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Scale-aware deterministic and stochastic parametrizations of eddy-mean flow interaction

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ABSTRACT

The role of mesoscale eddies is crucial for the ocean circulation and its energy budget. The sub-grid scale eddy variability needs to be parametrized in ocean models, even at so-called eddy permitting resolutions. Porta Mana and Zanna (2014) propose an eddy parametrization based on a non-Newtonian stress which depends on the partially resolved scales and their variability. In the present study, we test two versions of the parametrization, one deterministic and one stochastic, at coarse and eddy-permitting resolutions in a double gyre quasi-geostrophic model. The parametrization leads to drastic improvements in the mean state and variability of the ocean state, namely in the jet rectification and the kinetic-energy spectra as a function of wavenumber and frequency for eddy permitting models. The parametrization also appears to have a stabilizing effect on the model, especially the stochastic version. The parametrization possesses attractive features for implementation in global models: very little computational cost, it is flow aware and uses the properties of the underlying flow. The deterministic coefficient is scale-aware, while the stochastic parameter is scale- and flow-aware with dependence on resolution, stratification and wind forcing.

1. Introduction

Ocean mesoscale eddies, with scales of 10–100 km, are turbulent features in the ocean derived from barotropic and baroclinic instabilities, and are strongly influenced by wind forcing and stratification. Eddies play a key role in ocean circulation, including tracer transport, mixing and stirring, and actively participate in energy transfer between scales. The mesoscale eddy energy is particularly enhanced in the vicinity of western boundary currents and their extension (e.g. Gulf Stream and Kuroshio), and in the Southern Ocean. Eddies are crucial in the feedback of energy to the large-scale flow (e.g., Scott and Arbic, 2007) and in maintaining the jet extension via upgradient momentum fluxes leading to sharpening of gradients (Greatbatch et al., 2010).

Climate models from the Coupled Model Intercomparison Project (CMIP) archive (Taylor et al., 2012) used for the last Intergovernmental Panel on Climate Change (IPCC, 2013) have too coarse horizontal resolution to resolve these eddies. The effect of eddies on the large scale is parametrized in such coarse resolution models using the Gent-McWilliams parametrization (Gent and McWilliams, 1990; Gent et al., 1995). The parametrization has shown great success in reducing spurious convective instabilities in coarse-resolution models. The parametrization mimics the effects of baroclinic instability, converting available potential energy into kinetic energy, and acts on buoyancy and passive tracers, but neglects eddy Reynolds stresses and sub-grid scale fluctuations. The horizontal resolution of the most recent generation of global climate models has increased to a scale close to the Rossby radius of deformation. These models, often called eddy-permitting, are therefore starting to successfully capture some of the mesoscale eddy behaviour, especially at low- and mid- latitudes. However, eddy-permitting models remain unsuccessful at resolving the full mesoscale eddy field (Gnanadesikan and Hallberg, 2000; Hallberg, 2013) and its interaction with the large scales, and might not be able to do so in the near feature (Fox-Kemper et al., 2014). Therefore parametrizing sub-grid eddies, especially in eddy-permitting models, remains an important topic of research, as the previous generation of parametrizations, derived for coarse-resolution models, might not be able to successfully mimic the effects of the unresolved scales on the large-scale flow.

Sub-grid parametrization at eddy-permitting resolution is necessary not only to represent the unresolved scales but also to maintain numerical stability. Numerical dissipation is often

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achieved using Laplacian viscosity (or diffusion) with too large coefficients, or using hyperviscous parametrization (Holloway, 1992; Frisch et al., 2008) or biharmonic closure (Smagorinsky, 1963; Leith, 1990; Griffies and Hallberg, 2000) which dissipates enstrophy at the grid scale near the deformation radius and scales with model resolution. However, recent studies have shown that hyperviscosity, in addition to representing a direct enstrophy cascade (Bachman et al., 2017), spuriously dissipates energy at small scales (Arbic et al., 2007; Jansen and Held, 2014). Parametrization of sub-grid scale eddies for eddy-permitting regimes are therefore needed to either correct the spurious loss of energy resulting from the use of hyperviscosity (including modified hyperviscosity; Fox-Kemper and Menemenlis, 2008), or to replace hyperviscosity altogether. The aim of our paper is to introduce an eddy parametrization, derived for eddy-permitting models, that makes use of the resolved variability, mimics the behaviour of Reynolds stresses such as sharpening ocean jets, scales with resolution and the flow, and feeds back energy lost due to viscosity.

Jansen and Held (2014) propose to re-inject the energy lost at small scales using a negative viscosity determined by an energy equation following Eden (2010). Filtering of the velocities, as done for example in the Lagrangian-averaged Navier-Stokes-α model (Holm and Wingate, 2005; Holm and Nadiga, 2003), or the nonlinear gradient approximation (Nadiga and Bouchet, 2011) have shown promising results (see PMZ14 and Anstey and Zanna (2017) for comparisons between our proposed schemes and these studies). However, recent studies (Graham and Ringler, 2013) highlighted that these parametrizations can lead to a build-up of enstrophy at small scales and to numerical instability. Other approaches at eddy-permitting resolutions have argued for the use of a stochastic term for upgradient momentum fluxes and energy backscatter in spectral models (Kraichnan, 1976; Frederiksen and Davies, 1997; Duan and Nadiga, 2007; Nadiga, 2008; Kitsios et al., 2012; Grooms and Majda, 2013). The sub-grid forcing is generally constrained by an energy spectrum. In quasi-geostrophic models the need for upgradient momentum closures based on a stochastic model was also pointed out (Berloff, 2005b, 2015, 2016). However, all approaches require some a priori knowledge of sub-grid eddy statistics.

Here we implement a parametrization proposed by Porta Mana and Zanna (2014, referred to as PMZ14). In PMZ14 we diagnosed a relationship between the missing eddy forcing and a non-Newtonian stress divergence (Ericksen, 1956; Rivlin, 1957). The missing forcing is defined as the PV eddy flux divergence resulting from a high-resolution eddy resolving model compared to an eddy permitting model. The non-Newtonian stress divergence depends on the Lagrangian rate of change of the potential vorticity (PV) gradient and its local deformation. The relationship between the missing eddy forcing and a non-Newtonian stress divergence was inspired by general principles of potential vorticity conservation, frame-invariance, differential memory (Truesdell and Noll, 2004) and symmetry properties of the stress tensor (Bachman and Fox-Kemper, 2013). The relationship, more intuitively, is based on an argument that in eddy-permitting models the rate of strain, eddy shape and orientation, and the PV gradient can be used to mimic the evolution of the eddy PV forcing (Nadiga, 2008; Anstey and Zanna, 2017). The work argued that the parametrization could be efficient in a deterministic mode, with a coefficient for the parametrization that scales with model resolution. In addition, a stochastic parametrization was also presented, with a stochastic forcing term whose probability is conditional on the non-Newtonian forcing, wind forcing, stratification, and model resolution.

This paper is structured as follows. In Section 2 we briefly present the quasi-geostrophic model used in the current study. In Section 3 we discuss two implementations of the parametrization, one deterministic and one stochastic. In Section 4 we present the results of the two different implementations for the mean flow and variability. Section 5 is a discussion of the impact of the parametrized forcing on the momentum, energy and enstrophy budgets and presents ways forward for implementation in primitive-equations models. We briefly conclude in Section 6.

2. Model setup

The model used in the present study, PEQUOD, solves the forced dissipative baroclinic quasi-geostrophic (QG) potential vorticity (PV) equation on a beta plane in a square basin (e.g., Berloff, 2005a, 2005b). The main setup is similar to the one used in Porta Mana and Zanna (2014, PMZ14). The model is composed of three isopycnal layers with thicknesses H_m (with $m = 1, 2, 3$ for the upper, middle and bottom layer, respectively). For each layer m, the prognostic equation solved for the potential vorticity q is given by

$$\frac{\mathrm{D}q_m}{\mathrm{D}t} = \frac{\partial q_m}{\partial t} + \mathbf{u}_m \cdot \nabla q_m = \mathcal{D}_m + F_m^{\text{wind}} + F_m^{\text{eddy}}, \tag{1}$$

with

$$q_m = \nabla^2 \psi_m + \beta y + \frac{\partial}{\partial z}\left(\frac{f_0^2}{N^2}\frac{\partial \psi_m}{\partial z}\right). \tag{2}$$

The planetary vorticity is $f = f_0 + \beta y$, $\nabla = (\frac{\partial}{\partial x}, \frac{\partial}{\partial y})$ is the horizontal gradient, N is the Brunt–Väisälä frequency of the mean density stratification and ψ is the streamfunction derived from the non-divergent velocity such that $\mathbf{u}_m = (-\frac{\partial \psi_m}{\partial y}, \frac{\partial \psi_m}{\partial x})$.

The dissipation term is $\mathcal{D}_m = -r\nabla^2\psi\delta_{m,3} - \nu\nabla^6\psi_m$, where $\delta_{m,\,i}$ is the Kronecker delta function. The first term parametrizes the presence of a bottom Ekman layer with a bottom drag coefficient r. The second term is a horizontal biharmonic viscosity term, with viscosity coefficient ν, which scale-selectively dissipates enstrophy near the grid-scale. Note that PMZ14 used a Laplacian viscosity term rather than a biharmonic term for high-resolution and eddy-permitting runs (but not for coarse resolution runs). The use of hyperviscosity in the present study is to allow a setup that mimics current eddy-permitting ocean model setups, and ensures small-scale dissipation and numerical stability (we struggled to keep the model stable when using the deterministic parametrization; see Section 3). The hyperviscous term was calculated at the previous timestep for practical reasons (see Section 3b).

The forcing F_m, applied to the upper layer, is the curl of the wind stress τ:

$$F_m^{\text{wind}}(x, y) = \frac{(\nabla \times \tau)_z}{\rho_0\, H_1}\delta_{m,1}, \tag{3}$$

where ρ_0 is the reference density. The wind stress curl profile is identical to PMZ14 and spins up two gyres separated by a strong meandering jet emanating from the western boundary.

The term F_m^{eddy} is the eddy parametrization, which can take a deterministic or a stochastic form. We use different model configurations defined as follows:

i. The "truth": a high-resolution run with 7.5 km horizontal resolution. The eddy forcing term F_m^{eddy}, in Eq. (1), is set to 0.
ii. Low-resolution unparametrized runs: runs at eddy-permitting resolution with horizontal grid-spacing of 30 km and 60 km; and a coarse-resolution run at resolution of 120 km. No parametrization of eddy forcing is included, i.e. F_m^{eddy} is again set to 0.
iii. Low-resolution parametrized runs: Same as in (2), except for F_m^{eddy} being non-zero. The term F_m^{eddy} has a spatial and temporal dependence on the flow, which can be deterministic or stochastic as defined in Section 3.