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Parameterizing subgrid-scale eddy effects using energetically consistent backscatter

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ABSTRACT

In the near future we expect the resolution of many IPCC-class ocean models to enter the "eddy-permitting" regime. At this resolution models can produce reasonable eddy-like disturbances, but can still not properly resolve geostrophic eddies at all relevant scales. Adequate parameterizations representing sub-grid eddy effects are thus necessary. Most eddy-permitting models presently employ some kind of hyper-viscosity, which is shown to cause a significant amount of energy dissipation. However, comparison to higher resolution simulations shows that only enstrophy, but almost no energy, should be dissipated below the grid-scale. As a result of the artificial energy sink associated with viscous parameterizations, the eddy fields in eddy permitting models are generally not energetic enough.

To overcome this problem, we propose a class of sub-grid parameterizations which dissipate enstrophy but little or no energy. The idea is to combine a standard hyperviscous closure with some mechanism to return dissipated energy to the resolved flow. Enstrophy dissipation remains ensured because the energy is returned at larger scales. Two simple ways to return the energy are proposed: one using a stochastic excitation and one using a negative Laplacian viscosity. Both approaches are tested in an idealized two-layer quasi-geostrophic model. Either approach is shown to greatly improve the solutions in simulations with typical eddy-permitting resolutions. The adaptation of the proposed parameterization for use in realistic ocean models is discussed.

1. Introduction

It has become increasingly clear that the ocean circulation is strongly controlled by meso-scale turbulent eddies (e.g. Gill et al., 1974; Johnson and Bryden, 1989; Hallberg and Gnanadesikan, 2006; McWilliams, 2008; Waterman et al., 2011). However, most of the current generation of climate models, as for example appeared in the report of the Intergovernmental Panel on Climate Change (IPCC) (Flato et al., 2013), have too coarse of a resolution to resolve these turbulent motions.

Most current IPCC-class climate models use ocean components with typical horizontal resolutions of about one degree or less (Flato et al., 2013). At these resolutions turbulent eddies are largely absent and their effects on the transport of physical properties and tracers must be parameterized (e.g. Hallberg and Gnanadesikan, 2006). The most commonly used closures follow the arguments of Gent and McWilliams (1990) who proposed to parameterize eddy fluxes of buoyancy and passive tracers in terms of an advective process, which acts to flatten isopycnals at a rate proportional to the isopycnal slope itself. A closure of this form is motivated by the fact that eddies extract available potential energy stored in the mean flow, by rearranging water masses adiabatically (Gent et al., 1995).

Since any parameterization of this kind is associated with uncertain assumptions about the response of eddy transports to changes in the mean state and external parameters, there is a strong urge to increase the resolution of the ocean component in global climate models in order to resolve eddies explicitly. In the near future we expect the resolution of many IPCC-class climate simulations to increase to values around 1/4 of a degree. At this resolution ocean models can produce eddy-like disturbances generated by baroclinic instability of the flow. The resolution, however, is still insufficient to properly resolve eddies on all relevant scales (e.g. Hallberg and Gnanadesikan, 2006; Hallberg, 2013). These models are hence sometimes referred to as "eddy-permitting" models, as opposed to "eddy-resolving" models which should properly resolve eddies at least down to the deformation scale. In the near future, computational resources will limit our ability to perform longer-term global climate simulations using truly eddy-resolving ocean models. It is therefore necessary to understand the limitations of eddy-permitting models, and design ways to

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parameterize eddy fluxes which are absent or underrepresented due to the coarse resolution.

Some form of sub-grid-scale eddy parameterization, even in eddying models, is not only physically desirable, but generally required to obtain numerically stable results. The necessity of a sub-grid eddy closure is easily understood by noting that geostrophic turbulence, as found in eddying ocean models, transfers enstrophy (i.e. vorticity variance) to smaller and smaller scales (Charney, 1971). This enstrophy must be dissipated near the grid-scale to avoid accumulation. A common approach to achieve enstrophy dissipation is the use of a horizontal hyper-viscosity – typically biharmonic (i.e. 4th order) – which scale-selectively removes enstrophy near the grid-scale (e.g. Böning and Budich, 1992; Griffies and Halberg, 2000; Oschlies, 2002). Some models use biharmonic viscosities with non-constant, flow- and resolution-dependent viscosity coefficients, based on the seminal work of Smagorinsky (1963) and Leith (1996) (see also Fox-Kemper and Menemenlis, 2008 for a review). These approaches have the desirable property that they appropriately adapt to different flow regimes and resolutions. In particular energy dissipation by the parameterization vanishes in the limit of infinite resolution. However, for resolutions near the deformation radius (i.e. in the "eddy-permitting" regime) such closures dissipate not only enstrophy, but also a significant amount of energy, as will be illustrated in this study. This is problematic, since geostrophic turbulence does not in the net transfer energy to smaller scales, and thus does not provide a pathway to energy dissipation at small scales.

The goal of this study is to improve on the existing hyperviscous parameterizations, by accounting for the spurious energy dissipation generated by these closures. The general goal that guides the arguments presented here is to devise a parameterization that is as simple as possible, while fulfilling the two most basic properties dictated by the physics of geostrophic turbulence, dissipating enstrophy and conserving energy.

Sadourny and Basdevant (1985) proposed a parameterization which fulfills these criteria. The proposed parameterization can be understood as mimicking an up-wind advection scheme for potential vorticity, and like the latter is diffusive only in the along-flow direction. As a consequence the closure dissipates PV variance while exactly conserving energy. A disadvantage of the closure is that it is not Galilean invariant (Sadourny, 1986). We experimented with an upwind-biased variant of the Sadourny (1975) energy conserving scheme for the PV advection in a primitive equation ocean model. The approach was not by itself sufficient to stabilize the simulations, and lead to the spin-up of unrealistic zonal mean flows, consistent with the lack of Galilean invariance. It is possible that these deficiencies could be remedied by using a different implementation of the method. However, due to these initial results, we have not pursued this further.

Other promising approaches have been proposed to parameterize sub-grid scale eddy effects at eddy permitting resolutions. Most notably, we here want to mention the alpha-model approach and the nonlinear gradient approximation. The Lagrangian-averaged Navier–Stokes alpha model arises from a regularization of the fluid equations via a modification of the nonlinearity (Holm et al., 1998; Holm and Nadiga, 2003). In the quasi-geostrophic (QG) approximation, the alpha model corresponds to the advection of PV by a smoothed velocity field (Holm and Nadiga, 2003; Holm and Wingate, 2005). The equations conserve both energy and enstrophy under appropriately defined norms, which in the case of the energy includes a combination of both the full and smoothed velocity fields (Nadiga and Shkoller, 2001). The alpha model has been successfully tested in a two-layer barotropic double gyre model (Holm and Nadiga, 2003). The results suggest that the alpha term leads to more realistic gyre structures and smoother solutions at coarse resolution and with low values of viscosity. The recent results of Graham and Ringler (2013), analyzing two-dimensional isotropic turbulence forced by a spectrally localized forcing, instead are somewhat less encouraging. Graham and Ringler (2013) find that the alpha sub-grid term causes a forward transfer of energy and enstrophy at scales larger than the filter scale, and leads to an accumulation of enstrophy at small scales.

Another promising approach, related to the alpha model, is the non-linear gradient model (Meneveau and Katz, 2000; Bouchet, 2003; Nadiga and Bouchet, 2011, and references therein). The non-linear gradient model can be derived by applying an LES filter to the flow field and approximating the stress terms associated with the small scales by a leading order Taylor expansion of the large-scale velocity field. The result is a representation of the small-scale eddy PV flux by a quadratic nonlinear combination of the large-scale ("resolved") velocity gradient and PV gradient. The non-linear gradient model exhibits very promising results in so-called "a-priori" tests, where the nonlinear gradient term is computed from a filtered version of a high resolution reference simulation and then compared to the true small-scale eddy flux (Chen et al., 2003; Nadiga and Bouchet, 2011). However, used directly as a parameterization for sub-grid eddy effects, the non-linear gradient model is generally unstable, and thus needs to be augmented with an additional dissipative term or modified in other ways (Bouchet, 2003; Nadiga and Bouchet, 2011). As discussed in Bouchet (2003) the (unmodified) nonlinear gradient model conserves energy of the resolved flow. However, no general constraint exists for the enstrophy, which thus may grow, eventually leading to numerical instability.

In an effort to design a parameterization that can relatively easily be implemented in existing ocean general circulation models, we here propose to retain the usual hyperviscous parameterization, but augment the latter with an additional forcing term to account for the spurious energy loss. The forcing term is chosen such as to return energy otherwise lost to the hyperviscous dissipation. By implementing the forcing such that the energy is, on average, returned at larger scales, we further guarantee dissipation of enstrophy. The idea may be thought of in terms of a sub-grid eddy drain and backscatter, i.e. the hyperviscous closure represents/replaces nonlinear energy transfer to sub-grid scales ("drain"), while the forcing represents the backscatter of energy from the sub-grid scale to the resolved scales. The importance of backscatter has been pointed out by Nadiga and Bouchet (2011) and Nadiga (2010), and is reflected in the properties of the non-linear gradient model. Parameterizations based on an explicit drain viscosity and stochastic backscatter have also been proposed multiple times in the turbulence closure literature (e.g. Kraichnan, 1976; Leith, 1990; Frederiksen and Davies, 1997; Duan and Nadiga, 2007; Kitsios et al., 2013). The attraction of the approach proposed here is that it is based only on the property of geostrophic turbulence to transfer enstrophy but little or no energy to small scales. As a result, the proposed closure produces stable and skillful results, without requiring any a priori knowledge of sub-grid eddy statistics. Moreover, a version of it can be implemented in a primitive-equation OGCM, as will be discussed in Section 5.

This paper is structured as follows. In Section 2 we discuss a series of idealized reference simulations, using only a Leith-like hyperviscous closure. We discuss simulations at eddy resolving and eddy permitting resolutions, which clearly demonstrate the decline in the EKE at all scales, associated with the spurious loss of energy in the hyperviscous closure. In Section 3 we discuss the general idea of accounting for the spurious energy loss in viscous parameterizations by including an explicit representation of energy backscatter from the sub-grid scale. Two implementations, one stochastic and one deterministic, are proposed. Results of idealized simulations using these implementations are discussed in