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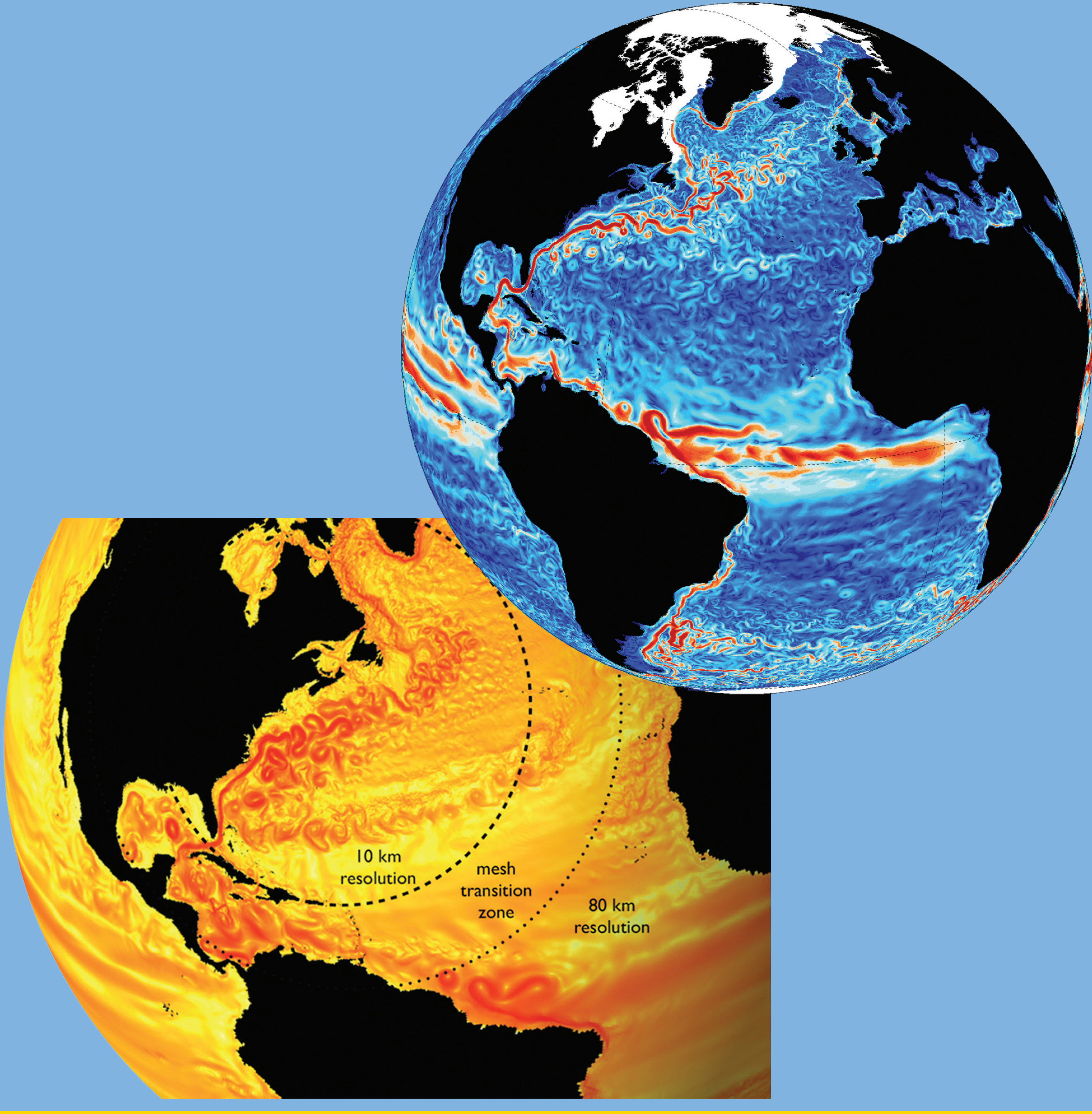

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Inserting tides and topographic wave drag into high-resolution eddying simulations

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1. Introduction

We report here on two of our recent development efforts for global high-resolution ocean models, undertaken in the HYbrid Coordinate Ocean Model (HYCOM; Chassignet et al., 2009). The simulations discussed here are "eddying" (Hecht and Hasumi, 2008), meaning that they include an energetic mesoscale eddy field. In one of our efforts (Arbic et al., 2010, 2012; Timko et al. 2012, 2013; Shriver et al. 2012, 2014; Richman et al., 2012), we have inserted tides into global eddying simulations. Tidal flows in a high-resolution global model with realistic rough topography generate internal tides-internal waves of tidal frequency. Similarly, geostrophic flows over rough topography generate internal lee waves (Bell, 1975). It is not yet possible to resolve internal lee waves in global models, but the impact of internal lee waves can be parameterised. In the other effort reported here, we have inserted parameterised topographic lee wave drag into global eddying simulations that do not include tides, with a preliminary focus on the resulting model energy budget (Trossman et al., 2013).

Global simulations of the tides and the atmospherically forced eddying general circulation have long been done separately. Global general circulation models began to resolve mesoscale eddies in the 1990's (e.g., McClean et al., 1997). Since then eddying models have become increasingly realistic (e.g., Hecht and Hasumi, 2008). Global modelling of internal waves is a newer endeavour. In the first global simulations of internal tides (Arbic et al., 2004; Simmons et al., 2004), only tidal forcing was employed, and the stratification was taken to be horizontally uniform. The insertion of tides into atmospherically forced general circulation models allows for internal tide propagation in a realistic horizontally varying stratification, for interactions between internal tides and eddies, and for the co-existence of tides and near-inertial waves, another important class of internal waves (e.g., Simmons and Alford, 2012). In global high-resolution models with simultaneous atmospheric and tidal forcing, the internal wave spectrum is beginning to be resolved, just as mesoscale eddies began to be resolved in global models two decades ago. Our simulations with simultaneous tidal and atmospheric forcing are being used to address a variety of scientific and operational questions.

The global energy budget has been a topic of great recent interest, largely because the mixing occurring when energy is dissipated may exert a strong control on the oceanic meridional overturning circulation (Munk and Wunsch, 1998). The mechanisms underlying the dissipation of the eddying oceanic general circulation are still under investigation. Candidate dissipation mechanisms include the transfer of energy from geostrophic flows to submesoscale motions in the upper ocean (e.g., Capet et al., 2008), bottom boundary layer drag (Sen et al., 2008; Arbic et al., 2009), and breaking of internal lee waves generated by geostrophic flows over rough topography (e.g., Naveira-Garabato et al., 2004). Nikurashin and Ferrari (2011) and Scott et al. (2011) estimated the globally integrated energy flux of geostrophic flows into internal lee waves over rough topography, and found it to be a substantial fraction of the ~1 TW of energy put by the wind into geostrophic flows (e.g., Wunsch, 1998, and others). Both the Nikurashin and Ferrari (2011) and Scott et al. (2011) estimates were "offline"; they utilised bottom flows from eddying simulations that did not employ topographic wave drag as they ran. In Trossman et al. (2013) we inserted inline topographic lee wave drag into eddying HYCOM simulations, thus ensuring feedbacks between the model bottom stratification and flow fields and the topographic internal lee wave drag.

The HYCOM simulations shown here are forced by output from the Navy Operational Global Atmospheric Prediction System (NOGAPS); going forward the simulations will be forced by the Navy Global Environmental Model (NAVGEM). The simulations shown here are run on a combination Mercator and tripolar grid with an equatorial grid resolution of 0.08° (8.9 km) and are coupled to a sea ice model at high latitudes. Global HYCOM simulations at 0.04° (4.5 km) have also been performed, but are not discussed here (see article by Chassignet et al. 2014, this issue). The model reproduces the general circulation of the global ocean, the strength and variability of the western boundary currents, such as the Gulf Stream and Kuroshio, and the mesoscale eddies generated by instabilities of the major currents (Thoppil et al., 2011).

2. Insertion of tides into eddying simulations

In our HYCOM simulations forced by both atmospheric fields and tides (Arbic et al., 2010, 2012), we include the four largest semidiurnal tidal constituents (M2, S2, N2, and K2) and the four largest diurnal tidal constituents (K1, O1, P1, and Q1). We use the parameterised topographic internal wave drag scheme of Garner (2005), modified to limit the maximum decay rates to (9 hours)$^{-1}$. The wave drag parameterisation represents the drag resulting from the generation and subsequent breaking of unresolved small-vertical scale internal waves by tidal flow over rough topography. Because the wave drags acting on tidal versus non-tidal motions have different strengths (Bell, 1975), tidal and non-tidal bottom flows are separated using a 25-hour running boxcar filter. Presently, the scalar approximation (Ray, 1998) is used for the self-attraction and loading term (Hendershott, 1972).

Barotropic tidal sea surface elevations in HYCOM have been compared to measurements made from tide gauges (Shum et al., 1997) and state-of-the-art data-assimilative barotropic tide models (Egbert et al., 1994). In Shriver et al. (2012) we also compared the modelled internal tide perturbation to sea surface height (SSH) - computed from a spatial high-pass of the total amplitude of tidal SSH - to internal tide perturbations computed from along-track satellite altimeter data (Ray and Byrne, 2010). Figure 1 shows global maps of the M2 internal tide amplitude in HYCOM versus along-track altimeter data. The hotspots around locations such as Hawai'i, the Aleutian Islands, the Tuamotu Archipelago in the tropical central South Pacific, and Madagascar match up reasonably well in the two maps. Furthermore, the root-mean-square (rms) perturbation magnitudes over the five hotspot regions delineated by boxes in the bottom panel of Figure 1 agree with the altimeter rms values to within about 20%. Comparisons of tidal currents, and their vertical structure, in HYCOM versus historical moored observations were made in Timko et al. (2012; 2013).

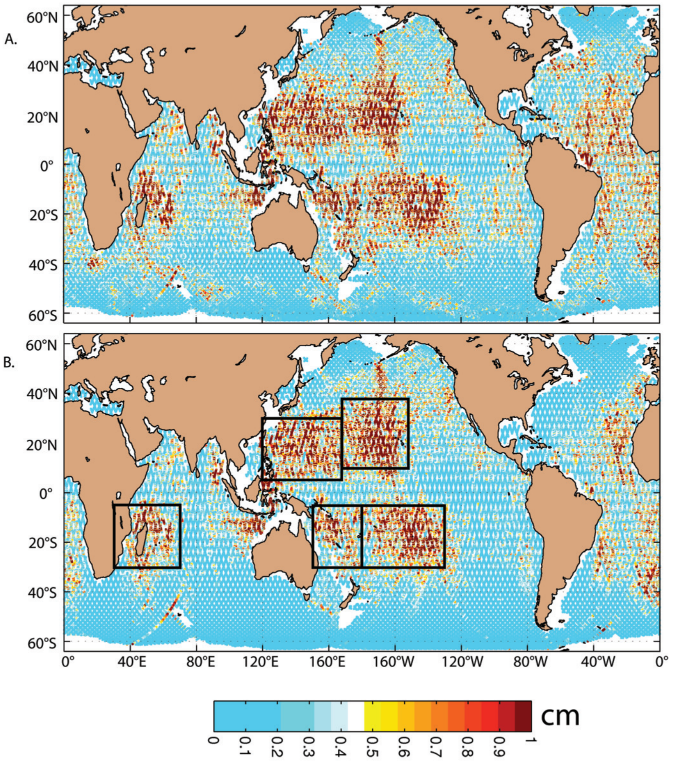

Figure 1. The internal tide amplitude of the principal lunar semidiurnal constituent M2 from the (a) altimetric-based and (b) HYCOM tidal analyses. The five subregions denoted by black boxes in (b) are used to compute area-averaged amplitudes in Shriver et al. (2012). From Shriver et al. (2012).

We have used the HYCOM tidal simulations to distinguish between tidal and non-tidal contributions to the wavenumber spectrum of SSH (Richman et al., 2012). The slope of the wavenumber spectrum is of great theoretical interest, as it contains clues about the dominant dynamics of low-frequency flows (e.g., LeTraon et al., 2008; Xu and Fu, 2011). Because of the 10-day repeat track time, current state-of-the-art TOPEX/JASON satellite altimeters alias tides into longer periods (Parke et al., 1987). In contrast, because our model output is written at hourly intervals, we can easily separate low- from high-frequency signals in HYCOM. In regions such as the Kuroshio, where low-frequency motions are more energetic than tidal motions, the wavenumber spectrum of SSH is dominated by low-frequency motions. However, in regions where internal tides are energetic, for instance near Hawai'i, high-frequency motions dominate the high-wavenumber end of the wavenumber spectrum. The results of Richman et al. (2012) imply that internal tides will have to be accurately removed from data taken by the planned high-resolution wide-swath satellite altimeter (Fu et al., 2012) before low-frequency oceanic motions can be investigated. The accuracy with which internal tides can be removed from altimeter signals depends on the degree of non-stationarity of the internal tides. Internal tide non-stationarity in HYCOM is investigated in Shriver et al. (2014).

3. Insertion of topographic wave drag into eddying simulations

In Trossman et al. (2013) we again use the topographic wave drag parameterisation of Garner (2005), this time applied to low-frequency motions. The Trossman et al. (2013) simulations did not include tides. For simplicity, we refer to the Garner (2005) scheme here as a "wave drag" scheme even though it includes effects of topographic blocking, which yields low-level turbulence, as well as lee wave production and breaking. Maps of energy dissipation by quadratic bottom drag and by the parameterised topographic lee wave drag, both averaged over one year, are shown in Figure 2. As in the "offline" estimates of Nikurashin and Ferrari (2011) and Scott et al. (2011), as well as the offline estimates done in Trossman et al. (2013), the inline estimates shown in the bottom panel of Figure 2 indicate substantial lee wave drag dissipation in the Southern Ocean. The globally integrated internal lee wave drag dissipation in the inline Trossman et al. (2013) estimates is 0.4 TW, comparable to that seen in the offline estimates of Nikurashin and Ferrari (2011), Scott et al. (2011), and Trossman et al. (2013). However, as anticipated, there is indeed a strong feedback between the internal lee wave drag and the model flows. Adding wave drag to HYCOM substantially changes the modelled near-bottom eddy kinetic energy and stratification fields (Trossman et al., 2013).

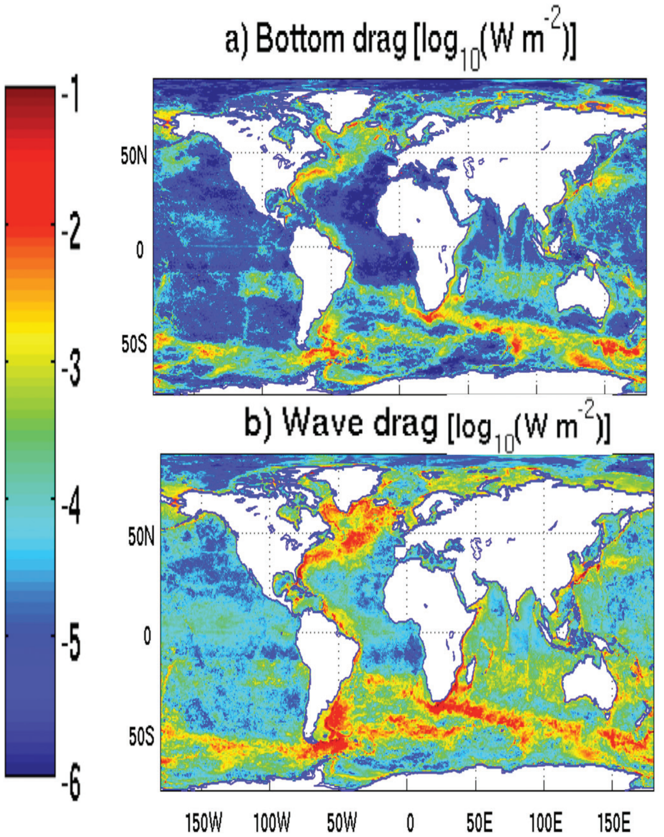

Figure 2. Log10 of the bottom and wave drag terms in the energy budget of 1/12 eddying HYCOM simulation with , where each drag term has units [W m-2]: (a) quadratic bottom boundary layer drag and (c) parameterised internal lee wave drag. Adapted from Trossman et al. (2013).

4. Ongoing and planned work

In ongoing and planned work with the HYCOM tide simulations, we are comparing the SSH frequency spectra in HYCOM versus tide gauges, as a measure of the accuracy of the partition of modelled low- versus high-frequency energy (Savage et al., paper in revision). We are estimating tidal aliasing errors in altimetrically-derived low-frequency wavenumber spectra and spectral fluxes (Savage et al., paper in preparation). We are also comparing the kinetic energy frequency spectra in HYCOM versus moored current meter records (Müller et al., paper in preparation). We are comparing both low- and high-frequency temperature variances (which are related to available potential energies) to temperature variances in moored historical records (Luecke et al. and Bassette et al., respective papers in preparation). To further elucidate the energetics of internal tides, we are preparing global maps of the baroclinic tidal energy fluxes and barotropic-to-baroclinic tidal energy conversions (Ansong et al. and Buijsman et al., papers in preparation). The latter work is part of the National Science Foundation-funded Climate Process Team project "Collaborative Research: Representing internal-wave driven mixing in global ocean models", which focuses on improving estimates of internal-wave mediated mixing in the ocean, and is led by Professor Jennifer MacKinnon of the Scripps Institution of Oceanography. Finally, our long-term goals for the HYCOM tides work include improvement of tidal accuracy through the inclusion of data assimilation and better estimates of the self-attraction and loading term, and usage of the global HYCOM tidal solution to force regional and coastal models at their open-water boundaries.

In ongoing and planned work on parameterised topographic lee wave drag, we will investigate whether the inclusion of wave drag into eddying models improves the comparison of the models with observations. We will also compare the dissipation predictions of the Garner (2005) and Bell (1975) schemes with dissipation inferred from microstructure observations. Finally, we will investigate the impact of a more complete parameterisation of the vertical deposition of internal lee wave drag on the energetics and abyssal circulation in eddying models. These projects are all led by co-author Trossman (papers in preparation).

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