

NOTES AND CORRESPONDENCE

A Conjecture on the Role of Bottom-Enhanced Diapycnal Mixing in the Parameterization of Geostrophic Eddies

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ABSTRACT

The parameterization of geostrophic eddies represents a large sink of energy in most ocean models, yet the ultimate fate of this eddy energy in the ocean remains unclear. The authors conjecture that a significant fraction of the eddy energy may be transferred to internal lee waves and oscillations over rough bottom topography, leading to bottom-enhanced diapycnal mixing. A range of circumstantial evidence in support of this conjecture is presented and discussed. The authors further propose a modification to the Gent and McWilliams eddy parameterization to account for the bottom-enhanced diapycnal mixing.

1. Introduction

The prevailing paradigm of baroclinic instability in the oceans, as articulated by Gent et al. (1995), is that geostrophic eddies adiabatically extract available potential energy from the mean state. This process is captured in the Gent and McWilliams (1990, hereafter GM) eddy parameterization through an eddy-induced transport velocity that adiabatically flattens isopycnals. When included in ocean general circulation models in place of horizontal diffusion, GM leads to an impressive list of model improvements including a sharper and more realistic pycnocline and removal of spurious overturning cells in the Southern Ocean (Danabasoglu et al. 1994). Most of these improvements can be attributed to the removal of horizontal diffusion across sloping isopycnals, thereby allowing the effective rate of diapycnal mixing in such models to be reduced from a magnitude of 10^{-4} to 10^{-5} $\text{m}^2 \text{s}^{-1}$, consistent with inferences from microstructure measurements (e.g.,

Gregg 1987) and tracer-release experiments (Ledwell et al. 1998) in the midlatitude pycnocline. However, these successes are, to some extent, countered by the assumption implicit in GM that eddy energy is dissipated adiabatically in the ocean.

In this note, we present an alternative conjecture on the fate of the energy extracted from the mean state by the baroclinic eddies. Motivated by recent observations in the Southern Ocean, we suggest that this energy may, in part, contribute toward substantial bottom-enhanced diapycnal mixing over regions of rough bottom topography. If confirmed, then this conjecture suggests that while an adiabatic eddy closure may be appropriate over much of the fluid column, enhanced diapycnal mixing may be required for energetic consistency in the deepest layers.

2. Energetics of baroclinic instability

The GM parameterization extracts available potential energy from the mean state at a rate

$$\begin{aligned} \frac{\partial P}{\partial t} &= \iiint \rho g w^* dx dy dz \\ &= - \iiint \rho \kappa_{\text{GM}} N^2 S^2 dx dy dz \end{aligned} \quad (1)$$

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(Gent et al. 1995). Here P is the available potential energy of the mean state, ρ is density, g is the gravitational acceleration, w^* is the vertical component of the eddy-induced transport velocity, κ_{GM} is the GM eddy transfer coefficient, N is the buoyancy frequency, and S is the slope of the isopycnals. Huang and Wang (2003) estimate this energy release to be roughly 1.3 TW, based on $k_{GM} = 10^3 \text{ m}^2 \text{ s}^{-1}$ and climatological observations of the density field. Wunsch and Ferrari (2004) suggest alternative values of 0.2 and 0.8 TW using the modified closures of Visbeck et al. (1997) and Danabasoglu and McWilliams (1995), respectively, with significant uncertainties attached to each. These values are dominated by contributions over the Antarctic Circumpolar Current (ACC) and are broadly consistent with estimates of the input of energy from the Southern Ocean winds (Wunsch 1998), as one would expect in dynamical equilibrium. Thus the transfer of energy from the mean state to the eddies constitutes a large contribution to the global energy budget of the oceans.

However, the fate of the energy taken up by the baroclinic eddies is less clear. Tandon and Garrett (1996) remark that the GM parameterization requires an implicit assumption of purely viscous dissipation of the released available potential energy, which they suggest is unlikely. Instead, they propose that the eddy energy may be dissipated in the ocean interior through internal wave breaking. This suggestion, in turn, requires an energy transfer from the baroclinic eddies to the internal wave field. This energy transfer may occur through interactions between the eddies and a preexisting internal wave field (Polzin 2008, manuscript submitted to *J. Phys. Oceanogr.*), although noninteraction theorems suggest such exchanges are very weak (Dewar and Killworth 1995) except in finite-aspect ratio, hydrostatic regimes (W. K. Dewar 2007, personal communication). Alternatively this energy transfer may occur through loss of balance. A recent series of papers (McWilliams et al. 1998, 2001; McWilliams and Yavneh 1998; Molemaker et al. 2000, 2005; Yavneh et al. 2001) has started to shed some light on the classes of instabilities that can transfer energy from balanced to unbalanced motions, although the magnitude of the resultant energy fluxes remains, as yet, undetermined.

If one assumes that all of the available potential energy released by baroclinic instability is dissipated locally by breaking internal waves, then the associated diapycnal mixing rate is

$$\kappa_v = R_f S^2 \kappa_{GM}, \quad (2)$$

where R_f is the flux Richardson number (Tandon and Garrett 1996). As noted by these authors, this implies a

diapycnal mixing rate in the ACC of $\kappa_v \sim 10^{-3} \text{ m}^2 \text{ s}^{-1}$. Such values may be plausible in the deepest layers (e.g., Watson and Naveira Garabato 2006) but not higher in the fluid column (Naveira Garabato et al. 2004). Moreover, scaled up to the global ocean, this implies a global-mean diapycnal mixing rate of $\kappa_v \sim 10^{-4} \text{ m}^2 \text{ s}^{-1}$, which paradoxically is precisely the level of diapycnal mixing the GM parameterization is intended to avoid and is inconsistent with inferences from microstructure and tracer-release experiments as discussed in section 1.

3. The role of bottom topography and barotropization

We propose that the resolution to this paradox may lie in the theory of geostrophic turbulence. In Fig. 1, we outline the dominant energy transfers associated with baroclinic instability in a theoretical two-layer quasi-geostrophic context (based on Salmon 1998). Large-scale baroclinic energy is cascaded downscale toward the Rossby radius of deformation, where baroclinic eddies are formed and energy is transferred on average to the barotropic mode. Once in the barotropic mode, energy undergoes an inverse cascade as the eddies grow in size and barotropicity. This inverse cascade is arrested meridionally at the Rhines scale (Rhines 1975), resulting in the generation of banded zonal jets. In the presence of variable bottom topography, energy can alternatively accumulate in recirculation gyres around closed topographic contours (Bretherton and Haidvogel 1976; see also the discussion of Adcock and Marshall 2000). This is so because, crucially, the systematic conversion of energy from the baroclinic to the barotropic modes that is implicit in the baroclinic instability process exposes the flow to the direct influence of bottom topography. As illustrated by Treguier and Hua (1988), the flow's response to this influence may exhibit a complex dependence on the nature of the forcing and the dimensions of the topography. Particularly notable among their findings is the character of wind-forced geostrophic turbulence over deformation-scale topographic roughness, which displays a direct energy cascade in the barotropic mode that short-circuits the recycling of energy toward large scales in a flat-bottomed ocean.

The relevance of geostrophic turbulence theory to ocean circulation is suggested by altimetric observations (Scott and Wang 2005). These reveal a ubiquitous source of eddy kinetic energy near the Rossby radius of deformation, consistent with the theoretical description of baroclinic instability. Eddy kinetic energy is observed to cascade predominantly upscale, as predicted by geostrophic theory for the barotropic mode (Salmon

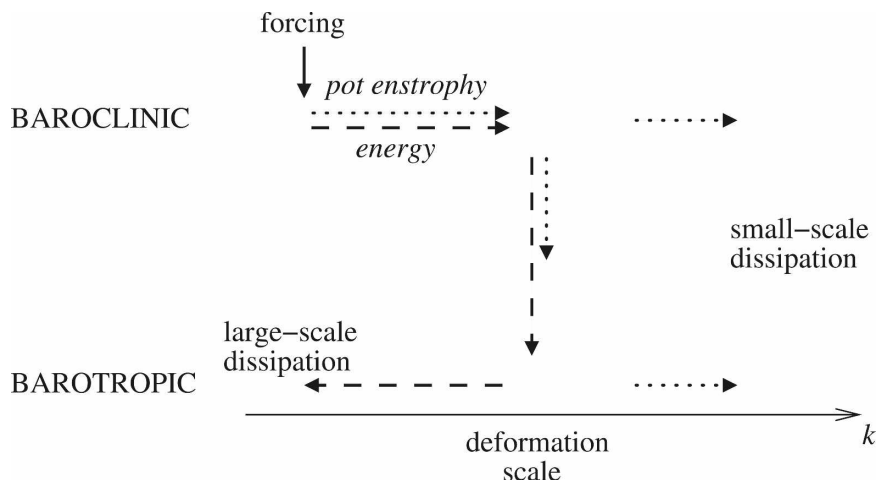


FIG. 1. A schematic diagram, adapted from Salmon (1998), showing the dominant transfer of energy (dashed) and potential enstrophy (dotted) in the ocean as a function of lateral wavenumber k . The upper level corresponds to the baroclinic modes and the lower level to the barotropic mode.

1998). More recently, Scott and Arbic (2007) indicate through numerical calculations that while baroclinic potential and total energy cascade downscale, the baroclinic kinetic energy also cascades upscale and indeed dominates the inverse kinetic energy cascade at the ocean surface; moreover they show that this result is consistent with a bottom energy sink. Further, Scott and Wang’s observation that the direct energy cascade toward wavelengths smaller than the Rossby radius is roughly 20% of the inverse energy cascade toward wavelengths larger than the Rossby radius suggests that the bottom boundary, rather than interior processes, is the dominant energy sink for the eddy field.

The wavelength at which the observed inverse cascade is arrested shows a broad correspondence with the Rhines scale over much of the oceanic domain considered by Scott and Wang (2005), again consistent with geostrophic turbulence theory. The one striking exception where the inverse cascade of eddy kinetic energy appears to be arrested at wavelengths well below the theoretical prediction is in the ACC. The explanation for this observation may relate to the barotropization that accompanies the inverse cascade being more fully developed in the ACC than elsewhere, owing to the energy source length scale (the Rossby radius) and the theoretical arrest length scale (the Rhines scale) being particularly distant. In this context, the barotropization process might directly cause a reduction on the magnitude of the altimetric signal that could be interpreted as an apparent arrest of the energy cascade. Nonetheless, an advanced barotropization stage would also foster eddy–topography interaction that, in the presence of a bottom dissipative mechanism, would result in a genu-

ine arrest of the cascade at a length scale shorter than the Rhines scale. The existence of such a dissipative mechanism is proposed by Gille et al. (2000), who interpret the global anticorrelation of mesoscale ocean variability in altimetric measurements with sea floor roughness as evidence of eddy kinetic energy dissipation over rough topography. A similar suggestion is put forward by Arbic and Flierl (2004) in the context of a numerical simulation of baroclinically unstable geostrophic turbulence with variable bottom friction. Their key finding reveals that a moderate bottom friction is required for the modeled geostrophic turbulence to reproduce the observed amplitude, vertical structure, and horizontal scales of midlatitude midocean eddies, as measured with a variety of moored current meter arrays.¹

What, then, might the near-bottom dissipative mechanism be? The obvious candidate is drag in bottom boundary layers, but this may not represent the only significant eddy energy sink. One may also speculate whether topographic form drag, which is key to the momentum budget of ocean circulation in general and the ACC in particular (Hughes and de Cuevas 2001), plays an important role in the energy balance of the oceanic mesoscale; however, this possibility can be

¹ As noted by a reviewer, the arrest of the inverse energy cascade below the Rhines scale in the ACC may also be related to the equatorward energy cascade described by Theiss (2004). However, it is unclear how this suggestion relates to the observation of zonal jets at fairly high latitudes in observations (Maximenko et al. 2005) and models (Richards et al. 2006).

readily discarded since there is no normal flow through the boundary for the pressure gradient force to work on (MacCready et al. 2003). A third candidate is the generation of internal oscillations and lee waves over small-scale topographic roughness, which numerical experiments suggest to be an efficient mechanism for transferring energy from the mesoscale flow to easily dissipated small-scale motions (Chapman and Haidvogel 1993; Aguilar and Sutherland 2006). In the following, we review a growing body of circumstantial evidence suggesting that turbulent kinetic energy dissipation is enhanced by the breaking of internal lee waves generated by subinertial flows as they interact with small-scale topography. We conjecture, based on this evidence, that the *near-bottom* internal wave field may be a major player in dissipating the energy of oceanic eddies.

The most remarkable illustration of this process may be found in a region of high baroclinic eddy activity, the ACC. As recently shown by Naveira Garabato et al. (2004), Sloyan (2005), and Kunze et al. (2006), following in the footsteps of Polzin and Firing (1997), observations of density and velocity fine structure reveal that intense turbulent diapycnal mixing and energy dissipation are common throughout areas of rough bottom topography within the ACC. The magnitude and vertical distribution of turbulent kinetic energy dissipation in those areas are suggestive of a subinertial energy source for the enhanced turbulence, indicating that the high rates of mixing and dissipation are likely associated with the internal lee-wave mechanism. Here we propose, based on the above theoretical arguments, that baroclinic instability is the most plausible process through which energy is transferred to the barotropic mode to fuel the observed vigorous turbulent diapycnal mixing and energy dissipation. This suggestion is further supported by the spreading of a natural tracer in the southwest Atlantic sector of the ACC, which reveals that turbulent energy dissipated by breaking internal waves is a significant fraction of the available potential energy released by the eddy-induced circulation in the same region (Naveira Garabato et al. 2007).

Although the extraordinarily intense wind work on subinertial motions, high levels of mesoscale eddy variability, and the extreme difference between the Rossby radius and the Rhines scale that characterize the ACC arguably provide the optimal conditions for internal lee-wave generation, there is no reason to believe that this eddy damping mechanism is exclusive to the ACC. On the contrary, an enhancement of internal wave energy levels, turbulent kinetic energy dissipation, and diapycnal mixing has been observed in other regions of vigorous baroclinic instability, most notably in sepa-

rated western boundary currents. An excellent illustration of this is provided by the study of the circulation in the Japan/East Sea by Shcherbina et al. (2003), who demonstrate that turbulent kinetic energy dissipation and upward-propagating internal wave energy are enhanced at sites where the mesoscale circulation interacts with prominent small-scale topographic features, as would be expected from the generation of internal lee waves by the subinertial flow. A comparable intensification of turbulent kinetic energy dissipation is reported by Walter et al. (2005) in association with low-frequency flow features in the North Atlantic, such as the western boundary current off the Flemish Cap and a prominent midbasin eddy. Similarly, K. L. Polzin and J. M. Toole (2007, personal communication) observe an enhancement of turbulent dissipation and mixing levels on the shoreward flank of the Gulf Stream near Cape Hatteras, although they propose an alternative topographic damping mechanism by which baroclinic instability over a corrugated boundary produces high-vertical-wavenumber subinertial fluctuations that are prone to shear instability.

4. Implications for diapycnal mixing

Thus there is a wide range of evidence consistent with our conjecture that a significant fraction of the energy in the geostrophic eddy field is dissipated through the generation and subsequent breaking of internal oscillations and lee waves over small-scale topographic roughness. If correct, then this conjecture has profound implications for the parameterization of geostrophic eddies in ocean models since the breaking internal oscillations and lee waves will result in bottom-enhanced diapycnal mixing. This conclusion is consistent with observations of both low levels of diapycnal mixing in the ocean pycnocline (e.g., Gregg 1987; Ledwell et al. 1998) and intense bottom-enhanced diapycnal mixing in energetic eddy fields over rough topography (e.g., Polzin and Firing 1997; Naveira Garabato et al. 2004). In contrast, bottom drag, which may represent a larger energy sink, provides weak viscous heating but is unlikely to contribute significant diapycnal mixing.

We therefore propose that the GM eddy parameterization and its variants (e.g., Visbeck et al. 1997) may need to be modified, as sketched schematically in Fig. 2. In the modified GM, tracers are still advected by an eddy-induced transport velocity and diffused along isopycnals. However, over the deepest layers (roughly the lowest kilometer) and in the presence of rough bottom topography, we suggest that enhanced diapycnal mixing should be introduced to parameterize the effect

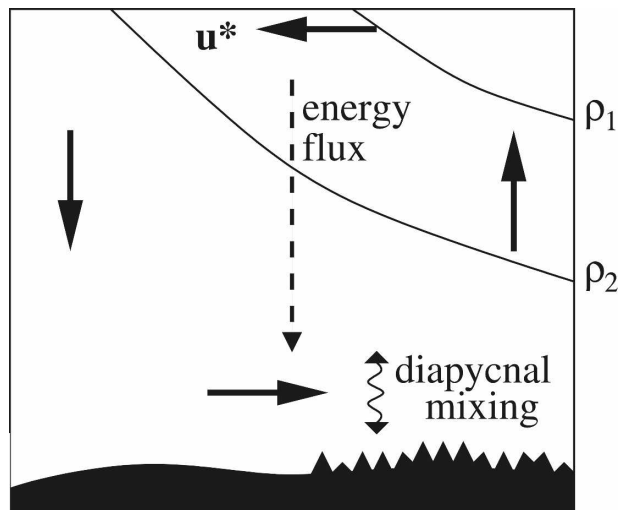


FIG. 2. A schematic diagram of the proposed modification to the GM eddy parameterization scheme. The flux of energy from the baroclinic modes to the barotropic mode in baroclinic instability continually exposes the eddy energy to the influence of the bottom topography. We propose that a significant fraction of this eddy energy is dissipated through the generation of internal waves and oscillations in the presence of topographic roughness, resulting in bottom-enhanced diapycnal mixing.

of the breaking internal oscillations and lee waves generated by the subinertial flow.

How can one determine the bottom-enhanced diapycnal mixing rate? The ultimate goal should be to develop an explicit parameterization for the geostrophic eddy energy, including all pertinent sources and sinks, and this could be used to solve for the diapycnal mixing rate. In the meantime, we can estimate an upper bound for the bottom-enhanced diapycnal mixing by assuming that all of the energy released to the eddies through baroclinic instability is through this process. Following the approach of Tandon and Garrett (1996), but now assuming that dissipation occurs within the bottom fraction δ of the fluid column, the upper bound for the diapycnal mixing rate is given as

$$\kappa_v \leq \frac{\langle R_f S^2 \kappa_{GM} \rangle}{\delta}, \tag{3}$$

where the angle brackets denote an average over the fluid column. Over the ACC, this implies an upper bound for the bottom-enhanced diapycnal mixing rate of roughly $\kappa_v \leq 5 \times 10^{-3} \text{ m}^2 \text{ s}^{-1}$, where we have taken $\kappa_{GM} \sim 10^3 \text{ m s}^{-1}$ and $\delta \sim 0.2$. This value is somewhat larger than observed (e.g., Watson and Naveira Garabato 2006), but clearly demonstrates that baroclinic instability is a viable energy source for the enhanced diapycnal mixing present in abyssal layers of the ACC. In practice, other mechanisms such as bottom drag are

also liable to contribute to dissipation of the eddy energy.

5. Concluding remarks

A large sink of energy in many contemporary ocean circulation models is the parameterization of geostrophic eddies. We have put forward the conjecture that a significant fraction of this energy may be transferred to the internal wave field over rough bottom topography, leading to bottom-enhanced diapycnal mixing. Furthermore, we have proposed a generic modification to the GM eddy parameterization to account for this bottom-enhanced diapycnal mixing.

While the modified GM eddy parameterization is intended for non-eddy-resolving ocean models, it is worth cautioning that a similar scheme will be required in eddy-permitting models. Roberts and Marshall (1998) have shown that the direct cascade of vorticity to high wavenumbers can lead to large, spurious diapycnal mixing, even with a highly scale-selective biharmonic diffusion of temperature and salinity (or indeed because of diffusion implicit in the numerical advection scheme; Griffies et al. 2000). Thus, even with a well-resolved geostrophic eddy field, it is necessary to ensure that eddies are dissipated adiabatically in the ocean interior. Moreover, irrespective of these complexities, it will always be necessary to parameterize the interactions between the (partially) resolved eddies and unresolved topographic roughness, and the resultant diapycnal mixing.

While we have presented a range of evidence consistent with our conjecture, the fate of the eddy energy in the ocean remains somewhat obscure. We suggest that the resolution of this issue calls for, on the one hand, targeted in situ observations of the energy budget of an energetic eddy field, resolving the contributions of bottom drag, internal lee-wave generation, and loss of balance and eddy-internal wave interaction to the budget, and, on the other hand, a series of high-resolution numerical calculations of baroclinic instability over rough and steep bottom topography. While the latter may be beyond the capabilities of current ocean models, new methods are currently under development exploiting dynamically adaptive, unstructured meshing (Pain et al. 2005) that should enable such calculations to be performed in the near future.

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