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The effect of topography-enhanced diapycnal mixing on ocean and atmospheric circulation and marine biogeochemistry ☆

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ABSTRACT

The impact of topographically catalysed diapycnal mixing on ocean and atmospheric circulation as well as marine biogeochemistry is studied using an earth system model of intermediate complexity. The results of a model run in which diapycnal mixing depends on seafloor roughness are compared to a control run that uses a simple depth-dependent parametrization for vertical background diffusivity. A third model run is conducted that uses the horizontal mean of the topographically catalysed mixing as vertical profile in order to distinguish between the overall effect of larger diffusivities and the spatial heterogeneity of the novel mixing parametrization.

The new mixing scheme results in a strengthening of the deep overturning cell and enhances equatorial upwelling. Surface temperatures in the Southern Ocean increase by about 1 K (in the overall effect) whereas cooling of a similar magnitude in low latitudes is generated by the spatial heterogeneity of the mixing. The corresponding changes in the atmospheric circulation involve a weakening of the southern hemispheric Westerlies and a strengthening of the Walker circulation. Biogeochemical changes are dominated by an improved ventilation of the deep ocean from the south. Water mass ages decline significantly in the deep Indian Ocean and the deep North Pacific whereas oxygen increases in the two ocean basins. The representation of the global volume of water with an oxygen concentration lower than 90 μmol/kg in the model is improved using the topography catalysed mixing. Furthermore, primary production is stimulated in equatorial regions through increased upwelling of nutrients and reduced in the oligotrophic gyres.

1. Introduction

Observational studies indicate weak, O (10^{-5} m^2/s), diapycnal mixing in the ocean's interior (Gregg, 1987; Kunze and Sanford, 1996; Kunze et al., 2006; Ledwell et al., 2011) and bottom-intensified mixing orders of magnitude larger in regions of rough topography (Gregg and Sanford, 1980; Toole et al., 1997; Polzin et al., 1997; Klymak et al., 2006; Aucan et al., 2006; Levine and Boyd, 2006). The diapycnal diffusivity, K_ρ, is therefore depth-dependent and patchily distributed in the horizontal in contrast to diffusivity parametrizations generally adopted in OGCMs, that often use horizontally homogeneous and vertically varying values for K_ρ (Bryan and Lewis, 1979).

A spatially varying mixing parametrization has been developed over the past decade by St. Laurent (1999), Jayne and Laurent (2001) and St. Laurent et al. (2002). This parametrization represents the first attempt to capture the spatial distribution of diapycnal mixing resulting from the local dissipation of internal tides at generation sites and has been implemented in recent modeling studies (e.g., Simmons et al., 2004, Saenko and Merryfield, 2005, Koch-Larrouy et al., 2007, Jayne, 2009).

The observed bottom-intensification of diapycnal mixing in regions of rough topography is the result of a large number of topography-catalysed mixing processes. However, it remains unclear what fraction can be ascribed to the local dissipation of internal tides. Tentative energy budgets (Munk and Wunsch, 1998; Wunsch and Ferrari, 2004) suggest that the tides supply no more than half of the mechanical energy available for diapycnal mixing in the abyssal ocean. Interaction of non-tidal internal waves with topography may be equally important, through for example reflection off a sloping bottom at the critical frequency (Eriksen, 1998; Nash et al., 2004) and scattering off rough topography (Müller and Xu, 1992). The combination of tidal motions with near-inertial internal waves generated by storms has also been observed to lead to enhanced mixing (Aucan and Merrifield, 2008). In addition, abyssal mixing can be sustained by instability of internal lee waves associated with mesoscale near-bottom currents over rough topography (Polzin and Firing,

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1997; Marshall and Garabato, 2008; Nikurashin and Ferrari, 2010), by hydraulic flow through constricted passages (Ferron et al., 1998; Thurnherr, 2006; St. Laurent and Thurnherr, 2007) and by episodic deep overflows (Lukas et al., 2001).

Dynamically, vertical gradients of the diapycnal diffusivity relate to the intensity of upwelling via the buoyancy equation and influence the horizontal circulation via vorticity dynamics (St. Laurent, 1999; Saenko and Merryfield, 2005). Circulation patterns calculated with spatially varying mixing can thus be expected to differ from those obtained with uniform mixing.

The sensitivity of the ocean circulation to the horizontal distribution of vertical mixing has been studied by a number of recent numerical studies (Hasumi and Suginohara, 1999; Simmons et al., 2004; Saenko and Merryfield, 2005; Emile-Geay and Madec, 2009; Jayne, 2009). In particular, horizontally non-uniform mixing has been shown to alter the abyssal circulation from the classical Stommel–Arons pattern (Huang and Jin, 2002; Katsman, 2006; Emile-Geay and Madec, 2009), to affect the deep ocean stratification (Hasumi and Suginohara, 1999; Saenko, 2006), to have a bearing on the depth and intensity of the Antarctic Circumpolar Current (Saenko and Merryfield, 2005; Jayne, 2009), as well as to yield improved temperature-salinity characteristics of simulated water masses (Simmons et al., 2004; Saenko and Merryfield, 2005; Koch-Larrouy et al., 2007). Zonally integrated quantities such as the meridional transport of heat and mass are found to be sensitive to the spatial distribution of diapycnal mixing in the deep Indian, Pacific and Southern Ocean basins (Saenko and Merryfield, 2005; Palmer et al., 2007) and down to thermocline depths in the Atlantic Ocean (Saenko and Merryfield, 2005; Griesel, 2005; Jayne, 2009).

Several studies have demonstrated the relationship between vertical mixing and biogeochemical parameters. Gnanadesikan et al. (2002) reported a doubling of new production in response to an increase of vertical diffusivity from 0.15 to 0.6 cm^2/s in the upper 2000 m of the water column. As the driving forces behind this doubling the study identified the increase in convection and in vertical diffusive and advective fluxes. Furthermore it was found that the location where vertical mixing is increased appears to be crucial for the response of new production. Gnanadesikan et al. (2004) showed that changes in vertical diffusion lead to changes in the radiocarbon budget and the distribution of this tracer in the ocean. The advective surface flux of young water masses to the Southern Ocean as well as the influx into the tropics at depth were found to be strengthened by an increase in vertical diffusion. In the presentation of a global marine ecosystem model Schmittner et al. (2005) tested the model's performance under different vertical mixing parametrizations. They revealed a large sensitivity of chlorophyll concentration to the vertical mixing scheme in particular in low latitudes. It was also shown that the delicate balance of diffusion and upwelling which sets the depth of the nutricline is altered in response to a change in vertical diffusion which results in shallower (deeper) nutricline for higher (lower) values of mixing.

The effects of changes in the strength of the overturning circulation (which is directly connected to diapycnal mixing) on ocean biogeochemistry have been investigated in numerous studies. Schmittner et al. (2005) and Menviel et al. (2008b) reported a decrease in global primary production in response to a major weakening of the Atlantic Meridional Overturning Circulation (AMOC) which was mostly caused by a decrease in the supply of nutrients from the deep ocean. Schmittner et al. (2007), Schmittner and Galbraith (2008) and Okazaki et al. (2010) demonstrated the coupling of North Pacific ventilation to the state of the AMOC. In both studies an increase in subsurface oxygen levels was observed concordantly as a consequence of a weakened AMOC.

In our present study we incorporate an empirically-derived topography-catalysed diapycnal mixing scheme (Decloedt and Luther, 2010) describing the spatial distribution of the mean background diffusivity K_ρ resulting from a broad range of mixing processes into an earth system model of intermediate complexity. The model includes a three-dimensional global model of the marine carbon cycle, a terrestrial vegetation model, a sea ice model, an OGCM and a simplified 3 dimensional dynamical atmosphere. Through this approach we are able to study the potential impact of spatially non-uniform mixing on ocean circulation, climate and the carbon cycle. Our primary intention is to elucidate the effects topography-catalysed mixing on the different compartments of the Earth system as well as to study the interactions.

The paper is organized as follows: after the description of the earth system model and the experimental setup in Sections 2 and 3, respectively, we give a brief explanation of the roughness diffusivity model in Section 4. Section 5 presents and discusses our main results. We summarize our main findings in Section 6.

2. Model configuration

We use the Earth system model of intermediate complexity LOVECLIM (version 1.1) (Goosse et al., 2010; Menviel et al., 2008b) which is based on 5 coupled subsystems.

The sea ice-ocean component (CLIO) (Goosse et al., 1999) consists of a primitive equation ocean general circulation model with $3^\circ \times 3^\circ$ resolution on a partly rotated grid in the North Atlantic. CLIO uses a free surface and is coupled to a thermodynamic–dynamic sea ice model (Fichefet and Morales Maqueda, 1997, 1999). In the vertical there are 20 unevenly spaced levels with a thickness ranging from 10 m near the surface to $\sim$700 m below 3000 m. Mixing along isopycnals, as well as the effect of mesoscale eddies on transports and mixing and downsloping currents at the bottom of continental shelfs are parametrized (Goosse et al., 2010). The different vertical mixing parametrizations employed in our study are described in the following two sections. Bering Strait is closed in our simulations which inhibits freshwater transport from the Pacific into the Arctic.

The atmosphere model (ECBilt) is a spectral T21 model, based on quasigeostrophic equations with 3 vertical levels and a horizontal resolution of about $5.625^\circ \times 5.625^\circ$. Ageostrophic forcing terms are estimated from the vertical motion field and added to the prognostic vorticity equation and thermodynamic equation. Diabatic heating due to radiative fluxes, the release of latent heat and the exchange of sensible heat with the surface are parametrized. The seasonally and spatially varying cloud cover climatology is prescribed in the ECBilt version employed here.

The ocean, atmosphere and sea ice components model are coupled by exchange of momentum, heat and freshwater fluxes. The hydrological cycle over land is closed by a bucket model for soil moisture and simple river runoff scheme. Due to the weakness of the tropical trade winds simulated by the model, the moisture transport from the Atlantic to the Pacific is underestimated. To generate an Atlantic salty enough for an Atlantic Meridional Overturning Circulation (AMOC), a correction for freshwater flux is prescribed redirecting 8–15% of precipitation over the Atlantic to the North Pacific.

The global dynamic terrestrial vegetation is modelled using VECODE (Brovkin et al., 1997). Annual mean values of precipitation and temperature are communicated to the vegetation from the atmospheric model. On the basis of these mean values the evolution of the vegetation cover described as a fractional distribution of desert, tree, and grass in each land grid cell is calculated once a year. In the current version, only land albedo (as seen by the atmospheric model) outside the icesheets is changed by VECODE. Other processes such as vegetation effects on evapotranspiration or surface roughness are neglected.