Ocean Modelling 85 (2015) 42–55

Contents lists available at ScienceDirect

Ocean Modelling

journal homepage: www.elsevier.com/locate/ocemod

Optimizing internal wave drag in a forward barotropic model with semidiurnal tides

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ARTICLE INFO

Article history:
Received 28 April 2014
Received in revised form 31 August 2014
Accepted 5 November 2014
Available online 22 November 2014

Keywords:
Barotropic tides
Global modeling
Linear wave drag

ABSTRACT

A global tuning experiment for the semidiurnal tide is performed with a barotropic model. The model is forced with the M_2 equilibrium tide and accounts for the self-attraction and loading (SAL) term. In addition to a quadratic drag, various linear internal wave drag terms adjusted by a scale factor of $\mathcal{O}(1)$ are applied. The drag terms include the original Nycander (2005) tensor scheme, the Nycander tensor scheme reduced at supercritical slopes, and their scalar sisters, a Nycander scalar scheme computed for additional abyssal hill roughness, and the Jayne and St. Laurent (2001) scalar scheme. The Nycander scheme does not have a tunable parameter, but to obtain the best tidal solutions, it is demonstrated that some tuning is unavoidable. It is shown that the scalar Nycander schemes yield slightly lower root-mean square (RMS) elevation errors vs. the data-assimilative TPXO tide model than the tensor schemes. Although the simulation with the optimally tuned original Nycander scalar yields dissipation rates close to TPXO, the RMS error is among the highest. The RMS error is lowered for the reduced schemes, which place relatively more dissipation in deeper water. The inclusion of abyssal hill roughness improves the regional agreement with TPXO dissipation rates, without changing the RMS errors. It is difficult to have each ocean basin optimally tuned with the application of a constant scale factor. The relatively high RMS error in the Atlantic Ocean is reduced with a spatially varying scale factor with a larger value in the Atlantic. Our best global mean RMS error of 4.4 cm for areas deeper than 1000 m and equatorward of 66° is among the lowest obtained in a forward barotropic tide model.

1. Introduction

The tidal motion of the world's oceans is powered by about 3.5 TW of energy input (Egbert and Ray, 2003). Initially it was believed that nearly all of this energy is dissipated through bottom friction in shallow coastal shelf seas where the barotropic tide velocities are large (Taylor, 1919). Hence, in early regional barotropic tide models, the tidal energy was dissipated with linearized or quadratic bottom drag that mostly operated in coastal oceans (Schwiderski, 1980; Le Provost et al., 1994). Often, the drag coefficients were tuned to improve the agreement with elevation observations.

Munk (1966) and Munk and Wunsch (1998) suggested, and indirectly showed, that there could be significant barotropic tidal dissipation in the abyssal ocean. Egbert and Ray (2000) inferred surface tide dissipation rates from an inverse barotropic tide model with assimilated satellite altimetry, and found that about a third of this barotropic tide dissipation occurs in the deep ocean, invalidating the early assumption that all tidal energy was dissipated in shallow water. Egbert and Ray (2000) associated the deep water dissipation with the energy transfer from the barotropic to the baroclinic tide at rough topography as suggested by Munk and Wunsch (1998). Linear theory for the generation of internal waves also predicts substantial barotropic tide dissipation in the deep ocean through the generation of internal tides (e.g. Nycander, 2005).

The energy conversion from the barotropic to the baroclinic tide at rough topography can be represented through the implementation of a linear wave drag (Stigebrandt, 1999). Jayne and St. Laurent (2001) applied a linear wave drag scheme in the momentum equation of a forward global barotropic tide model. This reduced the

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http://dx.doi.org/10.1016/j.ocemod.2014.11.003
1463-5003/

root-mean-square elevation error with observations from 16.4 to 10.1 cm, when 8 tidal constituents were used. Moreover, the barotropic dissipation rates predicted with their linear wave drag scheme are in agreement with rates derived from TPXO – an inverse tidal solution based on altimetry (Egbert et al., 1994). Similarly, Egbert et al. (2004), Arbic et al. (2004) and Green and Nycander (2013), who applied forward barotropic tide models, and Lyard et al. (2006), who applied a data-assimilative barotropic tide model, also found that tidal elevations and energetics improved when internal wave drag schemes, with and without tunable parameters, were applied.

Some schemes, e.g. by Jayne and St. Laurent (2001) and Zaron and Egbert (2006), are based on a linear scaling relationship and rely on a tunable parameter. Other drag schemes, e.g. by Egbert et al. (2004), Garner (2005) and Nycander (2005), are derived from linear theory similar to Bell (1975) and do not have a tunable parameter. Green and Nycander (2013) show that without tuning, the Nycander parameterization in a barotropic model predicts global dissipation rates close to TPXO7.2 rates. However, the use of schemes without a tunable parameter does not guarantee an optimal prediction of elevations and dissipation rates. For example, the dissipation rates and elevation root-mean-square errors may differ depending on the global bathymetry and stratification databases used. Another motivation for tuning is that the bathymetric databases do not resolve all abyssal features. Melet et al. (2013) demonstrated that the regional and global dissipation rates analytically computed with the Nycander scheme are increased due to the inclusion of abyssal hill roughness on ocean spreading ridges (Goff and Arbic, 2010). Moreover, a higher resolution bathymetric grid increases the linear wave drag strength (Nycander, 2005; Zilberman et al., 2009), implying the need for some tuning. Although the linear theory of these parameterizations is applicable from the acoustic limit (small excursion lengths) to quasi-steady flow (large excursion lengths) (Bell, 1975; Nycander, 2005), the theory breaks down on supercritical slopes, i.e. when the slope is steeper than the internal tide beam. Hence, these schemes overestimate the conversion at supercritical topography (Nycander, 2005). When a correction is applied at supercritical topography (Nikurashin and Ferrari, 2011; Scott et al., 2011) the overall drag is reduced (Melet et al., 2013), further justifying the application of a tunable parameter.

The schemes derived from linear theory by Bell (1975) are second order tensors, whereas the schemes based on a scaling relationship are scalars. The components of the tensor are functions of the directionality of the topographic roughness. As a consequence, dissipation strength is governed by the direction of the flow relative to the rough topography. In scalar schemes the dissipation is independent of the flow direction. According to Egbert et al. (2004), the scalar and tensor schemes they tested produced similar deep-water dissipation rates and patterns after tuning. This suggests that the directionality of the tensor scheme may not provide substantial additional benefit compared to the scalar schemes. This is relevant, because it is easier to implement a scalar than a tensor scheme in 3D models that have both tidal and atmospheric forcing (Arbic et al., 2010).

In this study we utilize the Nycander (2005) and Jayne and St. Laurent (2001) schemes, and their modifications, in global barotropic HYCOM forced with only the M_2 tide. The M_2 tide is the largest tidal constituent, comprising about 70% (2.4 TW) of the tidal energy input of 3.5 TW (Egbert and Ray, 2003). In comparison, the largest diurnal constituent, K_1, contributes only 10% to the total input. We test the effects of the correction at supercritical slopes and the enhanced roughness due to abyssal hill topography on the wave drag strength. The effects of the additional roughness due to abyssal hill topography have been studied in a linear analytical model by Melet et al. (2013) and a numerical three-dimensional model by Timko et al. (2009) but never in a barotropic tide model. We perform a tuning experiment for each drag scheme to check if the lowest root-mean square (RMS) elevation errors versus the altimetry-constrained TPXO8-atlas and 151 pelagic tide gauges (Ray, 2013) coincide with the most optimal global, basin-wide, and regional dissipation rates based on the TPXO4, TPXO6.2, TPXO7.2, and TPXO8-atlas inverse models. Although Green and Nycander (2013) compared the performance of the Jayne and St. Laurent (2001) and Nycander, 2005 schemes in a barotropic model, they did not explore whether their RMS elevation errors and dissipation rates could be improved by applying a scale factor. A better understanding of the performance of these internal wave drag schemes in tidal models is relevant for climate models that use similar parameterizations to represent the breaking of internal tides (Simmons et al., 2004b), which provide most of the vertical turbulent mixing in the deep ocean.

In the next section we discuss the model configuration, the linear wave drag schemes, and the model diagnostics. In the results section the model's elevation root-mean-square errors and dissipation rates are evaluated globally, per basin, and regionally. We finish in Section 4 with discussion and conclusions.

2. Methodology

2.1. Ocean model configuration

HYCOM is a community ocean model (http://hycom.org) that uses a generalized (hybrid isopycnal/terrain-following/z-level) vertical coordinate (Bleck, 2002). However, here we configure it for one layer and for tide forcing only. The generic one-layer shallow water momentum equation with tidal forcing and the continuity equation read

$$\frac{\partial \mathbf{u}}{\partial t}+\mathbf{u}\cdot\nabla\mathbf{u}+f\mathbf{k}\times\mathbf{u}=-g\nabla(\eta-\eta_{EQ}-\eta_{SAL})-\frac{C_D|\mathbf{u}|\mathbf{u}}{H}-\chi\frac{\mathbb{C}\cdot\mathbf{u}}{H}-\mathcal{F} \quad (1)$$

and

$$\frac{\partial \eta}{\partial t}=-\nabla\cdot([H+\eta]\mathbf{u}), \quad (2)$$

where t is time, $\mathbf{u}$ is the horizontal velocity vector, η is the tidal elevation, g is the gravitational acceleration, f is the Coriolis parameter, $\mathbf{k}$ is the vertical unit vector, H is the resting water depth, C_D is the quadratic bottom drag coefficient, $\mathbb{C}$ is a scalar or second-order tensor to represent the drag due to internal tide generation, χ a scale factor, $\mathcal{F}$ is the friction due to the eddy viscosity, and η_{EQ} and η_{SAL} respectively refer to the equilibrium tidal forcing and self attraction and loading term. The quadratic drag coefficient is 0.0025 in deep water and a function of depth in shallow water only when $C_D=[\kappa/\log(0.5H/z_0)]^2>0.0025$ (Schlichting, 1968), with the von Karman coefficient $\kappa=0.4$ and the bottom roughness $z_0=10$ mm.

The model spans the entire globe north of 86°S, with a Mercator grid from 66°S to 47°N, at a resolution of $0.08^\circ\cos(latitude)$ by 0.08° (latitude by longitude) and a bipolar Arctic patch north of 47°N, i.e. the model uses a tripole grid (Murray, 1996). The meridional (latitudinal) grid resolution is held constant south of 66°S for computational efficiency. The average zonal (longitudinal) resolution varies from 9 km at the equator to 7 km at mid-latitudes (e.g. at 40°N) and 3.5 km at the north pole. The bottom topography was constructed from the GEBCO_08 topographic database, version 20091120 (http://www.gebco.net), which has a resolution of 30 arc seconds. However, in the deep ocean the effective resolution is much coarser, and abyssal hills on ocean spreading ridges are not resolved (Goff and Arbic, 2010). The model's land-sea boundary is at the 0-m isobath but depths shallower than 5 m are set to 5 m. Numerous hand-edits have been performed to improve coastlines and sill depths in key straits and passages. In order to model the