Global modeling of internal tides and the internal gravity wave continuum spectrum

USING: Realistic HYCOM and MITgcm Simulations

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Background: Relevance of global internal tide and IGW continuum models

- Mixing: Breaking internal tides and internal gravity waves (IGWs) lie behind most sub-mixed layer ocean mixing.
- Operational oceanography: Internal waves impact acoustics and other operational considerations.
- Altimetry: Internal waves yield a measurable sea surface height (SSH) signal in altimetry.
  - Mapping/removing stationary internal tides will be challenging.
  - Non-stationary internal tides, and the supertidal IGW continuum, will be even more challenging.

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 (e.g., Dushaw et al. 1995, Ray and Mitchum 1996, 1997)
  - Nonlinear 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), and a background stratification.

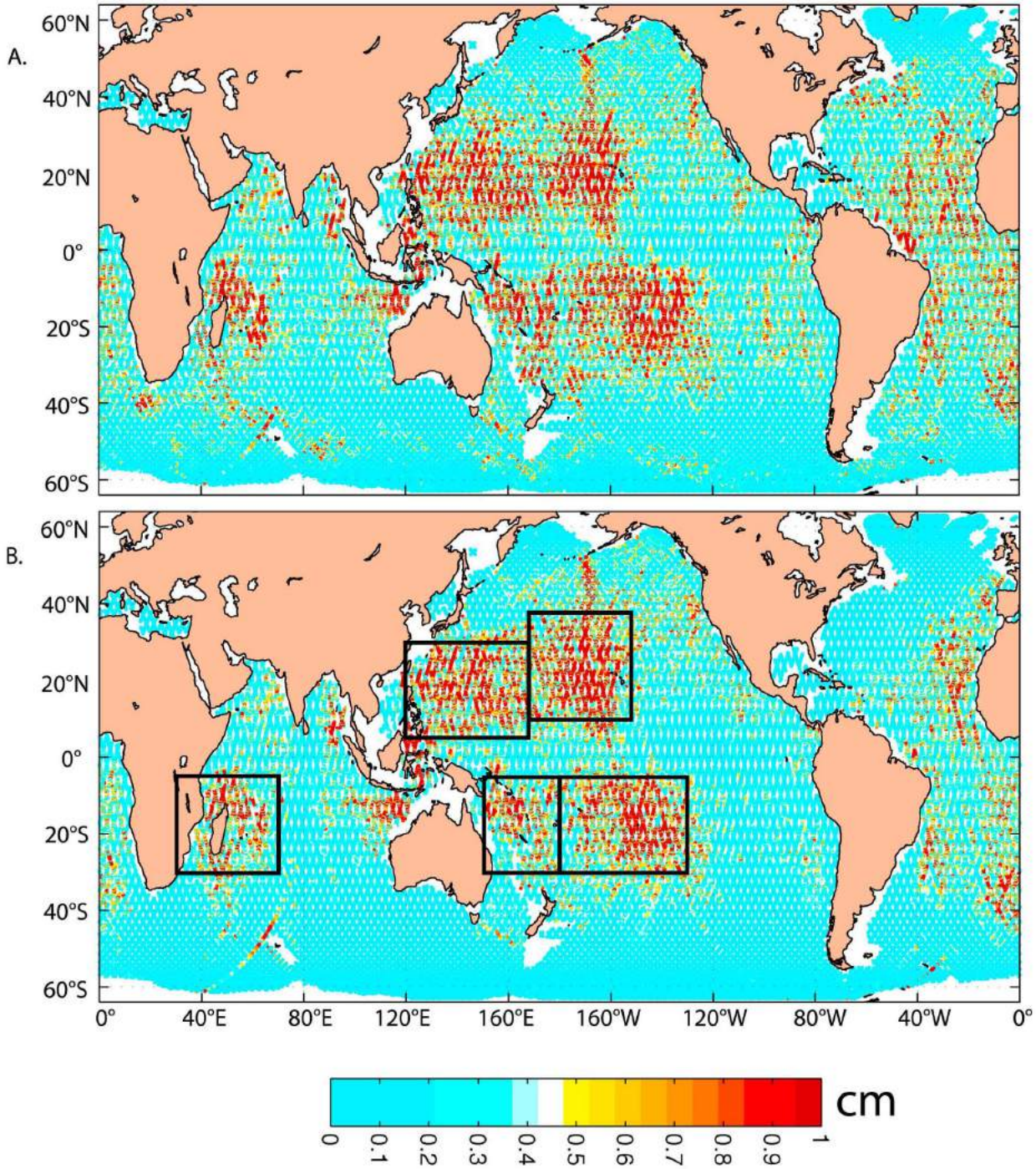
Background/history: Global internal tide and IGW continuum modeling

- Global tide modeling
  - Pioneering global barotropic tide models in 1970s by Hendershott and others.
  - Regional internal tide modeling→Holloway (1996)
  - Basin-scale internal tide modeling→Niwa and Hibiya (2001)
  - First global internal tide models→Arbic et al. (2004, Simmons et al. (2004), used simple horizontally uniform stratification
- Global "eddying general circulation" modeling
  - Pioneering efforts in idealized basins by Bill Holland
  - First realistic-domain "eddy permitting" simulations by Semtner and Chervin and others
  - "Eddying" basin-scale simulations by Paiva et al. (1999), Smith et al. (2000)
  - Global "eddying" simulations (1/10° or finer) by many groups now, including Navy HYCOM team, POP group, Mercator group, MITgcm

Tides + Atmospheric forcing + High-resolution = Fun

- First done in 1/12.5° HYCOM (Arbic et al. 2010).
- Other groups, including MITgcm, have followed suit.
- Get barotropic tides, internal tides, eddying general circulation all at once.
- HYCOM simulations continue to evolve: wave drag tuning, many comparisons to observations, horizontal resolution increased to 1/25°, data-assimilative machinery for eddies, Kalman Filter to improve tidal accuracy.
- Müller et al. (2015): HYCOM has a partial IGW continuum spectrum.
- Rocha et al. (2016a,2016b): So does MITgcm

Stationary internal tides



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

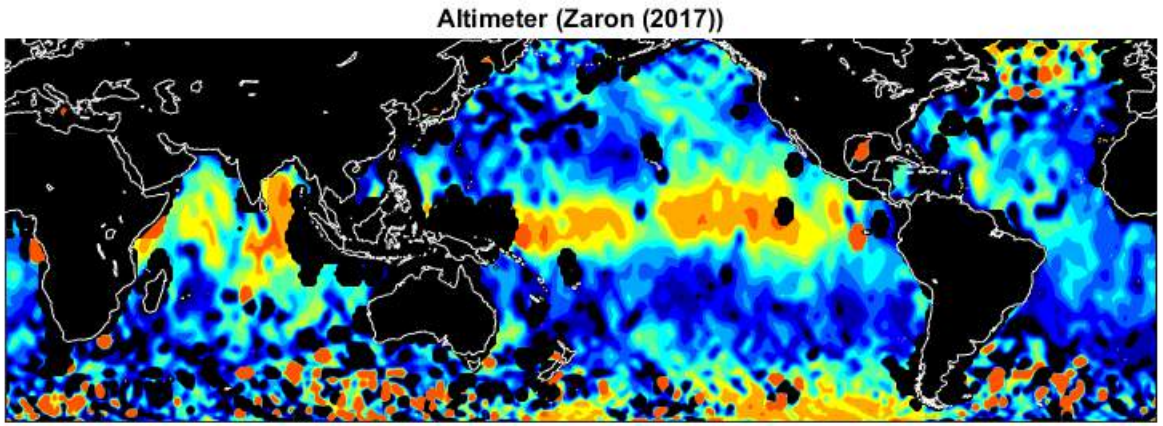
NOTE "dead spot" in equatorial Pacific in both plots

Shriver et al. (2012)

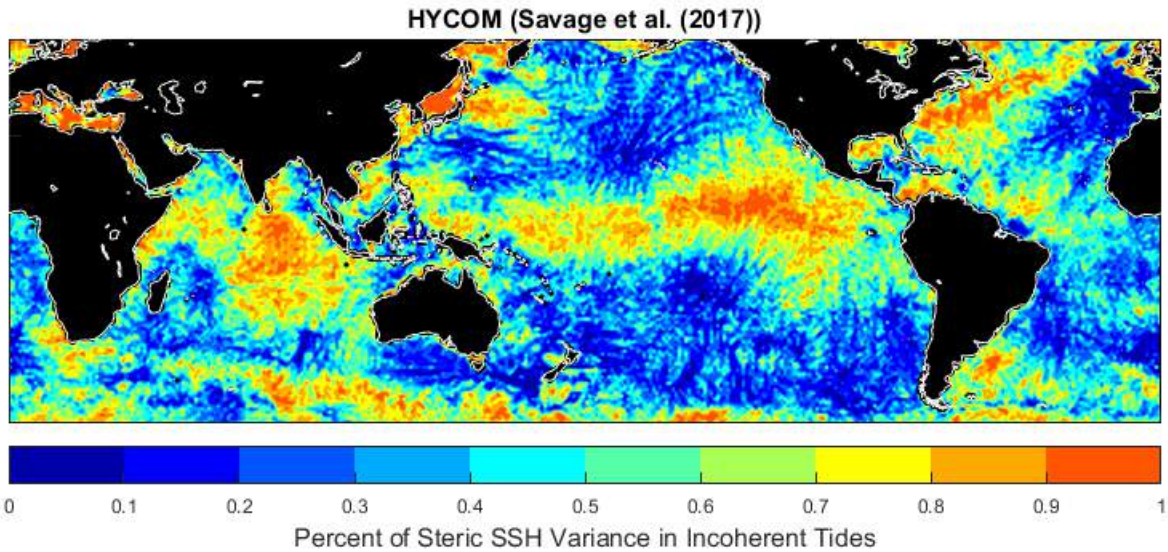
Non-stationary internal tides

- Examined in many regional models (e.g. Zaron and Egbert 2014)
- Examined in global HYCOM in Shriver et al. (2014), Ansong et al. (2017), Buijsman et al. (2017), Nelson et al. (in preparation)

Ratio of non-stationary to total semidiurnal band SSH variance



←As determined from altimeter wavenumber spectra by Zaron (2017)



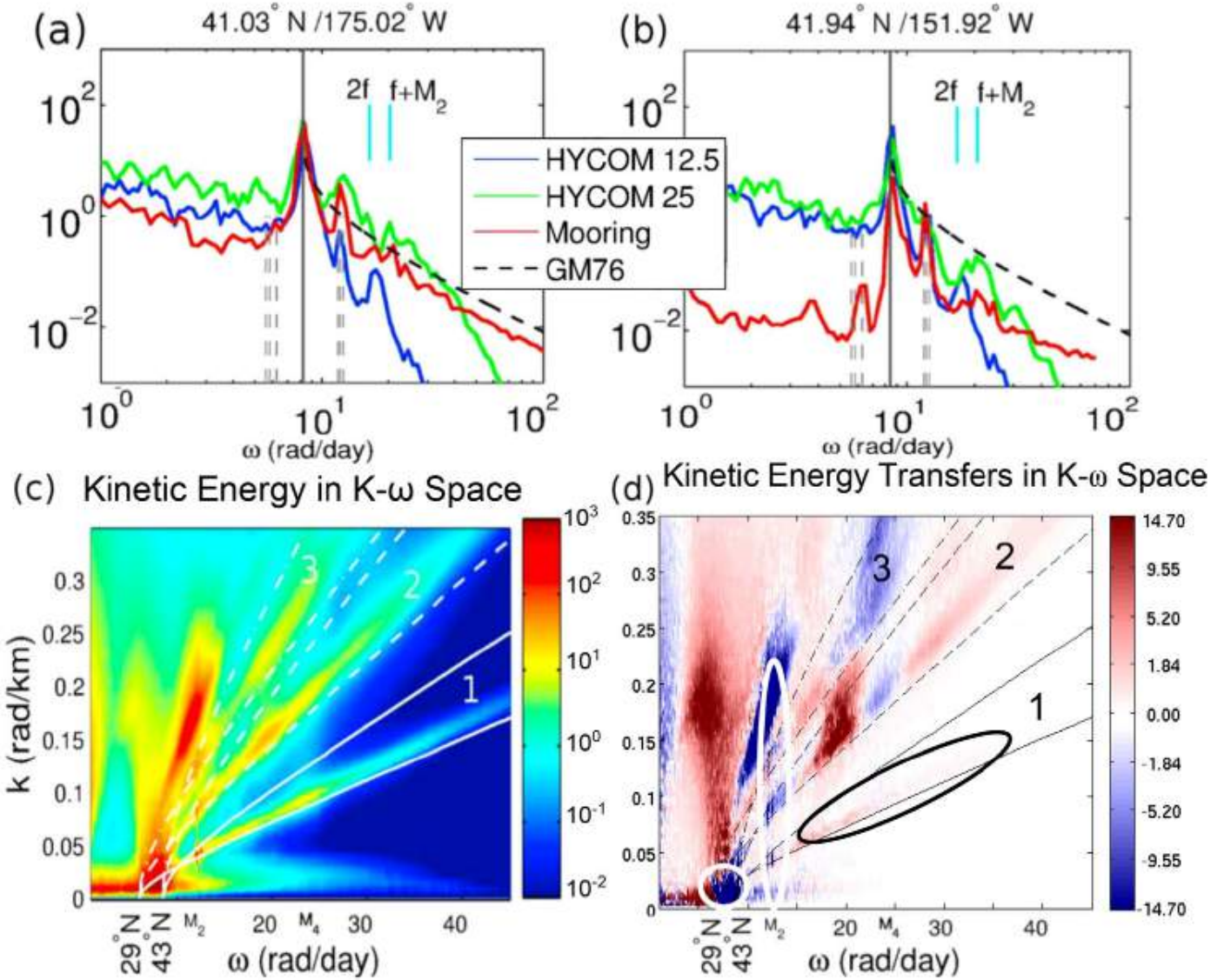
←As determined from HYCOM frequency spectra computed in Savage et al. (2017a).

Similar patterns in equator, where equatorial jets render tides non-stationary (Buijsman et al. 2017). Boundary current regions?

Nelson et al. (in preparation)

IGW continuum

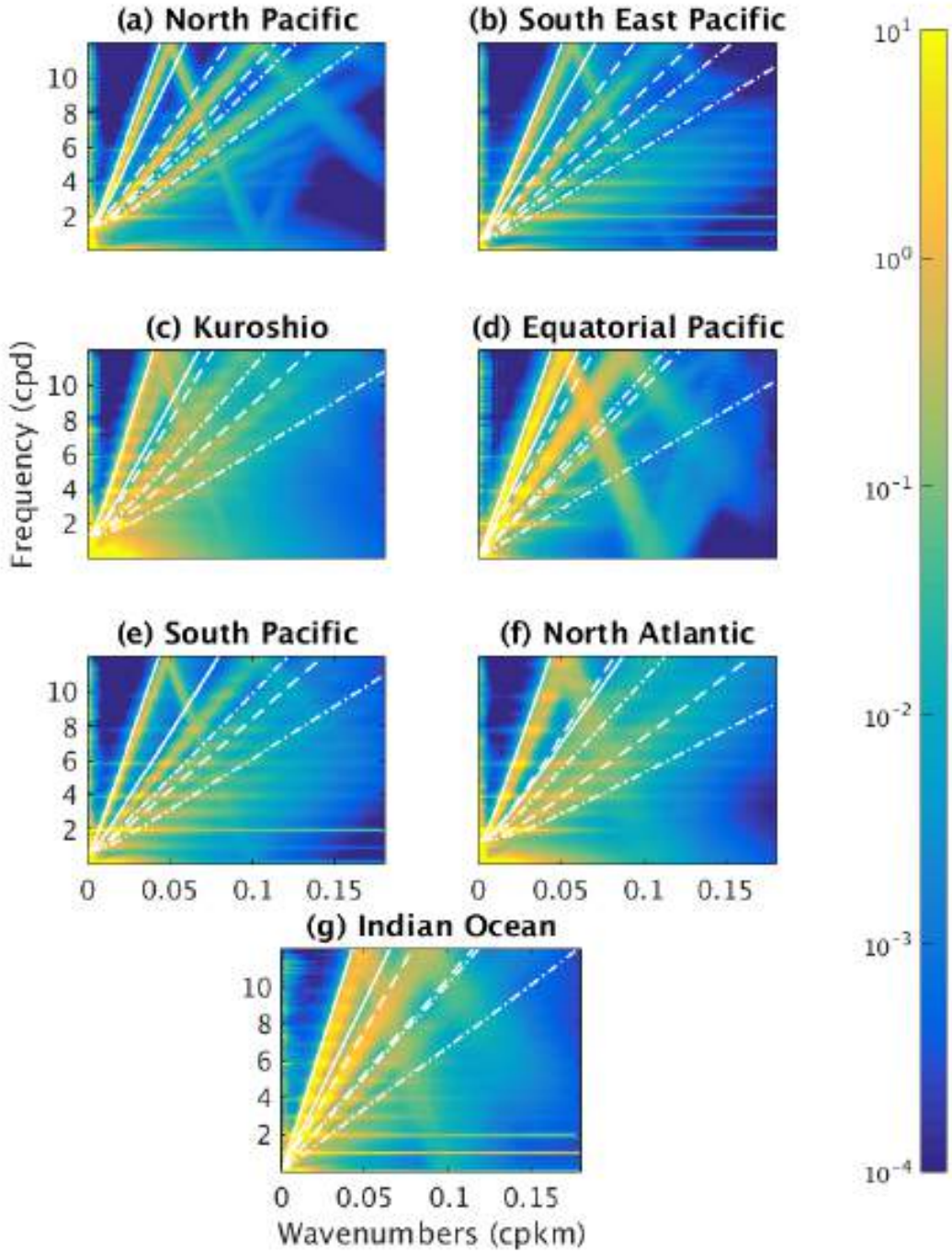
First evidence of IGW continuum in such models—analysis of kinetic energy in North Pacific region of global HYCOM (Müller et al. 2015; updated figure from Savage et al. 2017a)



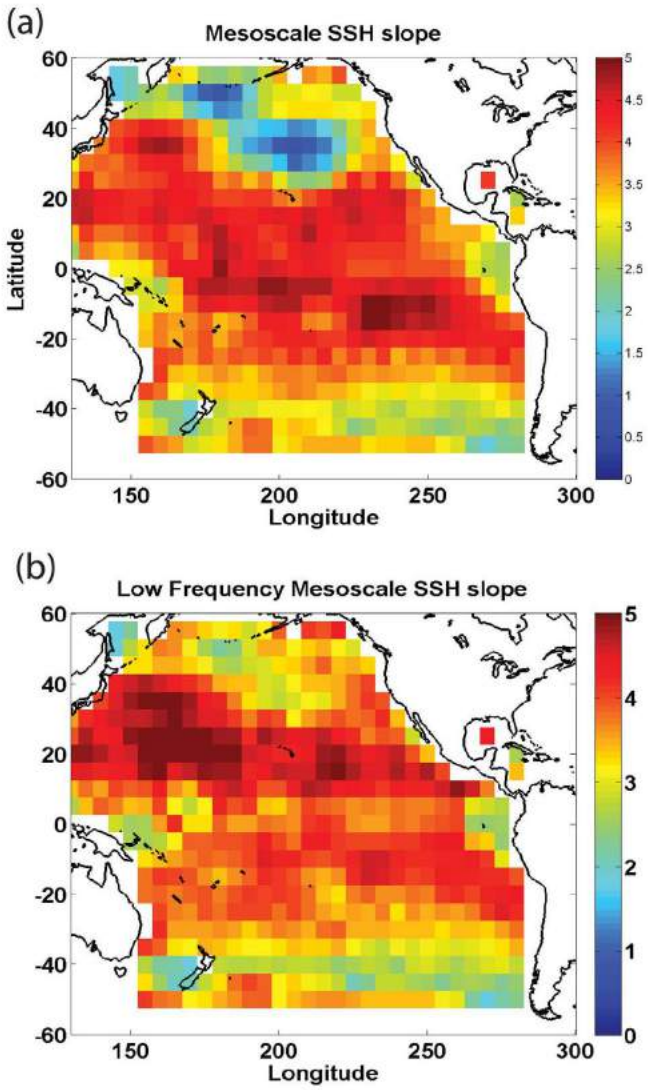
Building upon Müller et al. 2015

- In Savage et al. (2017b) and 3 in preparation papers led by Ansong, Luecke, and Arbic, we are building upon Müller et al. (2015):
  - MITgcm and HYCOM results side-by-side
  - Several oceanic regions
  - Temperature and SSH variance in addition to kinetic energy
  - Vertical wavenumber-frequency spectra

SSH variance frequency-horizontal wavenumber spectra density computed over seven regions from 1/48° MITgcm. Units are $\log_{10}[cm^2/(cpd * cpkm)]$. Savage et al. (2017b).



Relevance for SSH wavenumber spectrum and altimetry



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

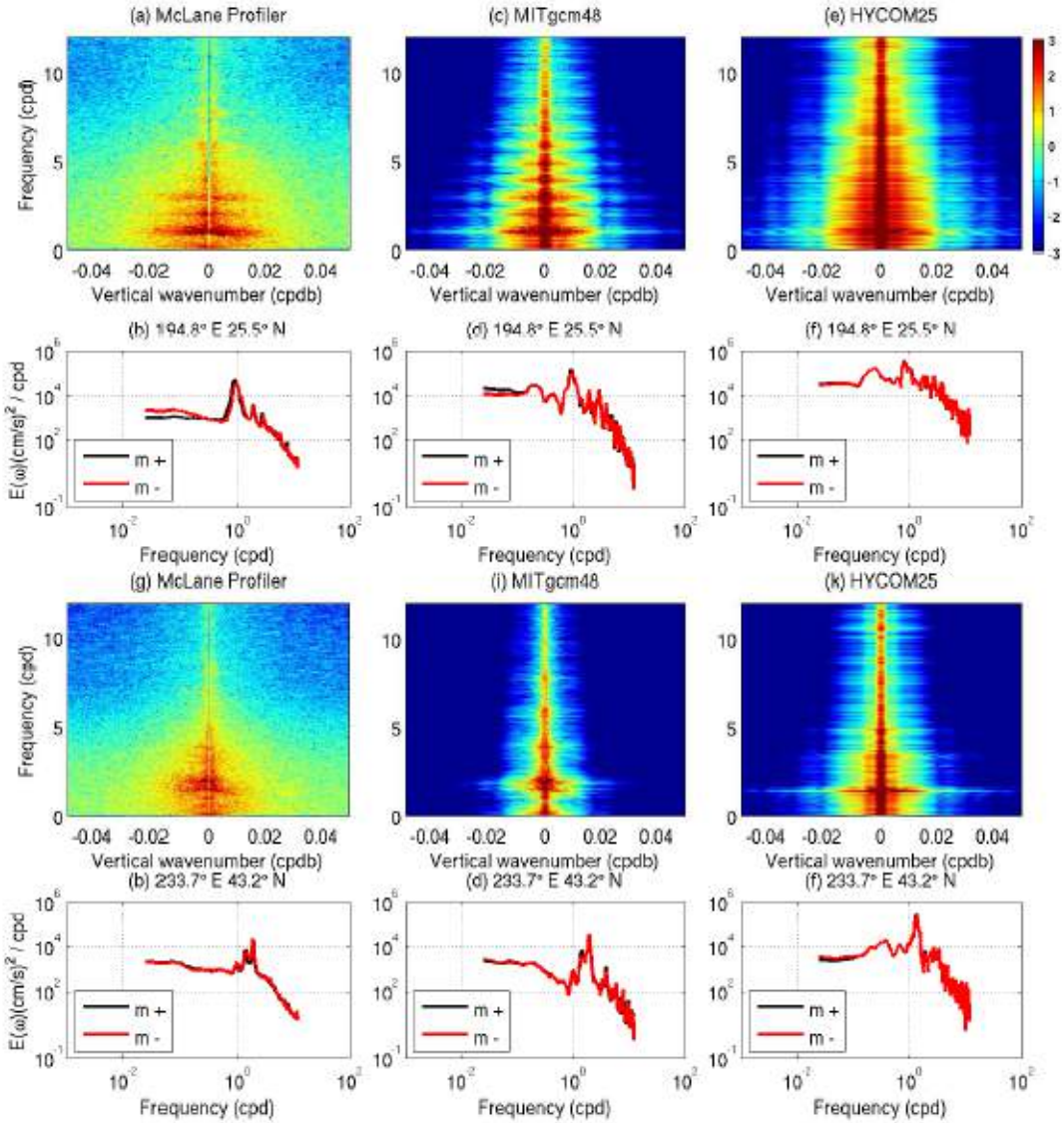
→Will make it more difficult to compare SWOT data with geostrophic turbulence theories, which suggest k^{-5} / $k^{-11/3}$ spectra for interior/surface quasi-geostrophic theory, respectively.

Richman et al. (2012)

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

Comparison to McLane profiler observations

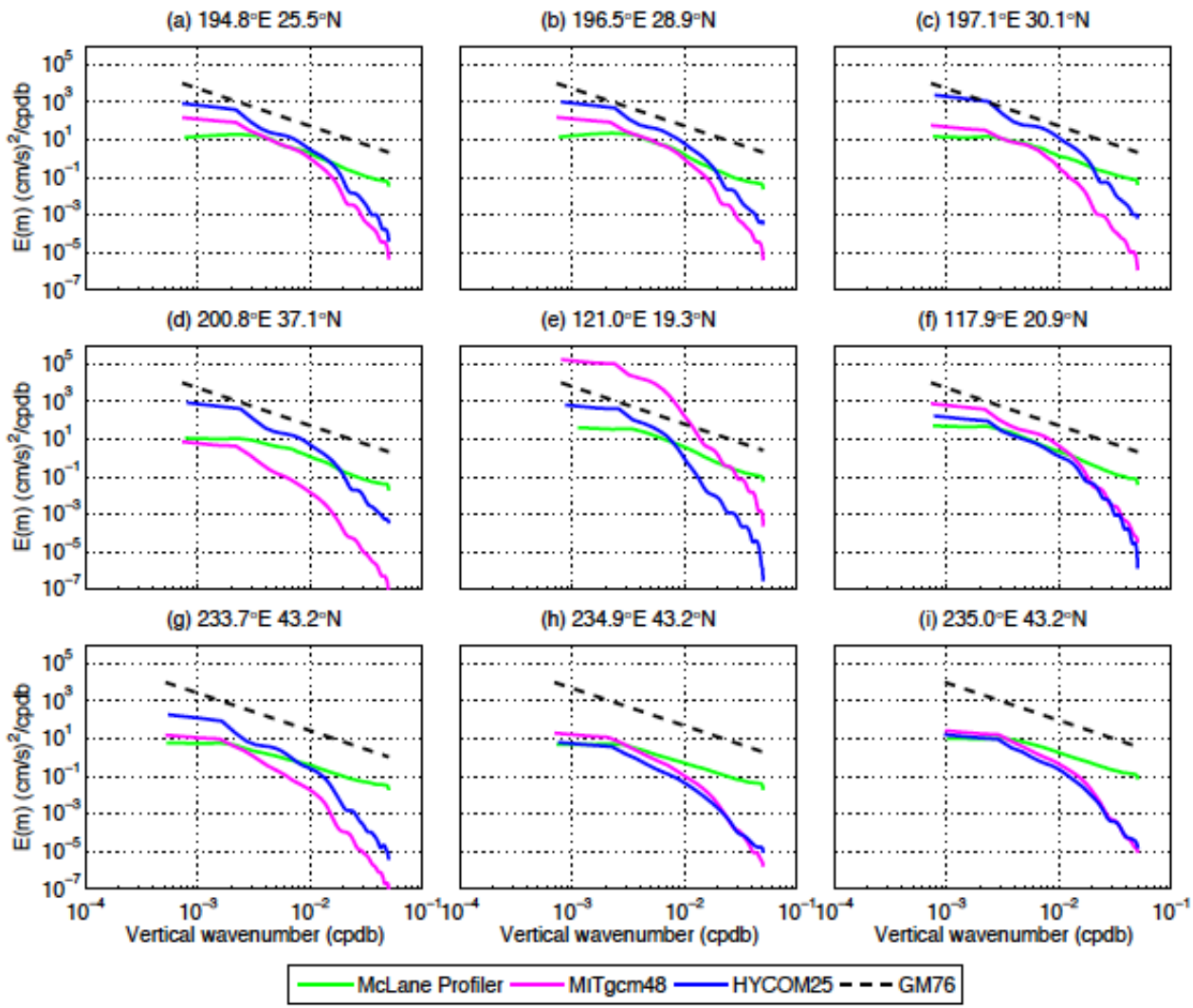
IGW kinetic energy vertical wavenumber-frequency spectra



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

Ansong et al. in preparation

IGW kinetic energy vertical wavenumber spectra

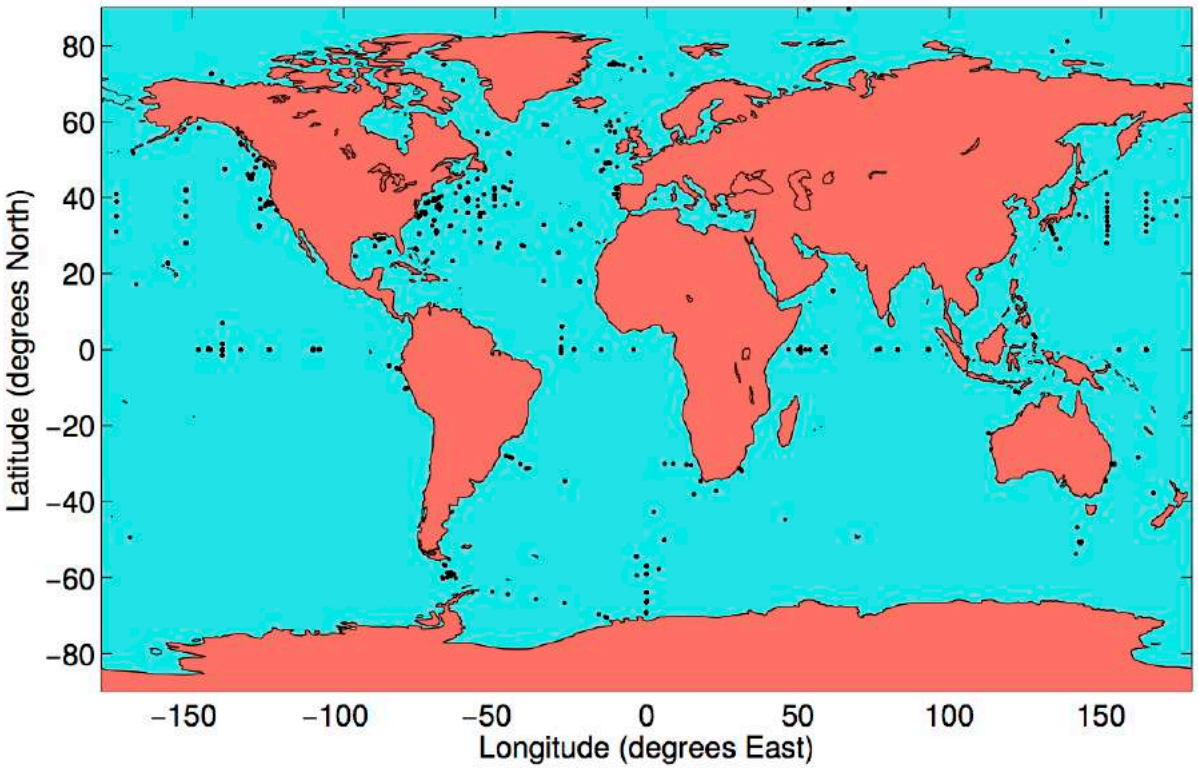


From McLane profilers, 1/48° MITgcm, and 1/25° HYCOM

Ansong et al. in preparation

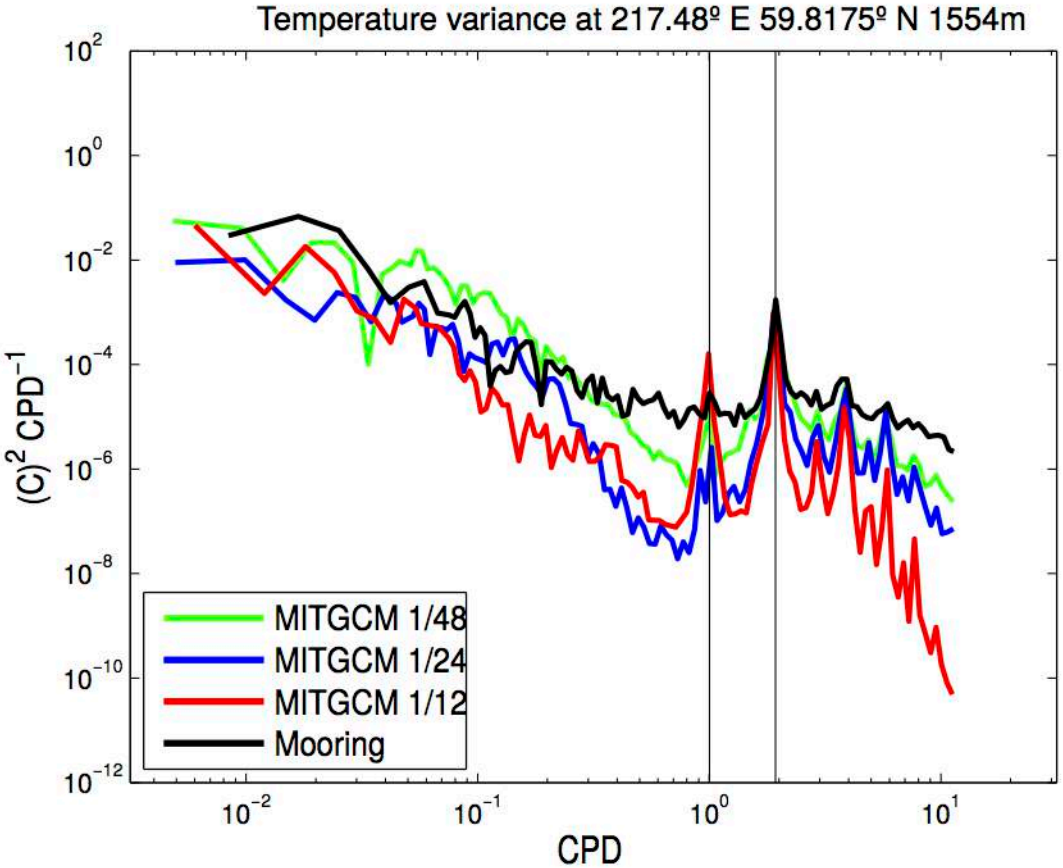
Comparison to historical mooring records

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

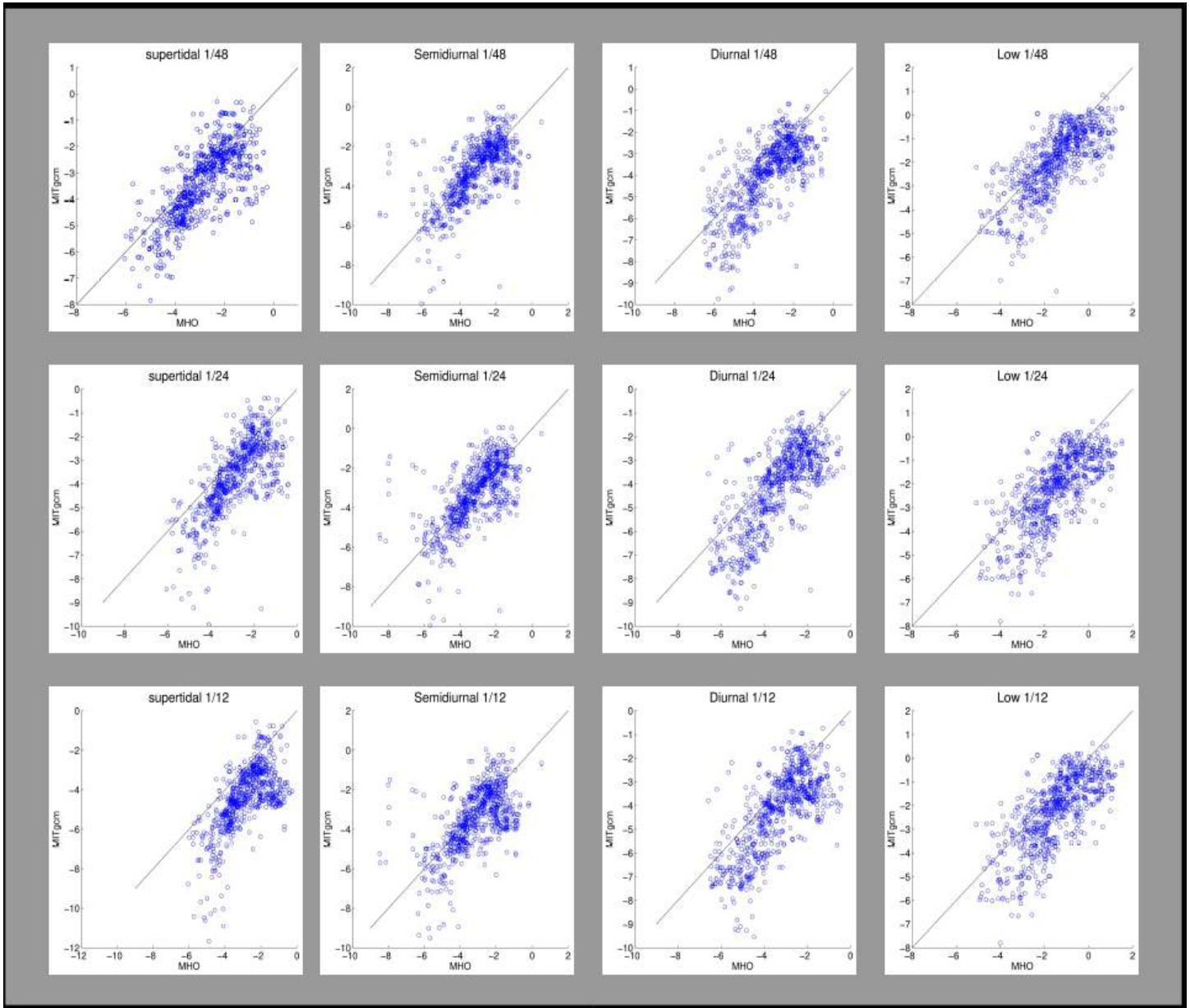


Luecke et al.,
in preparation

Example temperature variance spectra. Luecke et al., in preparation.



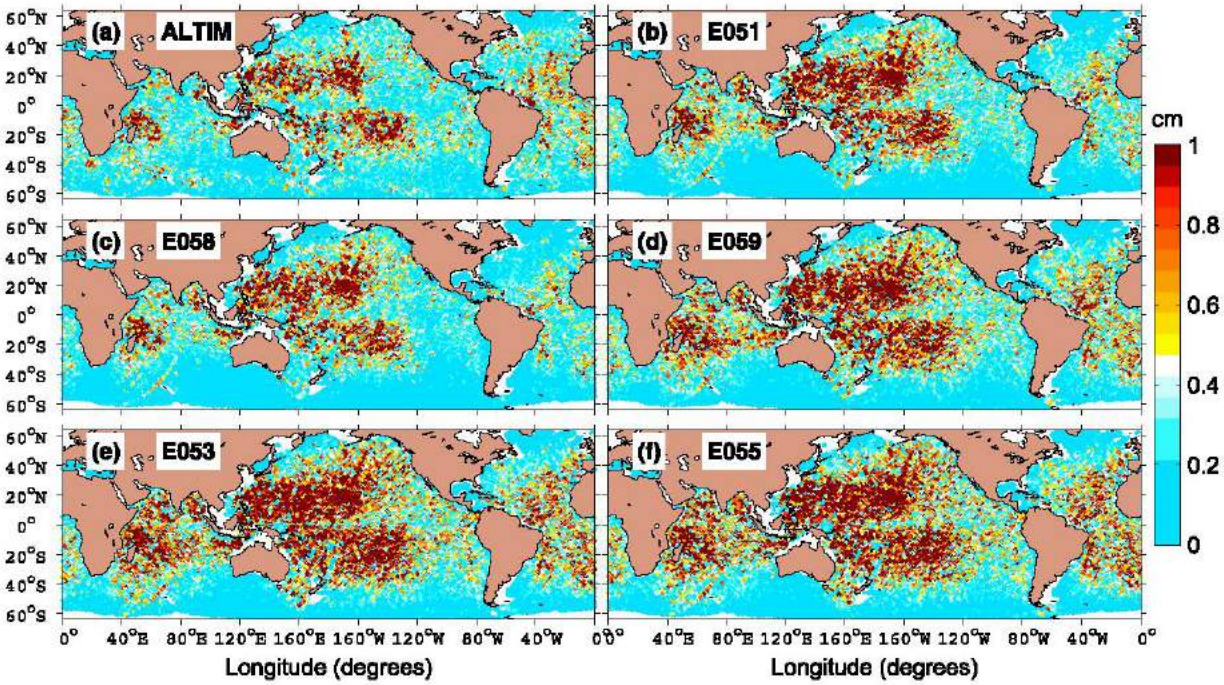
Band-integrated temperature variance in MITgcm vs. historical observations. Luecke et al., in preparation.



Units are $\log_{10}[(°C)^2]$

Kinetic energy results and HYCOM results (not shown) are similar

Wave drag and tidal energetics



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

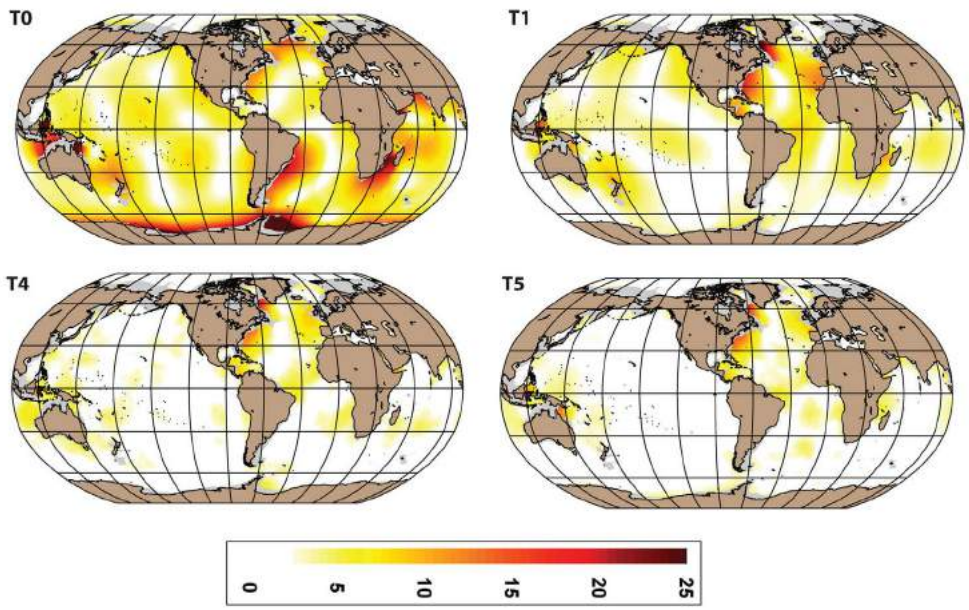
HYCOM amplitudes are too large in simulations with wave drag applied only to barotropic flow (d) or with no wave drag at all (e,f) than in simulations with wave drag (b, and especially c, where the wave drag is stronger).

→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 model accuracy



M_2 SSH tidal elevation error improvement from earlier Shriver et al. (2012) run (upper left) to run with improved SAL and Southern Ocean bathymetry (upper right) to runs with introduction of an Augmented State Ensemble Kalman Filter (ASEnKF)

Still relatively large errors in North Atlantic. We have some ideas as to why that is and how to fix it.

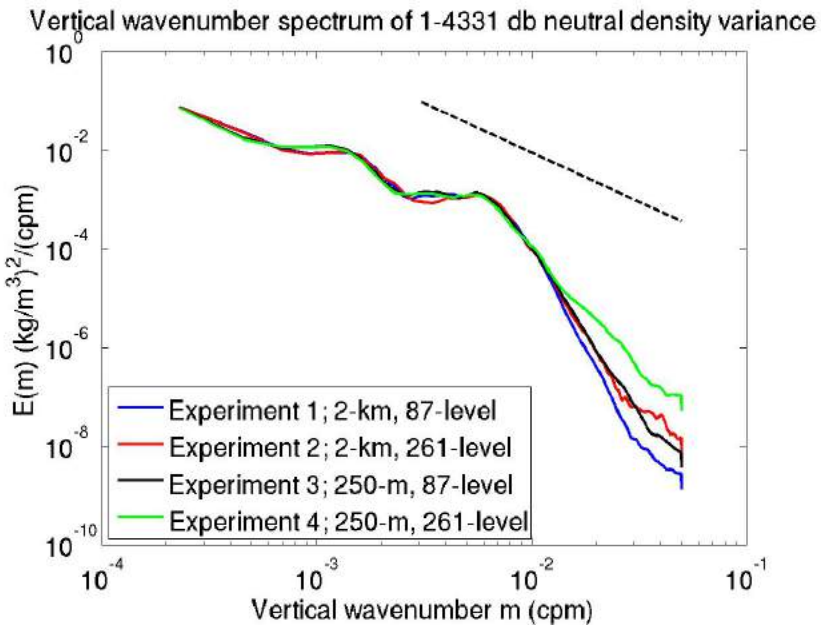
HYCOM and Mercator will seek to improve their barotropic tides, but will this yield improved internal tides??

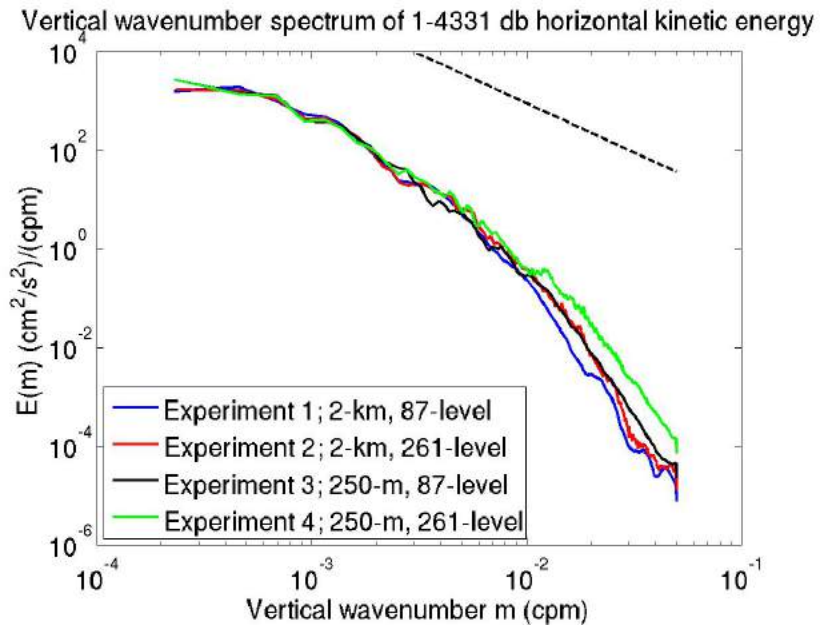
Will MITgcm group seek DA methods for tides?

Ngodock et al. (2016)

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, Nicolas Grisouard, Dick Peltier, and others)

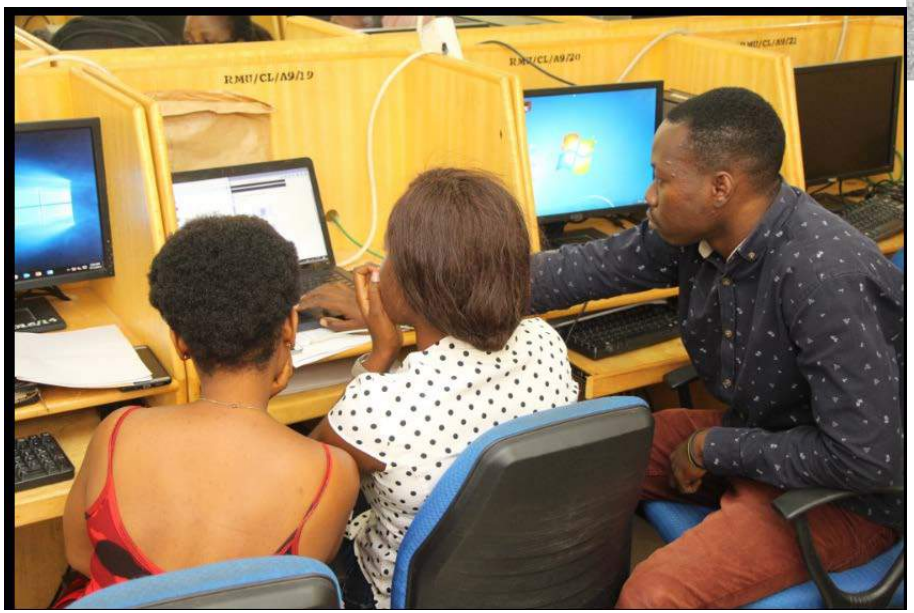




Vertical wavenumber spectra E(m) of 1-4331 db neutral density variance (left) and horizontal kinetic energy (right) in MITgcm simulations at a gridpoint near the SWOT fast phase California Current crossover point. Experiment 1 has horizontal and vertical resolutions equal to those of the global 1/48° MITgcm simulation. The other experiments have increasing vertical and horizontal resolutions, as indicated in the legend. Extra dashed line indicates predicted m^{-2} slope.

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

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



Summary

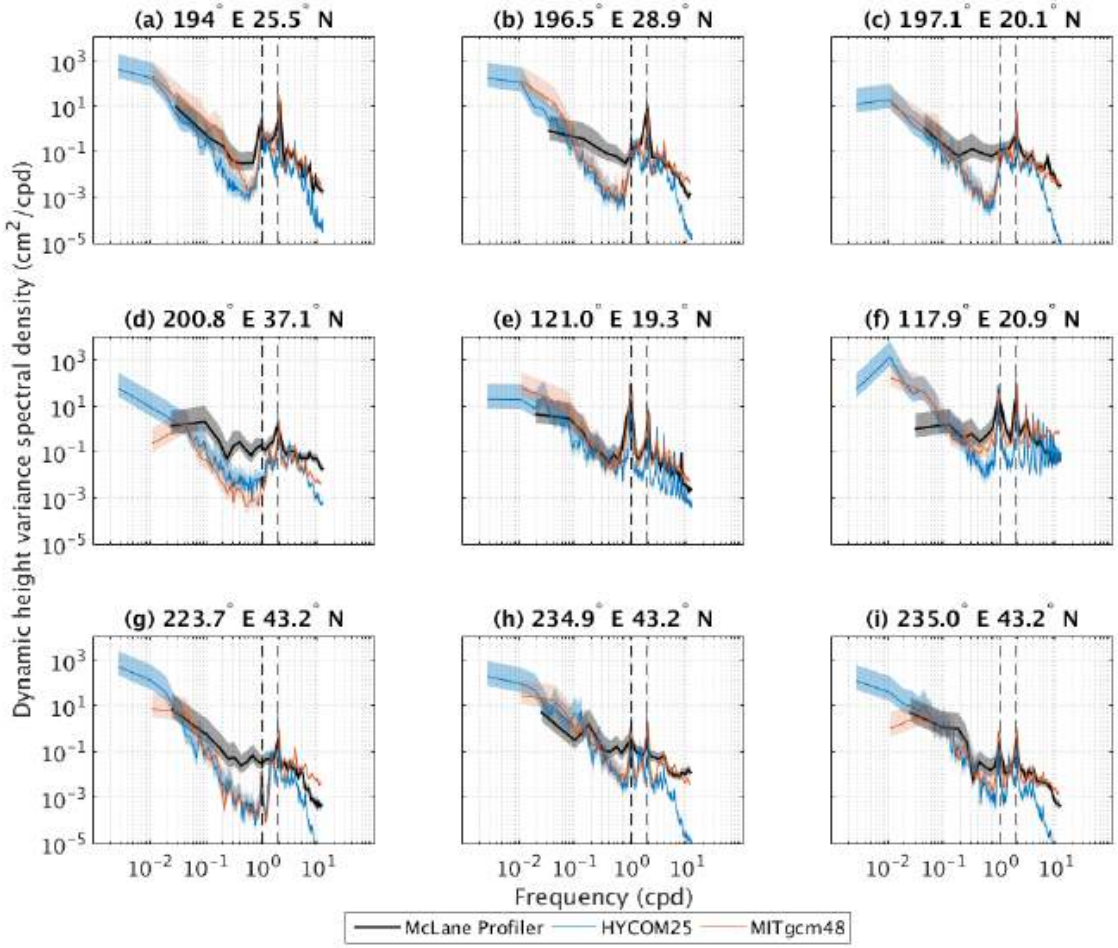
- Tides + Atmospheric forcing + High-resolution = Fun

Challenges for the future

- Still a new field so many challenges remain
  - 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 SWOT? Data assimilation will surely play a role here, but exactly how?
  - How will IGWs be impacted in a coupled ocean-atmosphere model, with data assimilation acting in both fluids?
  - How do we handle incomplete topographic roughness fields?
  - How do we compute SAL more accurately in a model with tidal and non-tidal motions?
  - How should we damp internal tides and the IGW continuum spectrum?
  - How do we go beyond saying "This has implications for mixing" to really doing something quantitative?
  - Can such models be used to study how the IGW continuum spectrum develops?

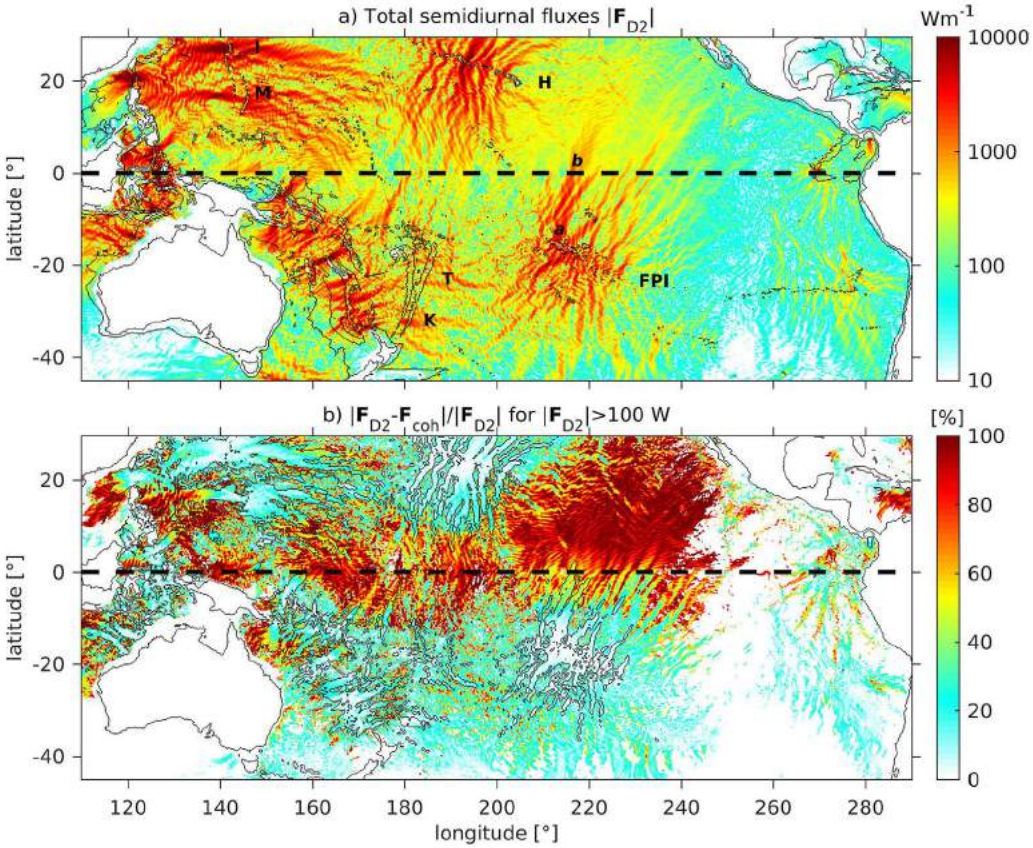
Extra slides

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



Savage et al. (2017b)

Near-equatorial Pacific semidiurnal energy fluxes in HYCOM



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

←But ratio of non-stationary/total flux increases greatly as one crosses the equator.

Non-stationarity is due to scattering by equatorial jet.

Buijsman et al. (2017)