Revelations about parameterizing lee waves in ocean models

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Abstract

Internal lee waves are generated when geostrophic flow impinges upon rough topography. Lee wave formation, radiation, and breaking are thought to contribute substantially to the oceanic momentum, vorticity, and energy budgets in the ocean. Because the relevant horizontal length scales of lee waves are generally smaller than the grid spacing of even state-of-the-art present-day ocean general circulation models, the effects of lee waves need to be parameterized in ocean models. However, ocean models are currently lacking such a parameterization. Here, the impacts of inserting a momentum sink associated with lee wave generation and topographic blocking into a high-resolution ocean simulation as it runs are assessed. Given the large uncertainty in estimates of energy conversion into lee waves and the unlikelihood of directly observing the global energy generation and dissipation rates, it is critical to compare predictions from lee wave closures with the sparse observations we have. The sensitivity of existing lee wave closures to environmental parameters is assessed and a comparison of their predictions with microstructure observations is performed in two regions of the Southern Ocean where geostrophic flows dominate over tides.

Motivation

- Mixing is enhanced in regions with rough topography (*Polzin et al.*, 1997; *St. Laurent et al.*, 2012)
- Models have been improved with wave drag parameterizations (*Palmer et al.*, 1986; *Jayne and St. Laurent*, 2001)
- Lee wave breaking mostly occurs in the Southern Ocean (*Nikurashin and Ferrari*, 2011; *Wright et al.*, 2014)
- Lee waves may significantly impact the water mass transformation (*Nikurashin and Ferrari*, 2013) and the overturning circulation (*Melet et al.*, 2014)
- Large range of estimates for global energy conversion rate into lee waves: 0.2-0.75 TW (*Nikurashin and Ferrari*, 2011; *Scott et al.*, 2011; *Wright et al.*, 2014)
- Predicted lee wave energy conversion rate is an order of magnitude larger than observed dissipation rate (*Waterman et al.*, 2013; *Sheen et al.*, 2013)

Lee wave closures

Features of *Garner* (2005):
- calculates an energy dissipation rate from physical space
- based on scaling arguments modifying linear theory after invoking the non-rotating ($f^2 \ll (\vec{u}\cdot\vec{k})^2$) approximation
- topographic blocking built into the scheme ($O(Fr^{-1})$ at smaller Fr, $O(Fr^{-2})$ at larger Fr)

Features of *Bell* (1975):
- calculates an energy conversion rate from wavenumber space
- based on linear theory
- needs a correction factor to account for blocking ($O(Fr^2)$)

Both *Garner* (2005) and *Bell* (1975):
- depend on stratification, velocity, and underlying topography
- invoke hydrostatic ($(\vec{u}\cdot\vec{k})^2 \ll N^2$) approximation
- assume that water column is semi-infinite in extent

Three configurations of underlying topography:
- Anisotropy, Isotropy - use parameters from *Goff and Arbic* (2010) and *Goff* (2010)
- Approximated Isotropy - use parameters from *Nikurashin and Ferrari* (2011)

Observational data:
- Southern Ocean Finestructure (SOFine) - over 50 CTD, ADCP, and microstructure profiles
- Diapycnal and Isopycnal Mixing Experiment in the Southern Ocean (DIMES) - less than 10 extra CTD, ADCP, and microstructure profiles

Model

Our results come from using the HYbrid Coordinate Ocean Model (HYCOM) and two lee wave closures: *Bell* (1975; *"B75"* hereafter) and *Garner* (2005; *"G05"* hereafter)

We use HYCOM with:
- 32 hybrid layers
- $1/12^o$, $1/25^o$ resolutions
- **Air-sea fluxes** - monthly mean ECMWF Re-Analysis (ERA-40; *Kallberg et al.*, 2004)
- **Winds** - monthly mean ERA-40 supplemented with 6-hourly 2003 fields of the Navy Operational Global Atmospheric Prediction System (NOGAPS; *Rosmond et al.*, 2002)
- **Horizontal viscosity** - ($\sim 10^2 - 10^3$ m^2 s^{-1}) includes the maximum of a Laplacian and a *Smagorinsky* (1993) parameterization with an additional biharmonic term
- **Vertical viscosity** - ($\sim 10^{-4} - 10^{-3}$ m^2 s^{-1}) multiply the vertical diffusivities from KPP (*Large et al.*, 1994) by a Prandtl number
- **Bottom drag** - quadratic in the momentum equations with coefficient, $C_d = 0.0025$ (*Taylor*, 1919; ...; *Arbic et al.*, 2009)
- **Wave drag** - *Garner* (2005) scheme is used with parameters from *Goff and Arbic* (2010) and *Goff* (2010) where there are abyssal hills

Full closure predictions are comparable with observations in bottom 500 meters

Averages are over 61 station locations where the energy dissipation rate from the microstructure observations integrated over the bottom 500 meters is 9.7×10^{-4} ($\pm 3.0 \times 10^{-4}$) W m^{-2}

Prediction	Percent difference with Obs (95% conf. int. of diff. with Obs)
B75 approx iso V N	1030% (3.5×10^{-4}, 1.3×10^{-2})
B75 iso V N	-65% (-1.9×10^{-3}, -7.2×10^{-5})
B75 aniso V N	16% (-7.7×10^{-3}, 3.4×10^{-2})
G05 aniso V N $Z = H_{rms}$	480% (8.9×10^{-4}, 3.2×10^{-2})
G05 aniso V N $Z = H_{ref}$	9.7% (-9.0×10^{-4}, 4.4×10^{-3})

Wave drag's impact on vertical structure of kinetic energy

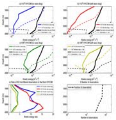

Figure 1: The kinetic energies (units in m^2 s^{-2} and put into 500 meter depth bins) geometrically averaged in the horizontal from the current meter database (averaged over the entire length of the time series) shown alongside those from the output of the various model simulations (averaged over the final year of the model simulations). Also shown are (e) the ratios of the average kinetic energies of the low-pass filtered observations to the output of the various model simulations and (f) the number of current meter observations as a function of depth. With the insertion of wave drag, the kinetic energy is reduced in the abyss and in a three-dimensional global integral, but slightly increased near the surface. The vertical structure of the kinetic energy is in better agreement with the observations when wave drag is included.

Wave drag's impact on sea surface statistics

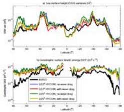

Figure 2: The zonal average of the (a) sea surface height (SSH) variance (units in m^2) and the (b) geostrophic surface kinetic energy (SKE) (units in m^2 s^{-2}) from the AVISO product (averaged over 1992-2008) and the output of the various model simulations (averaged over the final year of each model simulation). Both the SSH variance and geostrophic SKE are reduced on global average upon insertion of wave drag by more than twice the seasonal variability in these diagnostics, bringing them into slightly better agreement with the AVISO product. However, deficiencies in the gridded AVISO product make it difficult to determine whether the model is improved upon insertion of wave drag.

Assumption of momentum flux deposition all in bottom 500 meters is suspect

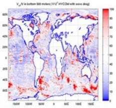

Figure 3: Shown is the ratio (given as a percent) of the effective velocity, V_{eff} =(total dissipation rate)/(horizontal momentum stress), to the velocity averaged over the bottom 500 meters, V, from the final year of the $1/12^o$ HYCOM simulation with wave drag. In blue regions, our assumption that the momentum flux occurs only in the bottom 500 meters results in too much wave drag so this figure suggests that one way to improve the wave drag parameterization is to allow the vertical deposition of lee wave momentum flux to be spatially heterogeneous.

Closure predictions are in worse agreement with Obs away from the seafloor

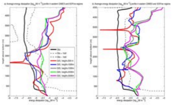

Figure 4: Shown are the horizontally averaged profiles of the energy dissipation rates inferred from the microstructure observations and the *G05* scheme over the western (panel a) and eastern (panel b) DIMES and SOFine station locations as a function of height above the deepest microstructure measurement ("bottom") for different assumed levels of vanishing drag. The vertical profile of dissipation predicted by the *G05* scheme tends to closely match the observed dissipation profile in the abyss, but not closer to the surface. Further, this depends upon the assumed level of vanishing drag. The lack of agreement closer to the surface is due in part to simplifications made by the *G05* scheme that are inappropriate for the oceanic context.

Conclusions

- Lee wave drag profoundly impacts abyssal kinetic energy, reduces barotropic kinetic energy, and slightly increases surface kinetic energy
- Lee wave drag applied in bottom 500 meters affects sea surface statistics very little
- Average abyssal closure predictions within factor of two of each other, keeping all factors consistent
- Average abyssal closure predictions match observations more closely if anisotropy in underlying topography is accounted for
- Cannot validate lee wave closures for problems associated with inadequate observational information (e.g., non-local effects, imperfect knowledge of underlying topography, and sampling issues)
- Problems with depositing momentum flux higher up in the water column due to oversimplifications in oceanic context (i.e., no wave-wave interactions, no rotation, and an infinite fluid column depth)

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