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Comments on the parameterization of barotropic tide-induced bottom friction mixing in ocean circulation models

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ABSTRACT

Results from an eddy-admitting and a non-eddy admitting ocean circulation model with parameterizations for barotropic tide-induced bottom friction mixing are compared to two observation data sets. The use of tide-induced vertical viscosity and diffusivity in addition to other large-scale drivers of ocean mixing processes such as wind and current shear leads to moderate improvements and more realistic upper-ocean temperature structures on larger scales. However, parameterized tide-induced mixing in the eddy-admitting model causes too strong mixing in shelf sea areas such as the British Channel/Irish Sea and the East China/Yellow Seas. The overall result from both models is that care must be taken when tidal mixing parameterizations are applied to ocean circulation models. Each individual use of a tidal mixing parameterization requires careful fine-tuning; and its impact on model skill should be considered together with other relevant parameterizations. We discuss possible reasons for the excessive vertical mixing and propose options which should lead to improved simulations with barotropic tidal mixing parameterizations.

1. Introduction

Ocean mixing, particularly diapycnal mixing, is critical in maintaining vertical stratification, driving the global overturning circulation (Munk and Wunsch, 1998; Ganachaud et al., 2000), redistributing heat and salt, and influencing climate, ocean dynamics and biological processes. Much of the mixing occurs in specific locations near topographic features, resulting from interactions of the tidal currents with topography (Garrett, 2003) and occurs throughout the water column. Mixing also varies in time, e.g. tidal mixing occurs episodically in response to the predominant diurnal, semi-diurnal and spring-neap tidal cycles.

The processes and associated energy rates by which barotropic tides lose energy and sustain diapycnal mixing amount to ≈3.5 TW (1 TW= 10^{12} Watts; Munk and Wunsch, 1998), of which ≈2.5 TW are lost by topographic wave drag and ≈1 TW through internal tide generation. The energy loss through bottom friction of barotropic tides parameterized in current models is achieved by either a topographic wave drag (e.g., Müller et al., 2010) or as additional barotropic mixing within the water column (e.g., Lee et al., 2006 LRS herafter).

Most state-of-the-art ocean circulation and climate models rely on sub-grid scale parameterizations of tidal mixing because higher modes of internal tides, their breaking and dissipation (the latter with scales of order 10^{-2} m) cannot be resolved explicitly. Examples of parameterized vertical tidal mixing in ocean models are the barotropic parameterization developed by LRS and the parameterizations for baroclinic tidal mixing developed by Jayne and Laurent (2001) and St Laurent et al. (2002). In the barotropic tidal mixing parameterization of LRS enhanced mixing is added to the water column. Baroclinic or internal tides occur in a stratified or layered water column and originate through interactions of the barotropic tide with rough topography, for example along continental shelves, ridges, seamounts, and island chains (Bell, 1975; Garrett and Kunze, 2007; Müller et al., 2010).

Inclusion of vertical tidal mixing parameterizations in ocean models has achieved some improved performance globally (Jayne, 2008) and regionally (LRS, Koch-Larrouy et al., 2010). The barotropic tidal mixing scheme by LRS is included in the Ocean Forecasting Australian Model Version 3 (OFAM3) (Oke et al., 2013). Likewise, tidal mixing was added to the ocean component of the Australian Community Climate Earth System Simulator (ACCESSo, O'Kane et al., in press), including both the barotropic tidal mixing of LRS and the baroclinic tidal mixing in the abyssal ocean by Jayne and Laurent (2001) and St Laurent et al. (2002). The ocean models OFAM3 and ACCESSo are based on the same GFDL Modular Ocean Model version 4 (Griffies, 2010).

The purpose of this study is to assess the performance of the LRS tidal mixing scheme in the two models, in an eddy-admitting (OFAM3) and a non-eddy admitting (ACCESSo) resolution, to compare the results with observations and to make some recom-

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mendations for improving the performance of ocean models which employ the LRS tidal mixing scheme. Section 2 contains a brief description of the two models and details about the LRS mixing scheme. In Section 3, we discuss the results and Section 4 contains the discussion, including some proposed improvements to the LRS scheme.

2. Description of models and experimental set-up

2.1. OFAM3

Briefly, the "Ocean Forecasting Australia Model version 3"(OFAM3) is a near-global eddy-admitting configuration 4p1 of the GFDL Modular Ocean Model (Griffies, 2010). The model grid has (1/10)° horizontal grid spacing between 75°S and 75°N. The vertical model coordinate is z^* (modified z coordinate which takes into account local free surface height and total depth, see Griffies, 2010) with 51 vertical levels and 5 m resolution near the surface. OFAM3 is forced with 3-hourly surface heat, freshwater, and momentum fluxes from ERA-interim (Dee and Uppala, 2009). The model forcing includes seasonal river forcing from climatology (Dai et al., 2009). River forcing is applied as a water flux, with the injection of zero-salinity water. Surface temperature is relaxed to monthly-averaged Reynolds SST (Reynolds et al., 2007) with a restoring time-scale of 10 days. Surface salinity is restored to monthly-averaged sea-surface salinity from CARS (Ridgway and Dunn, 2003) with a restoring time-scale of 180 days. OFAM3 uses the hybrid vertical mixing scheme described by Chen et al. (1994). The background vertical diffusivity and viscosity in OFAM3 are 1×10^{-5} m^2/s and 1×10^{-4} m^2/s, respectively. The explicit horizontal diffusion is zero. Horizontal viscosity is resolution- and state-dependent and uses a biharmonic Smagorinsky viscosity scheme (Griffies and Hallberg, 2000). Convective adjustment is applied to every time step using fully explicit mixing when the water column becomes unstable.

Because the focus of applications with OFAM3 is on the variability over the upper 2000 m depth, to avoid any significant drift in the deep ocean fields, model temperature and salinity fields are restored to climatology below 2000 m depth using a seasonal climatology (Ridgway and Dunn, 2003). This deep-ocean restoring is applied with a restoring time-scale of 365 days. Oke et al. (2013) provide a detailed description of OFAM3 and validate the model with observations of altimetry, SST and volume transports (also see Table 1 for a summary of OFAM3 and ACCESSo models).

2.2. ACCESSo

The Australian Community Climate Earth System Simulator-Ocean model (ACCESSo) is a configuration of the GFDL MOM4p1 ocean-ice code (O'Kane et al., in press). The ACCESSo experiments are forced with atmospheric fields from the Coordinated Ocean-ice Reference Experiments (COREs, Large and Yeager, 2004; Large and Yeager, 2009) and bulk formulas. CORE1 climatology fields are used to spin up the ACCESS ocean, while the CORE2 fields are 60 years of interannually varying fields, from 1948 to 2007. Weak restoring is applied to the surface salinity of the top layer (equivalent thickness of 10 m) which is relaxed to world ocean atlas (WOA09) fields with a time scale of 60 days to reduce drift. The model uses an eddy parameterization for the unresolved eddies (Gent et al., 1995) and the KPP mixing scheme for vertical mixing, which excludes bottom friction (Large et al., 1994; Griffies, 2010). The background vertical diffusivity and viscosity in ACCESSo are 2×10^{-5} m^2/s and 1×10^{-4} m^2/s, respectively.

Table 1
Summary of OFAM3 and ACCESSo.

	OFAM3	ACCESSo
Model code	MOM4p1	MOM4p1
Topography	Smith and Sandwell, 1997	GFDL bathymetry (Griffies et al., 2005) with modifications (O'Kane et al., in press)
Surface forcing	ERA-Interim, relaxation to Reynolds SST	CORE2, bulk formula
Horizontal resolution	0.1°	1°, higher resolution near equator and at high lat.
Vertical resolution	5 m resolution 0–40 m, 10 m resolution 40–200 m, 120 m at 1000 m depth, 1000 m near sea floor	10 m resolution 0–200 m, to 333 m at depth
Vertical mixing	vertical mixing (Chen et al., 1994), barotropic tides (Lee et al., 2006)	KPP vertical mixing (Large et al., 1994), barotrop. tides (Lee et al., 2006), barocl. tides with tidal dissipation efficiency = 0.3333, vertical decay scale = 300 m (St Laurent et al., 2002)
Tidal constituents (Lee)	M2, S2, N2, K2, K1, O1, P1, Q1	M2
Initial conditions	initialised with CARS (Ridgway and Dunn, 2003), spin-up from rest for 13 years	≈1400-year spin-up with CORE1, switch to CORE2 1948–2007

Experiments for both models were run with the following parameters: $K_{z\,tide}=0$, $p=2.5, p=0.25$ (no, reduced, full/default barotropic tidal parameterization).
Period studied in both experiments is January 2004 to December 2006.

The ACCESSo experiments are configured to be volume conserving, Boussinesq, using z^* depth coordinates scaled with height in the vertical. ACCESSo implements 50 model levels covering 0–6000 m with a resolution ranging from 10 m in the upper layers (0–200 m) to about 333 m for the abyssal ocean. The ACCESSo model employs a tripolar ocean grid that has a 360×300 logically rectangular horizontal mesh, overlying an orthogonal curvilinear grid whereby a singularity at the north pole is avoided by using a tripolar grid following Murray (1996). Along the curvilinear zonal direction ACCESSo has a regularly spaced grid with 1° resolution. In the meridional direction the grid spacing is nominally 1° resolution, with the following three refinements:

- tripolar Arctic north of 65°N,
- equatorial refinement to 1/3° between 10°S and 10°N, and,
- a Mercator (cosine dependent) implementation for the Southern Hemisphere, ranging from 0.25° at 78°S to 1° at 30°S.

The additional tidal vertical diffusivity is applied to the global domains of the respective model and combined with the vertical diffusivity from the Chen et al. (1994) scheme (OFAM3) and with the KPP scheme (Large et al., 1994) plus baroclinic tidal mixing from Jayne and Laurent (2001) and St Laurent et al. (2002) (ACCESSo). Furthermore, by assuming a unit Prandtl number the tidally-enhanced viscosity is computed as a four-point average of the tide-induced diffusivity and added to the background viscosities of OFAM3 and ACCESSo, respectively.