Global modeling of the oceanic internal gravity wave spectrum

USING: Realistic HYCOM and MITgcm Simulations

Workshop on “Scales and scaling cascades in geophysical systems”, Hamburg, 2018

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Before I begin talking about research…

- Dedication
- Educational/outreach work in Africa

Dedication
Joel Bernard Arbic
April 11, 1969-December 2, 2017

FAMILY


Brian and Joel, Dec 1969


Dan, Brian, Joel, Mom, Dad, late 1980s


Joel, Shantala, Rowan, Remy, 2017

OUR OUTDOOR TRIPS


Virgin River Narrows, Zion, 1997


Top of Half Dome, Yosemite, 1998


Austrian Alps, 2005

18 MONTH AROUND-THE-WORLD TRIP WITH SHANTALA


Namibia, 2007


Machapuchare Base Camp, Himalayas, 2008


Borneo, 2008

Oceanography in Africa…

- I’d like to see more African oceanographers, and other scientists, in international meetings.
- I’m running a school in Africa that arises from my history there…

Teaching in Ghana a long time ago…

Form 5 Science Class

Damongo Secondary School

1992

The Coastal Ocean Environment Summer School in Ghana (coessing.org)

First summer school held in August 2015, at Regional Maritime University

The Coastal Ocean Environment Summer School in Ghana (coessing.org)

Second summer school held in August 2016, at University of Ghana

The Coastal Ocean Environment Summer School in Ghana (coessing.org)

Third summer school held in August 2017, at Regional Maritime University

2018 School

- Will be held at University of Ghana
- Will include European participation
  - Riccardo Farneti of ICTP, which is providing substantial funding

Back to internal gravity waves…

Background: Relevance of global internal tide and IGW continuum models

- Mixing: Global models can provide clues about the geography of mixing due to breaking internal tides and internal gravity waves (IGWs).
- Operational oceanography: Internal waves impact acoustics and other operational considerations.
- Altimetry: Internal waves yield a measurable sea surface height (SSH) signal in altimetry. Global IGW models can help to map the geography of
  - Stationary internal tides.
  - Non-stationary internal tides, caused by temporal changes in stratification and interaction with mesoscale eddies.
  - The supertidal IGW continuum.
- Science questions: Global models may help us to understand IGWs better.
  - **How does the IGW spectrum develop?**
  - Is energy transferred between IGWs and low-frequency mesoscale eddies?

Background: Global internal tide and IGW continuum modeling

- **Classical paradigm of IGW continuum**
  - Fluctuating winds drive near-inertial waves
  - Barotropic tidal flow over rough topography yields internal tides
  - **Nonlinear triad interactions fill out the IGW continuum spectrum, i.e. the Garrett-Munk spectrum**
- → Global modeling of IGW continuum requires
  - high-frequency wind forcing
  - tidal forcing
  - high resolution (to allow nonlinear interactions)
  - background stratification

Some (selected) key recent steps

- Global internal tide modeling in Hallberg Isopycnal Model (Arbic et al. 2004, Simmons et al. 2004)
- Tidal + atmospheric forcing in high-resolution (1/12.5°) HYbrid Coordinate Ocean Model (HYCOM) simulations (Arbic et al. 2010)
- Continued improvements in HYCOM
  - wave drag tuning
    - wave drag controls HYCOM internal tidal amplitudes (Ansong et al. 2015)
  - many comparisons to observations
  - horizontal resolution increased to 1/25°
  - data-assimilative machinery for eddies
  - Augmented State Ensemble Kalman Filter (ASEnKF) to improve tidal accuracy
- Tidal + atmospheric forcing in 1/48° global MITgcm simulations

Animations

Review chapter in Chassignet, Pascual, Tintore, Verron GODAE 2018 volume

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

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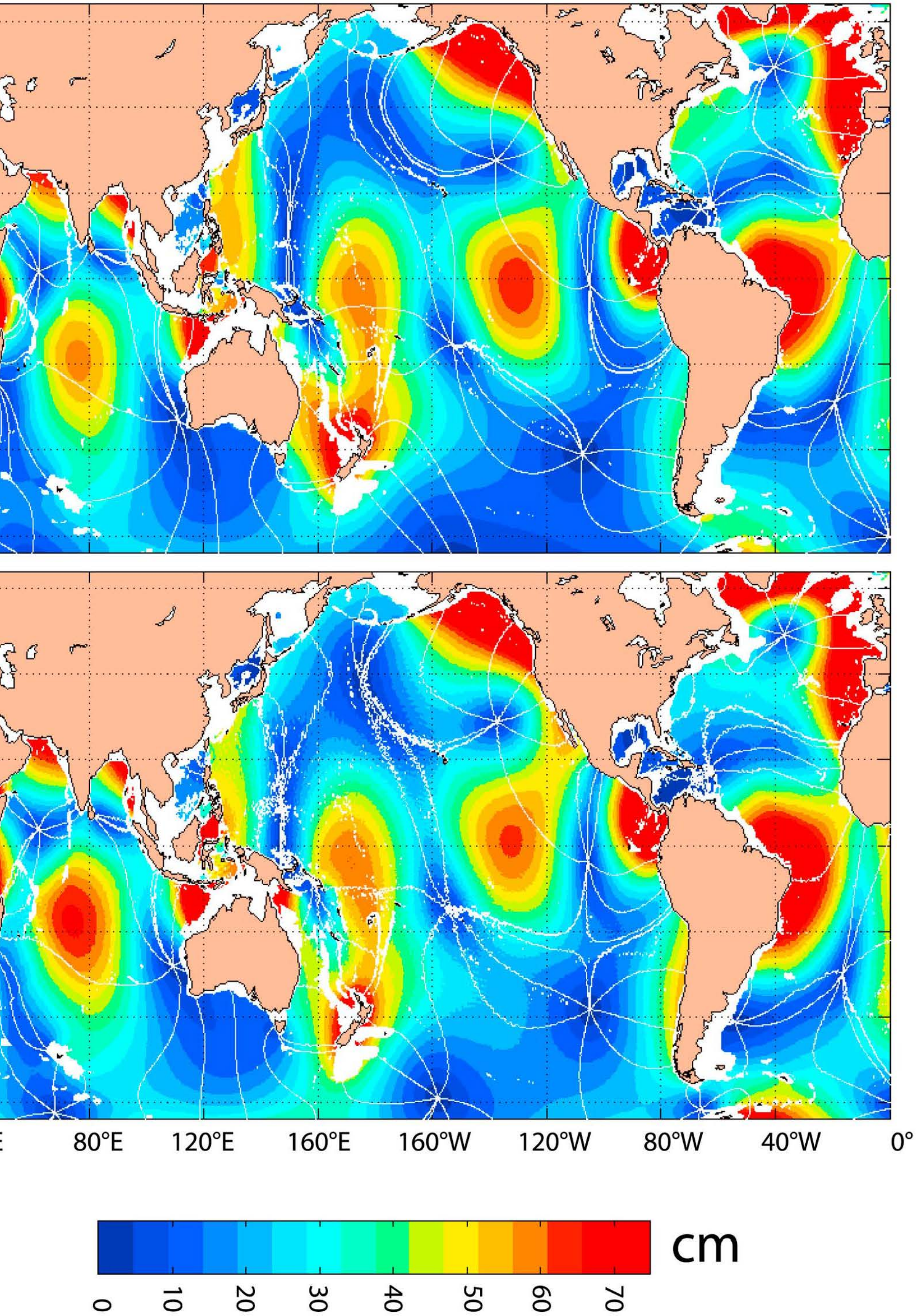
In recent years, high-resolution ("eddying") global ocean general circulation models have begun to include astronomical tidal forcing alongside atmospheric forcing. Such models can carry an internal tide field with a realistic amount of non-stationarity, and an internal gravity wave continuum spectrum 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 understanding satellite altimeter observations. Here we describe the most important technical details behind such models, including astronomical tidal forcing, parameterized topographic internal wave drag, self-attraction and loading, and the need for high horizontal and vertical resolution. 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, nonstationary

Model-data comparisons

- We start with comparisons to altimetry

M_2 SSH amplitude and phase

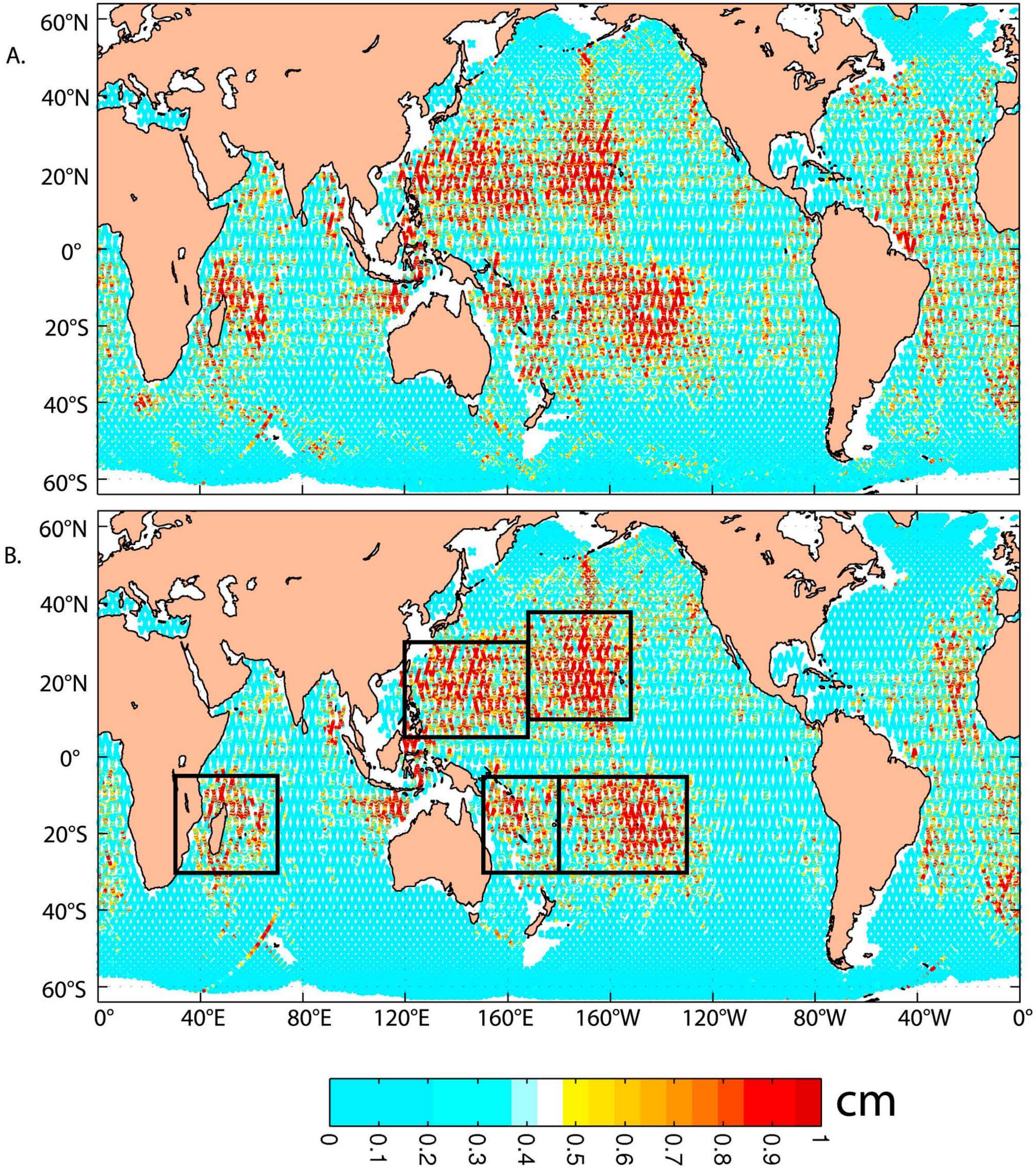


←TPXO (a highly accurate satellite-altimeter comstrained tide model)

←HYCOM results show many similarities to TPXO but also many differences

Shriver et al. (2012)

Stationary internal tides in HYCOM



Stationary M_2 internal tide SSH amplitude

Determined by high-passing amplitudes of total M_2 SSH (as in Ray and Mitchum 1996)

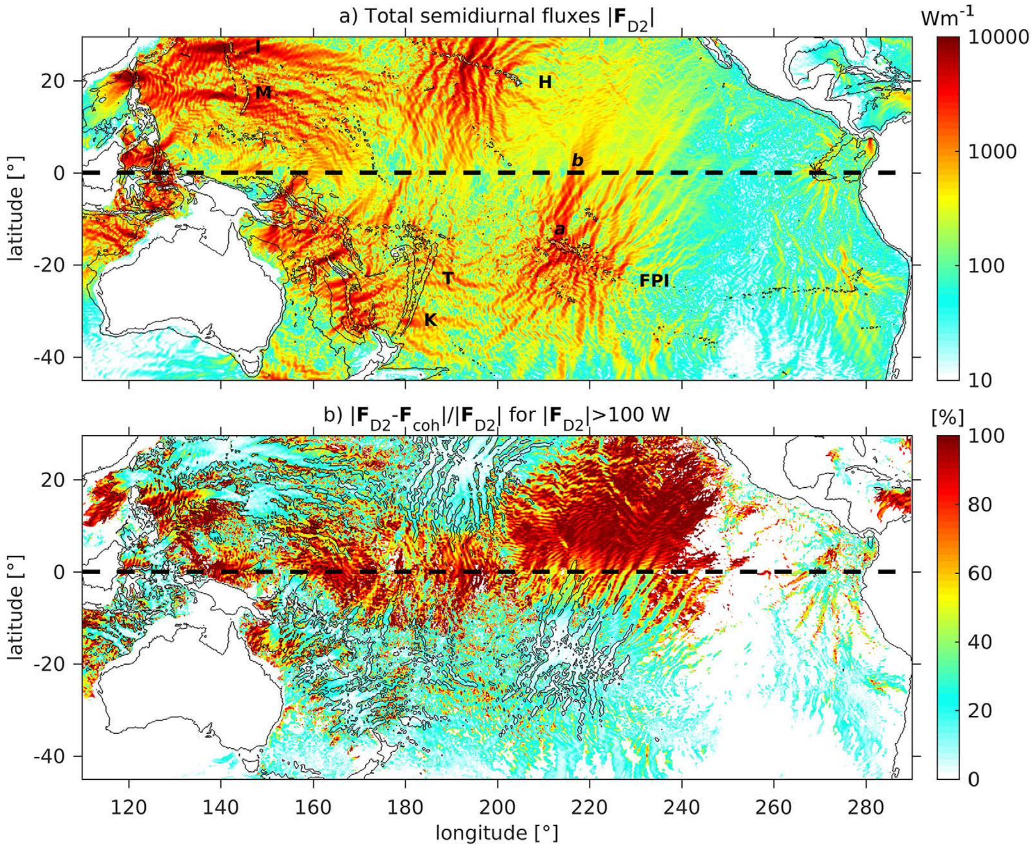
←Along-track altimeter data

←HYCOM patterns are grossly similar; noticeable differences in Atlantic

NOTE "dead spot" in equatorial Pacific in both plots

Shriver et al. (2012)

Internal tide non-stationarity



Near-equatorial Pacific semidiurnal energy fluxes in HYCOM

←Semidiurnal band fluxes radiating from the French Polynesian islands cross the equator.

←But ratio of incoherent/total flux increases greatly as one crosses the equator.

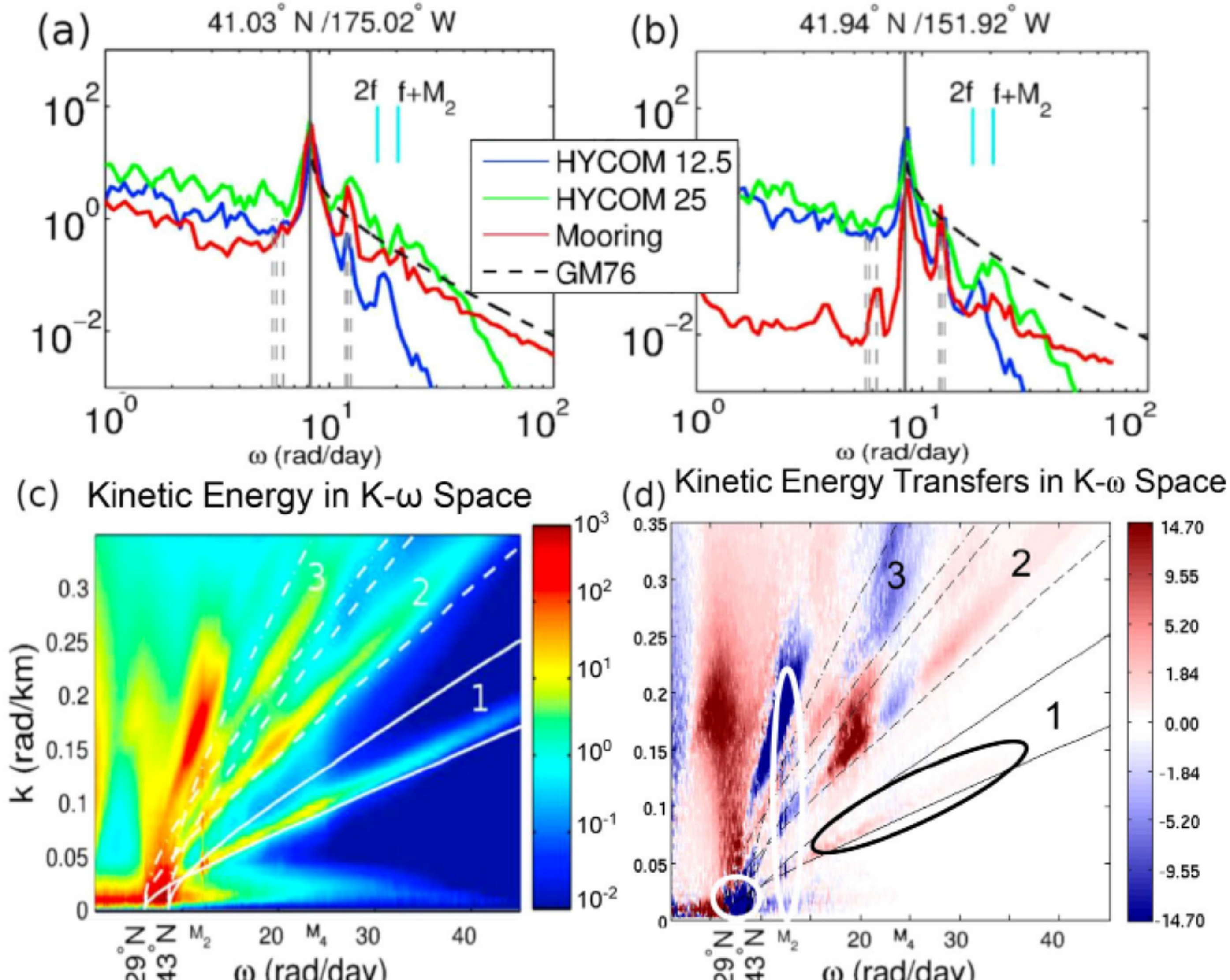
Incoherence is due to scattering by equatorial jet.

Buijsman et al. (2017)

IGW continuum

- Müller et al. (2015) -- first evidence for partial IGW continuum in global models (HYCOM)
- Rocha et al. (2016a,b)– continuum is also present in MITgcm
- Savage et al. (2017b), in preparation papers led by Ansong, Luecke—compare HYCOM and MITgcm with each other and observations

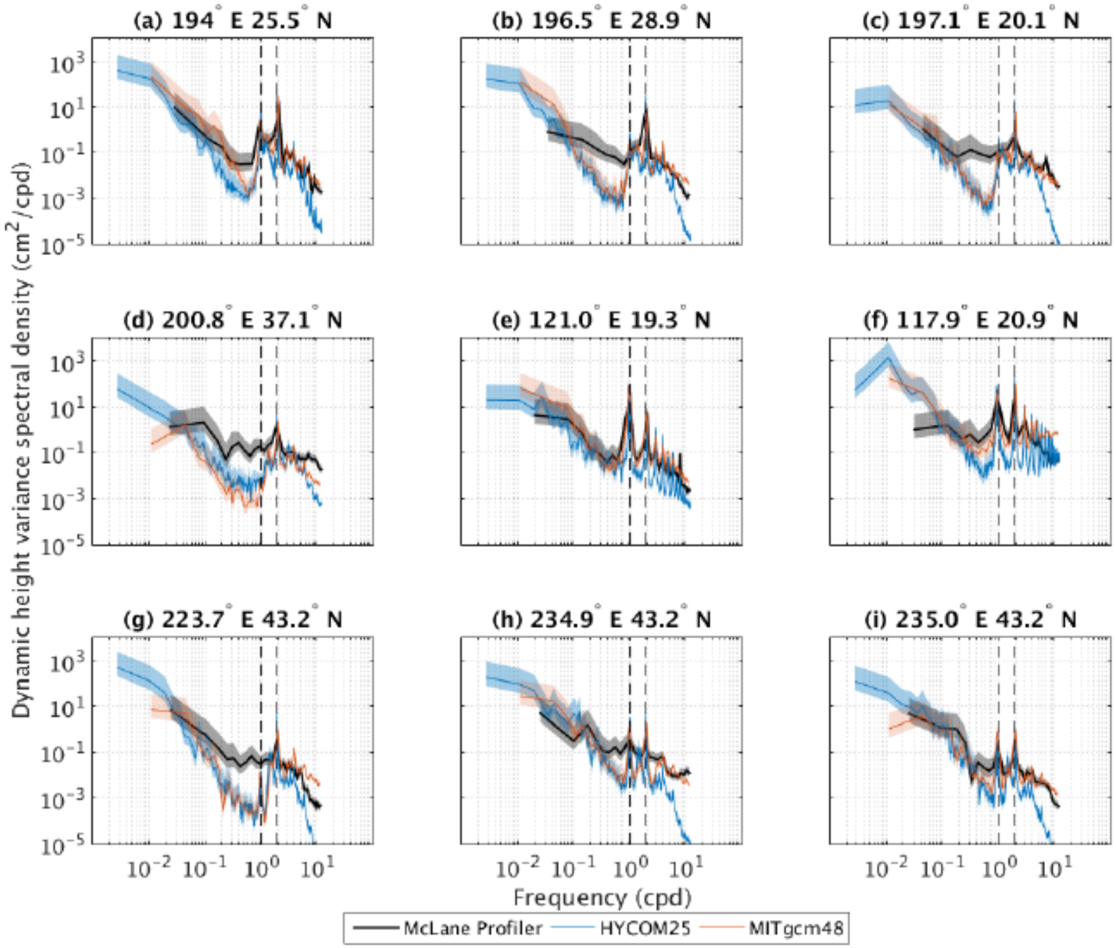
First evidence of IGW continuum in such models—analysis of suface kinetic energy in North Pacific region of global HYCOM (Müller et al. 2015; updated figure from Savage et al. 2017a)



Comparison to McLane profiler observations

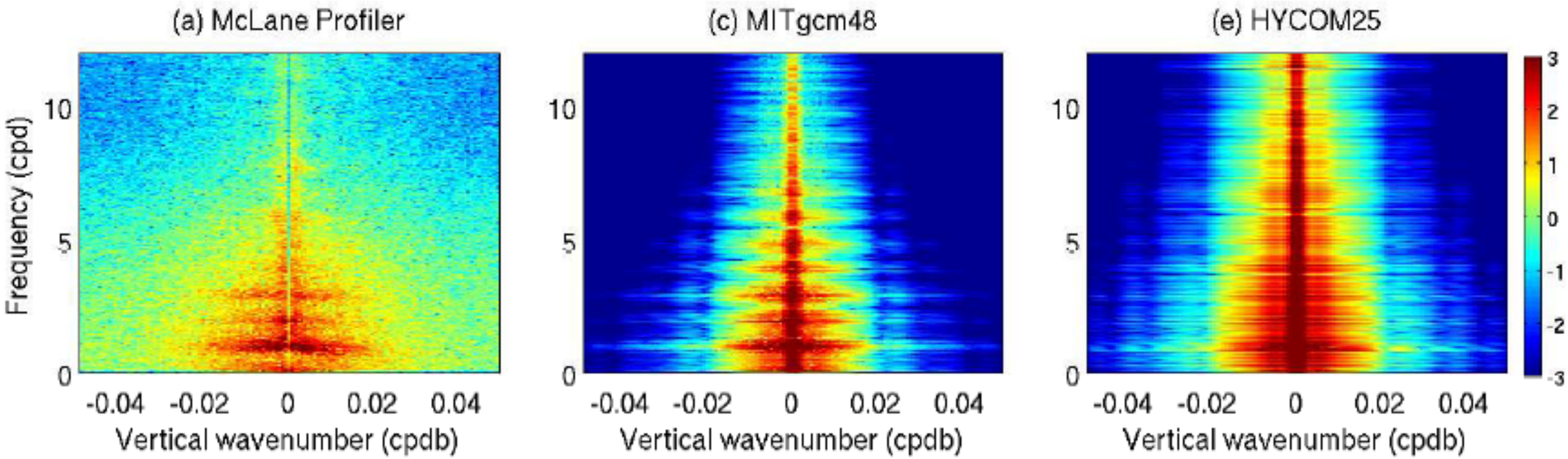
- Moored instruments can produce time series.
- Traditionally, moorings have a few instruments at selected depths.
- McLane profilers crawl up and down in the vertical direction.
- In “high-frequency mode”, the data can be interpolated in time and depth to produce a record with high resolution in both time and depth.

Dynamic height variance frequency spectra in 9 Pacific Ocean McLane profilers, 1/25° HYCOM, and 1/48° MITgcm



Savage et al. (2017b)

IGW kinetic energy vertical wavenumber-frequency spectra

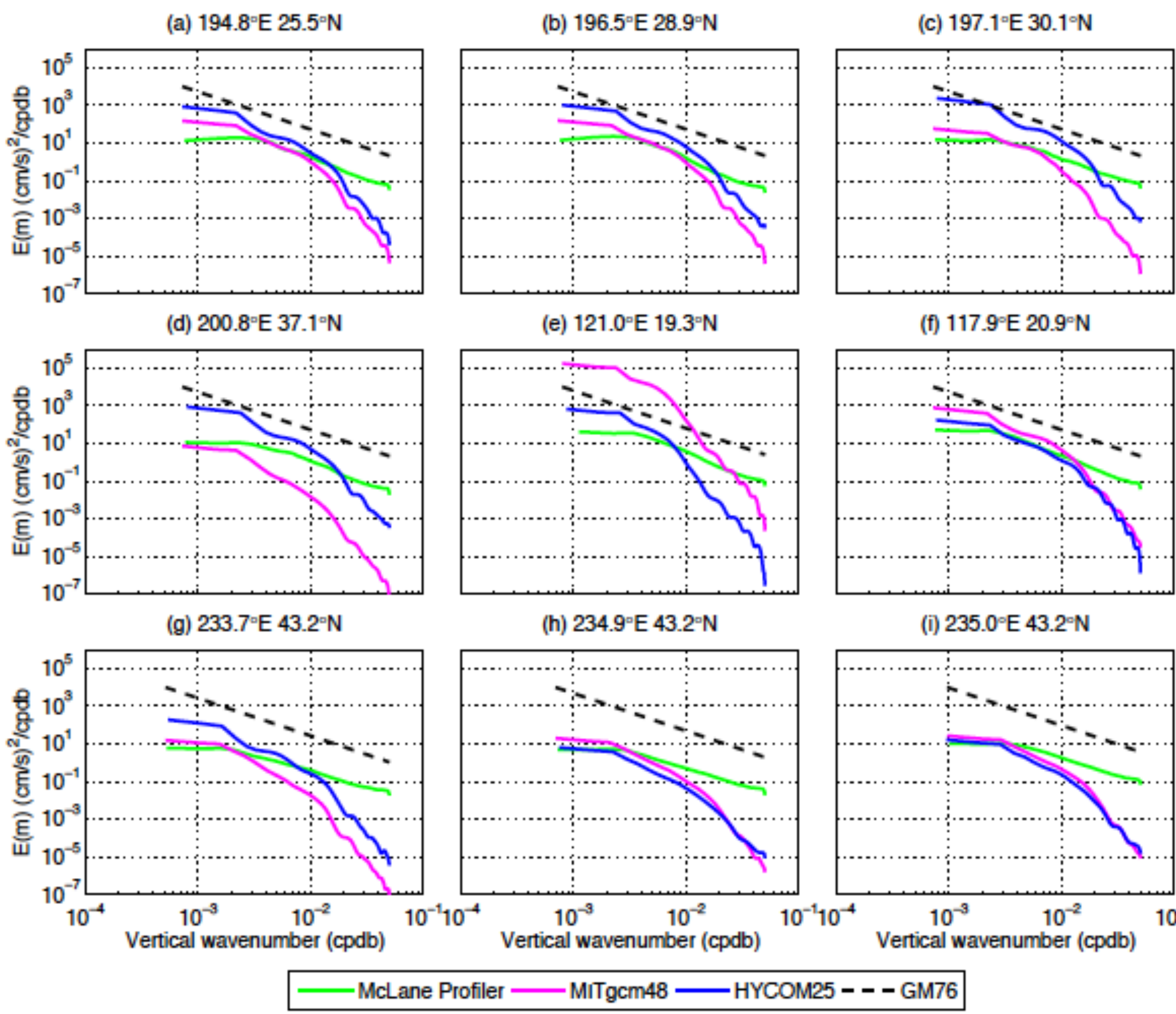


From McLane profiler, 1/48° MITgcm, and 1/25° HYCOM.

121.0°E, 19.3°N

Ansong et al. in preparation

IGW kinetic energy vertical wavenumber spectra



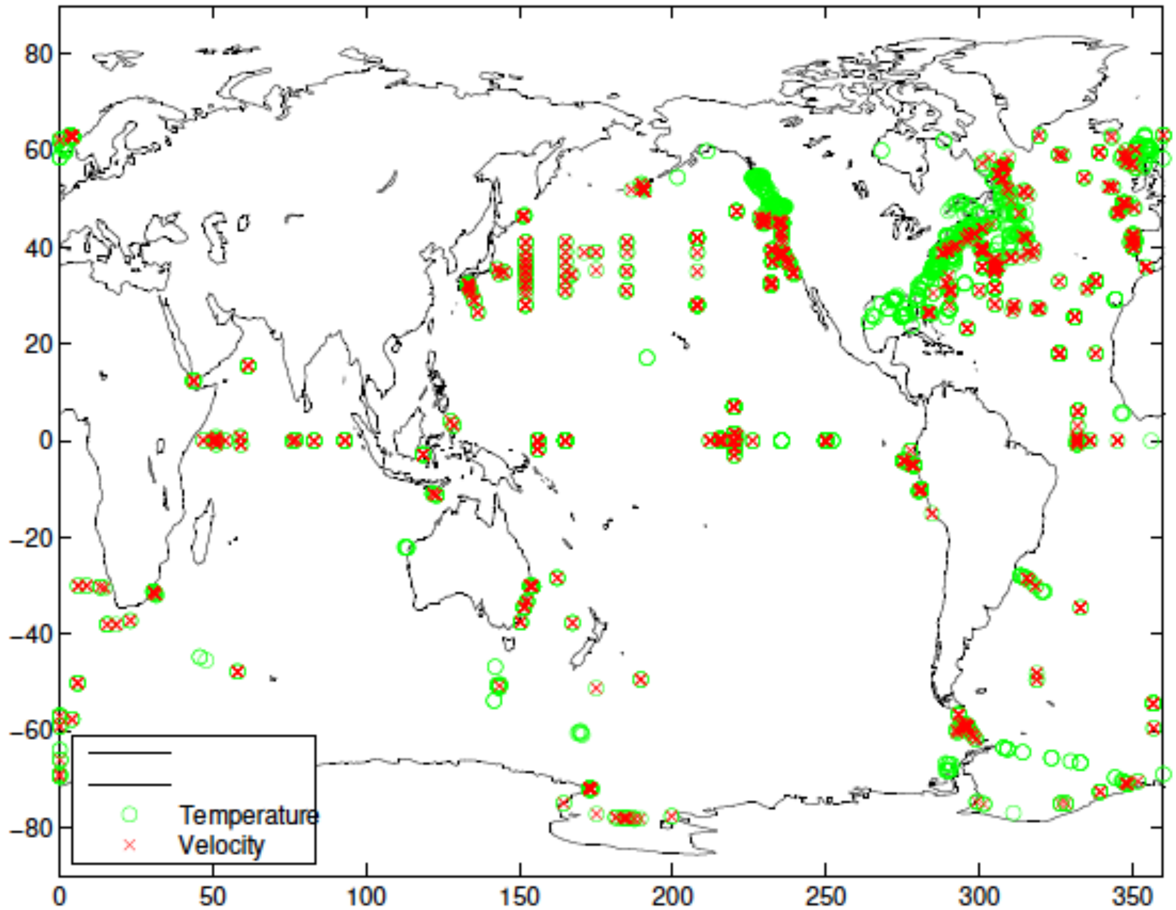
From McLane profilers, 1/48° MITgcm, and 1/25° HYCOM

Ansong et al. in preparation

Comparison to historical mooring records

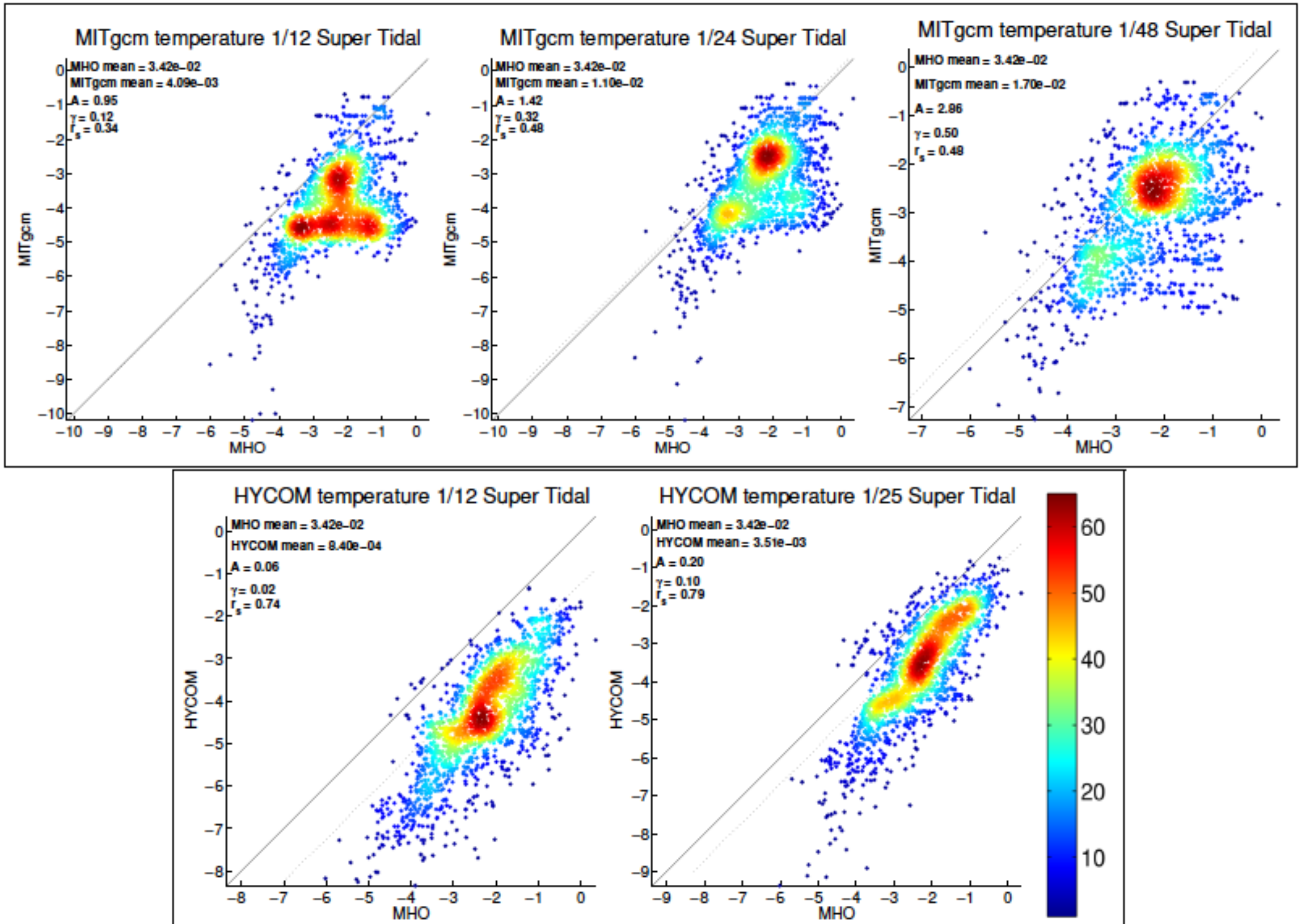
- **NOTE TO SELF: SKIP THESE SLIDES IF SHORT ON TIME**

Locations of (thousands of) historical moored temperature and velocity time series observations



Luecke et al., in preparation

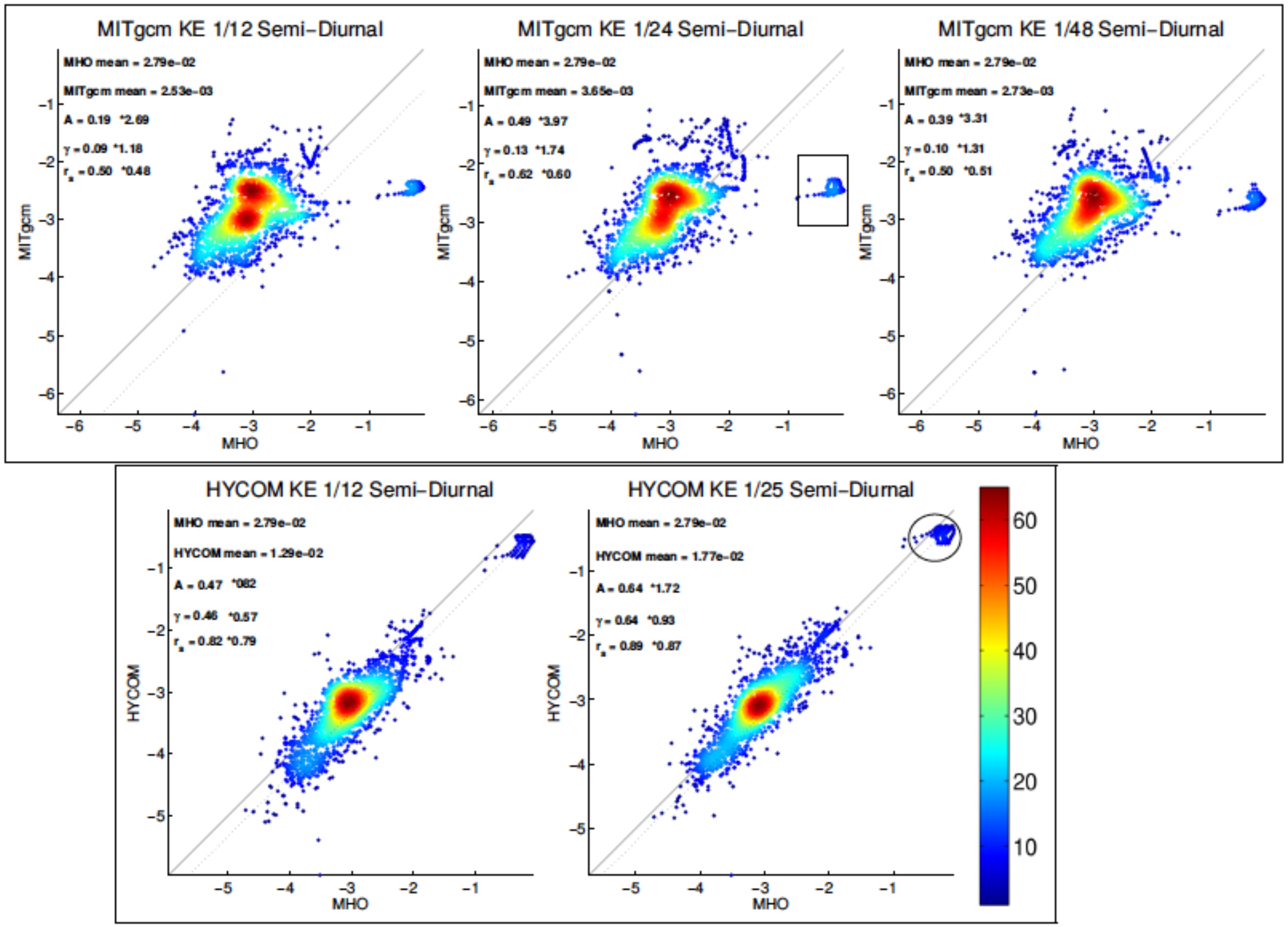
Band-integrated supertidal temperature variance in MITgcm and HYCOM vs. MHO (moored historical observations). Luecke et al., in preparation.



Units are $\log_{10}[(°C)^2]$

HYCOM levels are too low but show higher spatial correlations in this and most other frequency bands

Band-integrated semidiurnal kinetic energy in MITgcm and HYCOM vs. MHO (moored historical observations). Luecke et al., in preparation.

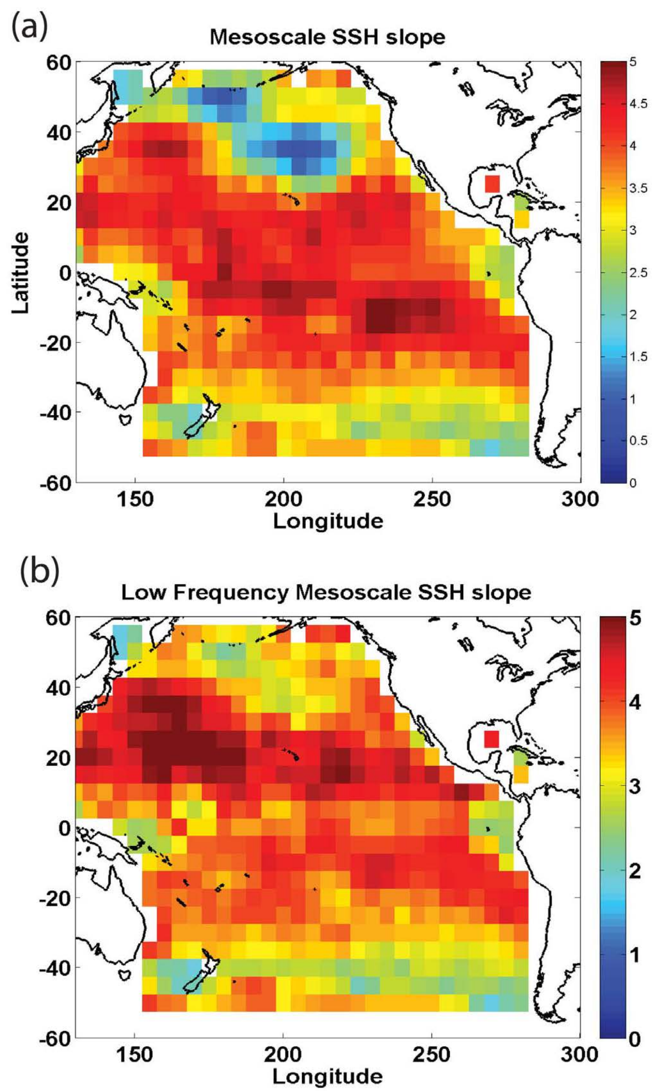


Units are $\log_{10}[(m/s)^2]$

Again HYCOM shows higher spatial correlations.

Very strong velocities some near-land regions such as Strait of Gibraltar (shown here) not handled well in MITgcm.

Relevance for SSH wavenumber spectrum and altimetry



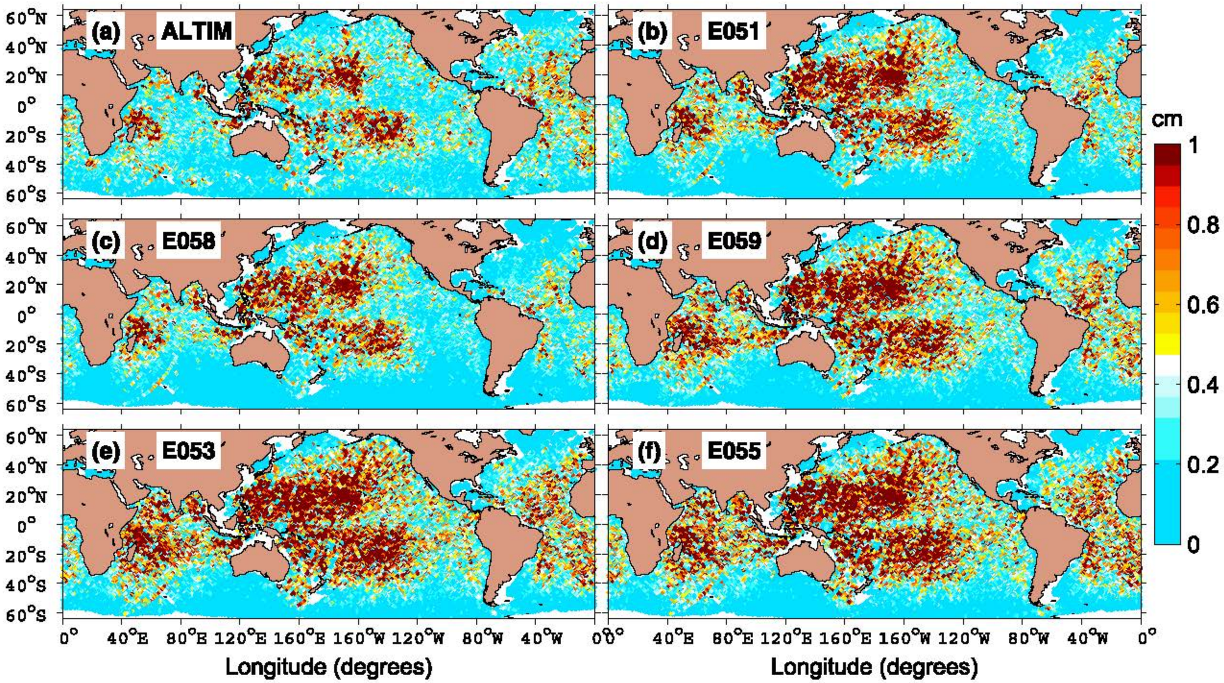
The slope of the wavenumber spectrum is flatter with internal waves (k^{-2}) present.

→Will make it more difficult to compare SWOT data with geostrophic turbulence theories, which suggest k^{-5} / $k^{-11/3}$ spectra for interior/surface quasi-geostrophic theory, respectively.

Richman et al. (2012)

See also Callies and Ferrari (2013), Rocha et al. (2016a), Savage et al. (2017b), Qiu et al. (2017)

Wave drag and internal tide damping



Global maps of M_2 internal tide SSH amplitudes in HYCOM simulations with different drag scenarios, vs. along-track altimetry.

HYCOM amplitudes are too large in simulations with wave drag applied only to barotropic flow (d) or with no wave drag at all (e,f) than in simulations with wave drag (b, and especially c, where the wave drag is stronger).

→Some damping of low mode internal tides is needed for agreement with altimetry.

Currently in HYCOM we damp with a wave drag. But in actual ocean there are likely other mechanisms.

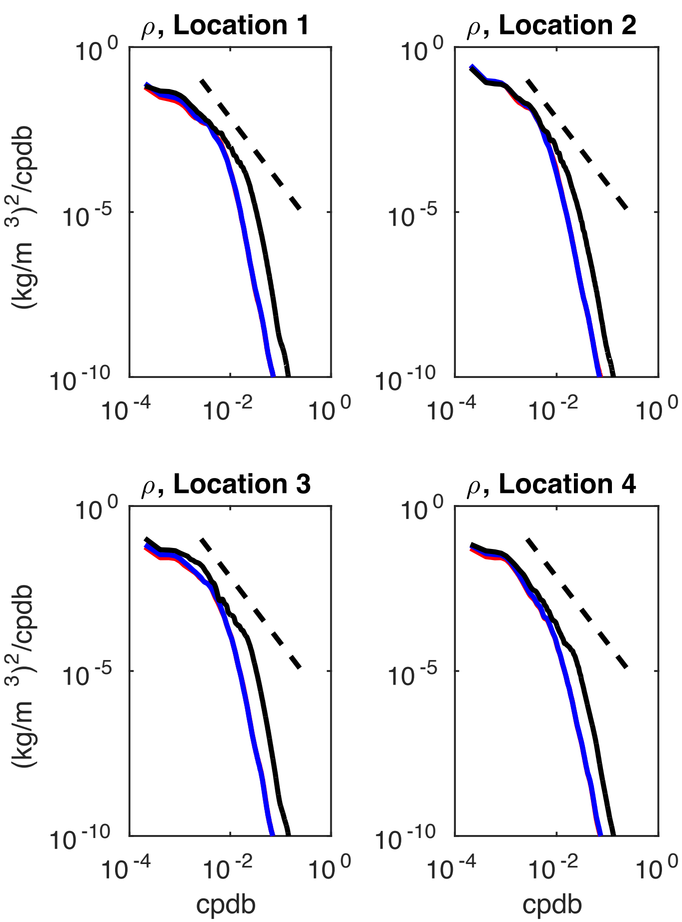
Ansong et al. (2015)

Improving tides in HYCOM

- Wave drag tuning
- Taking advantage of the “back-effect” of large coastal tides upon open-ocean tides (Arbic et al. 2007, 2009; Arbic and Garrett 2010)
  - Two-way nesting in regions of strong coastal tides
  - Targeted ASEnKF perturbations in such regions

Boundary forcing very-high resolution regional simulations

Impact of vertical and horizontal resolutions on vertical wavenumber spectra (Arbic et al., in preparation; collaboration with Dimitris Menemenlis, Arin Nelson, Dick Peltier, and others)



Vertical wavenumber spectra E(m) of 1-4911 db neutral density variance in MITgcm simulations at 4 locations with McLane profiler data (data not shown yet).

Red is from the global 1/48° MITgcm simulation.

Blue is from a regional simulation, boundary forced by the global simulation, with identical vertical and horizontal resolutions.

Black is from a regional simulation, with 8 times higher horizontal resolution (250 m) and 3 times higher vertical resolution (264 z-levels).

Extra dashed lines indicate predicted m^{-2} slope.

Currently running on Niagara supercomputer at University of Toronto.

Summary

- High-resolution simulations of HYCOM and MITgcm, with simultaneous atmospheric and tidal forcing, carry
  - stationary internal tides
  - non-stationary internal tides
  - partial IGW continuum
- Comparison of simulations to observations and to theoretical predictions is ongoing.
- The 1/48° MITgcm simulation is being used to boundary force very-high-resolution regional patches.

Challenges for the future

- This kind of modeling still very new, with many remaining challenges
  - How far can we get into the IGW (and mesoscale/submesoscale) spectrum with global models and how do we go the "rest of the way"—downscaling to regional models? Other methods?
  - Can global hydrodynamical models correct for any of the high-frequency signals—stationary internal tides, non-stationary internal tides, supertidal IGW continuum--relevant for altimetry?
  - How should we damp internal tides and the IGW continuum spectrum? How does this relate to the energy exchanges between IGWs and balanced motions?
  - How do we go beyond saying "These models have implications for mixing" to actually doing something quantitative?
  - **Can such models be used to study how the IGW continuum spectrum develops? Can theoreticians help us out here?**