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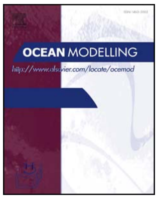

Estimating the numerical diapycnal mixing in an eddy-permitting ocean model

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ABSTRACT

Constant-depth (or “z-coordinate”) ocean models such as MOM4 and NEMO have become the de facto workhorse in climate applications, having attained a mature stage in their development and are well understood. A generic shortcoming of this model type, however, is a tendency for the advection scheme to produce unphysical numerical diapycnal mixing, which in some cases may exceed the explicitly parameterised mixing based on observed physical processes, and this is likely to have effects on the long-timescale evolution of the simulated climate system. Despite this, few quantitative estimates have been made of the typical magnitude of the effective diapycnal diffusivity due to numerical mixing in these models. GO5.0 is a recent ocean model configuration developed jointly by the UK Met Office and the National Oceanography Centre. It forms the ocean component of the GC2 climate model, and is closely related to the ocean component of the UKESM1 Earth System Model, the UK's contribution to the CMIP6 model intercomparison. GO5.0 uses version 3.4 of the NEMO model, on the ORCA025 global tripolar grid. An approach to quantifying the numerical diapycnal mixing in this model, based on the isopycnal watermass analysis of Lee et al. (2002), is described, and the estimates thereby obtained of the effective diapycnal diffusivity in GO5.0 are compared with the values of the explicit diffusivity used by the model. It is shown that the effective mixing in this model configuration is up to an order of magnitude higher than the explicit mixing in much of the ocean interior, implying that mixing in the model below the mixed layer is largely dominated by numerical mixing. This is likely to have adverse consequences for the representation of heat uptake in climate models intended for decadal climate projections, and in particular is highly relevant to the interpretation of the CMIP6 class of climate models, many of which use constant-depth ocean models at ¼° resolution

1. Introduction

The importance of using a correct distribution of the diapycnal mixing, and hence of the watermass transformation rate, to the large-scale ocean circulation in climate models is evident: the upwelling regions of the global overturning streamfunction are associated with mixing processes (Munk and Wunsch, 1998), while the formation of a realistic thermocline relies on appropriate rates of mixing above and below the thermocline (Luyten et al., 1983). In addition, the uptake of CO_2 and heat, both in the quasi-equilibrium state of control simulations and in simulations of anthropogenic warming, will be sensitive to the ocean stratification, while embedded biogeochemical systems will also have rather different mean states if the vertical mixing, and hence the stratification, are inconsistent with those in the real ocean. Small-scale turbulent mixing in ocean models is represented by a variety of parameterisations, including bulk schemes (e.g. Kraus and Turner, 1967), the KPP scheme (Large et al., 1994) and the turbulent kinetic energy (TKE) scheme (Gaspar et al., 1990); in these schemes, parameters are normally optimised in a more-or-less heuristic way to approximately reproduce the observed water mass structure.

So-called depth-coordinate ocean models, which represent the ocean as a stack of levels with constant vertical thickness, constitute the majority of ocean models used today: leading examples are NEMO (Madec, 2016) and version 4 of the GFDL Modular Ocean Model (MOM4, Griffies et al., 2008). We note that of the thirty-nine climate models contributing to the Intergovernmental Panel on Climate Change (IPCC) Fifth Assessment Report (IPCC, 2013), thirty-two used ocean components formulated with depth coordinates, three used terrain-following (sigma) coordinates, and four used an isopycnic (density-coordinate) ocean model. Numerical diapycnal mixing is an intrinsic property of the advection scheme in this class of models, and occurs whenever an advective flux crosses density surfaces, which in general do not follow the horizontal coordinate surfaces (Griffies et al., 2000). It may be reduced by the use of higher-order advection schemes (Hofmann and Morales Maqueda, 2006), and is absent, by construction, in the ocean interior in pure isopycnic models like MICOM (Bleck and

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Smith, 1990) and GOLD (Hallberg and Adcroft, 2009), where advection is along surfaces of constant potential density and diapycnal mixing occurs only as prescribed by the model mixing scheme.

There are indications that in some regimes the numerical mixing may be of comparable magnitude as (and even exceed) the mixing generated by the explicit mixing scheme of the model (Griffies et al., 2000; Lee et al., 2002). This leads over time to the unrealistic modification of critical watermasses, which is likely to have undesirable effects on timescales of a decade or longer, and this may be critical in climate simulations. Megann et al. (2010) carried out a comparison between the coupled climate models HadCM3 and CHIME, which differ only in that in the latter the depth-coordinate ocean component of HadCM3 is replaced with the hybrid isopycnic-coordinate HYCOM (Bleck, 2002). The model with an isopycnic ocean showed markedly superior representation of watermasses such as Antarctic Intermediate Water (AAIW) and Subantarctic Mode Water (SAMW), as well as of the subtropical thermoclines and the sill overflow waters in the North Atlantic, all consistent with substantially lower numerical mixing. A similar conclusion was reached in a similar experiment with two coupled models at GFDL, differing only in the replacement in one of the MOM4 ocean model by the GOLD isopycnic-coordinate model (Dunne et al., 2012).

Several approaches to diagnosing the numerical mixing in ocean models have been developed in recent years. Firstly there are what we might call “direct” methods, which evaluate the mixing generated by the advection scheme at each grid cell: these include the use of passive tracers (Getzlaff et al., 2012); and analysis of tracer variance decay (Burchard and Rennau, 2008). These may be distinguished from more indirect methods, which diagnose the effects of mixing over global or basin-scale spatial domains, and over time scales long compared with the model time step: these include the evaluation of changes in global available potential energy (Ilıcak et al., 2012) and the estimation of diapycnal mixing by evaluating fluxes across density surfaces (Lee et al., 2002).

The representation of the overturning circulation in density space (Walin, 1982) is potentially highly revealing of the mechanisms of watermass transformation. Marsh et al. (2000) used an isopycnic (density-coordinate) model to show that changes in density arising from surface buoyancy fluxes (which in a Lagrangian sense generally act to increase the density of water as it is advected poleward) are balanced by changes in density resulting from diffusive mixing in the ocean interior. Marsh (2000), and subsequently Grist et al. (2009), showed that surface fluxes, when cast into density classes, provide an informative proxy for the overturning circulation, where the latter is not trivial to estimate directly from the relatively sparse direct observations of the ocean interior. Lee et al. (2002) used this framework to diagnose the interior diapycnal mixing in the OCCAM ¼° global ocean model, and then, by relating this to the mean vertical density gradient, to estimate the effective vertical diffusivity as a function of density and latitude. They concluded that in the Southern Ocean the effects of numerical mixing led to values of the effective diffusivity that were large compared with those applied by the parameterised vertical mixing scheme in the model.

In this paper we use the technique of Lee et al. (2002) to analyse the contributions to watermass transformation in the GO5.0 ocean model, the configuration of the NEMO code used in the GC2 coupled climate model (Williams et al., 2015), and closely related to the ocean configuration of the UK Earth System Model UKESM1 that will be used in the CMIP6 intercomparison. This model will be shown to have a rather lower drift than OCCAM, as used by the former authors. We shall use a modified version of the method used by Lee et al. to derive an estimate of the numerical diffusivity that is compared with the explicit mixing coefficients used in the model. Where these latter authors examined the numerical mixing in the southern hemisphere, with a primary focus on the Southern Ocean, we evaluate the diapycnal transformation rates and effective diffusivities globally, as well as separately in the Atlantic and Indo-Pacific Oceans.

In Section 2 we describe the GO5.0 model configuration. In Section 3 we summarise the methodology of Lee et al. (2002), and describe the numerical method used in the current paper. In Section 4 we present the results of this method applied to the model output, deriving the diapycnal velocities and effective diffusivities, and comparing these with the explicit diffusivities applied by the model's mixing scheme. In Section 5 we relate the diapycnal mixing to small-scale vertical motions, and finally Section 6 is a summary and discussion.

2. Model description

The model configuration we describe here is GO5.0 (Megann et al., 2014), a standard ocean configuration developed jointly between the UK Met Office and the National Environment Research Council (NERC). It is used widely in forecasting and climate modelling: the current version of the UK Met Office's FOAM operational ocean forecasting system (Blockley et al., 2014) and the UK coupled climate model GC2 (Williams et al., 2015) use GO5.0 as their ocean component. The GC3 climate model (Williams et al., 2017) and the new UK Earth System Model UKESM1, both aimed at the IPCC Sixth Assessment Report, will both use an ocean component closely related to GO5.0, in particular sharing its horizontal and vertical grids (albeit with a southward extension in the more recent configurations to allow ice shelves to be simulated) and most of its physics choices.

GO5.0 is an implementation of version 3.4 of NEMO (Nucleus for European Models of the Ocean, Madec, 2016) on the global ORCA025 0.25° tripolar horizontal grid (Barnier et al., 2006), and has 75 constant-depth levels in the vertical, with level spacing increasing from 1 m at the surface to around 200 m at 6000 m depth. The parameters and physics choices are discussed in detail in Megann et al. (2014). The sea ice is version 4.1 of the Los Alamos National Laboratory sea ice model CICE (Hunke and Lipscomb, 2010). The integration described here is of the ocean-only GO5.0 model forced by CORE2 atmospheric fields (Large and Yeager, 2009), and is made over the 30 years from 1976 to 2005. Monthly precipitation and daily downward shortwave and longwave radiation are used to force the model directly, while six-hourly 10-m wind, 2-m air humidity and 2-m air temperature are used to compute turbulent air–sea and air–sea–ice fluxes during model integration, using the bulk formulae proposed by Large and Yeager (2009). This configuration has much higher horizontal and vertical resolutions than the ocean of HadCM3, so should permit much better representation of watermasses, but still includes the fundamental process of advection across density surfaces characteristic of this model type, and indeed Griffies et al. (2000) suggest that models with eddy-permitting or eddy-resolving resolutions may have higher numerical mixing because of the vertical motions associated with the eddies.

GO5.0 uses the total variance dissipation (TVD) scheme (Zalesak, 1979) for horizontal advection of tracers. The vertical mixing of tracers and momentum in the GO5.0 configuration is parameterised using a modified version of the Gaspar et al. (1990) turbulent kinetic energy (TKE) scheme (described in Madec, 2016). Unresolved vertical mixing processes are represented by a background vertical eddy diffusivity (controlled by the parameter *rn_avt0* in NEMO) which has a constant value of 1.2×10^{-5} m^2 s^{-1} at latitudes poleward of ± 15°, decreasing linearly to a value of 1.2×10^{-6} m^2 s^{-1} at ± 5° latitude (Gregg et al., 2003). This parameter imposes an absolute minimum value for the diffusivity at each grid point, and the contributions of other processes such as double diffusion and breaking internal waves are represented by positive-definite increments to this. In regimes where the vertical density profile is unstable, convection is simulated by an enhanced vertical diffusivity for tracers and momentum of 10 m^2 s^{-1}. The time-averaged value of the applied explicit vertical diffusivity is saved at each grid point in the routine model output. GO5.0 uses the UNESCO equation of state for seawater (Chen and Millero, 1987) as implemented by Jackett and McDougall (1995).