Ocean Modelling 39 (2011) 61–78

Contents lists available at ScienceDirect

Ocean Modelling

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

Parameterization of mixed layer eddies. III: Implementation and impact in global ocean climate simulations

B. Fox-Kemper[a,b,*], G. Danabasoglu[c], R. Ferrari[d], S.M. Griffies[e], R.W. Hallberg[e], M.M. Holland[c], M.E. Maltrud[f], S. Peacock[c], B.L. Samuels[e]

[a] Cooperative Institute for Research in Environmental Sciences (CIRES), University of Colorado, Boulder, CO, United States
[b] Dept. of Atmospheric and Oceanic Sciences (ATOC), University of Colorado, Boulder, CO, United States
[c] National Center for Atmospheric Research, Boulder, CO, United States
[d] Department of Earth, Atmospheric and Planetary Sciences, Massachusetts Institute of Technology, Cambridge, MA, USA
[e] NOAA Geophysical Fluid Dynamics Laboratory, Princeton, NJ, United States
[f] Los Alamos National Laboratory, Los Alamos, NM, United States

ARTICLE INFO

Article history:
Available online 17 September 2010

Keywords:
Submesoscale
Parameterization
Mixed layer
Boundary layer
Climate model

ABSTRACT

A parameterization for the restratification by finite-amplitude, submesoscale, mixed layer eddies, formulated as an overturning streamfunction, has been recently proposed to approximate eddy fluxes of density and other tracers. Here, the technicalities of implementing the parameterization in the coarse-resolution ocean component of global climate models are made explicit, and the primary impacts on model solutions of implementing the parameterization are discussed. Three global ocean general circulation models including this parameterization are contrasted with control simulations lacking the parameterization. The MLE parameterization behaves as expected and fairly consistently in models differing in discretization, boundary layer mixing, resolution, and other parameterizations. The primary impact of the parameterization is a shoaling of the mixed layer, with the largest effect in polar winter regions. Secondary impacts include strengthening the Atlantic meridional overturning while reducing its variability, reducing CFC and tracer ventilation, modest changes to sea surface temperature and air–sea fluxes, and an apparent reduction of sea ice basal melting.

© 2010 Elsevier Ltd. All rights reserved.

1. Introduction

The world ocean surface is filled with fronts. Many are formed by mesoscale eddies straining large-scale density gradients into concentrated filaments and fronts that are further sharpened near the surface by ageostrophic circulations (Hoskins and Bretherton, 1972; Pollard and Regier, 1992). Patchy mixing by isolated events (*e.g.*, hurricanes) combined with large-scale strain may also lead to horizontal density gradients (*e.g.*, Price, 1981; Ferrari and Rudnick, 2000; D'Asaro et al., 2007; Price et al., 2008). A front stores potential energy in the horizontal juxtaposition of dense and light water masses; slumping of the front releases potential energy. However, the energy release is limited by Rossby adjustment, where a Coriolis force develops with an along-front flow to balance the cross-front pressure gradient and prevent further slumping (*e.g.*, Tandon and Garrett, 1994). Rossby-adjusted density fronts are commonly observed throughout the ocean mixed layer (Rudnick and Ferrari, 1999; Ferrari and Rudnick, 2000; Hosegood et al., 2006).

Rossby-adjusted fronts are often unstable to mixed layer instabilities (MLIs: Boccaletti et al., 2007; Samelson and Chapman, 1995; Haine and Marshall, 1998). These ageostropic baroclinic instabilities grow and form mixed layer eddies (MLEs) when they reach finite amplitude. MLIs resemble the ageostrophic baroclinic instabilities studied by Stone (1970) in his analysis of the Eady (1949) problem of constant geostrophic shear (U/H) and stratification (N). Stone finds a linear growth rate of

$$\tau_s(k) = \frac{kU}{2\sqrt{3}}\left[1 - \frac{2k^2U^2}{15f^2}(1+\mathrm{Ri})\right], \tag{1}$$

$$\mathrm{Ri} = N^2\left|\frac{\partial \boldsymbol{u}_g}{\partial z}\right|^{-2} = \frac{N^2H^2}{U^2}. \tag{2}$$

The timescale of growth (τ_s) at each wavenumber (k) depends on the geostrophic-flow Richardson number, Ri (Boccaletti et al., 2007) and the Coriolis parameter (f). The fastest growing linear mode has length and time scales L_s and τ_s.

---

* Corresponding author at: Address: Cooperative Institute for Research in Environmental Sciences (CIRES), University of Colorado, Boulder, CO, United States. Tel.: +1 303 492 0532; fax: +1 303 492 1149.

E-mail addresses: bfk@colorado.edu, baylor@alum.mit.edu (B. Fox-Kemper).

1463-5003/$ - see front matter © 2010 Elsevier Ltd. All rights reserved.
doi:10.1016/j.ocemod.2010.09.002

$$L_s = \frac{2\pi}{k_s} = \frac{2\pi U}{|f|}\sqrt{\frac{1+\mathrm{Ri}}{5/2}}, \tag{3}$$

$$\tau_s(k_s) = \sqrt{\frac{54}{5}}\frac{\sqrt{1+\mathrm{Ri}}}{|f|}. \tag{4}$$

As MLIs become finite amplitude MLEs, the front slumps beyond the Rossby-adjusted state and continues to release potential energy. The overall slumping results in substantial restratification of the mixed layer and shields the themocline from subsequent mixing events.

Fox-Kemper et al. (2008b) propose a parameterization to predict this MLE-induced restratification and related effects. While much of the implementation is detailed in Fox-Kemper and Ferrari (2008), additional details necessary for implementing this parameterization in coarse-resolution global ocean models will be presented here. The parameterization has been extensively validated to approximate well the results of idealized high-resolution simulations of slumping of a single mixed layer front (Fox-Kemper and Ferrari, 2008), but this work extends the scaling for one front to a field of fronts based on frontal statistics from data and models.

The length and time scales of MLIs fall in the submesoscale O (1 km, 1 day) range, for typical mixed layer depth (H) and stratification (N) are small, and therefore MLI are smaller and faster than mesoscale instabilities. MLEs are somewhat larger in scale than MLIs due to an inverse cascade (Boccaletti et al., 2007), but remain limited to the submesoscale range (Fox-Kemper et al., 2008b). Thus, MLIs and MLEs will not be directly resolved in global-scale simulations for some time.

It will be shown here that MLE restratification, as represented by the parameterization, is important in coarse-resolution models despite the small size of individual MLEs. Basin-scale simulations at MLE-permitting 2 km resolution have shown bias reduction in near-surface properties (*e.g.,* Oschlies, 2002; Lévy et al., 2010), and preliminary results of the MLE parameterization effects in coarse models show encouraging bias reduction compared to climatology (Fox-Kemper et al., 2008a). This paper documents the most notable effects of the MLE parameterization by comparing global climate simulations using the parameterization with otherwise identical control simulations not using the MLE parameterization. These results are intended as a guide when considering and implementing the MLE parameterization in climate models. Readers interested only in the results of implementing the MLE parameterization and not the details of its implementation may skip ahead to Section 3.

Other submesoscale effects – wind-front and convection-front interactions, and frontogenesis – remain unparameterized at present. Thomas and Ferrari (2008) derive scalings and find comparable magnitudes for all of these physical phenomena. However, Mahadevan et al. (2010), Capet et al. (2008a) show that even in complex, realistic settings and in the presence of moderate winds, the MLE-induced overturning described here remains qualitatively adept at describing submesoscale restratification. Additional restratification and straining by mesoscale eddies (Lapeyre et al., 2006), restratification by up-front winds and destratification by down-front winds (Thomas and Lee, 2005), and restratification by symmetric instabilities (Taylor and Ferrari, 2009) remain unparameterized in the models presented here. These effects have been shown to affect the rate of MLE-induced overturning in some situations (Spall, 1995; Mahadevan et al., 2010) but do not systematically affect the mixed layer. By contrast, MLEs always tend to restratify. Mahadevan et al. (2010) conclude that 'the net advective buoyancy flux is the sum of the advective effect of eddies and the [wind-driven frontal overturning],' so it seems possible to parameterize these effects independently.

Submesoscale fronts and frontal restratification and instabilities also affect biology (Levy et al., 1999; Spall and Richards, 2000; Mahadevan and Archer, 2000; Klein and Lapeyre, 2009). The MLE parameterization described here will impact the physical environment and nutrient transport properties of the photic zone if used for biogeochemical modeling, but it is presently unclear whether the use of the MLE parameterization alone is beneficial to biogeochemical modeling. Other submesoscale dynamics are likely to impact biology to a similar degree and biology may interfere with the proper scaling of MLE nutrient transport (Section 2.1.2). Resolving relevant submesoscale dynamics in global models for century-long simulations will be too expensive for some time, so parameterized submesoscale processes is presently the only viable way to assess their global climate impact. This paper begins the process of understanding the impact of submesoscale physics on global climate, and future parameterization refinements are likely to further improve global climate modeling and understanding.

2. Implementation in global coarse ocean models

Fox-Kemper et al. (2008b) parameterization is cast as an MLE-induced overturning vector streamfunction ($\mathbf{\Psi}$), which produces an MLE-induced or quasi-Stokes velocity field ($\mathbf{u}^* = \nabla \times \mathbf{\Psi}$). Advection by the MLE-induced velocity acts to slump fronts and provides eddy fluxes of tracers ($\overline{\mathbf{u}'c'} = \mathbf{\Psi} \times \nabla\bar{c}$).

Three parameters enter in the parameterization: the mixed layer depth, the horizontal buoyancy gradient in the mixed layer, and the Earth's rotation rate. Buoyancy is the negative density anomaly rescaled to have dimensions of acceleration $b \equiv g(\rho_0 - \rho)/\rho_0$, where ρ_0 is the constant reference density associated with the Boussinesq approximation. Throughout, overlines are used to represent the fields in a coarse-resolution model, that is, one not resolving the submesoscale eddies. As will be shown below, a scaling factor will account for how coarse the model resolution is – it may be mesoscale resolving or coarser. In any case, the *primed quantities here always refer to submesoscale fluxes*, not to resolved or parameterized mesoscale fluxes. The MLE fluxes are to be added to resolved or parameterized mesoscale eddy fluxes and to any additional parameterized finescale turbulent fluxes.

The MLE parameterization of Fox-Kemper et al. (2008b) is given by

$$\mathbf{\Psi}_0 = C_e\frac{H^2\overline{\nabla\bar{b}}^z \times \hat{\mathbf{z}}}{|f|}\mu(z), \tag{5}$$

$$\mu(z) = \max\left\{0, \left[1 - \left(\frac{2z}{H}+1\right)^2\right]\left[1 + \frac{5}{21}\left(\frac{2z}{H}+1\right)^2\right]\right\},$$

where H is mixed layer depth, f is the Coriolis parameter, and $\hat{\mathbf{z}}$ is the unit vertical vector. The subscript *0* is to indicate that this is the original form appropriate for extratropical, mesoscale-resolving models. A modified form appropriate for coarse-resolution global models is given below. The overline with subscript z on $\overline{\nabla\bar{b}}^z$ is understood to be the depth-average of $\nabla\bar{b}$ over the mixed layer. The efficiency coefficient C_e is found to be 0.06–0.08 from MLE-resolving simulations (Fox-Kemper et al., 2008b).

An adaptation to (5) that is suitable and justified in a global coarse-resolution model is

$$\mathbf{\Psi} = C_e\frac{\Delta s}{L_f}\frac{H^2\overline{\nabla\bar{b}}^z \times \hat{\mathbf{z}}}{\sqrt{f^2+\tau^{-2}}}\mu(z). \tag{6}$$

The local coarse model gridscale dimension is Δs, and L_f is an estimate of the typical local width of mixed layer fronts (Section 2.1). No compelling theory for the width of oceanic mixed layer fronts is known to the authors (Hoskins and Bretherton, 1972; Blumen and Piper, 1999 discuss atmospheric frontal scales), but the observations

Download English Version:

https://daneshyari.com/en/article/4552399

Download Persian Version:

https://daneshyari.com/article/4552399

Daneshyari.com