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Impact of synthetic abyssal hill roughness on resolved motions in numerical global ocean tide models

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ABSTRACT

Global models of seafloor topography have incomplete and inconsistent resolution at horizontal wavelengths less than about 10–20 km, notably due to their inability to resolve abyssal hills in areas unsurveyed by ships (that is, about 90% of the global seafloor). We investigated the impact of this unresolved bottom roughness on global numerical simulations of the HYbrid Coordinate Ocean Model (HYCOM) that are forced exclusively by the M2 and K1 internal tides. Simulations were run with horizontal resolutions of 0.08° and 0.04°, 10 isopycnal layers in the vertical direction, and two versions of bathymetry: one derived from the SRTM30_PLUS global bathymetry model, and one merging SRTM30_PLUS with a synthetic fractal surface simulating the expected roughness of abyssal hills in the 2–10 km horizontal wavelength band. Power spectra of the two bathymetry versions diverge at wavenumbers of order 4^*10^{-4} radians/m and higher (wavelengths of order 15 km and lower), with more pronounced differences evident on the 0.04° grid, as the 0.08° grid has a more limited ability to capture bathymetric details at the abyssal hill scale. Our simulations show an increase in the amount of kinetic and potential energy in higher vertical modes, especially in the 0.04° simulation, when the synthetic roughness is added. Adding abyssal hills to the 0.04° simulation increases the M_2 kinetic energy for modes 3 and 4 by 12–18% and the potential energy by 5 – 15%. Adding abyssal hills to the 0.08° simulation yields a reduced, though still measurable, impact on simulated baroclinic tidal energies. Baroclinic tidal energy conversion rates increase by up to 16% in regions of high roughness, and by up to 3.4% in the global integral. The 3.4% increase in global conversion rates in the numerical simulations is less than the 10% increase computed from a linear analysis on a 0.008° grid because of the resolution limitations of the numerical simulations. The results obtained in the present study, though limited by the horizontal and vertical resolutions of the simulations, are consistent with those of previous studies indicating that abyssal hills on the seafloor transfer energy into higher vertical mode internal tides. The method employed here to add synthetic roughness could easily be replicated in other models, with higher resolution and/or more complex forcing.

1. Introduction

This paper proposes a method to account for unresolved small-scale seafloor roughness in ocean models. Seafloor roughness impacts oceanic flows in a variety of ways. To name one example, barotropic tidal flows over rough topography generate baroclinic tides which ultimately break, resulting in turbulence and mixing (Munk and Wunsch, 1998; Egbert and Ray, 2000, 2001, 2003). One of the limiting factors in ocean models, especially global ocean models, is the availability of high-resolution bathymetry data. For a regional model of limited geographic area, survey data of sufficiently high resolution may exist already or may even in some cases be captured in a new survey. However, on a global scale, at 1 minute resolution only 10% of the ocean floor has been mapped acoustically (Wessel and Chandler, 2011) and most of the regions mapped are coastal (Charette and Smith, 2010). At

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present, global bathymetric datasets such as the GEBCO_08 Grid (http://www.gebco.net) and SRTM30_PLUS (Becker et al., 2009; Sandwell and Smith, 2009) are available at resolutions of 30 arc seconds. However, many of the ocean depth values represented in global bathymetric datasets are estimated from satellite altimetry data, which is less accurate than acoustic soundings (Becker et al., 2009; Smith and Sandwell, 1994, 1997, 2004; Sandwell and Smith, 2009). Altimetry-based datasets are able to resolve features with horizontal wavelengths of order 10–20 km or larger, but they are not able to accurately map the structure of abyssal hills, which have characteristic length scales of 2 – 10 km, and which cover a large fraction of the seafloor, though not all of it (Goff and Jordan, 1988). Abyssal hill roughness is important because it generates substantial amounts of energy in high vertical mode internal gravity waves, which are more conducive to breaking and mixing than low-mode waves.

To account for the abyssal hill roughness missing in global bathymetry datasets, Goff and Arbic (2010) produced a synthetic global map of seafloor roughness based upon sediment thickness, seafloor spreading rates and ridge orientation. The Goff and Arbic (2010) map is based on a band-limited fractal model, whose parameters are taken from empirically-derived relationships with spreading rates and sediment thickness. Goff (2010) produced a map of one characteristic of seafloor roughness—the root-mean-square height—based upon satellite altimeter measurements. As discussed in Section 2 the Goff and Arbic (2010) and Goff (2010) synthetic roughness maps (or equivalent spectral representations) have been used in several studies that employ either a linear analytical model, or a parameterization inserted into a numerical model, to estimate energy conversion rates into internal tides or internal lee waves. None of the previous studies that have used the roughness maps feature numerically resolved internal gravity waves that are directly generated by the added roughness. In this paper, we examine the impacts of synthetic abyssal hill roughness on the resolved motions in global internal tide models.

For simplicity, the tide models employed in the present study are forced only by the astronomical tides; they are not simultaneously forced by atmospheric fields. We use global models because they enable us to examine the influence of abyssal hill roughness in different ocean basins, and because we are interested in the impact of abyssal hills on the global energy flux into internal tides, the latter being a topic of great ongoing interest in the community. The horizontal resolutions used in the simulations presented here are at the level of the state-of-the-art used in present high-resolution ocean models (e.g., Hecht and Hasumi, 2008). We employ a representative realization of the synthetic abyssal hill roughness map of Goff and Arbic (2010), averaged to the same 30 arc second grid used in SRTM30_PLUS. The realization is added to the SRTM30_PLUS bathymetry and then interpolated onto global ocean model grids of resolutions 1/12.5° and 1/25° We also interpolate the SRTM30_PLUS bathymetric data without the additional seafloor roughness onto the same 1/12.5° and 1/25° grids. By comparing outputs between model simulations performed with and without the added roughness we are able to estimate the influence that such additional structure has on the generation of internal tides in a global ocean model. We will show that the addition of synthetic abyssal hill roughness increases the barotropic to baroclinic tidal energy conversion rates and the energies in high vertical modes, without significantly impacting the area-averaged accuracy of the barotropic and low-mode baroclinic tides with respect to altimetric constraints. Although the focus of this paper is on global models forced only by tides, the methods we use to add synthetic roughness could easily be employed in higher-resolution regional models, and in models with more complex forcing.

In order to place the current study in context, in Section 2 we present a brief overview of previous studies of global internal tides, and a brief overview of previous uses of the Goff and Arbic (2010) and Goff (2010) abyssal hill roughness fields. In Section 3 we describe the global model configuration and initial conditions, and we provide a detailed description of our procedures for merging the synthetic abyssal hill map with an existing global bathymetry dataset. In Section 4, the overall accuracy of the large-scale barotropic tides and low-mode baroclinic tides in our solution is quantified through computation of the root mean square error of the modeled sea surface heights with respect to highly accurate satellite-altimetry constrained tide models, and through comparison of the internal tide signatures of sea surface heights in our simulations with along-track altimeter data. We also compare the barotropic kinetic energies of our simulations to those in a satellite-altimetry constrained model. In Section 5 we discuss the impacts of the synthetic abyssal hill roughness on the barotropic-to-baroclinic tidal conversion rates, and on the vertical mode structure of the baroclinic tidal energies. The synthetic roughness increases the barotropic to baroclinic tidal energy conversion in a manner that is approximately consistent with the linear analysis results of Melet et al. (2013), but that is limited by the resolution of the numerical simulations. Our results are also compared to the closely related results of Niwa and Hibiya (2011, 2014), who computed the increase in baroclinic tidal energy conversion in models as a function of the model resolution. As in the Niwa and Hibiya papers, we find that model resolution is a critical parameter in global internal tide models. The abyssal hill structure is an additional effect, on top of resolution considerations, that is demonstrated here.

2. Background

The conversion of large-scale geostrophic and tidal flows into internal gravity waves is a topic of great recent interest because the mixing that takes place when internal gravity waves break is thought to exert a strong control on the large-scale stratification and overturning circulation of the ocean (e.g., Munk and Wunsch, 1998). The impacts of internal tide mixing, and the dynamics of internal tide generation and propagation, have been examined in a number of recent studies. Exarchou et al. (2012) examined the sensitivity of tidal mixing schemes, and the impact on the general circulation in numerical simulations, to topographic roughness on scales of 15–200 km. The propagation of internal tides away from their generation sites at seafloor ridges has been observed with acoustic tomography (Dushaw et al., 1995) and satellite altimetry (Kantha and Tierney, 1997; Ray and Mitchum, 1996). Egbert and Ray (2000, 2001, 2003) estimated global tidal energy dissipation from altimetry data and concluded that the barotropic tides lose more energy in the deep ocean than can be accounted for by quadratic bottom boundary layer drag in shelf regions. One of the two classes of bottom topography found to be associated with the energy conversion of barotropic to baroclinic tides in the open ocean was small-scale roughness associated with mid-ocean ridges (Egbert and Ray, 2001). Garrett and Kunze (2007) provide a review of developments in the theory of internal tide generation in the deep ocean. The generation of internal tides by barotropic tidal flow over topography has been examined with linear analysis (e.g., Llewellyn Smith and Young, 2002; St. Laurent et al., 2003; Nycander 2005; Falahat et al., 2014), numerical regional ocean models (e.g., Cummins and Oey, 1997; Carter et al., 2012), and numerical global internal tide models (e.g., Arbic et al., 2004; Simmons et al., 2004; Niwa and Hibiya, 2011, 2014). Global internal tide modeling has only begun in the last decade, because internal tides have relatively small horizontal scales (∼100 km) and therefore can only be modeled in simulations with high horizontal resolution, which are expensive to perform on a global scale.