Validation of barotropic and internal tides in several hydrodynamical global ocean models

USING: Realistic Global Simulations of HYCOM, MITgcm, and Mercator/NEMO

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Motivation

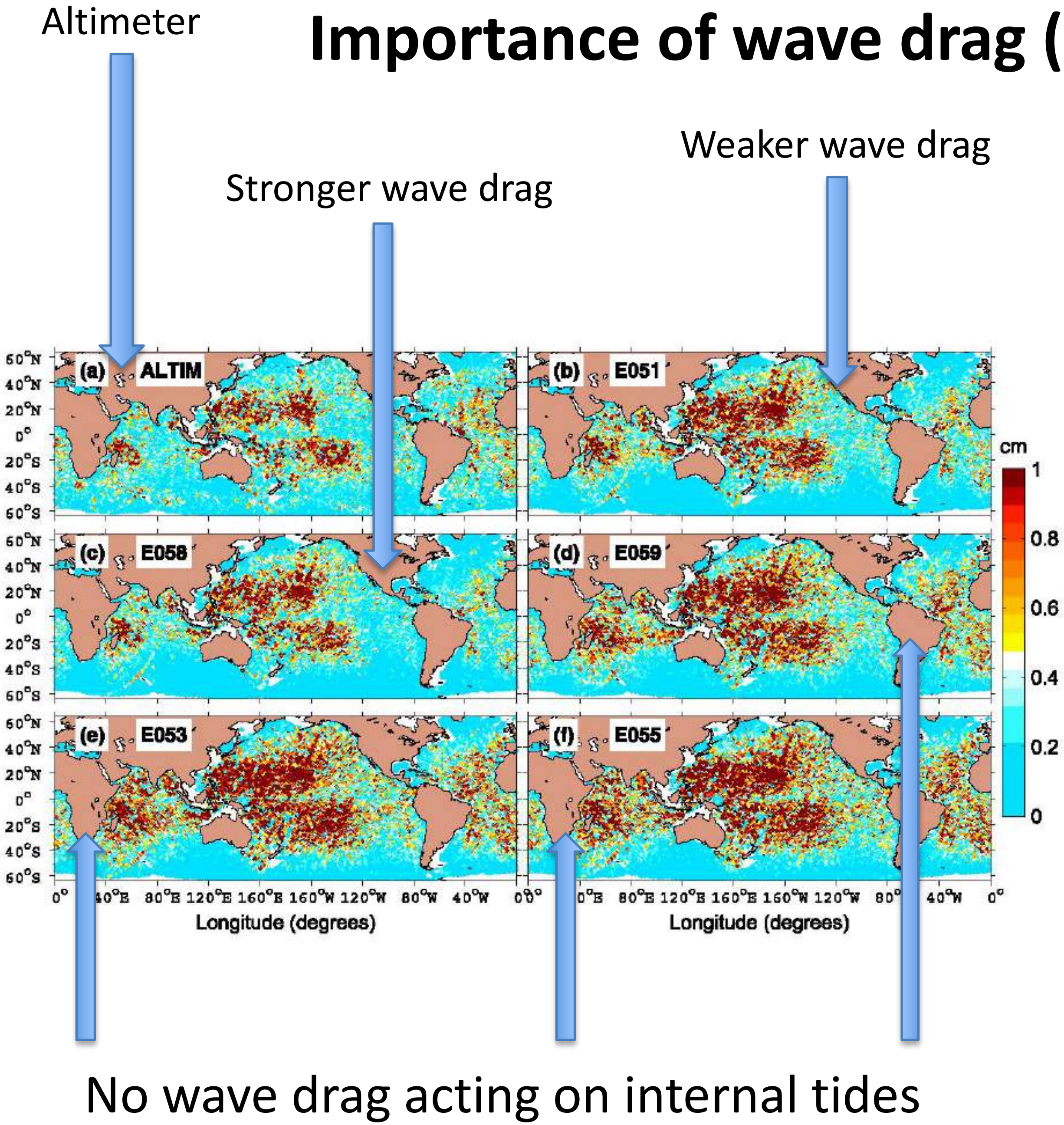
- Global hydrodynamical models of internal tides and internal gravity waves are potentially useful for several oceanography applications:
  - Understanding and mapping the global internal wave field:
    - near-inertial flows
    - stationary internal tides
    - nonstationary internal tides
    - supertidal internal gravity wave continuum spectrum
    - internal wave solitons
  - Understanding the 3-D oceanic mixing field
  - Operational oceanography
  - Planning for SWOT and space- plus airborne velocity missions e.g. SKIM, WACM, S-MODE EVST

- The internal tide field is an important part of the oceanic internal wave spectrum, and, along with its “parent” the barotropic tide field, needs to be compared to observations

Model-data comparisons shown here

- Global high-resolution hydrodynamical models used (all with atmospheric + tidal forcing)
  - NRL HYCOM
  - JPL MITgcm
  - NEMO
  - (Planned) MOM6
- Comparisons made
  - Internal tides, models vs. along-track altimetry
  - Barotropic tides, models vs. altimeter-constrained barotropic tide models
  - IF TIME:
  - Frequency spectra of different bands of motions, models vs. moored data
  - Geostrophic flows, models vs. AVISO

Importance of wave drag (Ansong et al. 2015)



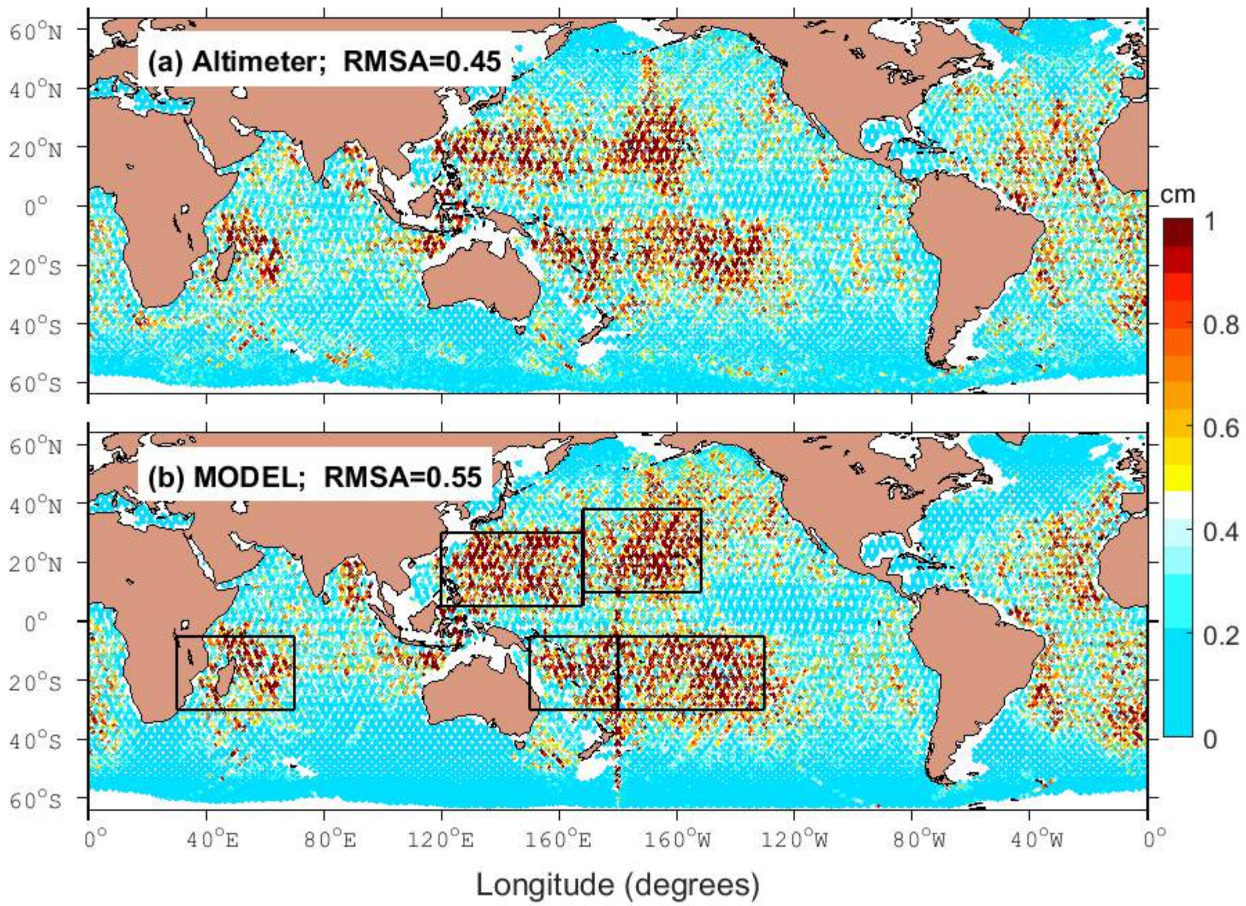
1/12° HYCOM results, from Ansong et al. (2015)

Some damping of low mode internal tides is needed to make HYCOM agree with altimetry.

Comparison of internal tides in global hydrodynamical models with along-track altimetry

- Analysis conducted by Joseph Ansong
- Stationary M_2 internal tides in models vs. along-track altimetry
- Results shown for:
  - 1/12° HYCOM with different wave drag strengths, including no wave drag
  - 1/12° Mercator/NEMO (no wave drag)
  - 1/48° MITgcm (no wave drag)
  - 1/12° MITgcm (no wave drag)
  - Hopefully: 1/12° MOM6 (no wave drag)

Mercator 1/12° NEMO (no wave drag)

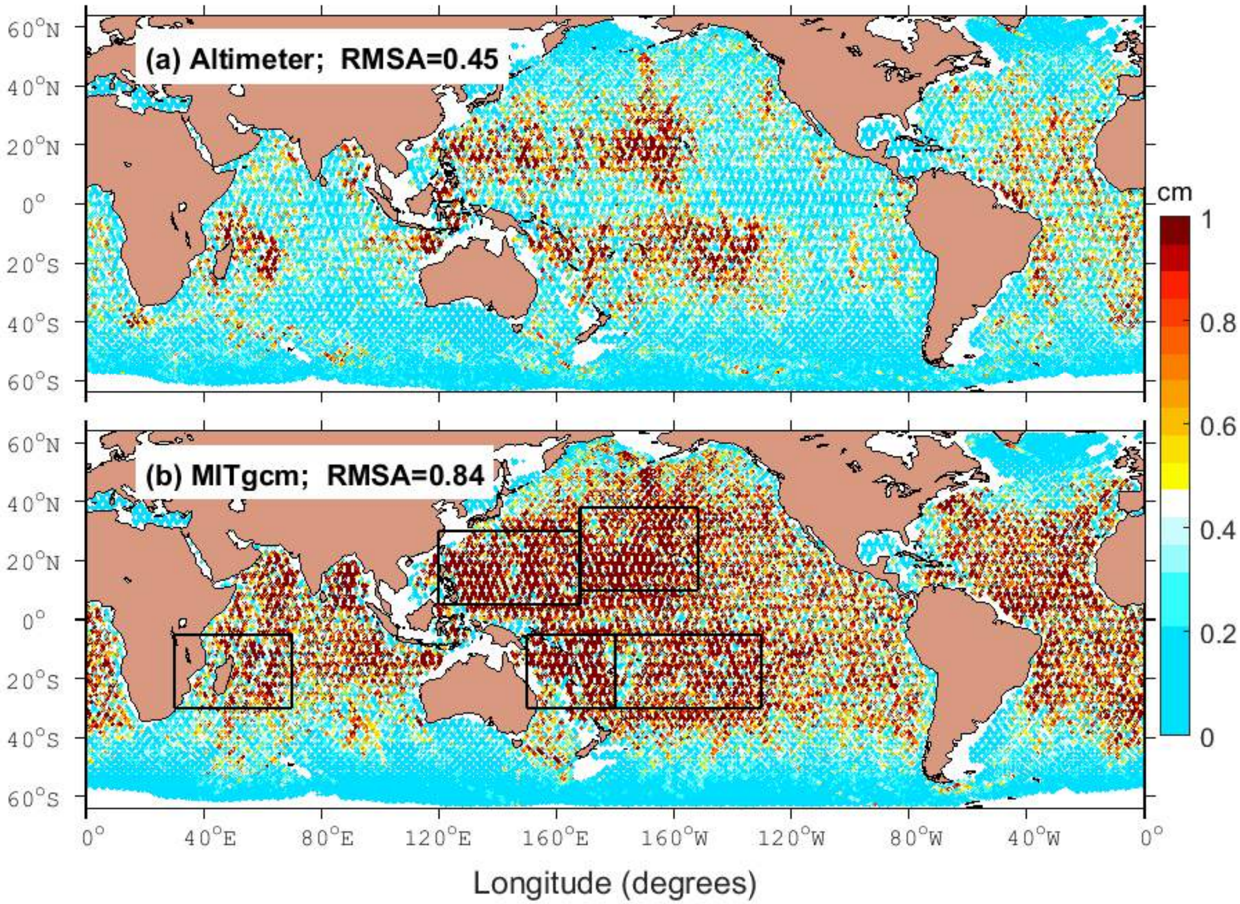


NEMO team is testing vertical coordinates and numerical schemes.

Hypothesis: less "viscous/diffuse" model
→ larger internal tides
→ must insert physical damping to obtain better agreement with altimetry.

Shown is a map from one year of analysis

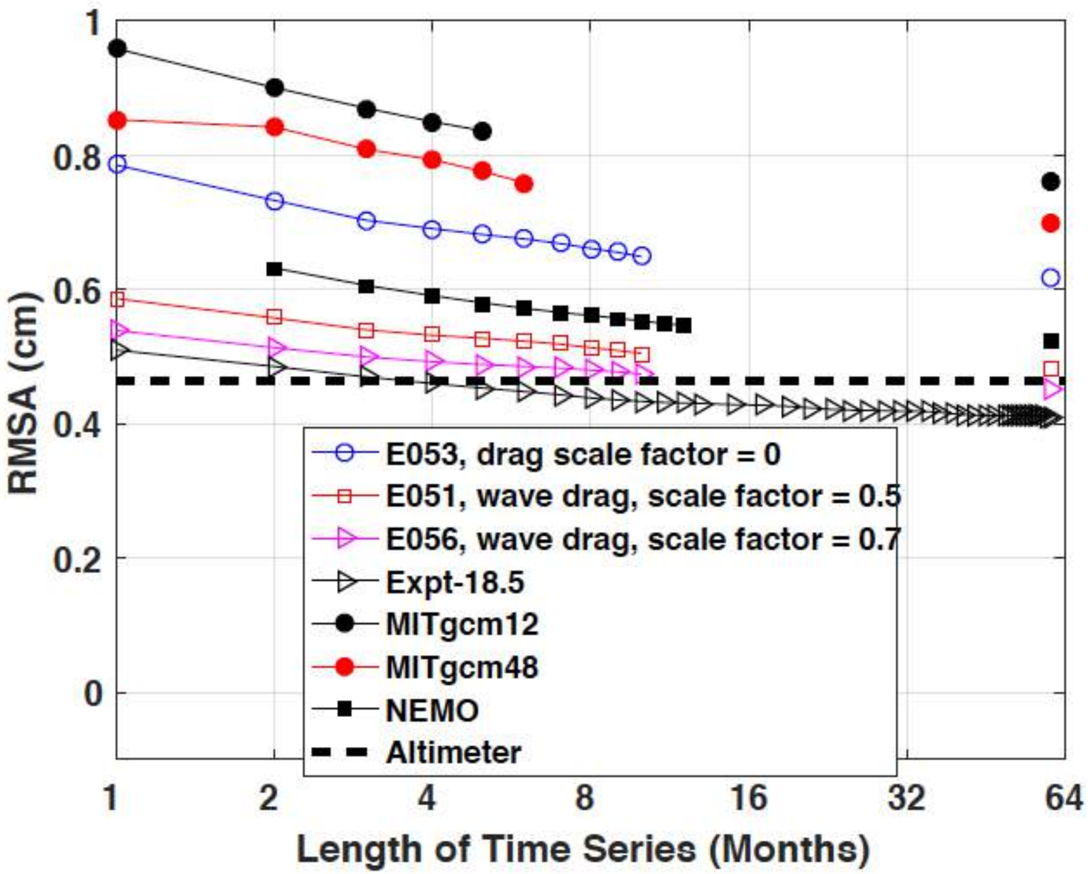
1/48° MITgcm (no wave drag)



Astronomical forcing was too large by factor of 1.121 (more later)

Shown is a map from only two months of analysis

Intercomparison of M_2 internal tide amplitudes (cm) in global hydrodynamical models and altimetry



Ansong et al., in preparation

MITgcm results should be reduced by 1.121 (more below)

More to be done on internal tide model vs. altimetry comparison

- Richard Ray: currently analyzing shorter altimeter records

- 12 months of MITgcm output?
- Analyze NEMO runs with less numerical damping

- Add MOM6 to the mix?

Why MOM6?
HYCOM numerical instability in North Pacific

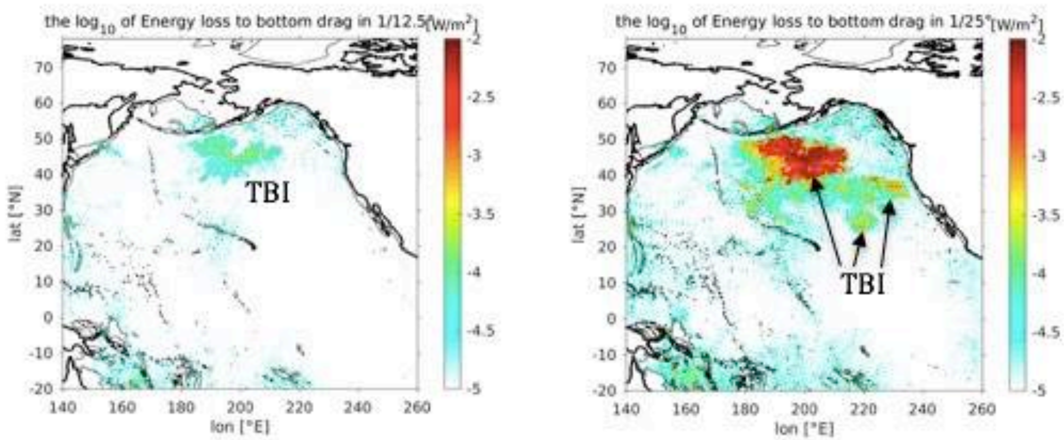


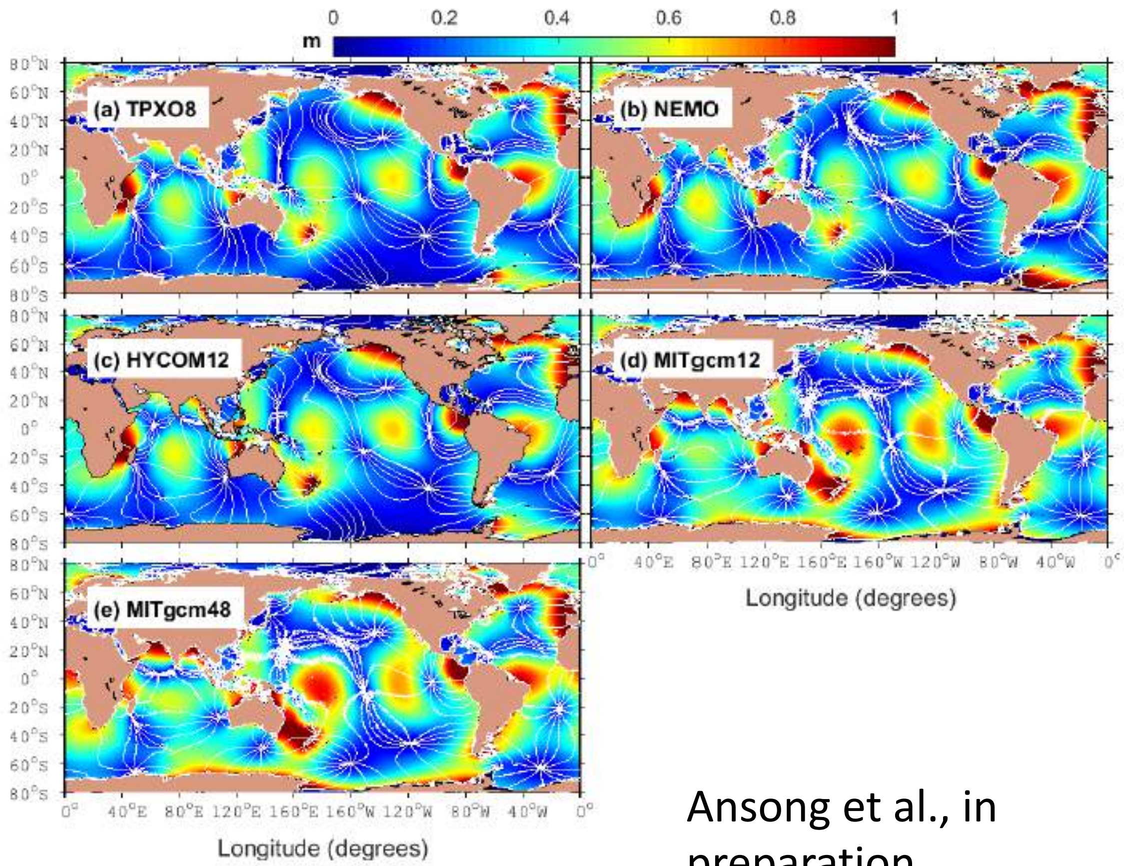
Figure 8. The thermobaric instability (TBI) occurs mostly in the North Pacific and manifests itself as high-mode waves that are partially dissipated by quadratic bottom drag. The TBI energy loss in the North Pacific is shown for the 1/12.5° (left) and 1/25° (right) HYCOM simulations. The TBI is worse in the higher resolution 1/25° simulation than in the 1/12.5° simulation. The energy loss in depths shallower than 2000 m are set to zero to emphasize the TBI losses in deep water. The 2000-m isobath and coastline are the thin and fat black curves.

How to fix? Instability apparently not present in MOM6, a model with a very similar structure to HYCOM→should work closely with NOAA MOM6 developers.

Comparison of barotropic tides in global hydrodynamical models with altimeter-constrained barotropic tide models

- Thanks to:
  - Dimitris Menemenlis
  - Rui Ponte
  - Matt Mazloff
  - Richard Ray

Comparison of barotropic tides in global hydrodynamical models with altimeter-constrained barotropic tide models



Ansong et al., in preparation

MITgcm amplitudes too large in many places

Our analysis of phase in the MITgcm has an error that we are currently fixing

Richard Ray has spot-checked Joseph's MITgcm analysis in 35 places where amplitudes are too large. He finds MITgcm amplitudes that are even larger, hence farther from observations, with phase errors of up to 50 degrees.

Why are barotropic tides too large in MITgcm?

- Astronomical forcing too large by factor of 1.121 (more below)
- No wave drag
- Clean numerics ☺

What could cause phase problems in MITgcm?

- SAL was apparently not accounted for (more below)
- Lack of SAL is known to cause phase errors of up to 30° (Hendershott 1972, Gordeev et al. 1977)
- Matt Mazloff thinks that there may be a half-hour phase lag in the forcing, translating to something like a 15° further phase problem for semidiurnal tides (to be discussed?)

How do amplitude and phase errors translate into RMS tidal errors?

See the Shriver et al. (2012) formula for mean-squared-error due to differences in amplitude and phase between a global hydrodynamical internal tide model such as HYCOM and an altimeter-constrained barotropic tide model such as TPXO:

$$MSE = \left[\frac{1}{2}(A_{HYCOM} - A_{TPXO})^2\right] + \left[A_{HYCOM}A_{TPXO}(1 - \cos(\phi_{HYCOM} - \phi_{TPXO}))\right], \qquad (3)$$

First term on right-hand side: amplitude-only error
Second term on right-hand side: amplitude-weighted phase error

An amplitude that is 30% too large, as Joseph's preliminary MITgcm analysis suggests, translates to an amplitude-only M_2 elevation error of 5.5 cm (assuming perfect phases)

If in addition the phase is off by 15°-45°, as Richard's spot-check MITgcm analysis suggests, there will be a 7.8-17 cm M_2 elevation error

After we fix the phase errors in our analysis we will be confident of the globally averaged M_2 elevation error in the MITgcm simulations

Calculation of tidal potential

For a semidiurnal tidal constituent, the equilibrium tide, denoted by η_{EQ} below, is given by

$$\eta_{EQ} = Af(t_{ref})(1 + k_2 - h_2)\cos^2(\phi)\cos[\omega(t - t_{ref}) + \chi(t_{ref}) + \nu(t_{ref}) + 2\lambda], \quad (5)$$

where A and ω are constituent-dependent forcing amplitudes and frequencies, φ is latitude, λ is longitude, t is time, t_{ref} is a reference time (which could represent, for instance, the starting time of a particular model run), and $\chi(t_{ref})$ is the constituent-dependent astronomical argument referenced to t_{ref} (e.g., Schwiderski, 1980; Pugh, 1987). The Love numbers h_2 and k_2, which are frequency-dependent especially in the diurnal band (Wahr and Sasao, 1981), respectively account for the deformation of the solid earth resulting from the astronomical forcing, and the resulting alteration in the gravitational potential due to the redistributed mass within the solid Earth. The solid-earth deformations arising in response to the astronomical forcing are known as the "body tide". Solid-

There are similar formulae for diurnal and long-period tides. Essentially, for every constituent added, one must add another term like (5).

Calculation of SAL

This section describes self-attraction and loading, an effect that those who are new to tidal research often find even more surprising than solid-earth body tides. In addition to its direct body-tide response to the astronomical tidal potential, the solid earth also compresses and expands due to the load of the ocean tide. Furthermore, the self-gravitation of both the ocean tide itself, and the load-deformed solid earth, alters the gravitational potential. Collectively, these effects are known as the self-attraction and loading (SAL) term (Hendershott, 1972; Ray, 1998). The η_{SAL} term is often computed in terms of a spherical harmonic expansion,

$$\eta_{SAL} = \sum_n \frac{3\rho_0}{\rho_{earth}(2n+1)}(1 + k'_n - h'_n)\eta_n, \tag{8}$$

where $\rho_0 \approx 1035$ kg m^{-3} is the average density of seawater, $\rho_{earth} \approx 5518$ kg m^{-3} is the average density of the solid earth, n is an index of the spherical harmonics, and the η_n's are the nth spherical harmonics of the tidal elevation η. The load numbers h'_n and k'_n, introduced in Munk and MacDonald (1960), respectively account for solid-earth yielding and the resulting perturbation potential. We see from equation (8) that the SAL term η_{SAL} depends on the tidal elevations η

How does one add tidal potential and SAL into a model?

In the case of a one-layer (barotropic) shallow-water model, if we assume a tensor form of the wave drag, the governing momentum equation is

$$\frac{\partial \vec{u}}{\partial t} + \vec{u} \bullet \nabla \vec{u} + f\hat{k} \times \vec{u} = -g\nabla(\eta - \eta_{EQ} - \eta_{SAL}) + \frac{\nabla \cdot [K_H(H+\eta)\nabla \vec{u}]}{H+\eta} - \frac{c_d|\vec{u}|\vec{u}}{H+\eta} + \frac{\overline{T}\vec{u}}{\rho_0(H+\eta)}, \tag{10}$$

and the governing mass conservation equation is

How to handle SAL—in general, and in MITgcm. llc runs?

How to deal with SAL?
--Compute it in the model as it is running (this has recently become feasible; Vinogradova et al. 2015, Schindelegger et al. 2018)
--Take maps from high-quality models such as TPXO, GOT, etc.
--Use a scalar approximation,

for which

$$\eta_{SAL} \approx \beta\eta, \tag{9}$$

where β is a constant, usually taken to be about 0.09. As Ray (1998) and others have shown, the scalar approximation is not accurate enough for the most exacting tidal applications. A more

In MITgcm llc runs, the scalar was taken to 0.1121, but instead of performing grad (eta – eta_{EQ} – 0.1121*eta), they effectively used grad(eta -1.1121* eta_{EQ})

In other words, the astronomical tidal potential was increased by 1.1121, and SAL was ignored.

How were barotropic tides added to MITgcm?

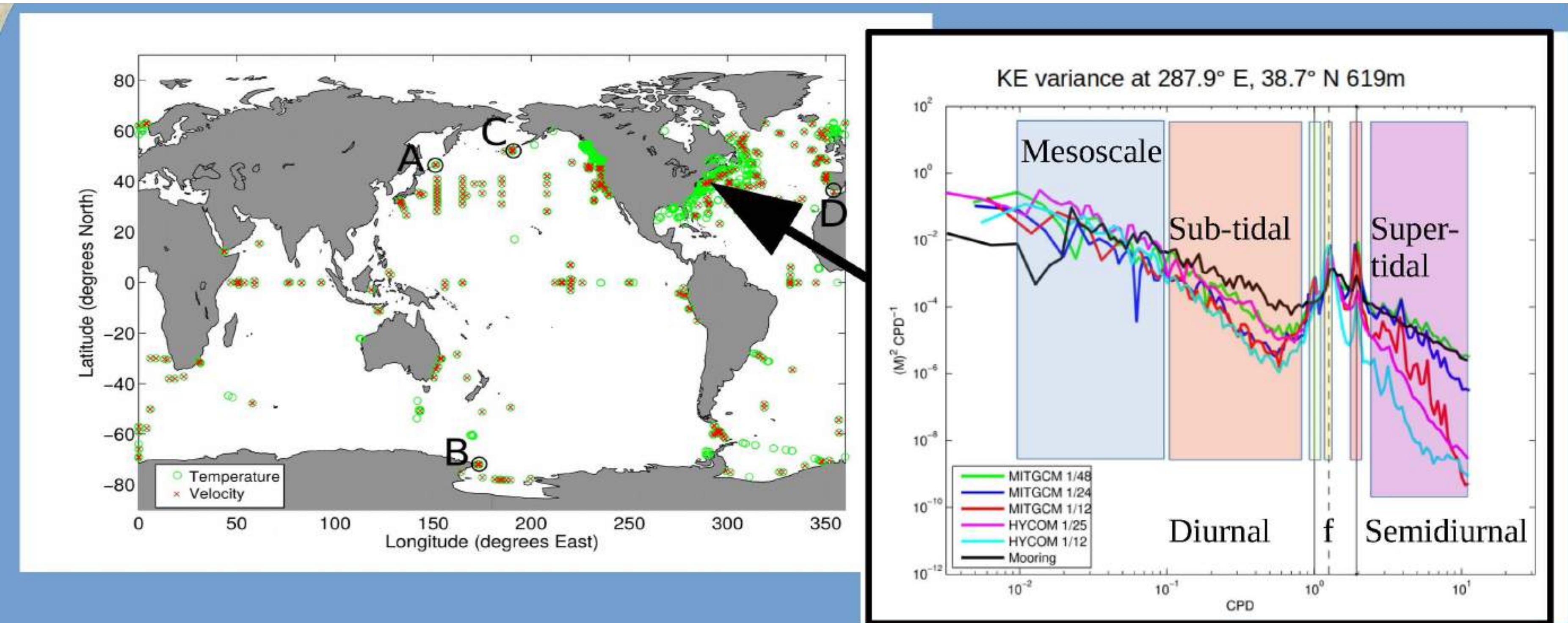
- Hourly fields of the tidal potential were created and added as if they were an additional pressure field. Interpolation used in between.
- This is non-standard. Effect of interpolation?
- More standard is to compute tidal potential at every timestep, using cos/sin(omega*t) computed at every time step for each tidal constituent, together with static fields of cos/sin(longitude/2*longitude), $\cos^2$(latitude), sin(2*latitude), etc.
- NEMO modelers have successfully added tidal potential to a z-level model

Summary

- MITgcm appears to have barotropic and baroclinic tides that are too large, and some problems in the phase of the barotropic tides
- We will be more sure after our harmonic analysis is improved
- Astronomical forcing can easily be improved if there is a “next round”
- SAL is missing; this can also be fixed
- Adding some physically motivated extra damping such as wave drag would help reduce amplitudes but that takes more effort

Extra slides

Current Meter Observations



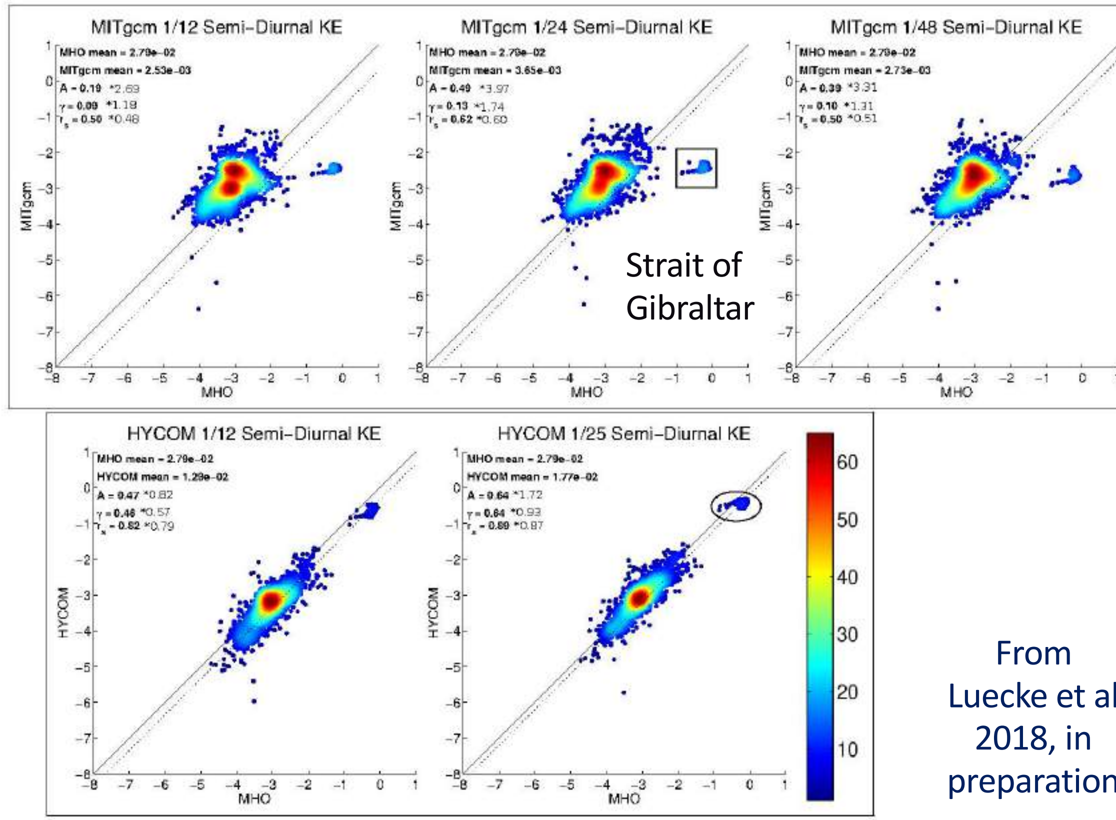
The regions A, B, C and D are locations (marginal seas) where MITgcm is under-energetic

The current meters are distributed around the globe with the majority in the North Atlantic and North Pacific with 2/3 of the observations in the upper 500 m

From Luecke et al 2018, in preparation

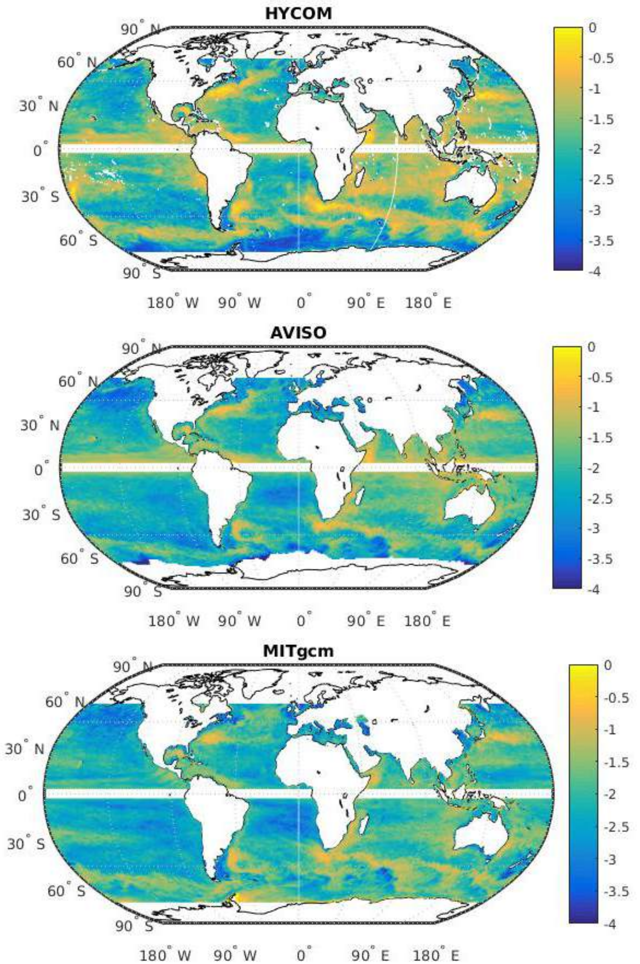
Semi-Diurnal Tidal Kinetic Energy

- The two models have very different methods to implement tidal forcing and damping.
  - Wave drag damping plays an important role in getting tidal energetics correct
- HYCOM:
  - Better spatial correlation than MITgcm
  - More realistic kinetic energy, with and without marginal seas
- MITgcm:
  - Under energetic in marginal seas
  - Too energetic when marginal seas removed



From Luecke et al 2018, in preparation

Comparison of Geostrophic Kinetic Energy to AVISO

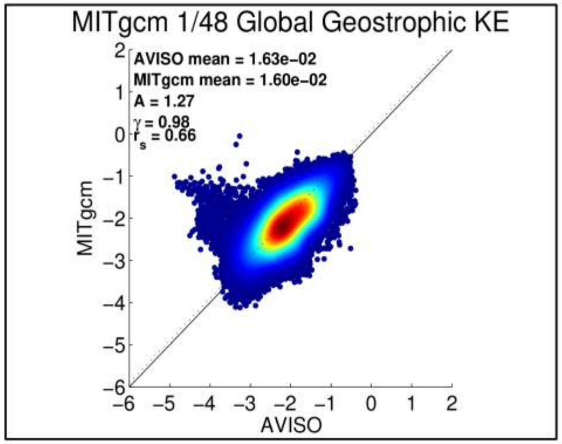


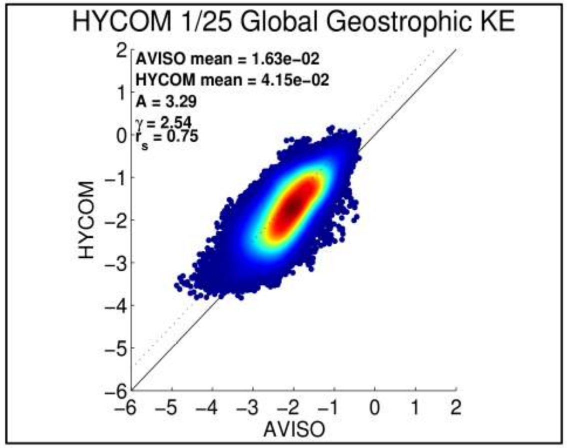
From Luecke et al 2018, in preparation

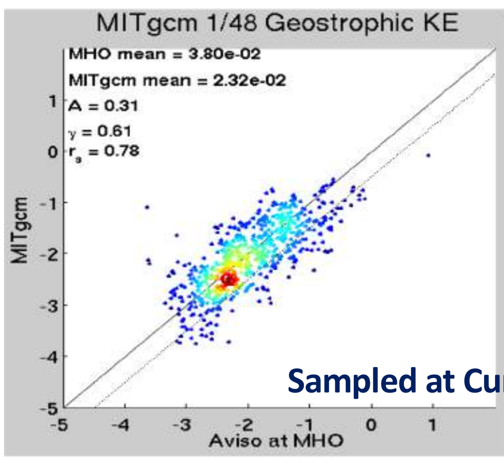
- Current meter observations are not uniformly distributed over the ocean
  - Small number of points can affect the gross statistics used in comparisons

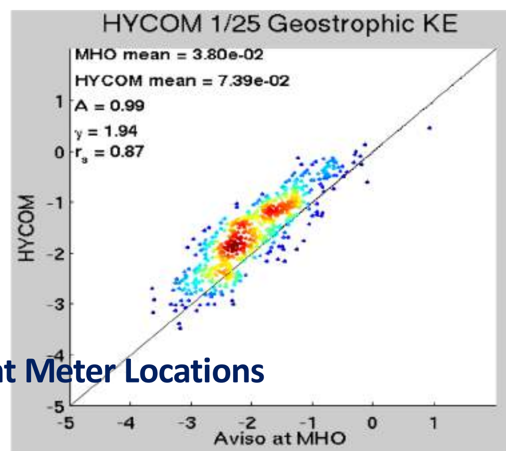
- Calculate Geostrophic KE from complete maps of SSH from AVISO and Models
  - Spatial correlation between the models (HYCOM and MITgcm) and Aviso map 'look good' globally.
  - HYCOM:
    - Overly energetic, particularly in Tropics and ACC.
    - More accurate in some areas such as the Gulf Stream.
  - MITgcm
    - Better averaged energetics.
    - Has a few regions of poor performance.

Comparison of Geostrophic Kinetic Energy to AVISO







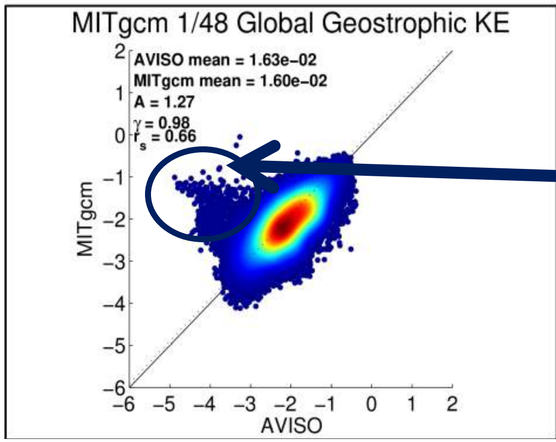


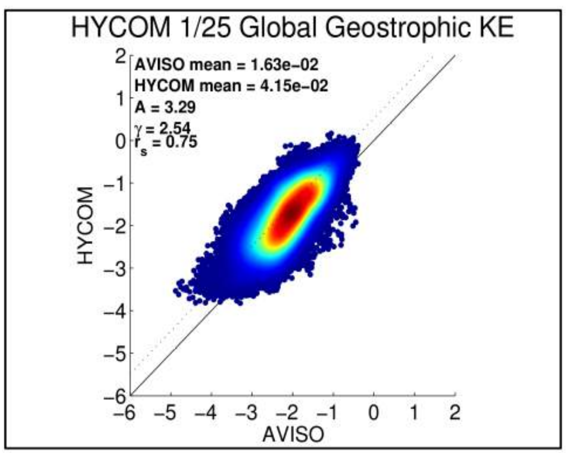
Sampled at Current Meter Locations

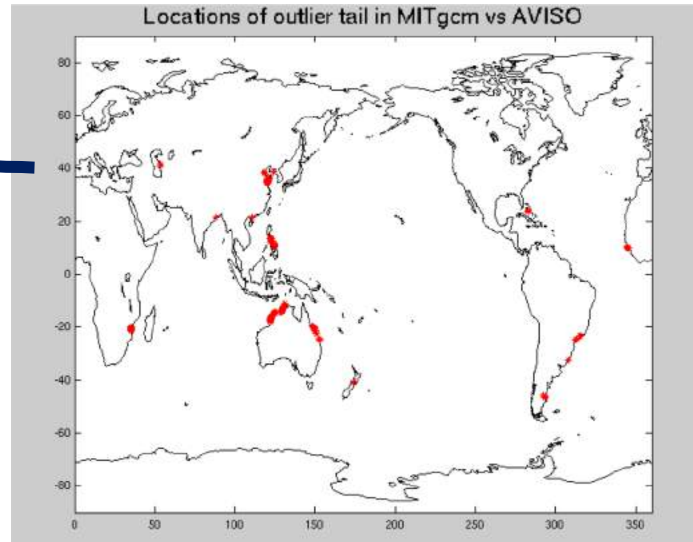
- Spatial correlations are generally good, but lower than moored observations
  - HYCOM has higher spatial correlations than MITgcm
  - When sampled at current meter locations, spatial correlations increase.
- HYCOM is more energetic
- MITgcm has regions with overly-energetic geostrophic velocities
  - These regions are not sampled by the historical observations

From Luecke et al 2018, in preparation

Comparison of Geostrophic Kinetic Energy to AVISO







From Luecke, et al 2018, in preparation

- The geostrophic KE in MITgcm is overly-energetic in regions near continental margins, straits and marginal seas
- This behavior is opposite of the high frequencies, which were under-energetic
- HYCOM doesn’t have the same tendencies in these regions