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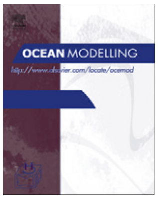

Parameterization of eddy-induced subduction in the Southern Ocean surface-layer

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ABSTRACT

The divergence of the eddy mass flux in the surface layer of the Southern Ocean makes an important contribution to subduction of fluid through the base of the mixed layer. Therefore, accurate parameterization of this process is needed to correctly represent the Southern Ocean ventilation in coarse-resolution models. We test a common approach to the parameterization of eddy fluxes (Gent and McWilliams, 1990) using output from the 1/6° eddy-permitting Southern Ocean State Estimate, which assimilates a variety of ocean observations using an adjoint method. When a constant diffusion coefficient of conventional magnitude O(1000 $m^2\,s^{-1}$) is used, the parameterized fluxes fail to reproduce the regional pattern and magnitude of eddy-driven subduction diagnosed from the model. However, when an appropriate choice is made for the diffusion coefficient, the parameterization does a good job of reproducing the distribution and strength of the eddy contribution to subduction. Using a spatially-varying coefficient is key to reproduce the regional pattern of the eddy-induced subduction. In addition, the magnitude of the subduction is correctly represented only with a diffusion coefficient that peaks at $10^4\,m^2\,s^{-1}$ in the most energetic areas of the Southern Ocean, a factor of ten larger than commonly used in coarse-resolution climate models. Using a diffusion coefficient that is too small will underestimate the contribution of eddies to the ocean sequestration of heat, salt and carbon.

1. Introduction

The Southern Ocean is one of the most energetic regions of the world ocean and it has long been known that mesoscale eddies play an important role in the dynamics of this region (Johnson and Bryden, 1989; Marshall et al., 1993; Marshall and Radko, 2003). The absence of land barriers in the latitude band of Drake Passage prevents any net meridional transport above the shallowest topography except through eddy fluxes and wind-driven Ekman fluxes. Therefore, Southern Ocean eddy fluxes greatly influence the oceanic general circulation by allowing transport across the strong Antarctic Circumpolar Current (ACC) and closure of the global meridional overturning circulation. Accurate representation of the effect of eddies in climate models is essential if such models are to correctly simulate the global ocean circulation and climate. However, observations of eddy fluxes are rare in the Southern Ocean: the few measurements are usually too sparse and time-series usually too short to allow assessment of the circumpolar influence of eddies in the Southern Ocean (e.g. Johnson and Bryden, 1989; Phillips and Rintoul, 2000).

To derive estimates of surface eddy fluxes in the Southern Ocean, a numerical parameterization has recently been applied to hydrographic observations (Karsten and Marshall, 2002; Marshall et al., 2006; Sallée et al., 2010). These studies have consistently described an intense southward eddy flux in the surface layer of the Southern Ocean, reaching a maximum near the Antarctic Circumpolar Current (ACC), that tends to counterbalance the northward Ekman transport. The adiabatic eddy-induced transport is parameterized in these studies using the Gent and McWilliams (1990, hereafter GM) parameterization. However, the GM parameterization commonly used in coarse-resolution models has not been tested in a quantitative way.

A number of theoretical, modeling and observational studies have focussed on the dynamics of eddy fluxes in the mixed-layer, leading to modifications of the GM parameterization near the ocean surface (e.g. Treguier et al., 1997; Ferrari et al., 2008, 2010). As the mixed-layer is approached, eddy fluxes develop a diabatic component and the adiabatic flux is reduced. Therefore, using the GM adiabatic formalism in the surface layer produced fluxes that are much larger than observed (e.g. Griffies, 2004). Treguier et al. (1997) proposed to smoothly and continuously reduce the GM parameterization in the surface layer. Alternative parameterizations by Greatbatch and Li (2000), Griffies (2004) and Ferrari et al. (2008, 2010) are essentially similar ways of continuously extending the interior eddy flux into the surface layer. In addition to this tapering of the adiabatic flux in the surface layer, recent studies have suggested parameterizations accounting for diabatic eddy flux and submesoscale processes within the mixed

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layer (e.g. Young, 1994; Fox-Kemper et al., 2008, in press; Fox-Kemper and Ferrari, 2008; Ferrari et al., 2008, 2010).

Despite the strong efforts to improve the eddy flux parameterization in the surface layer, the parameterization of the net adiabatic flux at the base of the surface layer has never been directly evaluated, primarily because of the lack of large-scale observation of this flux. Given that the net eddy flux through the base of surface-layer has a direct impact on water masses and tracer exchanges between the surface layer and the ocean interior, and therefore has a strong impact on climate, it is important to test the validity of this parameterization. In this study, we attempt to evaluate how well the GM parameterization can represent eddy fluxes through the base of the surface layers in coarse-resolution models, by comparing the explicit fluxes in an eddy-permitting model to the parameterized fluxes. In order to isolate the sole effect of the parameterization, the parameterized flux is computed from the outputs of the eddy-permitting simulation degraded to coarse resolution, rather than by integrating a coarse-resolution model. We focus on the ability of the model parameterization to represent the vertical eddy-induced flux across the base of the surface layer.

2. Data and methods

2.1. Eddy-induced flux and its parameterization

The water volume transport across a section of length dx, in a layer of thickness h and velocity v is: $T = v \cdot h \cdot dx$. Hence, the time-mean average transport is:

$$\overline{T} = \left(\bar{v} \cdot \bar{h} + \overline{v'h'}\right) \cdot dx, \tag{1}$$

where prime denotes an anomaly from the time average. The correlation between velocity anomaly and thickness anomaly $\left(\overline{v'h'}\right)$ produces an eddy-induced flux. Therefore, in addition to mixing, eddies advect tracer by the eddy-induced velocity, defined here by:

$$\mathbf{u}^* = \frac{\overline{\mathbf{v}'h'}}{\bar{h}}. \tag{2}$$

This eddy flux is usually parameterized assuming the flux to be down the large-scale mean gradient of tracers. However, previous attempts to evaluate this parameterization often found large discrepancies (Griesel et al., 2009; Eden et al., 2007). One reason for these large discrepancies is that the flux of any tracer $C\left(\overline{u'C'}\right)$ is composed of a rotational and a divergent component. The only term that enters the actual tracer balance and that is represented in the parameterization is the divergent component (Lau and Wallace, 1979; Marshall and Shutts, 1981; Eden et al., 2007; Griesel et al., 2009; Fox-Kemper et al., 2003). The rotational component does not contribute to the net local tracer budget as the tracer fluxes into and out of a region are balanced (Jayne and Marotzke, 2002).

To avoid this difficulty, we will focus in this study on evaluating the divergence of the eddy flux: $\nabla \cdot \left(\overline{u'C'}\right)$, which naturally removes the rotational contribution (Bryan et al., 1999). The divergence is really what models should get right, as this determines the exchange rate between the surface layer and the ocean interior, and sets the ocean's ability to sequester heat, carbon, and other climate properties.

Subduction is the rate at which ventilated fluid is permanently transferred from the ocean-surface layer to the interior across the base of the winter mixed-layer (Marshall et al., 1993; Sallée et al., 2010). Let σ_{wML} be the isopycnal at the base of the winter mixed layer. The mass transfer by eddies (S_{eddy}) between the surface layer and the permanent thermocline is:

$$S_{eddy} = \nabla \cdot \overline{\mathbf{v}'H'_{\sigma_{wML}}}, \tag{3}$$

where $H_{\sigma_{wML}}(t)$ is the depth of the isopycnal σ_{wML}.

Following GM and Treguier et al. (1997), the eddy-induced velocity is:

$$\mathbf{u}^* = \frac{\overline{\mathbf{v}'\mathbf{h}'}}{\bar{\mathbf{h}}} = \begin{cases} \frac{\partial}{\partial z}\left[\kappa \cdot \frac{\overline{\nabla \bar{b}}}{\overline{b_z}}\right] = \frac{\partial}{\partial z}[\kappa \cdot \bar{\mathbf{s}}], & \text{below the mixed layer} \\ [\kappa \cdot \bar{\mathbf{s}}]_{z=-H} \cdot \frac{\partial \mu(z)}{\partial z}, & \text{in the mixed layer,} \end{cases} \tag{4}$$

where κ is the GM eddy diffusion coefficient, b is the buoyancy in the ocean and $\mathbf{s}$ is the slope of the isopycnals (i.e. $\bar{\mathbf{s}} = \nabla\bar{b}/\overline{b_z}$), and z is positive upward. $\mu(z)$ is a tapering function that smoothly decays from 1 at the base of the mixed layer to 0 at the surface, which is used to extend the horizontal eddy-induced mass transport occurring below the mixed layer through the entire mixed layer (e.g. Treguier et al., 1997; Ferrari et al., 2008, 2010).

No large-scale continuous velocity observations of the Southern Ocean at the base of the surface layer exist yet. Therefore, here we used output from an eddy-permitting model to diagnose the eddy-flux divergence and test how well it can be represented by the parameterization in Eq. (4). To have a realistic and physically consistent eddy field, we use a reanalysis of Southern Ocean observations: the Southern Ocean State Estimate (Mazloff et al., 2010). Once integrated above the base of the winter mixed layer, the vertical eddy-induced flux becomes:

$$\nabla \cdot \overline{\mathbf{v}'H'_{\sigma_{wML}}} = \nabla \cdot [\kappa.\bar{\mathbf{s}}]_{\sigma_{wML}}. \tag{5}$$

The definition of time-mean and anomaly is not straightforward as there is no clear gap in frequency between low and high frequency motions. Previous Southern Ocean studies have shown that eddies have energy with periods as long as several months (Nowlin et al., 1985; Phillips and Rintoul, 2000; Sallée et al., 2008). To ensure we include the entire eddy energy spectrum in our analysis we define the time-mean as the average of the full length of the model run (2 years), and the anomaly as the difference from this mean. The surface mixed-layer depth has a strong seasonal cycle that would be included in this definition of anomaly, but by integrating to the depth of the base of the winter mixed-layer we minimize the seasonal effects.

2.2. The Southern Ocean State Estimate

We use model output from the Southern Ocean State Estimate (SOSE; Mazloff et al., 2010) constrained by observations over the period 2005–2006. SOSE is an assimilation of ocean observations with a high-resolution ocean model. The one-sixth of a degree MITgcm ocean model has been optimized to physical observations in a weighted least squares sense. The adjoint method is used to assimilate observations in this model (Mazloff et al., 2010). This method ensures a dynamical solution consistent with observations. *In situ* profile observations (Argo, CTD, elephant seal CTD observations, XBTs) are assimilated as well as remote sensing observations of sea surface height and temperature.

The GM parameterization is used in SOSE to represent advection by eddies at scales smaller than the grid. However, the value of the diffusion coefficient is 10 $\text{m}^2\,\text{s}^{-1}$, much smaller than conventional values (e.g. Griffies et al., 2009), reflecting the fact that SOSE resolves much of the eddy scales.

The Southern Ocean has been relatively well observed in the past decade, and the State Estimate is consistent with this wealth of data (Mazloff et al., 2010). Fig. 1 compares the 2005–2006 mean Eddy Kinetic Energy (EKE) resulting from the assimilation with the EKE from the Aviso merged and gridded altimetry product during the same period. The observed EKE is approximatively twice the intensity of the modeled EKE (median value of 2.3; Fig. 1c). SOSE reproduces enhanced variability in the western boundary current, and along the path of the ACC, with peaks where the ACC interacts with bathymetry.