Global internal wave modeling

USING: Realistic HYCOM and MITgcm Simulations

SWOT Science Team meeting, 15 June 2016

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Type of models discussed in this talk

- Global models with simultaneous tidal and atmospheric forcing, run at high vertical and horizontal resolution
- Can be used to examine
  - High- vs. low-frequency contributions to wavenumber spectrum (Richman et al. 2012, Rocha et al. 2016)
  - Internal tide non-stationarity (Shriver et al. 2014)
  - Internal gravity wave (IGW) continuum
- Tides + near-inertial waves + non-linear interactions → an IGW continuum spectrum
  - First demonstration of an IGW continuum spectrum in a global model done in HYCOM (Müller et al. 2015)
  - Ongoing work on IGW spectrum being done in HYCOM simulations and MITgcm simulations performed by Dimitris Menemenlis (Rocha et al. 2016 and continuing work, Jinbo Wang's work, Savage et al. in prep, Ansong et al. in prep, Luecke et al. in prep)

Differences between global HYCOM and MITgcm simulations

- HYCOM / MITgcm
  - ~12 published model-observational comparisons, motivated by Navy operational needs
  - Much newer; no published vetting of global barotropic and internal tides
  - Impact of IGWs on wavenumber spectra in Drake Passage examined in Rocha et al. (2016)

  - Winds updated every 1-3 hours
  - Winds updated every 6 hours→less good for near-inertial waves

  - Includes a topographic wave drag parameterizing breaking of unresolved high vertical modes
  - No wave drag

  - Can include data assimilation (Cummings 2005, Cummings and Smedstad 2013) acting on mesoscale eddies and an Augmented State Ensemble Kalman Filter (ASEnKF) acting on tides (Ngodock et al. 2016)
  - No data assimilation on eddies or tides (idea has been put forward to do an ECCO-style state estimate with tides)

  - 41 hybrid vertical coordinate layers, horizontal resolutions of 1/12.5° and 1/25°
  - 90 z-levels, horizontal resolutions of 1/12°, 1/24° and 1/48°

  - Not currently easily available; we are working on that
  - Currently, more widely available

Impact of damping on low-mode internal tides (Ansong et al. 2015)

Journal of Geophysical Research: Oceans 10.1002/2015JC010998

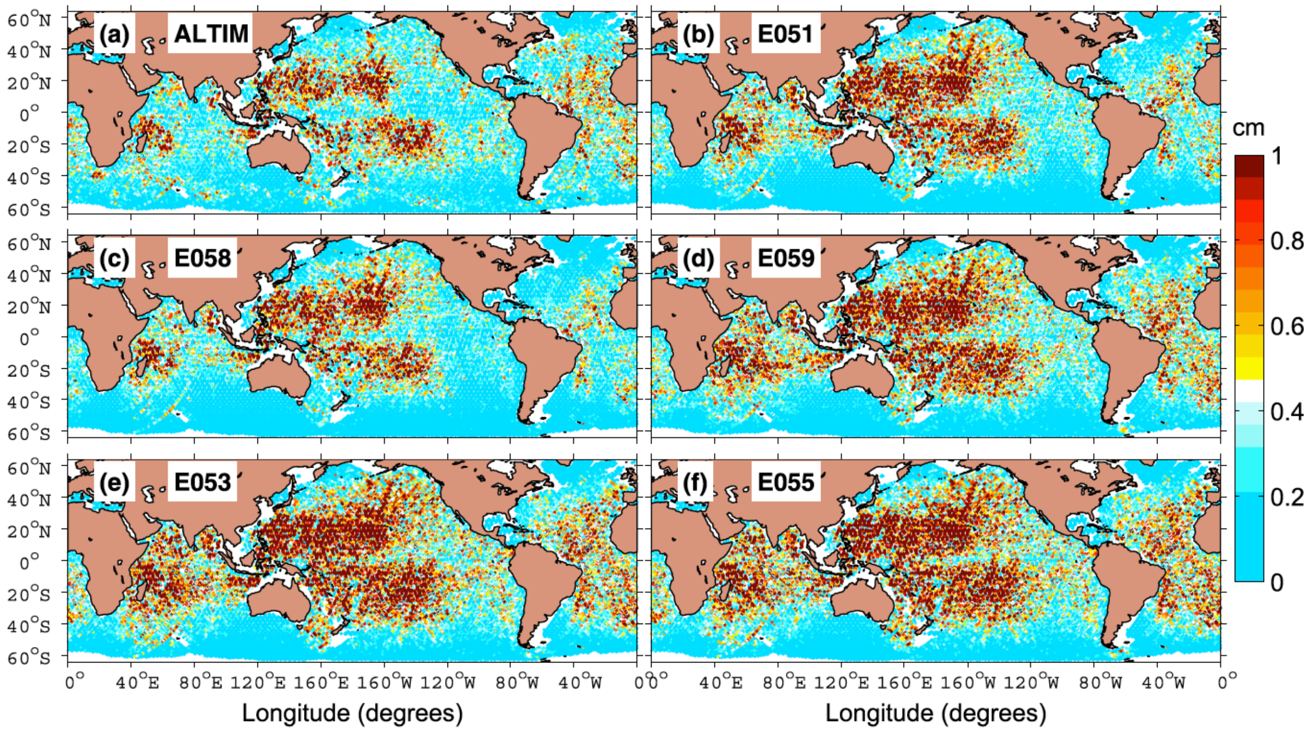
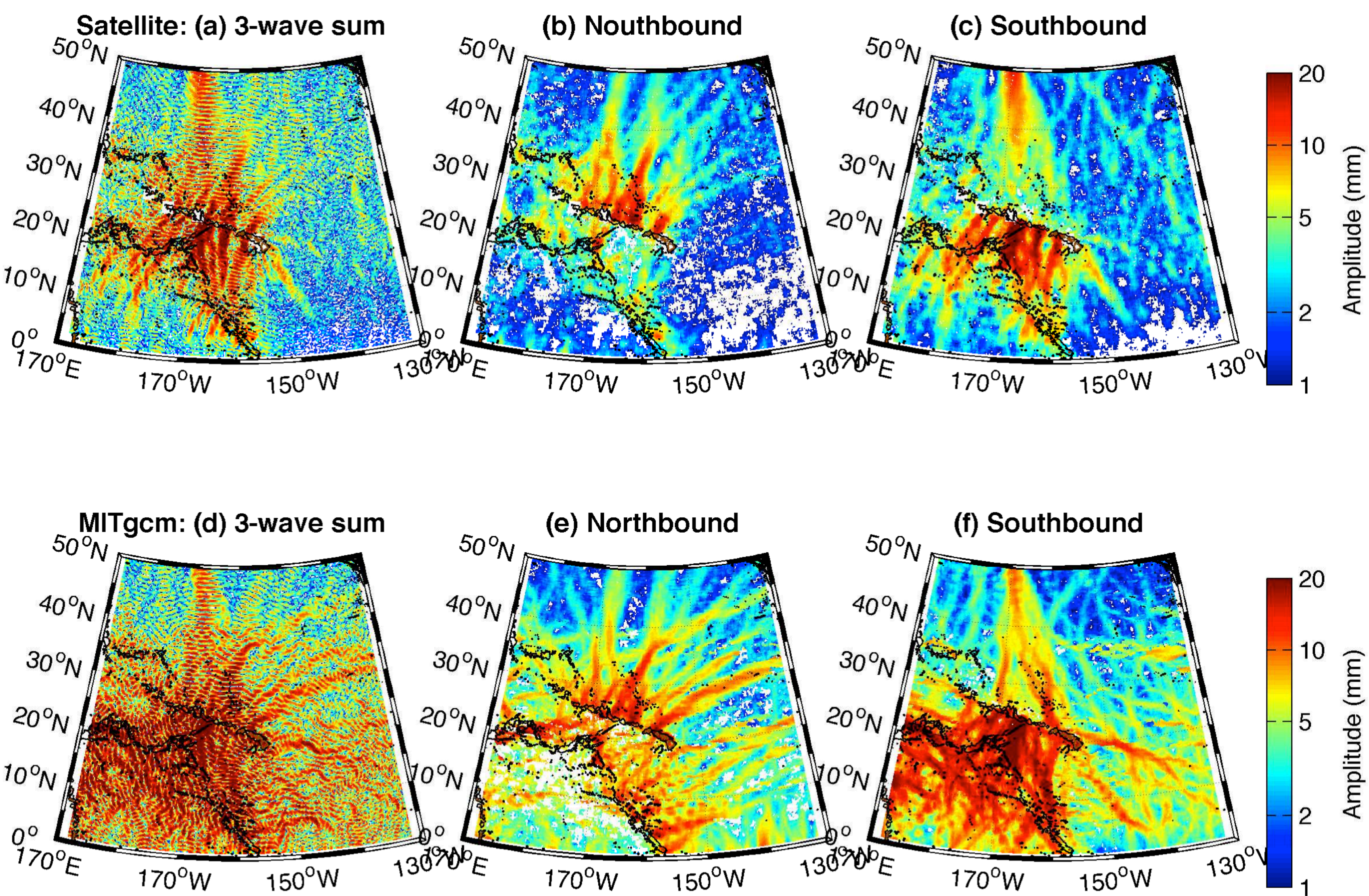


Figure 5. Amplitude (cm) of M_2 internal tide in (a) along-track altimeter-based analyses, and in HYCOM simulations (b) E051; with wave drag (scale factor = 0.5) applied to the bottom flow, (c) E058; with wave drag (scale factor = 1.0) applied to the bottom flow, (d) E059; with wave drag (scale factor = 1.0) applied to only the barotropic flow, (e) E053; without wave drag, (f) E055; without wave drag but with quadratic bottom friction increased by about 100 times along the continental shelves. The amplitudes of the HYCOM simulations are computed from 3 months of SSH output.

Internal tides in MITgcm (Dimitris Menemenlis) vs. altimetry (Zhongxiang Zhao)



Improving HYCOM barotropic tides with an Augmented State Ensemble Kalman Filter (ASEnKF; Ngodock et al. 2016)

24 H.E. Ngodock et al. / Ocean Modelling 97 (2016) 16–26

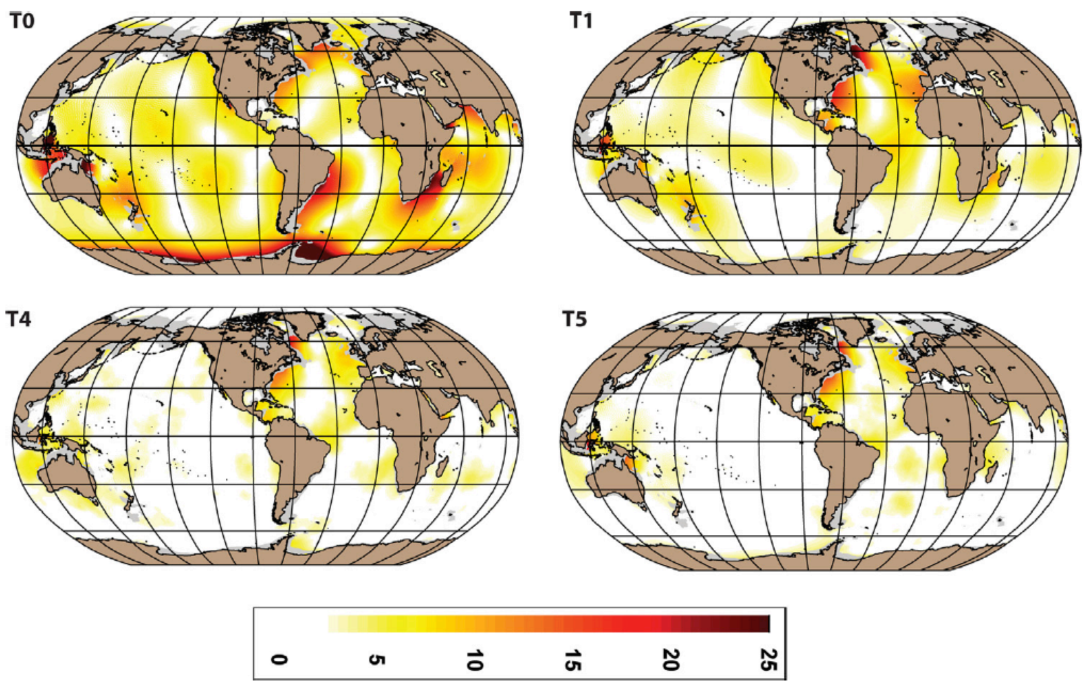


Fig. 6. Maps of the M_2 RMS error (cm) between the HYCOM simulations and TPXO8: **T0**, initial 8 constituent simulation with scalar SAL and Garner (2005) wave drag; **T1**, intermediate 5 constituent simulation with bathymetry extended to include floating Antarctic ice shelves, tuned Jayne and St. Laurent (2001) wave drag, and iterated SAL; **T4**, ASEnKF predicted tide using a 0.5 mm constant global observation error; **T5**, Blended ASEnKF predicted tide combining an Atlantic-only prediction with 1 cm observation error and **T3** for the rest of the ocean.

Need to go further. Motivated by the "back-effect" of coastal tides upon open-ocean tides (Arbic et al. 2007, 2009; Arbic and Garrett 2010), we are

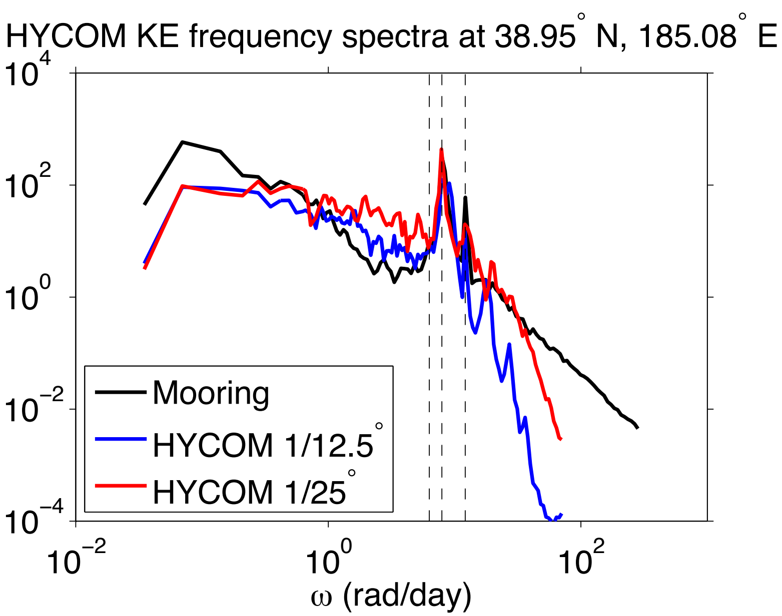
--attempting to improve our ASEnKF perturbations with incorporation of smaller scales along coasts

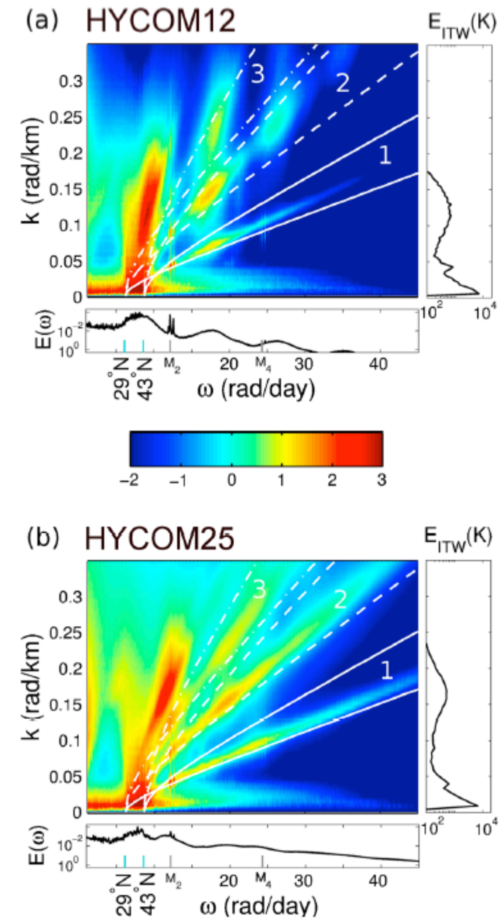
--attempting to improve coastal bathymetries

Demonstration of an internal gravity wave spectrum in HYCOM (Müller et al. 2015)

Kinetic energy frequency-horizontal wavenumber spectrum

Kinetic energy frequency spectrum





Revisiting conclusions of Richman et al. (2012)

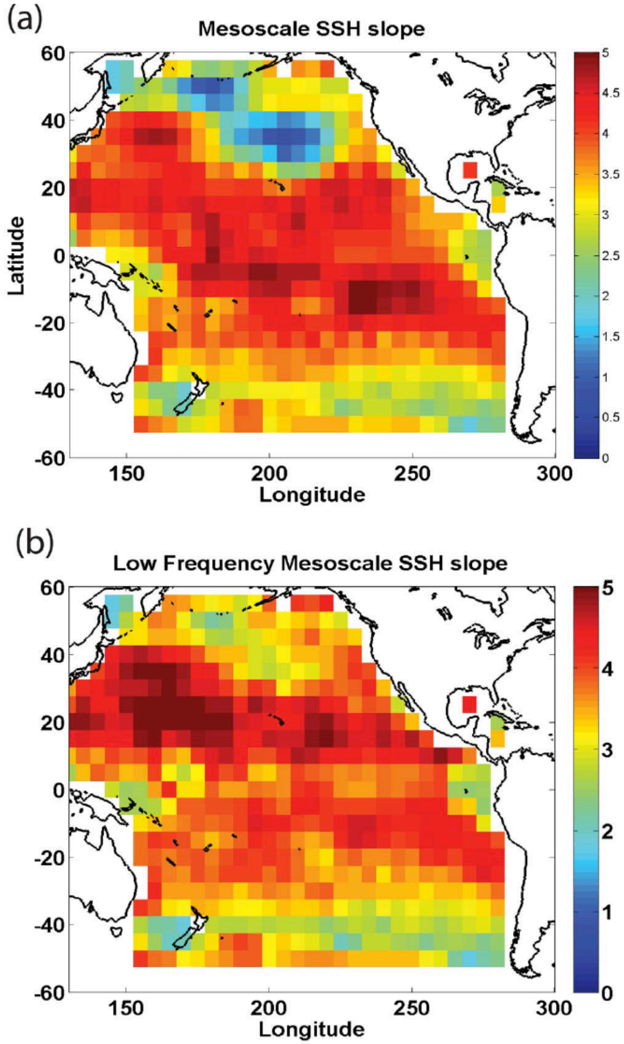


Figure 7. Least squares estimate of the slope of the SSH wavenumber spectrum in the North Pacific, computed over a 70–250 km band in HYCOM. Slopes are computed from spectra of (a) total SSH and (b) low frequency SSH. As in Figure 6, all slopes are multiplied by −1 to make them positive.

In Richman et al. (2012) we said that internal tides flatten wavenumber spectra

But the low- and high-passing used in that paper did not allow us to distinguish the effects of internal tides and the IGW continuum

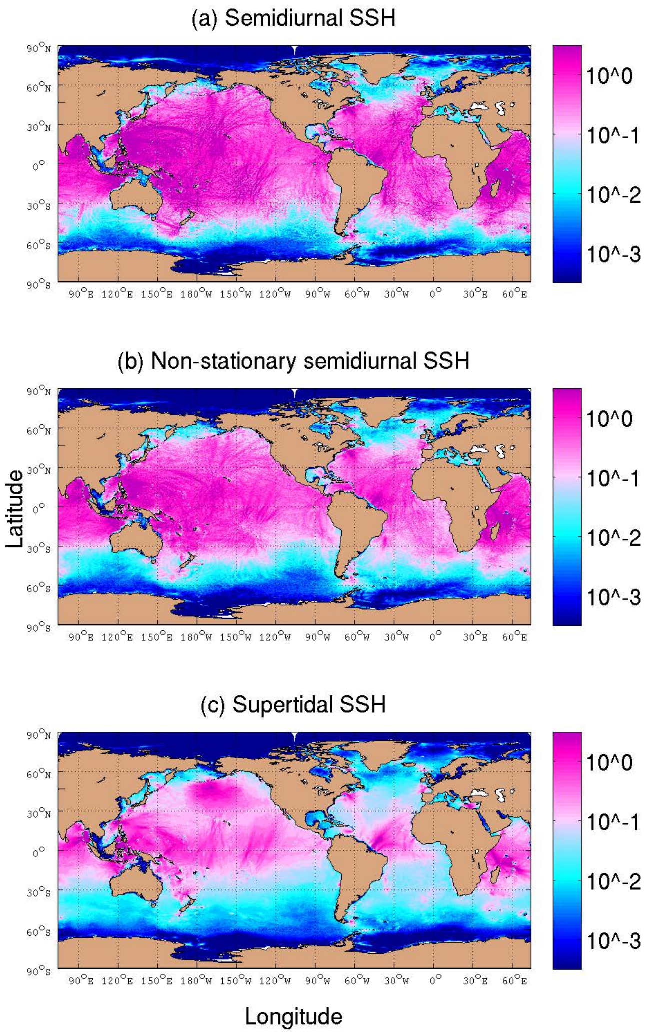
We now realize that the model has an IGW continuum and that the continuum impacts the wavenumber spectra

See also Rocha et al. (2016)

Quantifying the global IGW SSH variance with frequency spectra

- Much faster to work with than frequency-horizontal wavenumber spectra
- Steric component separates out small scales

Preliminary steric SSH variance (cm^2) from one year of 1/25° HYCOM (Savage et al., in preparation)



Area-weighted values in deep ocean

Total semidiurnal tides
1.33 cm^2

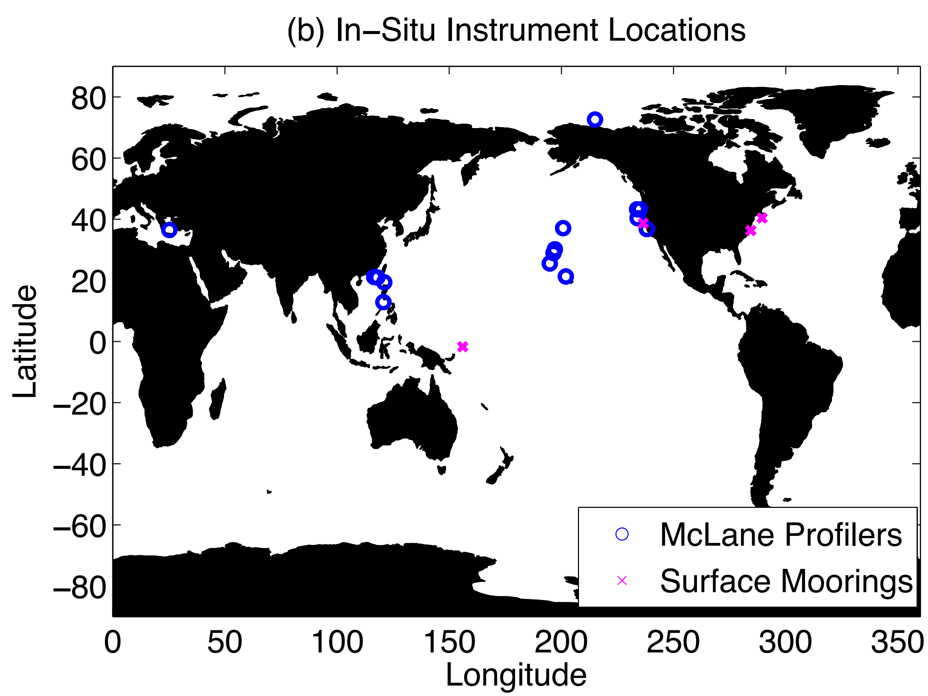
Non-stationary semidiurnal tides
0.67 cm^2

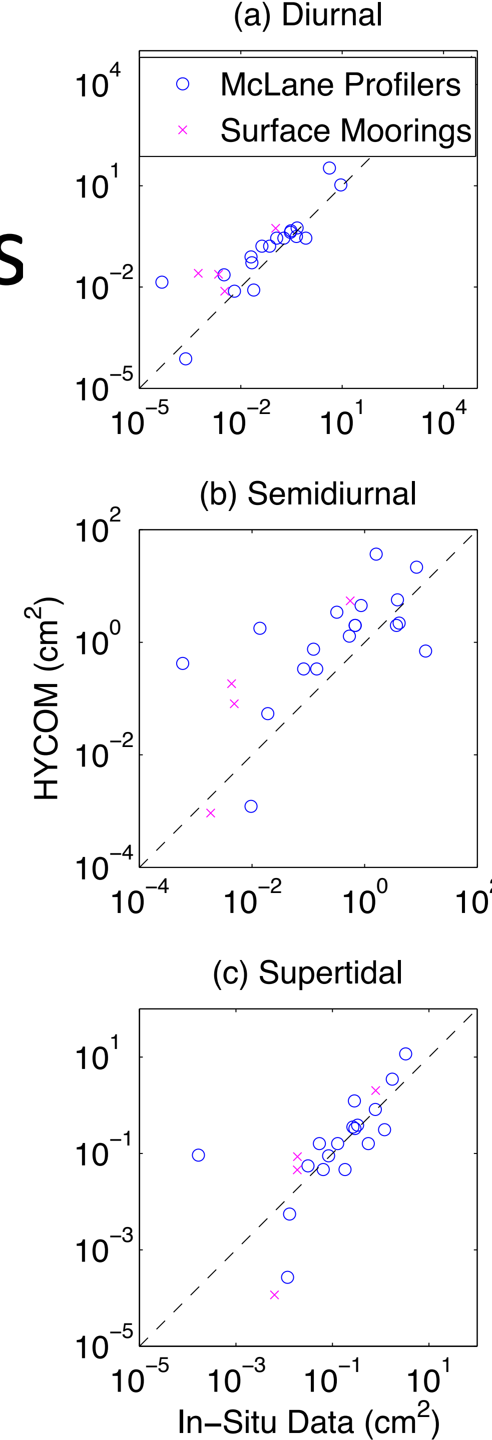
Supertidal internal gravity wave continuum
0.26 cm^2

Coherent internal tides, incoherent internal tides, and the internal gravity wave continuum all have substantial SSH signatures

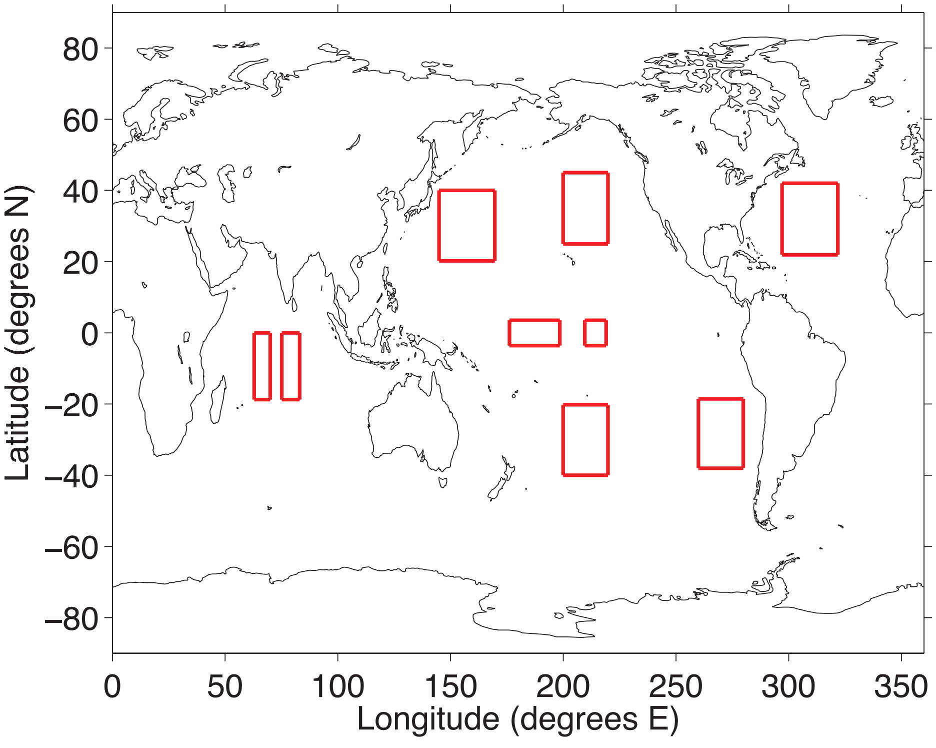
Preliminary Steric SSH in 1/25° HYCOM vs. In-Situ Observations

Computed from frequency spectra for now, but frequency-wavenumber spectra will be done very shortly after this meeting in collaboration with Tom Farrar and Matthew Alford

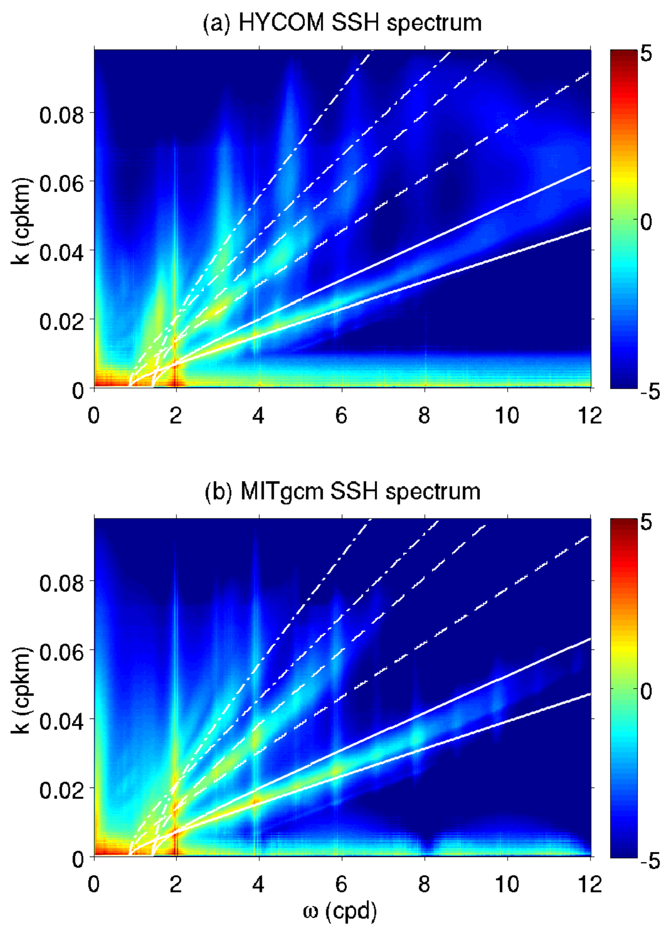




Boxes for horizontal wavenumber/ frequency analyses of HYCOM/ MITgcm

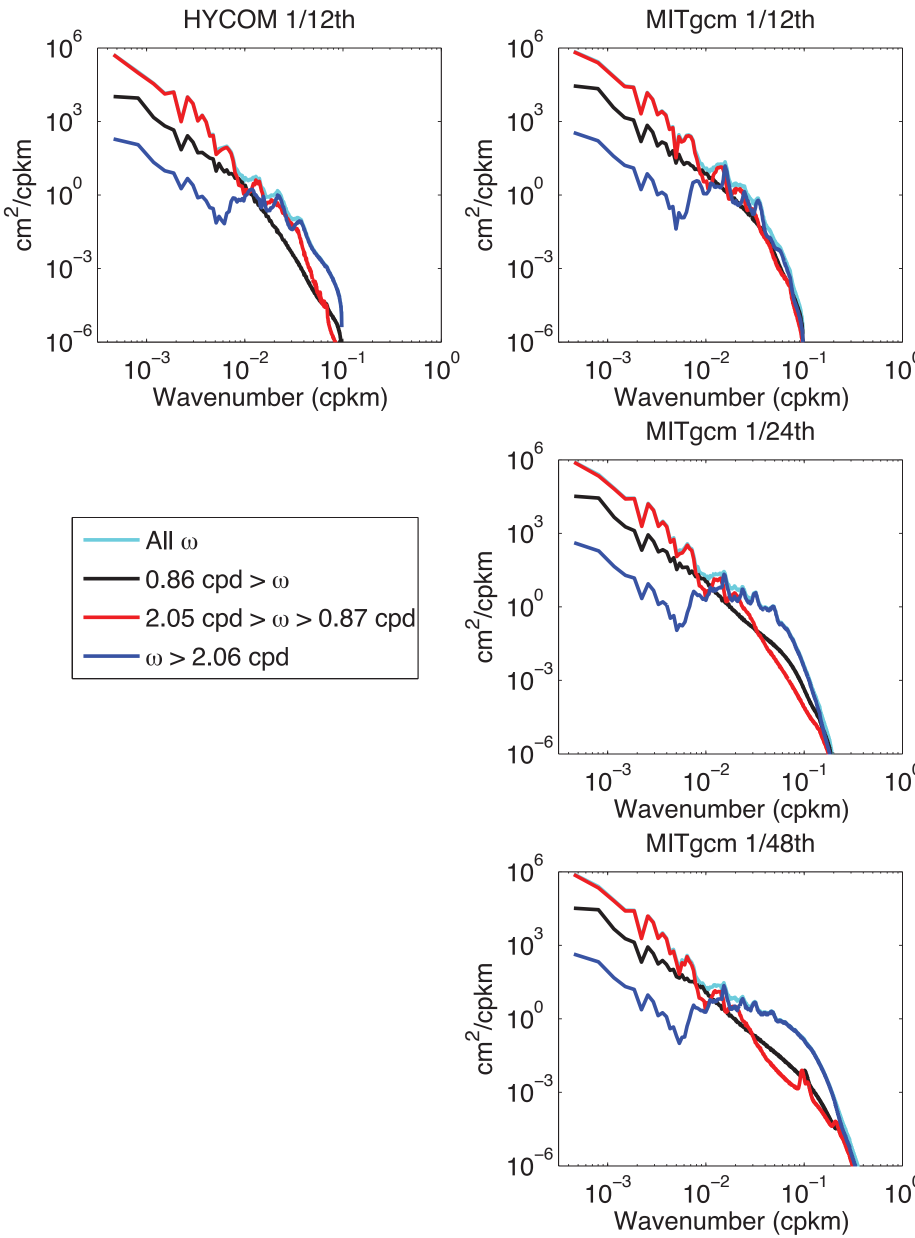


Preliminary North Pacific horizontal wavenumber-frequency spectrum of SSH variance in 1/12.5° HYCOM and 1/12° MITgcm (Savage et al. in preparation)

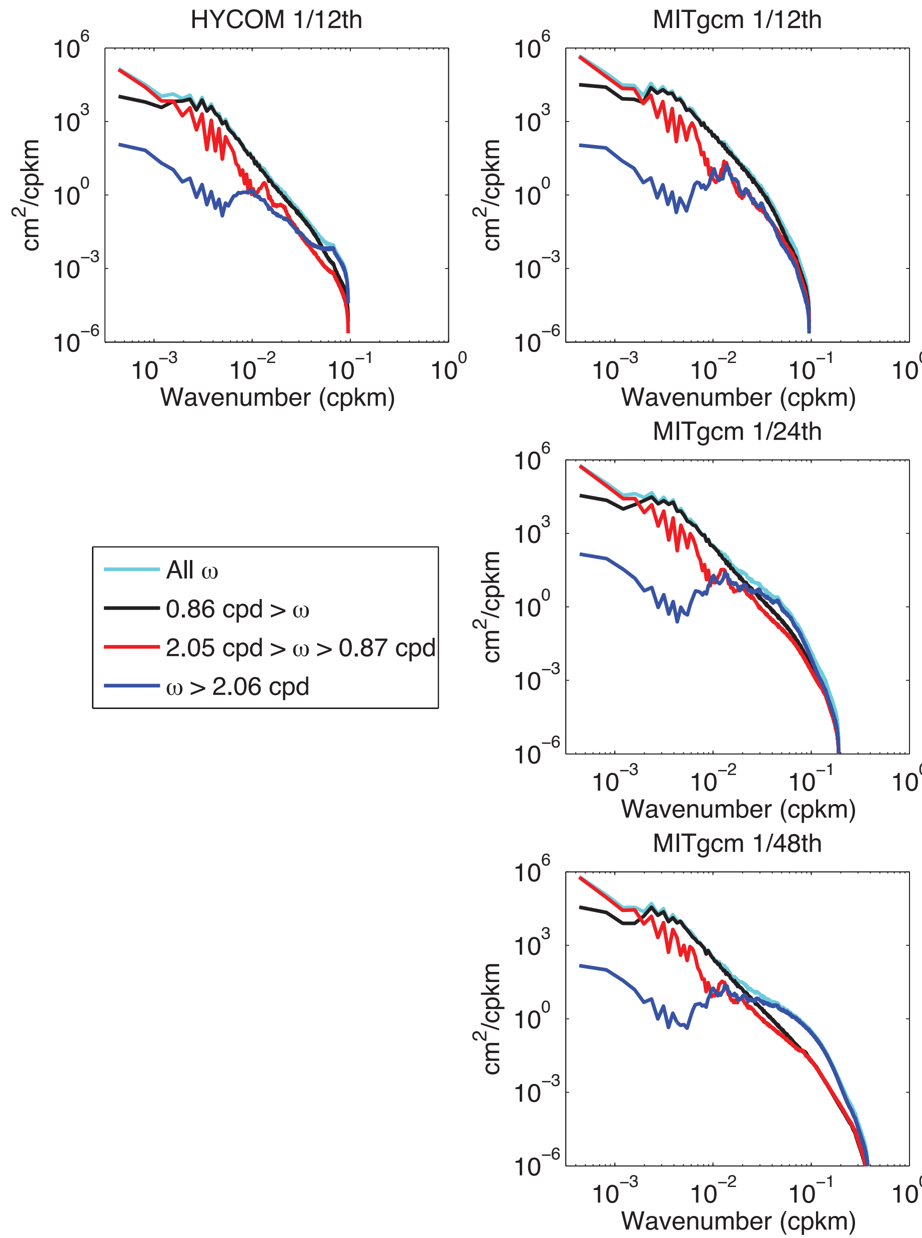


Spectral units are $\log_{10}$ [cm^2 / (cpd)(cpkm)]

Preliminary SSH wavenumber spectra in North Pacific (Savage et al., in preparation)



Preliminary SSH wavenumber spectra in Kuroshio (Savage et al., in preparation)



Where is this kind of work headed?

- Increasing computer power → solutions move closer to observations

- How big can the simulations get? Are we as ocean modelers at the cutting edge of supercomputing technology?

Cutting edge in geophysical simulations. Way ahead of us.

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IBM

Gordon Bell Prize Awarded for Most Realistic Simulation of the Dynamics of Earth's Interior to Date; Opens Path to Better Understanding of Earthquakes and Volcanoes

IBM POWER supercomputer simulated the entire Earth's mantle and plate motion efficiently

Nov 20, 2015, 12:06 ET from IBM

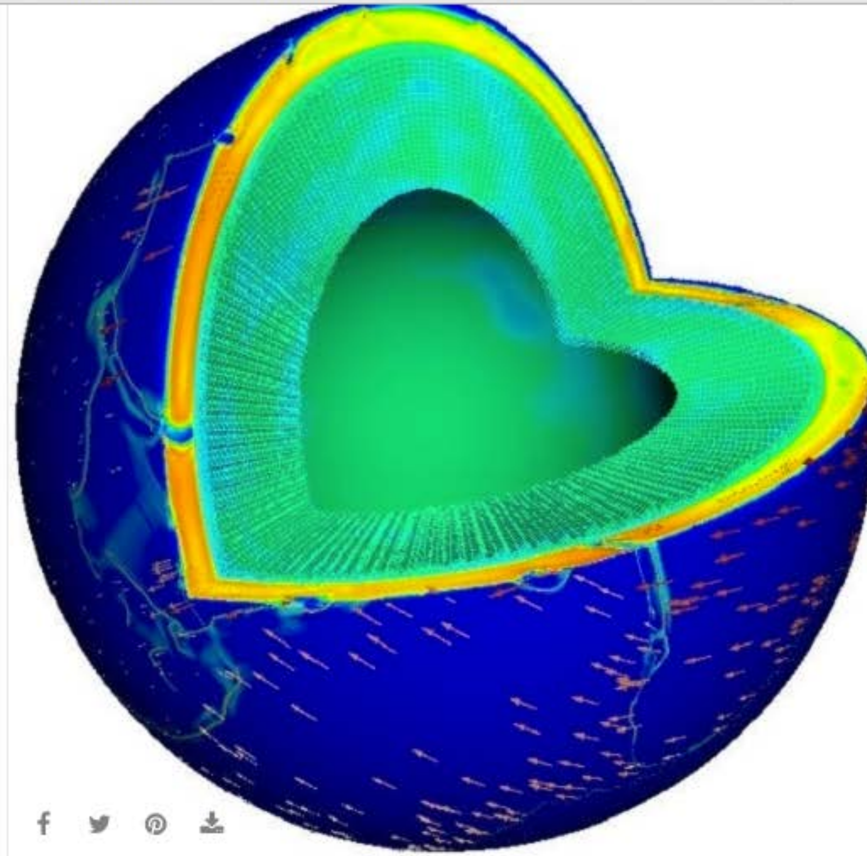
AUSTIN, Texas, Nov. 20, 2015 /PRNewswire/ -- Scientists at the University of Texas at Austin, IBM Research (NYSE: IBM), New York University and the California Institute of Technology have been awarded the 2015 Gordon Bell Prize for realistically simulating the forces inside the Earth that drive plate tectonics. The team's work could herald a major step toward better understanding of earthquakes and volcanic activity.

www.prnewswire.com/news-releases/gordon-bell-prize-awarded-for-most-realistic-simulation-of-the-dynamics-of-earths-interior-to-date-o...

algorithms for a mathematical approach called an "implicit solver" to realistically simulate Earth features at unprecedented resolution and accuracy. The team was able to predict the motions of the Earth's plates and the forces acting on them while also simulating the flow of mantle. Remarkably, the simulation involved more than 600 billion nonlinear equations, a major milestone in computational science and engineering

The simulations were performed on Sequoia, which consists of 96 IBM BlueGene/Q racks, reaching a theoretical peak performance of 20.1 petaflops. Each rack consists of 1,024 computer nodes, hosting 16 core POWER processor chips designed for Big Data computations that are running at 1.6 GHz.

The team's code reached an unprecedented 97 percent parallel efficiency in scaling the solver to 1.6 million cores, a new world record. This milestone was achieved by rethinking the end-to-end computational framework, from the mathematical model to the numerical algorithms to the massively parallel implementation. The team devised a numerical algorithm that could tackle the vast range of scales present in Earth's mantle while also mapping efficiently to the massively parallel architecture of the BlueGene/Q supercomputer.



Scientists at IBM Research, the University of Texas at Austin, New York University and the California Institute of Technology have been awarded the 2015 Gordon Bell Prize for realistically simulating the forces inside the Earth that drive plate tectonics. The work paves the way toward better understanding of earthquakes and volcanic activity. The accomplishment was made using 1.6 million cores on the 96 racks of "Sequoia" - the IBM BlueGene/Q system located at the Lawrence Livermore...

What could we do with regular access to 1.6 million cores?

- Dimitris Menemenlis MITgcm simulation
  - 50,000 cores → global 1/50°, 90 z-levels
- With 1.6 million cores we could do global 1/100°, 300 z-levels
  - Push farther into submesoscale regime
  - Push farther into IGW spectrum

Last topic…model intercomparisons and ground truthing

- Both internal tide/wave models and SWOT must be compared with in-situ data as well as each other.
- The SWOT Cal/Val offers a big opportunity.
- Another effort that could be considered is to put out small arrays around the world ocean to validate global internal tide/wave models
  - Inspired to some extent by bottom pressure recorder arrays (Ray 2013) used to validate global barotropic tide models as in Stammer et al. (2014)

EXTRA SLIDES

Impact of model resolution on vertical wavenumber spectrum

Vertical wavenumber spectrum of high-passed potential density variance over 90-1388 db from MITgcm and from Matthew Alford's McLane profiler data at a North Pacific location near Hawai'i.

Extra dashed line denotes Garrett-Munk m^{-2} prediction..

Have begun discussions with Dimitris Menemenlis and Chris Hill to perform MITgcm simulations with even higher resolution in regions where McLane profiler data exists.