) and Eden et al. (2007), also agree in the finding of large K in the upper thermocline and small values below, which motivated Ferreira and Marshall (2006) and later Danabasoglu and Marshall (2007) to investigate the impacts of using K proportional to the square of the buoyancy frequency (N^2) in a model. This choice was motivated by the finding that N^2 shows a similar vertical structure as the diagnosed K in Ferreira et al. (2005), Eden et al. (2007) and Eden (2006). Our experiment NSQR is identical to experiment ITN2 discussed in Danabasoglu and Marshall (2007).

An alternative closure which we consider here (experiment EG) is a simplified version of the parameterisation of Eden and Greatbatch (2008b). It is based on a mixing length approach by Green (1970) and Stone (1972) and a prognostic budget for eddy kinetic energy with parameterised sources (due to baroclinic and barotropic instability), transports and sinks (dissipation). A simplified and localised form of the closure (as used here in experiment EG) was shown to agree in mid-latitudes with the scaling laws of Larichev and Held (1995) and Held and Larichev (1996). We consider this closure here because it combines vertical variations with horizontal ones.

It was found in Eden and Greatbatch (2008b) that the application of this new closure did not change much a North Atlantic model simulation of $\mathcal{O}(1^\circ)$ resolution compared to a simulation using a constant value of K. This result is qualified here since in agreement with Danabasoglu and Marshall (2007) we find indeed certain improvements of a global ocean model simulation of $\mathcal{O}(3^\circ)$ resolution and it is our aim to document these improvements. We also report some systematic model dependencies of the circulation on the value of the thickness diffusivity, such as the strength of the subpolar gyre with impacts on convective activity and ventilation rates of the North Atlantic, and the depth of the equatorial thermocline with potential effects on coupled climate models. The next section will describe the model and the details of the experiments, the third section will discuss the results and the last section provides a summary and a discussion.

2. Numerical experiments

In all experiments, a state-of-the-art coarse-resolution ocean model based on the Parallel Ocean Program of the Los Alamos National Laboratory (Smith and Gent, 2004) is used, which is also the (coarse resolution version) ocean component of the Community Climate System Model (CCSM). It is a global, z-level-coordinate model with the grid North Pole displaced into Greenland with nominal 3° horizontal resolution (Yeager et al., 2006).[1] There are 25 vertical levels, monotonically increasing from 8 m near the surface to about 500 m in the abyssal ocean. The surface forcing is given by the normal-year forcing data provided by Large and Yeager (2004) at T62 resolution. There is no active sea ice model. The vertical mixing coefficients are determined using the K-Profile Parameterisation of Large et al. (1994), as modified by Danabasoglu et al. (2006). More details about the model setup can be found in, e.g., Danabasoglu et al. (2008). In the following we only discuss issues relevant for the thickness diffusivity.

In each experiment, a preliminary version of the near-surface eddy flux parameterisation of Ferrari et al. (in press), as implemented by Danabasoglu et al. (2008), is used in the model tracer equations. In this new approach, a transition layer separates the quasi-adiabatic interior where eddy fluxes are oriented along isopycnals from the diabatic, near-surface regions (e.g., the boundary layer) where diapycnal meso-scale fluxes are directed along the ocean surface. In the interior, eddy fluxes are still represented using the isopycnal diffusion tensor (Redi, 1982; Cox, 1987) and the Gent and McWilliams (1990) parameterisation for eddy induced advection with spatially varying identical diffusivities for both (see below). As the surface is approached, the meso-scale eddy fluxes become parallel to the ocean surface, crossing outcropping density surfaces. This behaviour is parameterised using a down-gradient horizontal diffusion with a mixing coefficient of K_H, which has the same value as the interior isopycnal/thickness diffusivity, i.e., K, indicating that the interior and near-surface mixing rates remain the same. A linear combination of horizontal and isopycnally-oriented mixing occurs within the surface diabatic layer. The eddy-induced velocity is parallel to the ocean surface and has no vertical shear within the boundary layer. It must then develop vertical shear within the transition layer to match the interior values. We use the mixed layer depth as defined in Large et al. (1997) to represent the diabatic layer depth in the present simulations. We note that this new scheme eliminates the need for any ad-hoc, near-surface taper functions usually used with the Gent and McWilliams (1990) scheme. Further details of the near-surface eddy parameterisation are given in Danabasoglu et al. (2008).

In the quasi-adiabatic interior, four different choices for the thickness diffusivities are used. We note that in each experiment both thickness and isopycnal diffusivities are modified identically, i.e. they have the same value. This choice is supported by the identical diffusivity tensors for thickness and isopycnal mixing obtained as a result of the adiabatic stochastic theory of tracer transport, e.g. Dukowicz and Greatbatch (1999), and by a recent diagnosis of isopycnal diffusivities using results from a high-resolution model simulation (Eden and Greatbatch, submitted for publication). One often assumes that the choice for the value of isopycnal diffusivity does not effect much the buoyancy (the effect is due to mixing of different watermasses in the presence of a non-linear equation of state) and thus have a negligible effect on the dynamics. We note, however, that ocean model solutions can show sensitivities to various choices of isopycnal diffusivity (Danabasoglu and Marshall, 2007) and that isopycnal diffusivity can play a larger role than one might expect when changes in watermass characteristics become large (Sijp et al., 2006). Although a detailed investigation of the sensitivities of model solutions to isopycnal diffusivity changes is beyond the scope of the present work, we present a brief discussion of this issue when we consider an ideal age tracer because for passive tracers with large gradients on isopycnals the choice of isopycnal diffusivity becomes important.

The main experiments (CONST, VMHS, NSQR and EG) have been integrated for 500 years each. We note that this integration length might be too short for a complete diffusive equilibrium of the ocean model, for which the time scale would be several thousand years. Consequently, in this study we focus on the dynamical effects of the thickness diffusivity, for which the integration length should be sufficient (compare for instance Figs. 2a and 3. of Danabasoglu (2004)). Furthermore, for a longer integration period we do not expect changes in the differences between the four main individual experiments on which we build our conclusions. Note also that the diffusive equilibrium will also depend to a large extent on parameterisation of diapycnal diffusivity and surface forcing, issues which are left aside in the present study. Additional sensitivity experiments are integrated for 100 years each, for which we also expect to obtain the important differences between the experiments during this integration period. In the remainder of this section, a large number of relevant model details are discussed separately for each experiment.

[1] Zonal resolution is uniform at 3.6°, but the meridional resolution varies from 0.4° to 0.6° in the subpolar northeast Atlantic and at the equator, respectively, to about 3° in the Southern Hemisphere mid-latitudes and northwest Pacific.

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