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# Impact of parameterized lee wave drag on the energy budget of an eddying global ocean model

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ABSTRACT

The impact of parameterized topographic internal lee wave drag on the input and output terms in the total mechanical energy budget of a hybrid coordinate high-resolution global ocean general circulation model forced by winds and air-sea buoyancy fluxes is examined here. Wave drag, which parameterizes the generation of internal lee waves arising from geostrophic flow impinging upon rough topography, is included in the prognostic model, ensuring that abyssal currents and stratification in the model are affected by the wave drag.

An inline mechanical (kinetic plus gravitational potential) energy budget including four dissipative terms (parameterized topographic internal lee wave drag, quadratic bottom boundary layer drag, vertical eddy viscosity, and horizontal eddy viscosity) demonstrates that wave drag dissipates less energy in the model than a diagnostic (offline) estimate would suggest, due to reductions in both the abyssal currents and stratification. The equator experiences the largest reduction in energy dissipation associated with wave drag in inline versus offline estimates. Quadratic bottom drag is the energy sink most affected globally by the presence of wave drag in the model; other energy sinks are substantially affected locally, but not in their global integrals. It is suggested that wave drag cannot be mimicked by artificially increasing the quadratic bottom drag because the energy dissipation rates associated with bottom drag are not spatially correlated with those associated with wave drag where the latter are small. Additionally, in contrast to bottom drag, wave drag is a non-local energy sink.

All four aforementioned dissipative terms contribute substantially to the total energy dissipation rate of about one terawatt. The partial time derivative of potential energy (non-zero since the isopycnal depths have a long adjustment time), the surface advective fluxes of potential energy, the rate of change of potential energy due to diffusive mass fluxes, and the conversion between internal energy and potential energy also play a non-negligible role in the total mechanical energy budget. Reasons for the <10% total mechanical energy budget imbalance are discussed.

## 1. Introduction

In this paper, we investigate the impact of parameterized topographic internal lee wave drag on the input and output terms in the total mechanical energy budget of a high-resolution ("eddying") global ocean model. We are motivated by the potentially important role of topographic internal lee wave drag in mixing the abyssal ocean. In recent years, there has been great interest in the ocean energy budget, largely because the mixing associated with energy dissipation is thought to exert an important control on the large-scale circulation. Munk and Wunsch (1998) and St. Laurent and Simmons (2006) have suggested that about 2–3 TW of mixing energy is required to raise diffusivity enough to maintain the abyssal stratification in the presence of the 30 Sverdrups ($Sv = 10^6\ \mathrm{m}^3\ \mathrm{s}^{-1}$) of deep water formation. However, Webb and Suginohara (2001) have suggested that maintaining 9 Sv of Ekman suction in the Southern Ocean while vertically mixing 17 Sv of North Atlantic Deep Water would reduce the required energy dissipation rate in the abyssal ocean to as little as 0.6 TW.

Recently, intense research interest has focused on the sources and sinks of mixing energy in the ocean. Almost all of the 60–68

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terrawatts (TW) of wind power put into the surface waves is dissipated near the surface (Wang and Huang, 2004; Ferrari and Wunsch, 2010) and most of this wind power input is thought to enhance vertical shear of the mean currents (Large et al., 1994) and vertical mixing (Wang et al., 2010; Shu et al., 2011; Qiao and Huang, 2012) in the upper ocean. About 0.4 TW of wind power is put into near-inertial motions in the mixed layer (Watanabe and Hibiya, 1239; Alford, 2003; Furuichi et al., 2008). Early estimates (Wunsch, 1998; Scott and Xu, 2009) of the wind power put into the ocean general circulation, which includes low-frequency currents and mesoscale eddies, were found to be about 0.9 TW. However, Zhai et al. (2012) suggest that only about 0.5 TW of wind power is put into the general circulation because higher frequency wind variability generates shear, mixing, and near-inertial waves in the surface layer rather than deep ocean mixing.

The energy sinks of the low-frequency eddying oceanic general circulation are just beginning to be estimated on a global scale. Topographic internal lee wave drag is a potentially critical component of the mechanical energy budget. Naveira-Garabato et al. (2004), Marshall and Naveira-Garabato (2008), and Nikurashin (2008) suggested that energy is transferred to internal lee waves when geostrophic flow impinges upon rough topographic features and is eventually dissipated, especially in the Southern Ocean where geostrophic flows are strong and the bottom is rough. This energy dissipation mechanism, which is the main focus of the present study, will be referred to simply as “wave drag” hereafter.

Other postulated energy dissipation mechanisms for the eddying general circulation include quadratic bottom boundary layer drag (hereafter, “bottom drag”; *Sen et al.*, 2008; *Arbic et al.*, 2009; and references therein); energy scattering into high-wavenumber vertical modes (Zhai et al., 2010; Saenko et al., 2012); and catalyzed energy exchanges via inviscid balanced flow-boundary interaction (Dewar and Hogg, 2010; Dewar et al., 2011). In ocean models, energy is also dissipated by the vertical eddy viscosity (Large et al., 1994) and horizontal eddy viscosity (Smagorinsky, 1993) that must be employed to make up for the lack of resolved small-scale processes. Vertical eddy viscosity (“vertical viscosity” hereafter) represents processes associated with vertical shear instabilities. Horizontal eddy viscosity (“horizontal viscosity” hereafter) is meant to represent processes that can remove vorticity and momentum at the boundaries of ocean basins (Fox-Kemper and Pedlosky, 2004). Arguably, horizontal viscosity also very roughly represents small-scale processes – for instance, energy transfer from mesoscale eddies to either internal waves (Polzin, 2008) or submesoscale eddies (Müller et al., 2005) – which are not explicitly resolved by any existing numerical global ocean model.

Here, we quantify the relative amounts of energy dissipation of low-frequency flow in an eddying ocean model due to bottom drag, wave drag, horizontal viscosity, and vertical viscosity. Previous estimates suggest that bottom drag and wave drag both contribute substantially to the energy budget of low-frequency flows. For example, Sen et al. (2008)[1], Wright et al. (2012),[2] and Arbic et al. (2009)[3] have argued that bottom drag dissipates at least 0.2 TW of low-frequency mechanical energy. Arbic and Flierl (2004) and Wright et al. (2013) further argued that some of the energy dissipation that is typically attributed to bottom drag in both models and observations should actually be attributed to wave drag. Nikurashin and Ferrari (2011) estimated the rate of energy dissipation by breaking lee waves to be about 0.2 TW by assuming that this rate is a fraction of the energy conversion rate into internal lee waves. In contrast, Scott et al. (2011) estimated the rate of energy conversion into internal lee waves to be about 0.34–0.49 TW. Both the Nikurashin and Ferrari (2011) and Scott et al. (2011) estimates are based on bottom stratification fields taken from observations in concert with bottom flows in global ocean models which did not utilize wave drag.

A key contribution of the present manuscript is the prognostic calculation of wave drag and an evaluation of the alterations in kinetic energy, stratification, and sources and sinks of the total mechanical energy budget due to wave drag implementation. Our insertion of wave drag into a global ocean general circulation model is motivated, in part, by demonstrations (e.g., Jayne and St. Laurent, 2001), that the energy budget and accuracy of global forward tide models are impacted to first order by wave drag. Jayne and St. Laurent (2001) found that roughness sufficient to generate internal lee waves occurs quite commonly in the open ocean. Because bottom drag only depends on the bottom velocities and not the roughness, a model simulation that includes a wave drag parameterization should have more dissipation in open ocean regions than a model simulation that only includes a bottom drag parameterization. In addition, there is ample evidence from both observations (Polzin et al., 1997; Naveira-Garabato et al., 2004; St. Laurent et al., 2012) and very high-resolution numerical ocean process models that include bottom drag and wave drag (Nikurashin et al., 2013) that turbulent mixing is enhanced when low-frequency flows encounter rough topography.

While global ocean general circulation models tend to be deficient in bottom kinetic energy relative to current mooring observations (Scott et al., 2011), the correlation between vertical profiles of kinetic energy in ocean models versus observations may be a more important statistic to improve. This is because each ocean model grid point represents an average over a large area, thus tending to smooth the kinetic energy at each model grid point relative to the points at which current meter measurements are taken. Ocean models' simulated kinetic energy increases with finer model resolutions (Thoppil et al., 2011). Therefore, in ocean model simulations without wave drag, bottom kinetic energy may be closer to that of current mooring observations than ocean model simulations with wave drag for the wrong reasons (i.e., inadequate resolution in combination with a lack of abyssal drag such as wave drag). It will be left to a future manuscript to discuss whether the correlation between the kinetic energy profiles in ocean models versus current meter observations is improved with the addition of wave drag.

In this paper, we analyze the global total mechanical energy budget of the total (mean plus eddy) flow, using global nominally 1/12° simulations of the HYbrid Coordinate Ocean Model (HYCOM; http://www.hycom.org; Bleck, 2002; Chassignet et al., 2003; Halliwell, 2004) with and without wave drag. We will not analyze the following: (1) the eddy kinetic energy budget, as was done by Treguier (1992) using a $1/3^\circ \times 2/5^\circ$ ocean model of the North Atlantic; (2) the generation and conversion rates between gravitational potential energy and kinetic energy, as was done by Oort et al. (1994) using observations; (3) the mean kinetic energy and gravitational potential energy, as was done by Aiki et al. (2011) using a 1/10° global ocean model; (4) the Lorenz oceanic energy cycle, as was done by von Storch et al. (2012) using a 1/10° global ocean model; or (5) the kinetic plus available potential energy budget, as was done by Hogg et al. (2013) using an idealized 1/4° ocean model that mimicked the Atlantic Ocean. The conversion of kinetic energy to potential energy involves work done by several processes, some of which include horizontal pressure gradients, vertical velocities that result from the convergence or divergence of both the barotropic and baroclinic components of the horizontal velocities, and Reynolds stresses that are mediated by eddy kinetic

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[1] They made use of the Deep Water Archive and Buoy Group Archive. (http://cmdac.oce.orst.edu/cds.html or http://cmrecords.net)

[2] They made use of the more extensive Global Multi-Archive Current Meter Database (http://stockage.univ-brest.fr/scott/GMACMD/updates.html).

[3] They utilized multiple eddying ocean models.