Ocean Modelling 115 (2017) 42–58

Contents lists available at ScienceDirect

Ocean Modelling

journal homepage: www.elsevier.com/locate/ocemod

Evaluation of scale-aware subgrid mesoscale eddy models in a global eddy-rich model

Brodie Pearson[a,1,*], Baylor Fox-Kemper[a], Scott Bachman[b], Frank Bryan[c]

[a] Department of Earth, Environmental and Planetary Science, Brown University, Providence, USA
[b] Department of Applied Mathematics and Theoretical Physics, University of Cambridge, UK
[c] NCAR, Boulder, USA

ARTICLE INFO

Article history:
Received 30 November 2016
Revised 31 March 2017
Accepted 17 May 2017
Available online 18 May 2017

Keywords:
Mesoscale eddies
Large eddy simulation
Global climate models
Subgrid models

ABSTRACT

Two parameterizations for horizontal mixing of momentum and tracers by subgrid mesoscale eddies are implemented in a high-resolution global ocean model. These parameterizations follow on the techniques of large eddy simulation (LES). The theory underlying one parameterization (2D Leith due to Leith, 1996) is that of enstrophy cascades in two-dimensional turbulence, while the other (QG Leith) is designed for potential enstrophy cascades in quasi-geostrophic turbulence. Simulations using each of these parameterizations are compared with a control simulation using standard biharmonic horizontal mixing.

Simulations using the 2D Leith and QG Leith parameterizations are more realistic than those using biharmonic mixing. In particular, the 2D Leith and QG Leith simulations have more energy in resolved mesoscale eddies, have a spectral slope more consistent with turbulence theory (an inertial enstrophy or potential enstrophy cascade), have bottom drag and vertical viscosity as the primary sinks of energy instead of lateral friction, and have isoneutral parameterized mesoscale tracer transport. The parameterization choice also affects mass transports, but the impact varies regionally in magnitude and sign.

1. Introduction

Mesoscale eddies are a ubiquitous component of the dynamical ocean system. These eddies mix momentum and tracers along isopycnal surfaces[2], contain a substantial fraction of the ocean's kinetic energy, and can act as a source or sink of energy for fronts and the mean flow. Standard resolution ocean models, such as those used in recent IPCC reports (horizontal resolution $\Delta_h \geq 1^\circ$), cannot resolve mesoscale eddies, but the next generation of ocean models ($\Delta_h \ll 1^\circ$) can resolve the largest mesoscale eddies across much of the global ocean. The former, 'coarse resolution', models must parameterize the effects of all mesoscale eddies, while the latter, 'eddy-resolving', models need only parameterize the effects of unresolved eddies and smaller phenomena, such as boundary layer turbulence (Large et al., 1994), breaking internal waves (MacKinnon et al., 2013) and submesoscale eddies (Fox-Kemper et al., 2011).

Increasing horizontal resolution to resolve mesoscale eddies has lead to increased realism in ocean models (Smith et al., 2000; Roberts et al., 2004; Maltrud and McClean, 2005; Hallberg and Gnanadesikan, 2006; Kirtman et al., 2012; Graham, 2014; Jansen et al., 2015b), and shows potential for improving the coupling of the ocean to other components of the Earth system (Hallberg and Gnanadesikan, 2006; Frenger et al., 2013; Bryan et al., 2014). The positive effects of resolving mesoscale eddies emphasize the importance of simulating these eddies with high fidelity, and part of this challenge is to accurately parameterize the effects of unresolved mesoscale eddies.

The strength of horizontal mixing by unresolved mesoscale eddies is typically parameterized through an eddy viscosity (ν) and diffusivity (κ, perhaps paired with related advective transport), which represent eddy stresses and tracer fluxes, respectively. There are two primary factors motivating the choice of ν and κ, and the form of the mixing parameterization. First, the parameterization should represent the primary physical effects of unresolved mesoscale eddies. Second, the mixing must be strong enough to maintain numerical stability by damping extreme events (Griffies and Hallberg, 2000; Lucas et al., 2013), but not so strong as to

---

[*] Corresponding author.
E-mail addresses: brodie_pearson@brown.edu, brodiecraigpearson@gmail.com (B. Pearson).

[1] Present Address: Department of Earth, Environmental and Planetary Science, Brown University, Providence, RI 02906, USA.

[2] More precise statements of energy constraints can be found elsewhere (McDougall, 1987; Young, 2010; Nycander, 2011), here we use along-isopycnal as a shorthand for a more complete description.

http://dx.doi.org/10.1016/j.ocemod.2017.05.007
1463-5003/© 2017 Elsevier Ltd. All rights reserved.

over-damp the resolved flow (Delworth et al., 2012; Hallberg, 2013; Jansen and Held, 2014). Many parameterizations assume that mixing occurs across gradients and acts through a Laplacian operator in a manner analogous to molecular (Fickian) diffusion; e.g. $\nabla_h \cdot (\nu \nabla_h \phi)$, where ϕ is the diffused property and the subscript h denotes horizontal derivatives. There are also parameterizations based on higher-order derivatives such as biharmonic operators ($\nu \nabla_h^4 u$; Semtner and Mintz, 1977), which aim to damp the flow at smaller scales than Laplacian operators. Finally, some mixing schemes pay particular attention to reducing mixing across isopycnals (Redi, 1982; Gent and McWilliams, 1990), but these schemes are rarely used in eddy-resolving models (Roberts and Marshall, 1998). In both eddy-resolving and coarse resolution models, the ocean structure is affected by the choice of both ν (Griffies et al., 2000; Smith and McWilliams, 2003; Bryan et al., 2007; Jochum et al., 2008; Ilıcak et al., 2012; Arbic et al., 2013) and κ (Maes et al., 1997; Gent et al., 2001; Pezzi and Richards, 2003; Kuhlbrodt et al., 2012).

Significant spatial variations in the strength of mixing and transport by mesoscale eddies have been seen in observations (Eden, 2007; Chelton et al., 2011; Abernathey and Marshall, 2013; Klocker and Abernathey, 2014) and in eddy-resolving models (Visbeck et al., 1997; Abernathey et al., 2010; Fox-Kemper et al., 2013; Bachman et al., 2015). For example, intense eddy mixing occurs in the Southern Ocean and in Western Boundary Currents (WBCs; Abernathey and Marshall, 2013). These variations in κ occur in both the horizontal and the vertical (Ferreira et al., 2005), and cover more than an order of magnitude (Zhurbas and Oh, 2003; Cole et al., 2015). Including a spatially varying κ in coarse resolution models can significantly improve the resolved flow (Danabasoglu and Marshall, 2007; Eden et al., 2009; Berloff, 2015), and spatially-varying viscosity in simple models may improve their dynamical realism (Fox-Kemper and Pedlosky, 2004; Fox-Kemper, 2004). Pezzi and Richards (2003) show that spatially varying ν and κ are required for their ocean model to be comparable to observations.

In coarse resolution models, viscosity acts horizontally but the mixing of tracers is often oriented along isopycnals using the Gent-McWilliams and Redi parameterizations (Redi, 1982; Gent and McWilliams, 1990). The combined “GM-Redi” parameterization advects and diffuses tracers along isopycnals (Fox-Kemper et al., 2013). The along-isopycnal diffusive component of the parameterization does not affect the density field, but the advective component can re-arrange fluid parcels of different densities and in doing so it converts available potential energy to kinetic energy (Gent et al., 1995; Griffies, 1998). Parameterizing along-isopycnal diffusion of tracers conserves water mass properties and has led to significant improvements in ocean models relative to assuming horizontal diffusion (Veronis, 1975; Danabasoglu and McWilliams, 1995; Lengaigne et al., 2003). Orienting eddy momentum fluxes along isopycnals is not required for dynamics in the quasi-geostrophic regime, as the vertical velocities vanish to leading order and so the covariance corrections are negligible.

The present generation of eddy-resolving models for the global ocean typically have horizontal resolution of $O(1/10°)$ which means that the largest mesoscale eddies (~30 km and larger) are resolved almost everywhere (Hallberg, 2013), but the smallest mesoscale eddies are typically less than 10 km and the effects of these unresolved eddies should be parameterized. In eddy-resolving models the values of ν and κ are often chosen for numerical stability and used with a horizontal biharmonic operator rather than the GM-Redi scheme (Maltrud et al., 2010; McClean et al., 2011; Delworth et al., 2012; Bryan et al., 2014), but this can increase spurious diapycnal mixing and extract too much energy from the resolved flow (Roberts and Marshall, 1998; Jansen and Held, 2014). Some attempts have been made to parameterize unresolved eddy mixing in eddy-resolving models using stochastic parameterizations (Mana and Zanna, 2014), additional equations in the model for subgrid kinetic energy and mixing length (Eden and Greatbatch, 2008; Jansen et al., 2015a), or switches that turn off parameterizations in regions where the largest mesoscale eddies are resolved (Hallberg, 2013) – all of which attempt to account for the spatial heterogeneity of mixing.

Large eddy simulation (LES) is an approach used to simulate turbulent flows in which the largest scales are resolved, but the smallest scales must be parameterized. Unlike coarse resolution approaches, LES uses the resolved flow to improve the subgrid closure. Subgrid closures in LES often rely on the presence of an ‘inertial cascade’ of a flow property, from large scales down to unresolved scales, by the turbulence (Kolmogorov, 1941; Kraichnan, 1967). In LES, ν and κ are chosen to provide damping that is consistent with an appropriate inertial cascade, while avoiding damping at scales above the grid scale (Smagorinsky, 1963; Leith, 1996). The values of ν and κ have an intrinsic dependence upon the local flow field and the grid resolution. For geophysical applications, LES is often used to simulate 3D turbulence, such as that in ocean boundary layers, using a traditional Smagorinsky subgrid scheme (Smagorinsky, 1963). The Smagorinsky subgrid scheme has been applied to ocean models (Griffies and Hallberg, 2000), but it extracts too much energy from the resolved flow (Jansen and Held, 2014) and much recent work has sought to provide backscatter or other stochastic schemes to re-inject energy into the resolved scales (Jansen et al., 2015b; Grooms et al., 2015; Zurita-Gotor et al., 2015). Mesoscale turbulence is not typical 3D turbulence because the effects of rotation and stratification confine the motions of mesoscale eddies to isopycnal surfaces. Recent work has developed and used LES techniques for 2D turbulence (Leith, 1996; Fox-Kemper and Menemenlis, 2008; Nadiga and Bouchet, 2011; Nguyen et al., 2011; San et al., 2011; 2013; Pietarila Graham and Ringler, 2013). Bachman et al. (2017) extended these ‘Leith’ or ‘mesoscale ocean large eddy simulation’ (MOLES) techniques to apply to the quasi-geostrophic (QG) turbulence regime in which mesoscale eddies reside. They found that idealised simulations of a frontal spin-down using a quasi-geostrophic extension of Leith (1996), or QG Leith, produced kinetic energy spectra which were more consistent with theory and exhibited less spectral roll-off at the grid-scale than simulations using a variety of other common mixing parameterizations. In addition, they showed that the 2D Leith and QG Leith schemes can be used to prescribe the GM-Redi parameters, so that the horizontal eddy momentum fluxes, and the along-isopycnal eddy tracer fluxes and tracer advection are parameterized consistently for the unresolved part of the mesoscale spectrum. Importantly, the amount of subgrid eddy tracer transport and restratification is *not* sufficient to fully replace that expected from unresolved eddies in the Bachman et al. (2017) scheme, but it is enough to regularize the tracer and density transport and provide consistent dissipation of potential vorticity by diffusion of buoyancy and viscosity.

In this paper we apply the 2D Leith and QG Leith parameterizations for eddy stresses and tracer transports within a global eddy-resolving ocean model, and compare the resultant simulations with those using a standard (biharmonic) subgrid scheme. The simulations, and the 2D Leith and QG Leith parameterizations, are described in Section 2. In Section 3, we compare these Leith simulations with simulations using a biharmonic mixing scheme. The results are discussed and summarized in Section 4.