Ocean Modelling 112 (2017) 125–138

Contents lists available at ScienceDirect

Ocean Modelling

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

Emergent eddy saturation from an energy constrained eddy parameterisation

J. Mak[a,*], D.P. Marshall[b], J.R. Maddison[a], S.D. Bachman[c]

[a] School of Mathematics and Maxwell Institute for Mathematical Sciences, University of Edinburgh, Edinburgh, EH9 3FD, United Kingdom
[b] Department of Physics, University of Oxford, Oxford, OX1 3PU, United Kingdom
[c] DAMTP, Centre for Mathematical Sciences, Wilberforce Road, Cambridge, CB3 0WA, United Kingdom

ARTICLE INFO

Article history:
Received 4 October 2016
Revised 18 February 2017
Accepted 24 February 2017
Available online 24 February 2017

Keywords:
Geostrophic turbulence
Mesoscale eddy parameterisation
Gent–McWilliams
Eddy saturation

ABSTRACT

The large-scale features of the global ocean circulation and the sensitivity of these features with respect to forcing changes are critically dependent upon the influence of the mesoscale eddy field. One such feature, observed in numerical simulations whereby the mesoscale eddy field is at least partially resolved, is the phenomenon of eddy saturation, where the time-mean circumpolar transport of the Antarctic Circumpolar Current displays relative insensitivity to wind forcing changes. Coarse-resolution models employing the Gent–McWilliams parameterisation with a constant Gent–McWilliams eddy transfer coefficient seem unable to reproduce this phenomenon. In this article, an idealised model for a wind-forced, zonally symmetric flow in a channel is used to investigate the sensitivity of the circumpolar transport to changes in wind forcing under different eddy closures. It is shown that, when coupled to a simple parameterised eddy energy budget, the Gent–McWilliams eddy transfer coefficient of the form described in Marshall et al. (2012) [*A framework for parameterizing eddy potential vorticity fluxes*, J. Phys. Oceanogr., vol. 42, 539–557], which includes a linear eddy energy dependence, produces eddy saturation as an emergent property.

1. Introduction

Studies of the response of the large-scale ocean circulation to changing forcing scenarios in numerical ocean models require long time integrations that are prohibitively expensive even at mesoscale eddy permitting resolutions. Since this is expected to remain the case for the foreseeable future, an ongoing challenge in numerical ocean modelling is the representation of the unresolved mesoscale eddy field in coarse resolution models. A particularly successful scheme that is employed is the Gent–McWilliams (GM) parameterisation (Gent and McWilliams, 1990; Gent et al., 1995), which parameterises mesoscale eddies via the introduction of a non-divergent eddy transport velocity. The eddy transport velocity can be interpreted as arising from the difference between the Eulerian average of the velocity at fixed height and the thickness-weighted average of the velocity at fixed density (McDougall and McIntosh, 2001), and modifies the advective transport of tracer quantities. By definition, the non-divergent eddy transport velocity conserves all moments of the advected quantities, and is thereby adiabatic. The property of adiabatic stirring is particularly attractive, being shown to remove spurious heating and cooling in the deep ocean, such as that associated with the Deacon cell in the Southern Ocean (Danabasoglu et al., 1994).

To this point, studying the modelled oceanic response to changing atmospheric forcing in conjunction with the GM parameterisation is of particular importance for emergent climatologies under different forcing scenarios. Two important large-scale Southern Ocean phenomena are of particular interest in this regard. The first is "eddy saturation", originally discussed in Straub (1993) from an argument based on critical stability, and here to be understood as the relative insensitivity of the time-mean circumpolar transport with respect to wind forcing changes. The other is "eddy compensation", here to be understood as the reduced sensitivity of the residual meridional overturning circulation with wind forcing changes (e.g., Meredith et al., 2012; Viebahn and Eden, 2012; Munday et al., 2013), which has consequences for the meridional transport of important tracers such as heat, salt and carbon. This article focuses on eddy saturation.

As argued by Straub (1993), if fluid interaction with topography is the main sink for momentum input by wind stress, and consequently the zonal abyssal flow is weak, then thermal wind shear is

* Corresponding author.
E-mail address: julian.c.l.mak@googlemail.com (J. Mak).

http://dx.doi.org/10.1016/j.ocemod.2017.02.007
1463-5003/

the dominant contribution to circumpolar transport; Peña-Molino et al. (2014) suggest that thermal wind shear accounts for at least 75% of the net circumpolar transport in the Southern Ocean. Thus circumpolar transport is intimately linked to isopycnal slope, with the slope steepness limited by baroclinic instability. Eddy saturation arises through a balance between steepening of isopycnals by wind stress, and flattening of isopycnals by the presence of the mesoscale eddy field. While the question of whether the ocean is in an eddy saturated state remains unconstrained by current observations, the reduction in circumpolar transport sensitivity with varying wind stress has been observed in a variety of numerical models that at least partially resolve a mesoscale eddy field (e.g., Hallberg and Gnanadesikan, 2006; Hogg and Blundell, 2006; Hogg et al., 2008; Farneti and Delworth, 2010; Farneti et al., 2010). In Munday et al. (2013), an eddy permitting one-sixth degree model of a 20° wide ocean sector was integrated with varying wind forcings. This eddy permitting model, employing a very small value of the GM eddy transfer coefficient, showed near complete eddy saturation. By contrast, in lower resolution half degree and two degree variants of the same model, where larger values of the GM eddy transfer coefficient were utilised, the resulting time-mean circumpolar transport displayed significant sensitivity with respect to the wind forcing. Hogg and Munday (2014) found that although the value of the time-mean circumpolar transport was affected by the domain geometry, the relative insensitivity with changing wind stress at eddy permitting resolution was robust.

Thus it has been found that the GM scheme with a spatially and temporally constant GM eddy transfer coefficient is unable to represent eddy saturation (see also Farneti et al., 2015). With increased wind forcing, a more vigourous eddy field is to be expected. Since the GM eddy transfer coefficient in some sense specifies the intensity and efficiency of the parameterised eddy field, it is expected that a positive correlation between the strength of wind forcing and the magnitude of the GM coefficient eddy transfer is minimally required for emergent eddy saturation. Various proposals already exist with a non-constant GM eddy transfer coefficient. In Visbeck et al. (1997), using linear stability arguments, a GM eddy transfer coefficient is proposed which depends upon the stratification profile, as well as a mixing length. In Ferreira et al. (2005) the eddy-mean-flow interaction in a global ocean model is determined via an optimisation procedure, yielding diagnosed values for the GM eddy transfer coefficient. Their optimisation is used to infer a GM eddy transfer coefficient which depends on the vertical stratification, and has subsequently been incorporated into a number of ocean general circulation models (e.g., Danabasoglu and Marshall, 2007; Gent and Danabasoglu, 2011). The simulations described in Gent and Danabasoglu (2011) do show some eddy compensation, as a consequence of the dependence of the GM eddy transfer coefficient on Southern Ocean stratification. However, as discussed in Munday et al. (2013), this mechanism precludes the model from achieving full eddy saturation.

Through the consideration of the eddy kinetic energy budget, Cessi (2008) proposes a mixing length based eddy parameterisation, with a GM eddy transfer coefficient depending on the ocean state and explicitly depending on the strength of the bottom drag. An approach also based upon consideration of the eddy kinetic energy budget is discussed in Eden and Greatbatch (2008) (see also Marshall and Adcroft, 2010), also employing a mixing length argument but utilising a local parameterised eddy kinetic energy budget to inform the magnitude and spatial structure of the resulting GM eddy transfer coefficient. While there is no conclusive observational evidence to suggest that the ocean is in an completely eddy saturated regime, there is ample evidence from mesoscale eddy-permitting model experiments that coarse resolution models with current parameterisations appear unable to replicate eddy saturation in a self-consistent way (e.g., the work Fyfe et al., 2007 varies the GM eddy transfer coefficient manually with changing wind stress).

In Marshall et al. (2012) a geometric interpretation of the eddy-mean-flow interaction for the quasi-geostrophic equations was derived. A horizontally down-gradient closure for the horizontal eddy buoyancy fluxes leads to a GM eddy transfer coefficient of the form

$$\kappa = \alpha E \frac{N}{M^2}, \tag{1}$$

where E is the total (kinetic plus potential) eddy energy, and $N/M^2 = T$ is an Eady time-scale which depends on the mean stratification, with $N^2 = -(g/\rho_0)\partial\overline{\rho}^z/\partial z$ and $M^2 = (g/\rho_0)|\nabla_H\overline{\rho}^z|$, where g is the gravitational acceleration, ρ_0 is a reference density, $\overline{\rho}^z$ is the mean density averaged at fixed height, and ∇_H is its horizontal gradient operator. A crucial point is that, if the eddy energy is known, there are no undetermined dimensional parameters; the only freedom is to specify the non-dimensional geometric parameter α of magnitude less than or equal to one (see, e.g., Bachman et al., 2017). A form similar to (1) also appears in Jansen et al. (2015) — implied by their Eqs. (9) and (11) — but with the eddy kinetic energy in place of the full eddy energy, and motivated by the inverse energy cascade being controlled by the rate of eddy energy generation through baroclinic instability as per Larichev and Held (1995). However the form derived in Marshall et al. (2012) provides an explicit upper bound on the relevant geometric parameter α; no other dimensional scaling is possible provided the geometric parameter α is bounded away from zero. Moreover, here the eddy energy is determined prognostically via the solution of a dynamical equation which is coupled to the equations for the mean state.

This article assesses the ability of the Marshall et al. (2012) GM eddy transfer coefficient to reproduce eddy saturation, via numerical calculations in an idealised, zonally averaged, two-dimensional ocean channel model. The idealised numerical model is motivated by the physical model discussed in Marshall et al. (2017), where eddy saturation was demonstrated through considerations of the momentum and eddy energy budget, together with the scaling for the GM eddy transfer coefficient given by Eq. (1). The ability of the Marshall et al. (2012) scheme to produce eddy saturation is compared against a number of alternative approaches, including approaches based upon mixing length arguments, and based upon the Visbeck et al. (1997) proposal. Since the Marshall et al. (2012) variant requires information about the eddy energy, the evolution of the mean state is coupled to a prognostic equation for the parameterised domain integrated eddy energy (cf. the local budget for the eddy kinetic energy in Eden and Greatbatch, 2008).

The paper proceeds as follows. In Section 2 the GM scheme and the Marshall et al. (2012) parameterisation variant are revisited, focusing in particular on the energetics of the problem, and providing physical and mathematical arguments as to why the Marshall et al. (2012) variant may be expected to have skill in producing emergent eddy saturation. Section 3 contains the details of the idealised numerical model and of the other parameterisation variants considered in this work. The implementation of the parameterisation variants and their results are presented in Section 4 for a case where the GM eddy transfer coefficient is assumed to be constant over the domain, and in Section 5 for a case where the GM eddy transfer coefficient is spatially varying, focusing on the case where a spatial structure depending upon the vertical stratification is enforced. The paper concludes in Section 6, where the results are discussed, and a recipe for implementation in a global circulation models is proposed.