Simulation of eddies and tides in global HYCOM

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Collaborators

- Naval Research Laboratory Stennis Space Center: Joe Metzger, Hans Ngodock, Jim Richman, Jay Shriver, Alan Wallcraft, Luis Zamudio

- University of Southern Mississippi: Maarten Buijsman

- University of Michigan: Joseph Ansong, Steve Bassette, Conrad Luecke, Anna Savage, David Trossman

- Bangor University: Patrick Timko

- Norwegian Meteorological Institute: Malte Müller

- University of Brest and The University of Texas at Austin: Rob Scott

- NASA Goddard: Richard Ray

- Florida State University: Eric Chassignet

- Others including many members of the NSF-funded Climate Process Team led by Jennifer MacKinnon of Scripps

Outline of talk

- Motivation and Movies

- Technical challenges

- Applications

Motivation

• Ocean mixing driven partly by breaking internal gravity waves, which source partly from tides. First global models of internal tides, run with Hallberg Isopycnal Model (Arbic et al. 2004, Simmons et al. 2004), included only tidal forcing and were run with horizontally uniform stratification.

• Desirable to have model in which generation and propagation of internal (baroclinic) tides takes place in more realistic, horizontally varying stratification, and potential exists for interactions between tidal and non-tidal flows.

• Recent simulations have accomplished this: several multi-year global runs of HYbrid Coordinate Ocean Model (HYCOM) with 32 and 41 layers in the vertical direction, $1/12.5°$ and $1/25°$ horizontal resolution, and astronomical tidal potential forcing in addition to wind- and buoyancy-forcing.

• Realistic environment to study many interesting scientific and operational questions.

Applications/sub-projects

–global 3-D tidal velocity maps

–comparison of internal tide signature at sea surface in model vs along-track altimeter data

–high- vs low-frequency contributions to sea surface height (SSH) wavenumber spectrum

–internal tide stationarity

–SSH frequency spectra

–development of an internal gravity wave spectrum in global models

–model/data temperature variance comparison

Movies

• Early global simulations of internal tides with horizontally uniform stratification (Arbic et al. 2004, Simmons et al. 2004)

• HYCOM simulations with tidal and atmospheric forcing (Arbic et al. 2010, 2012)

Implementation and technical challenges

- Solid-earth body tides and astronomical tidal potential

- Self-attraction and loading

- Topographic wave drag

Implementation of astronomical tidal potential

• To illustrate how tidal potential is implemented in an ocean model, we show the one-layer shallow-water momentum equations with tidal forcing:

$$\frac{\partial \vec{u}}{\partial t} + \vec{u} \bullet \nabla \vec{u} + f\hat{k} \times \vec{u} = -g\nabla(\eta - \eta_{EQ} - \eta_{SAL}) +$$
$$Friction$$

• Symbols above are standard. We will shortly discuss:
  –Astronomical tidal potential η_{EQ}
  –Self-attraction and loading term η_{SAL}

Solid earth body tides and astronomical tidal potential

- Elastic solid earth responds directly to astronomical forcing.

- Direct response known as the body tide.

- Ocean tides impacted by solid earth body tides (Hendershott 1972):

  – water column depth measured against deformed seafloor
  – gravitational potential altered by self-gravitation of deformed earth

- Effects accounted for by Love numbers h_2 and k_2, which are frequency dependent due to free-core nutation resonance (Wahr 1981).

- Example: equilibrium tide for one semidiurnal tidal constituent is

$$\eta_{EQ} = A(1 + k_2 - h_2)cos^2(\phi)cos(\omega t + 2\lambda),$$

where A is amplitude, ϕ is latitude, ω is frequency, t is time, λ is longitude

Self-attraction and loading

- Solid earth also yields to load of ocean tide.

- Solid-earth load deformation, impacts of self-gravitation of deformed earth (and ocean itself) on gravitational potential known as self-attraction and loading (SAL) term (Hendershott 1972).

$$\eta_{SAL} = \sum_n (1 + k_n' - h_n') \frac{3\rho_{water}}{\rho_{earth}(2n + 1)} \eta_n$$

- Challenging to implement because spherical harmonics η_n are computationally expensive.

- Currently using "scalar approximation" $\eta_{SAL} \approx 0.06\eta$

- Better (iterative) methods on the way.

Topographic wave drag e-folding time in first run (Arbic Wallcraft Metzger 2010)

Tidal Drag E-Folding Time (days)
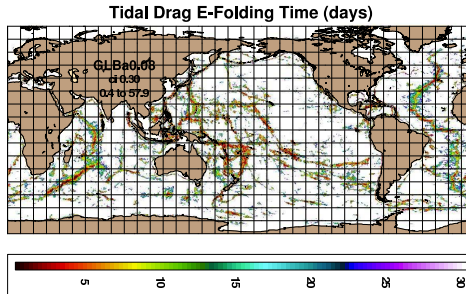
New complication for topographic drag in HYCOM wind-plus-tides simulation

• Topographic wave drag probably acts on low-frequency motions (Nikurashin and Ferrari 2011; Scott et al. 2011; Trossman et al. 2013) as well as tides.

• But the action is different for the two types of motions (Bell 1975).

• Therefore, a separation of the model bottom flows into tidal versus non-tidal components is desirable.

• This separation is done with running averages and must be done carefully to avoid numerical problems.

Some results from first paper (Arbic Wallcraft Metzger 2010)

- Importance of horizontally varying stratification.

- Snapshots of steric and non-steric sea surface height.

- Snapshots of tidal velocity vertical structure.

Importance of horizontally varying stratification: Amplitude (cm) of M_2 internal tide signature in steric SSH in (a) two-layer tide-only run and (b) 32-layer wind-plus-tides run
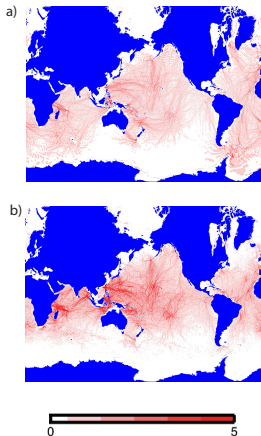
Snapshots of non-steric (TOP) and steric (BOTTOM) SSH (m) in southwest Pacific: June 30, 2006 00Z

(a)

(b)
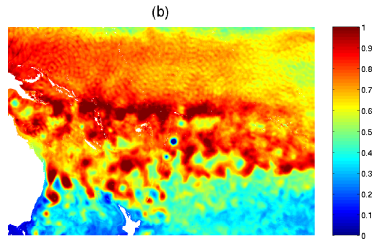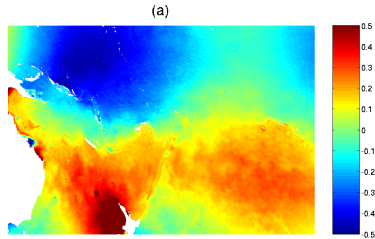
Snapshots of vertical structure of tidal velocity (cm s^{-1}) near Hawai'i (June 30, 2006)
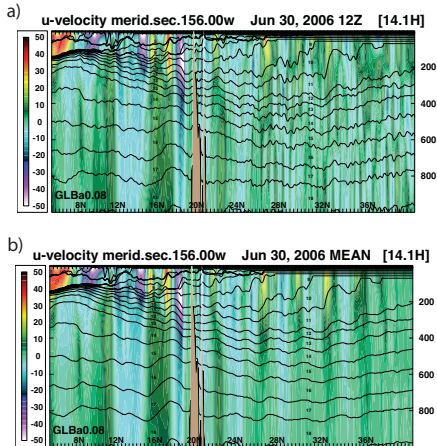
Moving on to more recent results...

Tidal current vertical structure–at a particular location (Timko et al. 2013)

TIMKO ET AL.: SKILL TESTING A 3-D GLOBAL TIDE MODEL
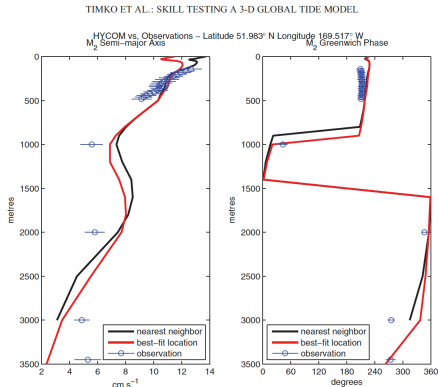
Figure 2. Comparison of M_2 semimajor axis and Greenwich phase in HYCOM and in a particular ADCP record as a function of depth. See plot title for ADCP location. The circles represent the value estimated from the observations and the line through the circle represents the 95% confidence intervals using harmonic tidal analysis. The black line shows HYCOM model values for the model grid point nearest the observation and the red line shows the model values for the best-fit neighbor from a 9 point block of grid cells surrounding the observation.

Tidal kinetic energy vertical structure–averaged over thousands of current meter locations in Rob Scott's archive (Timko et al. 2013)
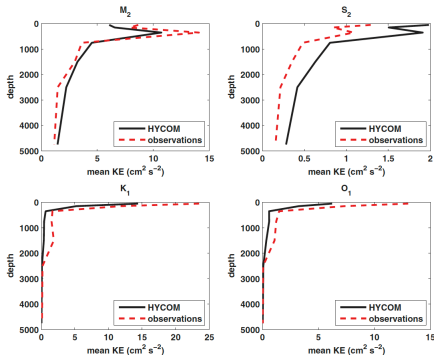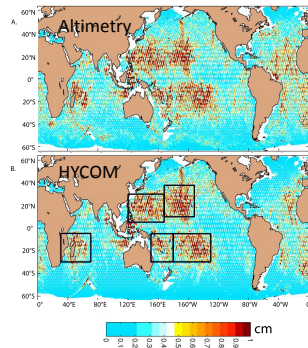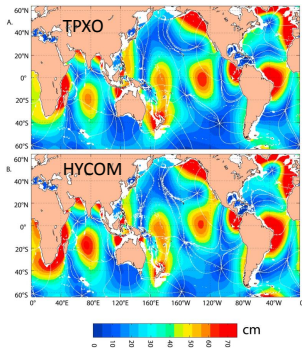

Figure 5. Vertical profiles of the average HYCOM and observed tidal kinetic energy averaged over seven depth bins for the global ocean in deep water (water column depth greater than 1000 m).

Barotropic and baroclinic M₂ tides in HYCOM vs. TPXO and along-track altimetry (Shriver et al. 2012)

Note apparent death of internal tides in equatorial Pacific—more later

HYCOM vs along-track altimetric estimates of surface signature of K_1 internal tides (Shriver et al. 2012)
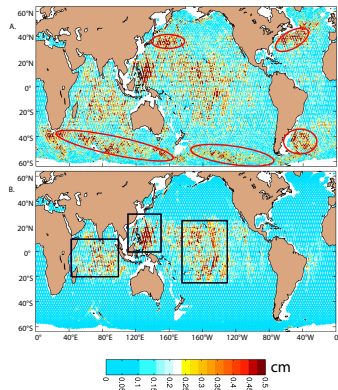
Figure 8. The K_1 internal tide amplitude from the (a) altimetric-based and (b) HYCOM tidal analyses. Areas where mesoscale variability contaminates the altimetric-based tidal analysis are identified by the red circles in (a). The three subregions denoted by black boxes in (b) are used to compute the area-averaged amplitudes in Table 3.
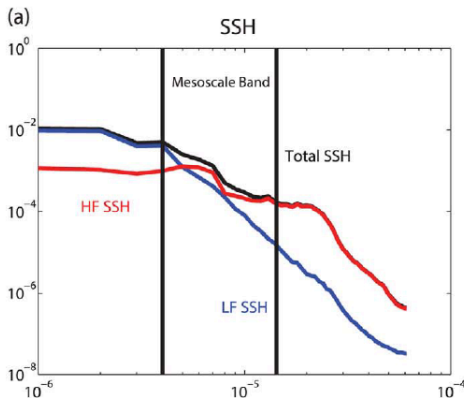
# Impact of internal tides on wavenumber spectrum of sea surface height (Richman et al. 2012)

(a)

SSH Spectrum Gulf Stream

Mesoscale Band

Total SSH

Low Frequency SSH

High Frequency SSH
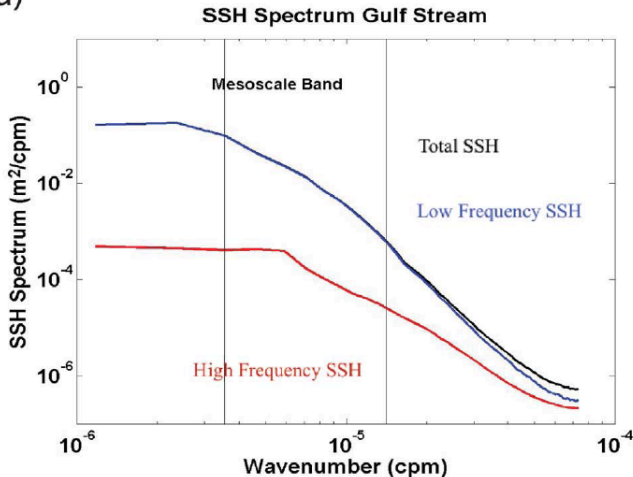
Impact of internal tides on wavenumber spectrum of sea surface height (Richman et al. 2012)
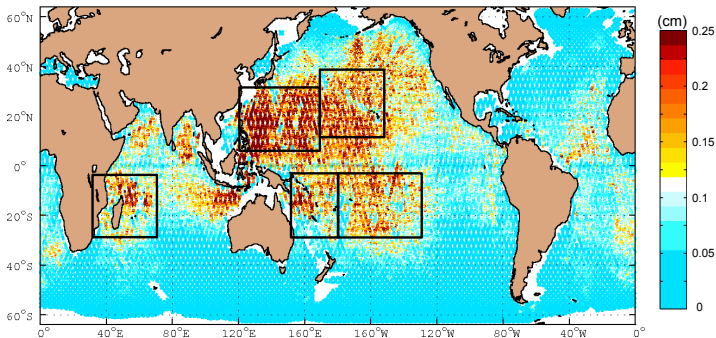
- SSH spectrum North of Hawai'i

(a)

SSH

Mesoscale Band

Total SSH

HF SSH

LF SSH

Impact of internal tides on wavenumber spectrum of sea surface height (Richman et al. 2012)
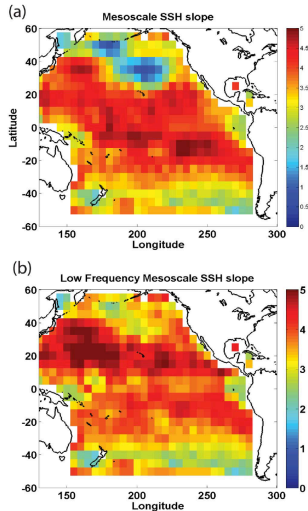
M$_2$ 1/12° Global HYCOM amplitude standard deviation, using 183-day windows
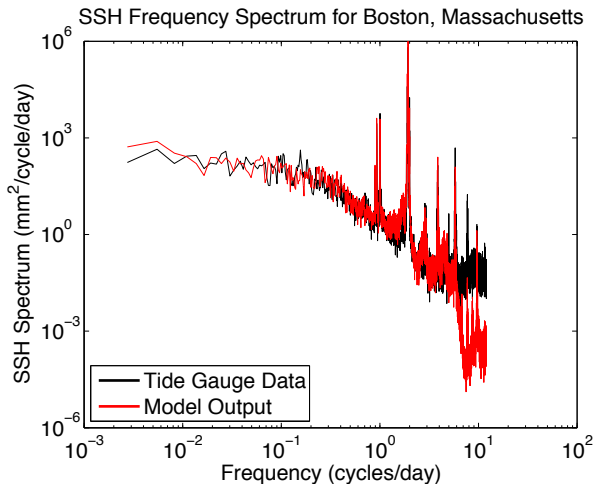
Frequency spectra of sea surface height in tide gauges versus HYCOM–Savage et al. 2014, in revision

• Map of tide gauges used; 3 years continuous hourly data (U-Hawai'i Sea Level Center)–NOTE NOT MANY GAUGES AROUND AFRICA!!
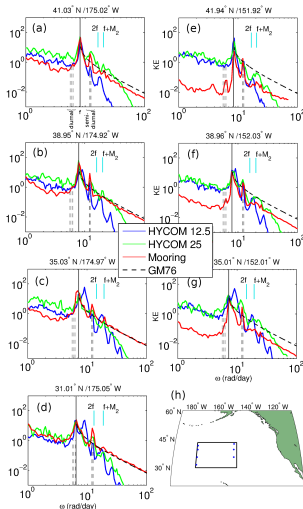

Map of Tide Gauges

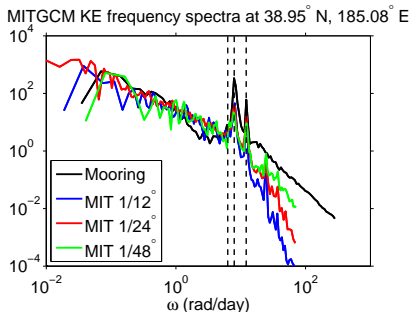SSH Frequency Spectrum for Boston, Massachusetts

Internal gravity wave kinetic energy frequency spectra (Müller et al. 2015)
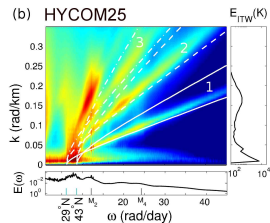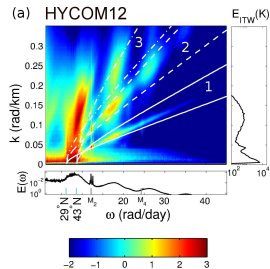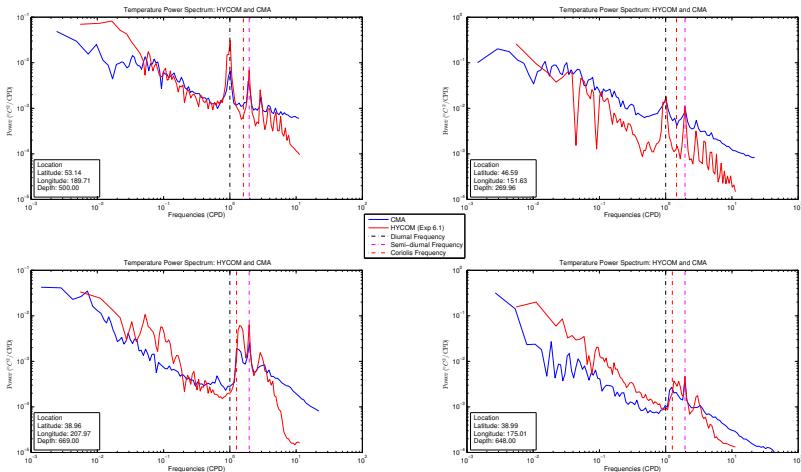
- Note logarithmic smoothing employed.

PRELIMINARY frequency spectra of MITGCM kinetic energy (thanks to Clement Ubelmann, Dimitris Menemenlis and MITgcm/ECCO collaborators)

Internal gravity wave kinetic energy frequency-horizontal wavenumber spectra (Müller et al. 2015)

Frequency spectra of temperature (Bassette et al. and Luecke et al. in preparation)

Relevant papers

- **First paper** Concurrent simulation of the eddying general circulation and tides in a global ocean model.

  Arbic et al., Ocean Modelling, 2010.

- **Overview** Global modeling of internal tides within an eddying ocean general circulation model.

  Arbic et al., Oceanography, 2012.

- **North Atl. tidal currents** Skill tests of three-dimensional tidal currents in a global ocean model: A look at the North Atlantic.

  Timko et al., Journal of Geophysical Research, 2012.

- **Global tidal currents** Sill testing a three-dimensional global tide model to historical current meter records.

  Timko et al., Journal of Geophysical Research, 2013.

Relevant papers

- **Model/altimetry comparison** An evaluation of the barotropic and internal tides in a high resolution global ocean circulation model.
  Shriver et al., Journal of Geophysical Research, 2012.

- **Wavenumber spectra** Inferring dynamics from the wavenumber spectra of an eddying global ocean model with embedded tides.
  Richman et al., Journal of Geophysical Research, 2012.

- **Internal tide non-stationarity** How stationary are the internal tides in a high-resolution global ocean circulation model?
  Shriver et al., Journal of Geophysical Research, 2014.

- **Comparison of state-of-the-art barotropic tide models** Accuracy assessment of global barotropic ocean tide models
  Stammer et al., Reviews of Geophysics, 2014.

• **Tuning the tide model** Optimizing internal wave drag in a forward barotropic model with semidiurnal tides.
  Buijsman et al., Ocean Modelling, 2015.

• **A first look at the internal gravity wave spectrum** Toward an internal gravity wave spectrum in global ocean models.
  Müller et al., Geophysical Research Letters, 2015.

• Papers in press, in review, in prep by Ansong, Buijsman, Luecke, Ngodock, Savage, Shriver, Timko.

Summary

• Concurrent simulation of tides and eddying general circulation achieved in global HYCOM.

• HYCOM simulations represent considerable improvement over first global baroclinic tide simulations; horizontally varying stratification, much more validation work performed.

• HYCOM with tides simulations already being used, or will be used, in a host of operational and scientific studies.

• Models with concurrent atmospheric and tidal forcing are beginning to develop an internal gravity wave spectrum, especially as resolution increases.