Recent progress in global (and regional) hydrodynamical internal tide and gravity wave modeling

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SWOT Science Team Meeting

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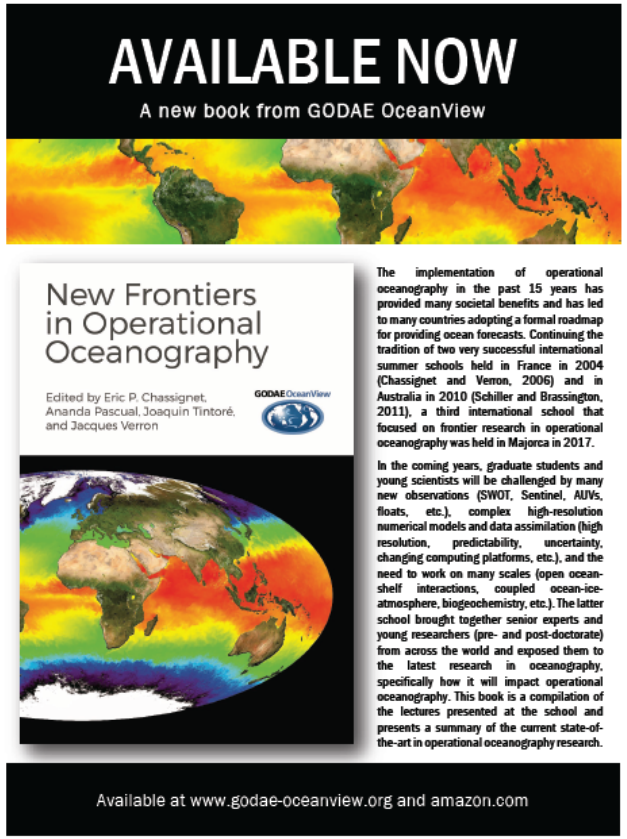
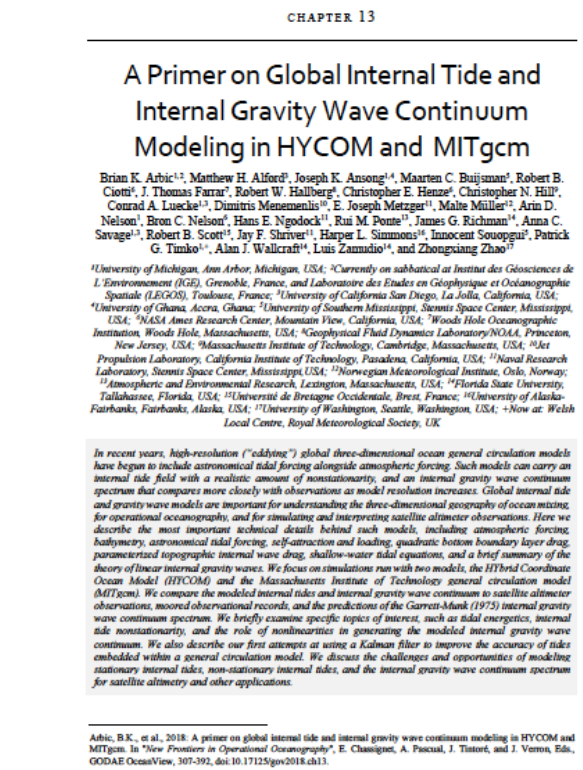
Thanks to a very long list of collaborators, and to DOE for additional funding.





CHAPTER 13

A Primer on Global Internal Tide and Internal Gravity Wave Continuum Modeling in HYCOM and MITgcm

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In recent years, high-resolution ("eddying") global three-dimensional ocean general circulation models have begun to include astronomical tidal forcing alongside atmospheric forcing. Such models can carry an internal tide field with a realistic amount of nonstationarity, and an internal gravity wave continuum spectrum that compares more closely with observations as model resolution increases. Global internal tide and gravity wave models are important for understanding the three-dimensional geography of ocean mixing, for operational oceanography, and for simulating and interpreting satellite altimeter observations. Here we describe the most important technical details behind such models, including atmospheric forcing, bathymetry, astronomical tidal forcing, self-attraction and loading, quadratic bottom boundary layer drag, parameterized topographic internal wave drag, shallow-water tidal equations, and a brief summary of the theory of linear internal gravity waves. We focus on simulations run with two models, the HYbrid Coordinate Ocean Model (HYCOM) and the Massachusetts Institute of Technology general circulation model (MITgcm). We compare the modeled internal tides and internal gravity wave continuum to satellite altimeter observations, moored observational records, and the predictions of the Garrett-Munk (1975) internal gravity wave continuum spectrum. We briefly examine specific topics of interest, such as tidal energetics, internal tide nonstationarity, and the role of nonlinearities in generating the modeled internal gravity wave continuum. We also describe our first attempts at using a Kalman filter to improve the accuracy of tides embedded within a general circulation model. We discuss the challenges and opportunities of modeling stationary internal tides, non-stationary internal tides, and the internal gravity wave continuum spectrum for satellite altimetry and other applications.

Arbic, B.K., et al., 2018. A primer on global internal tide and internal gravity wave continuum modeling in HYCOM and MITgcm. In *"New Frontiers in Operational Oceanography"*, E. Chassignet, A. Pascual, J. Tintoré, and J. Verron, Eds., GODAE OceanView, 307-392, doi:10.17125/gov2018.ch13.

Arbic et al. (2018) book chapter

Arbic 2022 in-press review article

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Incorporating tides and internal gravity waves within global ocean general circulation models: A review

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ABSTRACT

Until recently, high-resolution global modeling of tides has been done separately from high-resolution global modeling of the atmospherically-forced oceanic general circulation. Here we review the emerging class of high-resolution global models that are simultaneously forced by both atmospheric fields and the astronomical tidal potential. Such models simulate barotropic (surface) tides, internal tides, near-inertial motions, the eddying general oceanic circulation, and a partially resolved internal gravity wave (IGW) continuum spectrum (Garrett-Munk spectrum) simultaneously. We review the technical aspects of such global models and their myriad applications, for example, in satellite oceanography, operational oceanography, boundary forcing of regional models, tidal-cryosphere interactions, and assessment of future coastal flooding hazards in a changing climate with altered tides.

1. Introduction

Tides have fascinated humankind for thousands of years (Cartwright, 1999). Accurate analysis and prediction of tides in ports and harbors has been practiced since the 1800s. The advent of the TOPEX/JASON satellite altimetry series (Fu & Cazenave, 2001; Stammer & Cazenave, 2017; International Altimetry Team, 2021) revolutionized physical oceanography by allowing for highly accurate global maps of surface tidal elevations (e.g., Le Provost, 2001; Egbert & Ray, 2017; Ray & Egbert, 2017) and other oceanic motions. The TOPEX/JASON tidal maps build upon work demonstrating the feasibility of tidal mapping with the earlier Seasat and Geosat altimeters (e.g., Cartwright, 1983; Mazegga, 1985; Woodworth & Cartwright, 1986; Cartwright & Ray, 1990). Despite the advent of accurate tidal maps from altimetry, many questions about tides remain, including the response of tides to climate change, the details of tide-cryosphere interactions and open-ocean tidal dissipation mechanisms, the predictability of internal tides, and the impact of tides on upcoming remote sensing missions. Some of these questions are addressable with global high-resolution simulations that incorporate tidal and atmospheric forcing simultaneously, a frontier direction in ocean modeling that is the subject of this paper.

1.1. Background and definition of terms

Tides are best known for effecting a periodic rise and fall of the sea surface height (SSH). The large-scale motions that dominate SSH are variously known as surface tides or barotropic tides. The surface tides are arguably weakly resonant in the open-ocean (e.g., Wunsch, 1972; Garrett & Greenberg, 1977; Heath, 1981; Arbic et al., 2009), because the spatial structures and frequencies of oceanic normal modes (e.g., Platzman et al., 1981; Platzman, 1991; Zahel & Müller, 2005; Müller, 2007) match those of the astronomical forcing reasonably well. The weakly resonant open-ocean tides drive strong tides in coastal regions (e.g., Hudson Strait, the Bay of Fundy, the Patagonian and Northwest European Shelves, and others) that are well-shaped for resonance (e.g., Garrett, 1972; Clarke, 1991; Cummins et al., 2010).

The SSH perturbations are driven by converging and diverging barotropic (depth-independent) flows. When barotropic tidal currents flow over topographic features they initiate vertical motions, which in a stratified fluid such as the ocean implies the existence of tidal oscillations along the interfaces between layers of different densities (e.g., Bell, 1975; Wunsch, 1975; Baines, 1982; St. Laurent & Garrett, 2002; Lahaye et al., 2020; amongst many). The heaving of interfaces below the sea surface at tidal frequencies, known as the internal or baroclinic tide, is associated with temperature perturbations, as we will show later in frequency spectra of temperature, and brings about a considerable baroclinic (depth-dependent) component in tidal velocities (see, for instance, Figs. 2 and 5 of Timko et al., 2013). Internal tides can be divided

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Outline

- Internal tide correction studies using HYCOM
- Boundary forcing regional models with global internal wave models
- Selected model-observational comparisons
- Proposed work on NOPP project

Internal tide correction studies using HYCOM

- In theory, the Navy operational global HYCOM simulations have all the necessary ingredients to phase-predict stationary and non-stationary internal tides
  - Tidal forcing yields stationary internal tides which then interact with eddies
  - Assimilation of nadir altimetry data improves stratification and puts eddies in the correct locations

Internal tide correction studies using HYCOM

- Arin Nelson Wednesday oceanography lightning talk: Straight-up comparison of stationary tides in HYCOM vs. altimetry
- Ritabrata Thakur US HR modeling talk: Use EOF/PCA technique of Egbert and Erofeeva 2021, but applied globally
- Hann Wang last talk of this session: Apply machine learning to HYCOM solutions

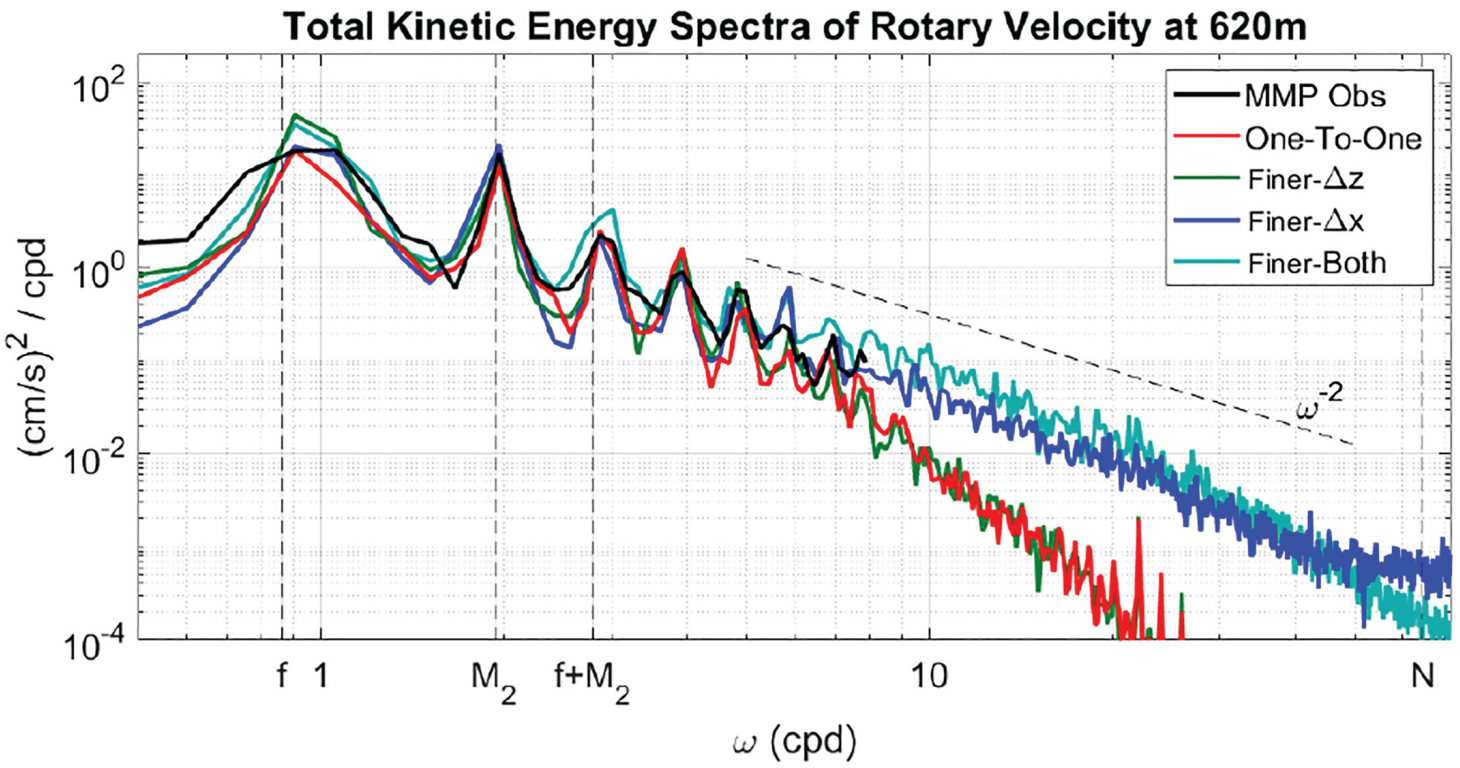
Boundary forcing regional models with global internal wave models

- Global HYCOM coupled to ROMS simulation of California Current:
  - Oladeji Siyanbola talk in this session: carefully setting up the boundary conditions
  - Audrey Delpach talk in US HR modeling session: internal wave interactions with eddies and the atmosphere
- Global MITgcm coupled to a regional MITgcm patch near Hawai'i
  - Ritabrata Thakur talk in US HR modeling session: turning off KPP background yields more accurate vertical structure in internal wave field
  - Kayhan Momeni Wednesday oceanography lightning talk: KPP statistics and vertical profiles of diffusivity
  - These latter two studies build upon:
    - Nelson et al. (2020): internal wave spectrum fills out with higher resolution

Improved IGW frequency spectra in a regional model forced by the global MITgcm simulation (Nelson et al., 2020)

- Mazloff et al.: w/o internal tide boundary conditions, a regional model has an insufficiently energetic IGW spectrum

- This work: with internal tide boundary conditions + increase in resolution, IGW continuum energy goes up



Selected model-observational comparisons

- Comparison of HYCOM and MITgcm vs. ~2000 moored records of temperature and velocity: Luecke et al. 2020
- Comparison of HYCOM and MITgcm vs. undrogued and drogued drifters: Arbic et al. in-revision
  - Accurate near-inertial band requires frequent atmospheric forcing.
  - Accuracy of modeled internal tides depends on damping parameterizations.
- Intercomparison of several hydrodynamical global internal tide models with altimetry (Ansong et al. in preparation)
  - Models without extra damping (e.g., parameterized topographic wave drag) tend to have internal tide fields that are too large
- See also many other model-observational comparison studies:
  - Shriver et al. (2012), Timko et al. (2012, 2013), Ansong et al. (2015, 2017), Buijsman et al. (2016, 2020), + others

Proposals for NOPP call

Four related proposals to current NOPP call aim to improve global internal wave models and to test them with arrays of in-situ instruments (and altimetry)