Comparison of global and regional internal tide and gravity wave models with observations

Brian K. Arbic, University of Michigan

and many co-authors

Many collaborators, including

Alistair J. Adcroft, NOAA GFDL
Matthew H. Alford, Scripps Institution of Oceanography
Joseph K. Ansong, University of Michigan
Romain Bourdalle-Badie, Mercator Ocean
Frédéric Briol, Collecte Localisation Satellites, Toulouse, France
Maarten C. Buijsman, University of Southern Mississippi
Loren Carrère, Collecte Localisation Satellites, Toulouse, France
Jérôme Chanut, Mercator Ocean
Eric P. Chassignet, Florida State University
Gerald Dibarboure, Centre National d'Etudes Spatiales, Toulouse, France
J. Thomas Farrar, WHOI
Robert W. Hallberg, NOAA GFDL
Chris N. Hill, MIT
Ariane Koch-Lourray, LEGOS
Conrad A. Luecke, University of Michigan
Florent Lyard, LEGOS
Matthew Mazloff, Scripps Institution of Oceanography
Dimitris Menemenlis, NASA JPL
E. Joseph Metzger, Naval Research Laboratory
Yves Morel, LEGOS
Malte Müller, Norwegian Meteorological Institute
Arin D. Nelson, University of Michigan
Hans E. Ngodock, Naval Research Laboratory
An T. Nyugen, The University of Texas at Austin
Nicolas Picot, Centre National d'Etudes Spatiales, Toulouse, France
Rui M. Ponte, AER
Richard D. Ray, NASA Goddard
James G. Richman, Florida State University
Anna C. Savage, University of Michigan
Michael Schindelegger, University of Bonn, Germany
Robert B. Scott, Université de Bretagne Occidentale
Jay F. Shriver, Naval Research Laboratory
Harper L. Simmons, University of Alaska
Innocent Sououpgui, University of Southern Mississippi
Patrick G. Timko, Royal Meteorological Society
Alan J. Wallcraft, Florida State University
Luiz Zamudio, Florida State University
Zhongxiang Zhao, APL University of Washington

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Background and motivation: I

- Global- and basin-scale models with eddying resolution + atmospheric forcing fields + tidal forcing are still relatively new.
  - First done in US Navy HYCOM simulations (Arbic et al. 2010, 2012, 2018, references therein)
  - Higher-resolution simulations performed in NASA JPL runs of MITgcm (Rocha et al. 2016, others)
  - Now being done in US NOAA model MOM6, as well in three different simulations of NEMO—North Atlantic 1/60° (Grenoble), global 1/12° (Toulouse), global 1/12° (Nadia Pinardi group in Italy)
- Such models carry stationary internal tides, nonstationary internal tides, and a partial internal gravity wave (IGW) continuum
  - The latter was first shown in Müller et al. 2015 paper using HYCOM results
  - Subsequently shown in several papers using HYCOM and MITgcm
- Because internal tides and gravity waves will have strong signatures in observations from SWOT and the velocity-measuring missions S-MODE/SKIM/WACM, such models are being used to plan these missions.

- Important to compare such models to observations.

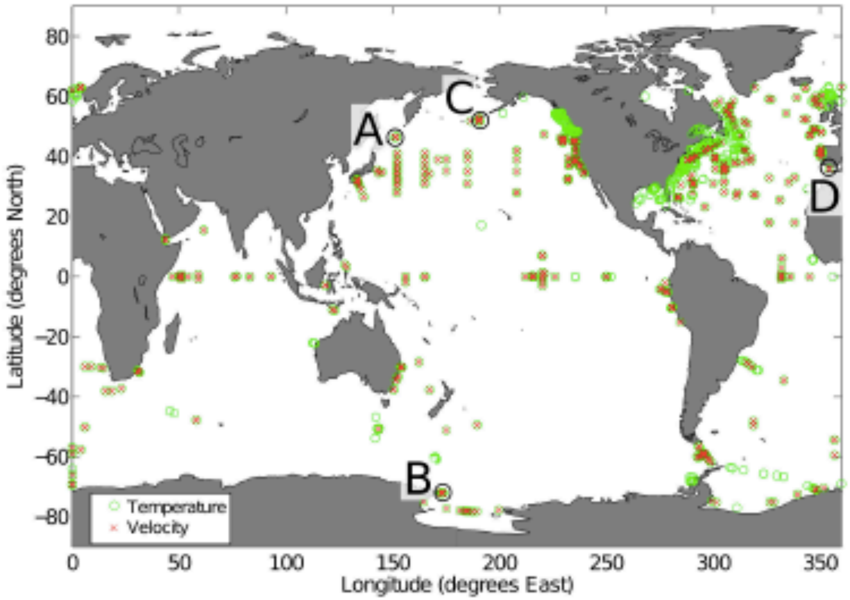
Background and motivation: II

- Here we will show some model comparisons with
  - Historical current meters
  - AVISO
  - McLane profilers
  - Along-track altimetry
  - Surface drifters
- NOTE Chereskin talk, Soares poster—include comparisons of along-track wavenumber spectra in models vs. ADCP data
- NOTE Buijsman poster—include comparisons of depth-integrated dissipation in models vs. fine- and micro-structure observations

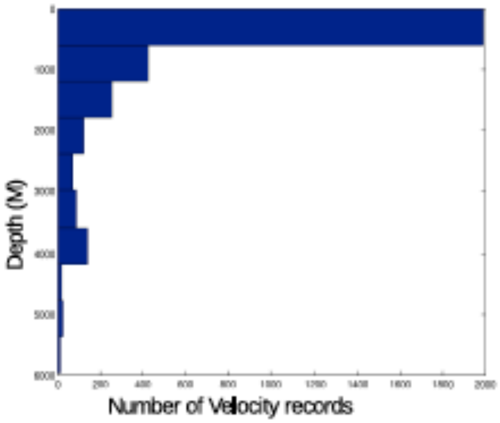
Historical current meter archive

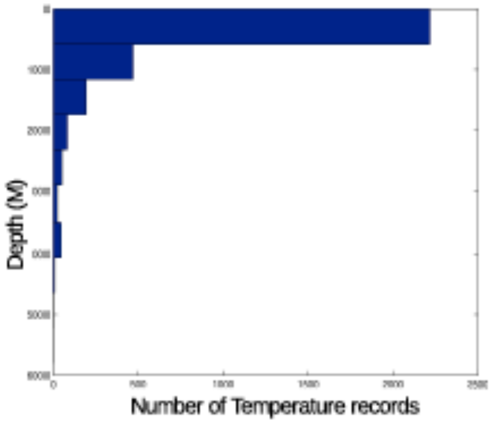
- Not great vertical coverage, but thousands of instruments…

Models vs. historical mooring archive (Luecke et al., in review)



Geographical distribution





Vertical distribution

Compute frequency spectra of temperature variance
and KE in:
- --moorings
- --1/12.5° + 1/25° HYCOM
- --1/12° + 1/24° + 1/48° MITgcm

Integrate over bands of interest:
- --mesoscale
- --subtidal
- --diurnal
- --near-inertial
- --semidiurnal
- --supertidal

Make scatterplots, compute correlation coefficients and other statistics

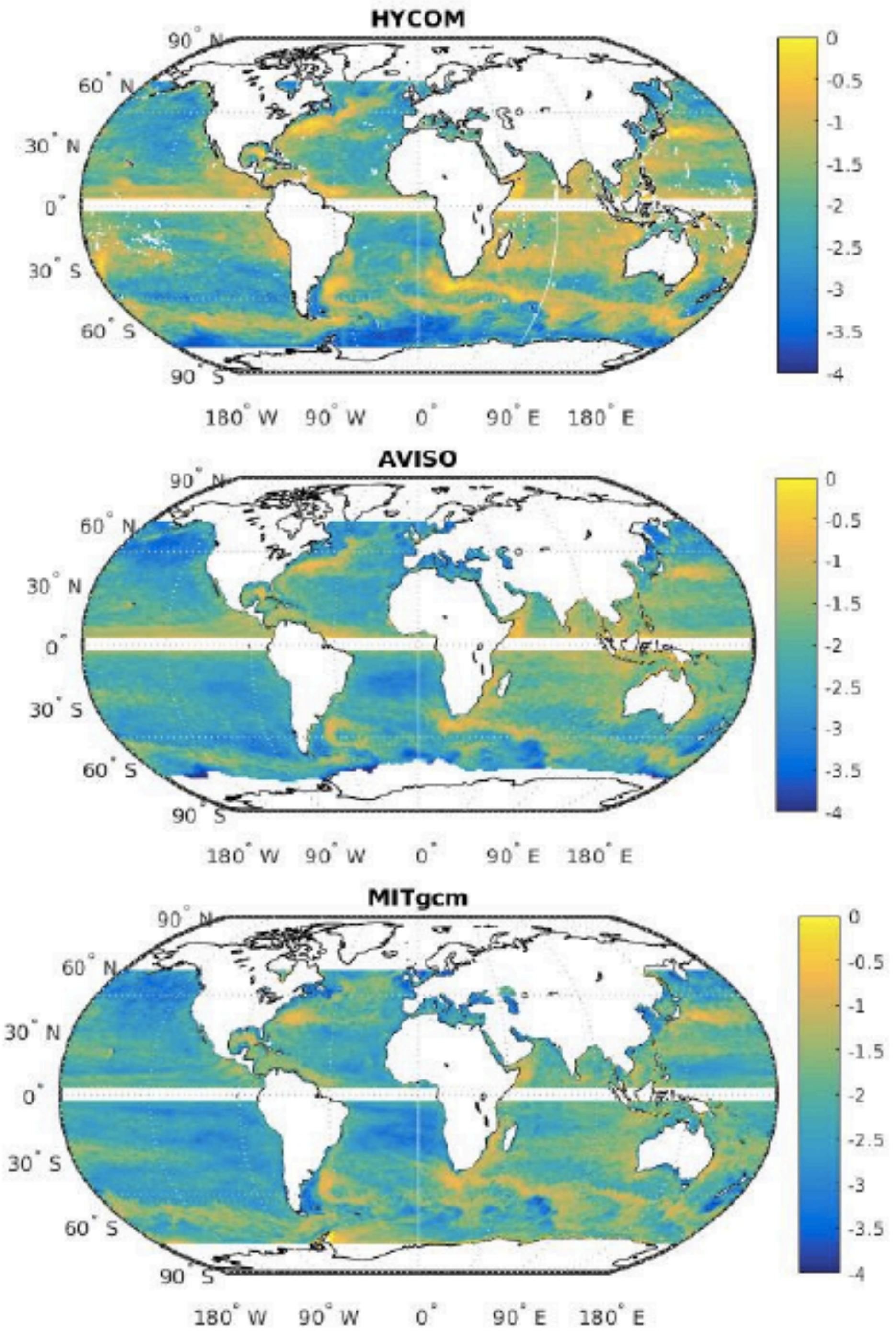
Spatial correlations and energy levels in model vs. mooring comparisons

1/12.5° + 1/25° HYCOM has a higher spatial correlation with observations than 1/12° + 1/24° + 1/48° MITgcm, across all frequency bands examined

Why?

Speculation: as an operational model, HYCOM has been tuned to accurately capture western boundary currents, stratification, etc.

Advantage of MITgcm lies in supertidal band—more realistic energy levels (consistent with Savage et al. 2017)



Models vs. AVISO (Luecke et al., in review)

Use AVISO to get more spatial coverage for a specific band (low-frequency geostrophic flow).

HYCOM has higher spatial correlation but too much energy, relative to AVISO.

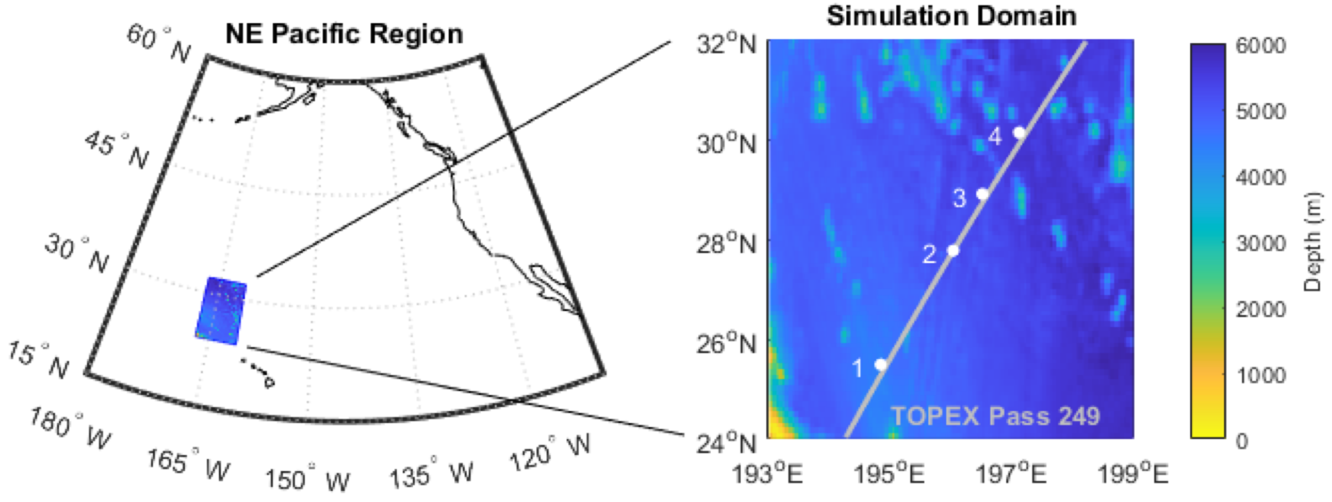
McLane profilers

- Fantastic vertical coverage, but not many of them.
- We are examining vertical wavenumber spectra but will only show frequency spectra here.

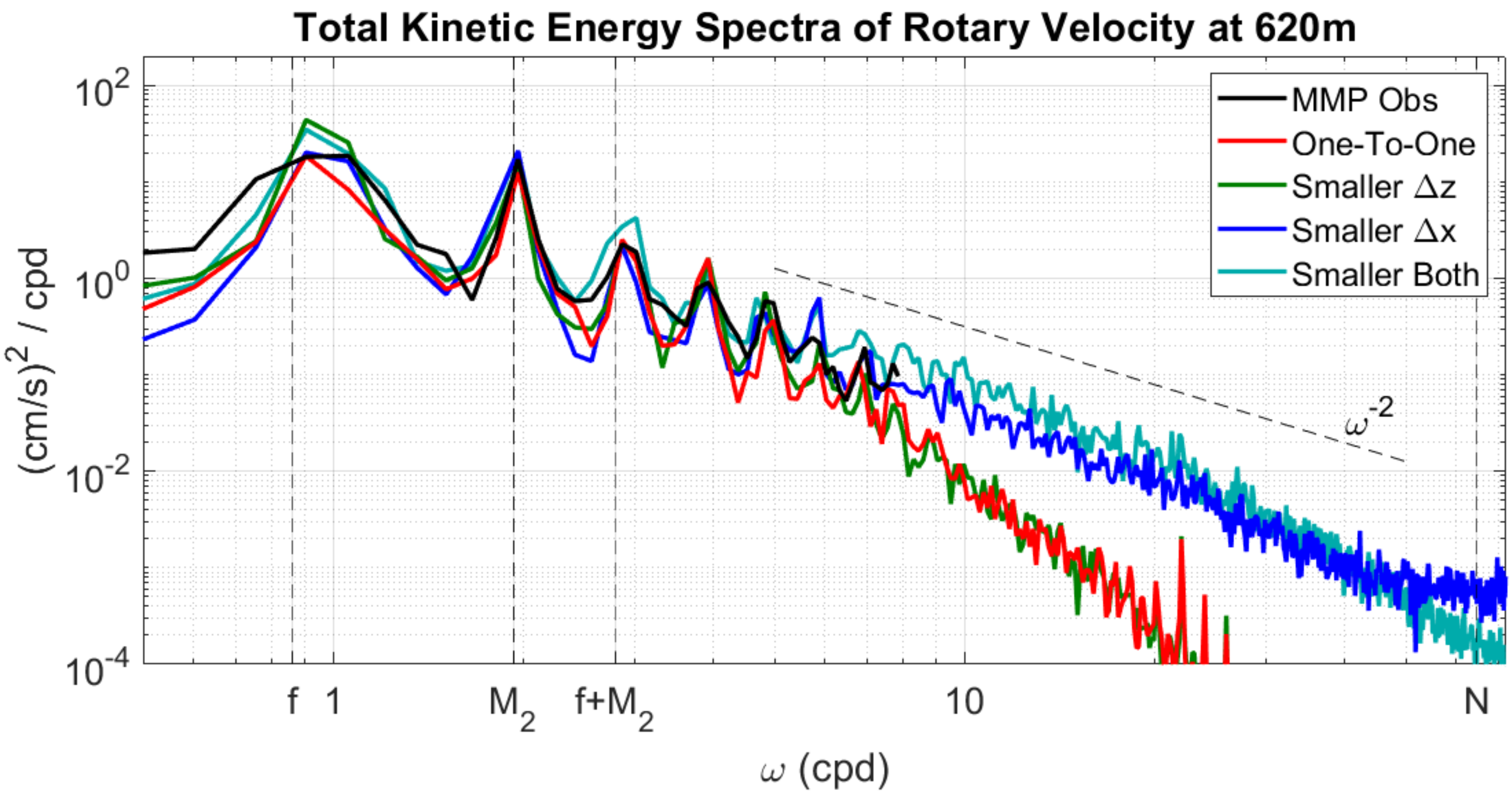
- We show results using a regional model, forced at the boundaries with the global 1/48th degree MITgcm, with more frequent output (10 minutes, vs. hourly), and:
  - one-to-one resolution (same as global model)
  - increased horizontal resolution (X8)
  - increased vertical resolution (X3)
  - increased resolution in both horizontal and vertical directions

Model domain, high-resolution regional simulation

--Performed on Niagara supercomputer at University of Toronto



From Arin Nelson et al., in preparation



Terri Chereskin's talk: w/o internal tide boundary conditions, a regional model has an insufficiently energetic IGW spectrum

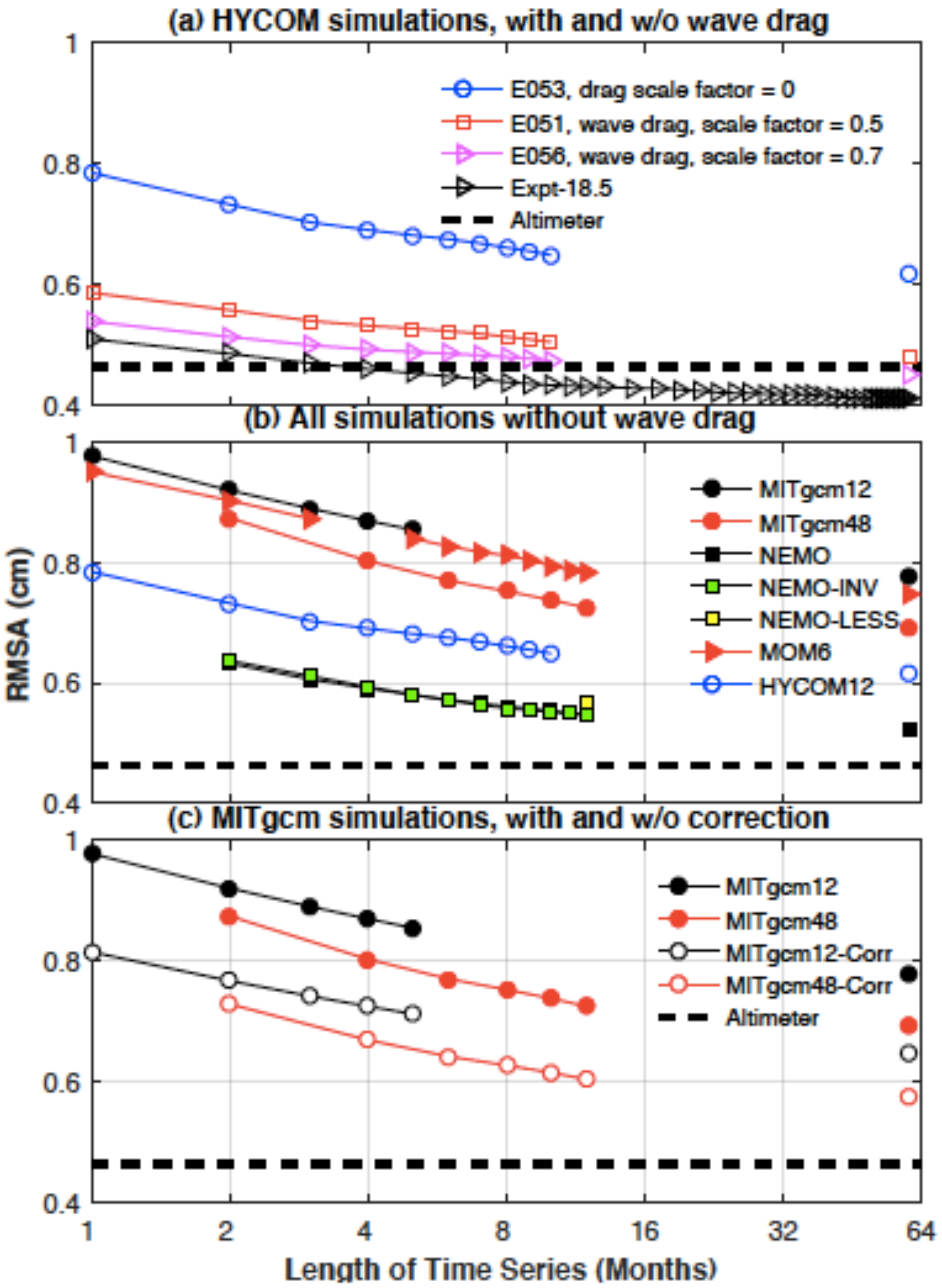
From Arin Nelson et al., in preparation

This work: with internal tide boundary conditions + increase in resolution, IGW continuum energy goes up

Along-track altimetry

- We compare both stationary and non-stationary internal tides to results computed from altimetry

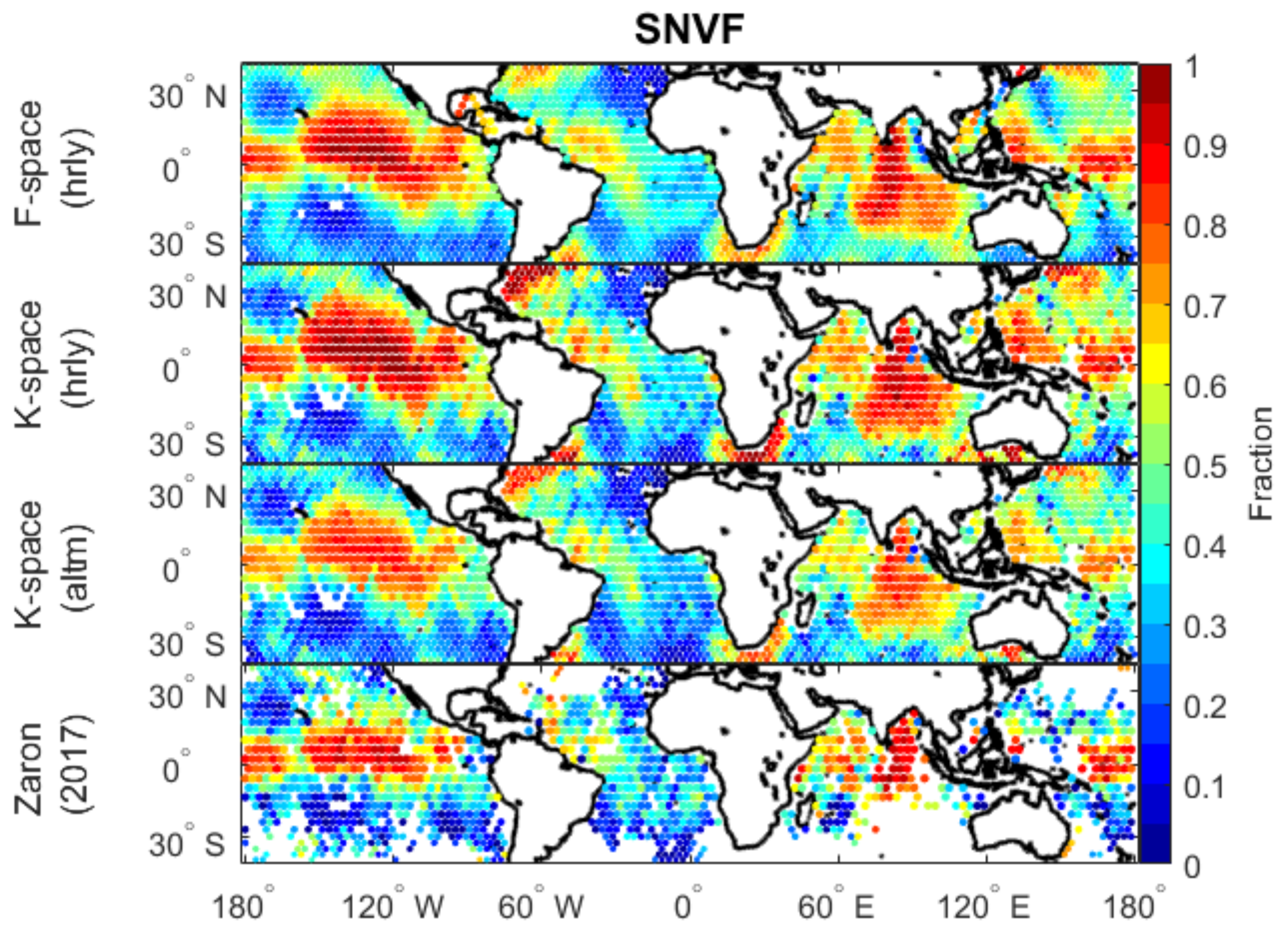
Globally averaged M_2 stationary internal tide SSH amplitudes (cm) in global hydrodynamical models and along-track altimetry (Ansong et al., in preparation)



Tidal forcing in MITgcm runs

- Overly large internal (and barotropic) tides are in part due to lack of wave drag.
- But large errors in the barotropic tides also stem from the astronomical forcing.
- The intent was to solve du/dt + … = $-\nabla(\eta-\eta_{EQ}-\eta_{SAL})$, with the SAL term η_{SAL} approximated by $0.1121*\eta$ (scalar approximation)
- Instead they solved du/dt + … = $-\nabla(\eta-1.1121*\eta_{EQ})$
- The astronomical forcing was too large by about 11% and there was no SAL
- SAL omissions are known to cause large phase errors (Hendershott 1972, Gordeev et al. 1977)

Semi-diurnal nonstationary variance fraction (SNVF) in HYCOM vs. altimetry (Nelson et al. 2019)



Large nonstationarity in equatorial regions consistent with results of Buijsman et al. (2017)

Surface drifters

- Yu et al. (2019) compared surface kinetic energy in MITgcm to drifters.
  - Near-inertial motions too weak
  - Tidal motions too strong
- Preliminary results with a short HYCOM record suggest
  - Near-inertial motions closer to observations due to more frequent coupling with atmosphere
  - Tidal motions closer to observations due to wave drag (and more correct forcing)
- Analysis of one-year HYCOM record ongoing

Summary

- Comparisons of internal tides and gravity waves in four global simulations (HYCOM, MITgcm, NEMO, MOM6) with observations are ongoing.
- We use
  - Historical current meters
  - AVISO
  - McLane profilers
  - Along-track altimetry
  - Surface drifters
- Some general conclusions:
  - Higher horizontal and vertical resolution (especially in MITgcm) makes for a better-represented internal gravity wave continuum spectrum
  - HYCOM has a higher spatial correlation with observations than MITgcm, probably due to substantial tuning done for operational purposes
  - MITgcm, MOM6, HYCOM, NEMO internal tides run without extra damping such as topographic wave drag are larger than in altimetry
  - HYCOM tide simulations predict the geography of non-stationary internal tides relatively well.
  - Preliminary HYCOM comparison to surface drifters indicates closer agreement than MITgcm in near-inertial and tidal bands
- Suggested grand challenge for SWOT: test the ability of HYCOM/NEMO/MITgcm to accurately phase-predict non-stationary internal tides?
- Suggestion brought up at SWOT meeting: should the project invest in several moorings placed around the global ocean to validate both empirical and hydrodynamical global internal tide/wave models?

Extra slides

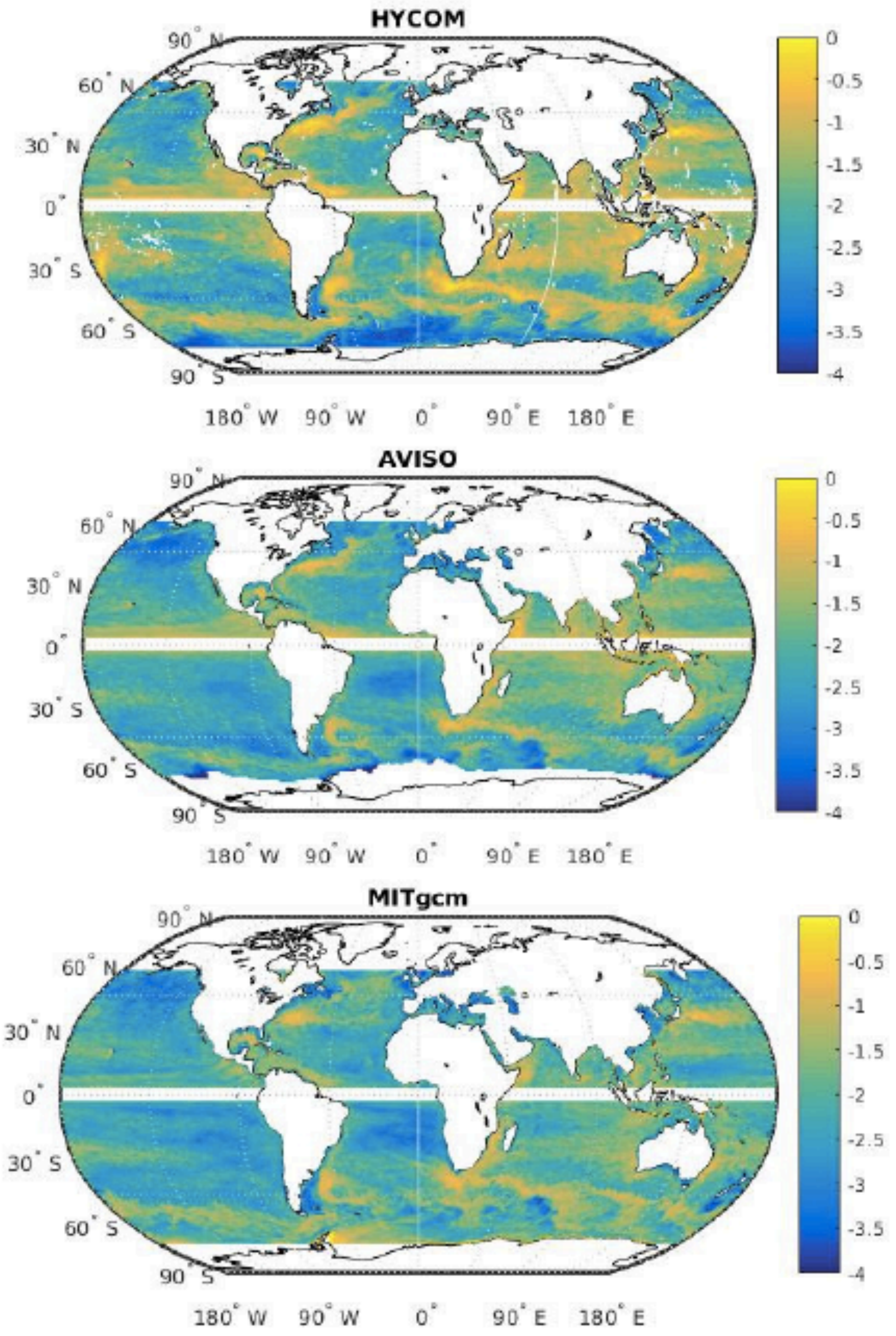
A Primer on Global Internal Tide and Internal Gravity Wave Continuum Modeling in HYCOM and MITgcm

Brian K. Arbic[1,2], Matthew H. Alford[3], Joseph K. Ansong[1,4], Maarten C. Buijsman[5], Robert B. Ciotti[6], J. Thomas Farrar[7], Robert W. Hallberg[8], Christopher E. Henze[6], Christopher N. Hill[9], Conrad A. Luecke[1,3], Dimitris Menemenlis[10], E. Joseph Metzger[11], Malte Müller[12], Arin D. Nelson[1], Bron C. Nelson[6], Hans E. Ngodock[11], Rui M. Ponte[13], James G. Richman[14], Anna C. Savage[1,3], Robert B. Scott[15], Jay F. Shriver[11], Harper L. Simmons[16], Innocent Souopgui[5], Patrick G. Timko[1,+], Alan J. Wallcraft[14], Luis Zamudio[14], and Zhongxiang Zhao[17]

[1]University of Michigan, Ann Arbor, Michigan, USA; [2]Currently on sabbatical at Institut des Géosciences de L'Environnement (IGE), Grenoble, France, and Laboratoire des Etudes en Géophysique et Océanographie Spatiale (LEGOS), Toulouse, France; [3]University of California San Diego, La Jolla, California, USA; [4]University of Ghana, Accra, Ghana; [5]University of Southern Mississippi, Stennis Space Center, Mississippi, USA; [6]NASA Ames Research Center, Mountain View, California, USA; [7]Woods Hole Oceanographic Institution, Woods Hole, Massachusetts, USA; [8]Geophysical Fluid Dynamics Laboratory/NOAA, Princeton, New Jersey, USA; [9]Massachusetts Institute of Technology, Cambridge, Massachusetts, USA; [10]Jet Propulsion Laboratory, California Institute of Technology, Pasadena, California, USA; [11]Naval Research Laboratory, Stennis Space Center, Mississippi,USA; [12]Norwegian Meteorological Institute, Oslo, Norway; [13]Atmospheric and Environmental Research, Lexington, Massachusetts, USA; [14]Florida State University, Tallahassee, Florida, USA; [15]Université de Bretagne Occidentale, Brest, France; [16]University of Alaska-Fairbanks, Fairbanks, Alaska, USA; [17]University of Washington, Seattle, Washington, USA; +Now at: Welsh Local Centre, Royal Meteorological Society, UK

In recent years, high-resolution ("eddying") global three-dimensional 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 nonstationarity, 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 simulating and interpreting satellite altimeter observations. Here we describe the most important technical details behind such models, including atmospheric forcing, bathymetry, astronomical tidal forcing, self-attraction and loading, quadratic bottom boundary layer drag, parameterized topographic internal wave drag, shallow-water tidal equations, and a brief summary of the theory of linear internal gravity waves. 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, non-stationary internal tides, and the internal gravity wave continuum spectrum for satellite altimetry and other applications.

Arbic, B.K., et al., 2018: A primer on global internal tide and internal gravity wave continuum modeling in HYCOM and MITgcm. In "*New Frontiers in Operational Oceanography*", E. Chassignet, A. Pascual, J. Tintoré, and J. Verron, Eds., GODAE OceanView, 307-392, doi:10.17125/gov2018.ch13.



Models vs. AVISO (Luecke et al., in review)

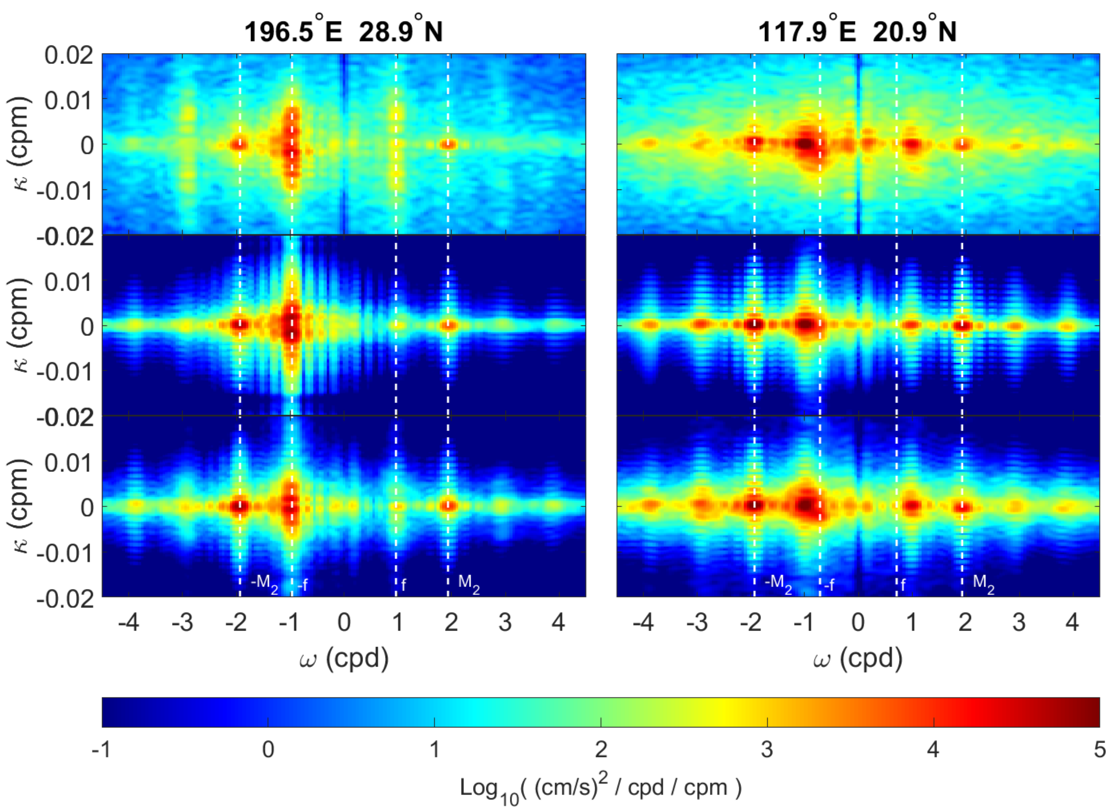
Use AVISO to get more spatial coverage for a specific band (low-frequency geostrophic flow).

HYCOM has higher spatial correlation but too much energy, relative to AVISO.

One more note on high-resolution simulation

- Yulin Pan, Arbic, Nelson, Menemenlis, Peltier, Xu, and Li: recently submitted a paper elucidating the mechanism behind the IGW continuum spectrum in the Toronto run.
- Answer: Induced diffusion.

Rotary spectra of kinetic energy at two McLane Profiler Locations



WKB-stretched over 200-1000 meters

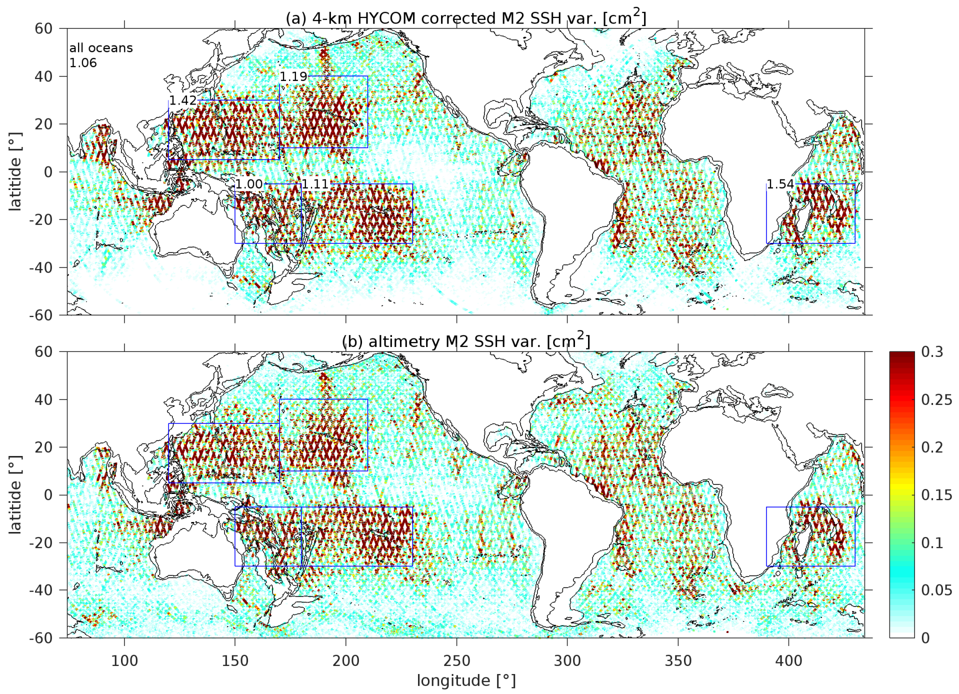
McLane Profilers

Global 1/25° HYCOM

Global 1/48° MITgcm

--From Ansong et al., in preparation
--McLane Profiler data from Matthew Alford (thanks also to Gunnar Voet)
--Model/data comparison by Arin Nelson
--Following initial calculations by Joseph Ansong and critique by Matthew Alford and Eric Kunze

HYCOM-altimeter comparison of stationary internal tides



Amplitude (cm) of the stationary component of the principal lunar semidiurnal tide M_2 in HYCOM (top) and altimetry (bottom). The HYCOM amplitudes have been corrected for the effects of the short duration of the model output record. Numbers represent the fraction of HYCOM variance to altimetry variance.

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

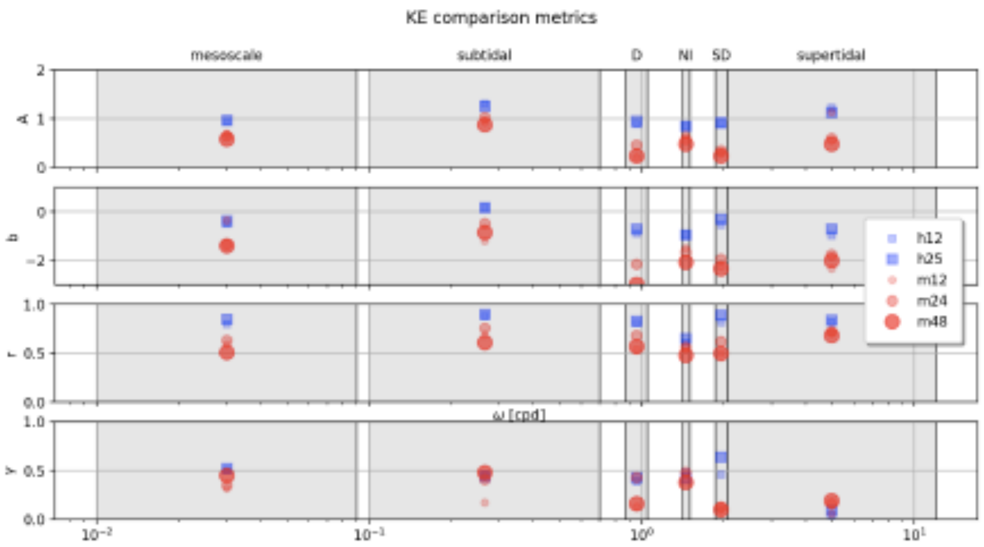
NOTE “DEAD SPOT” IN EQUATORIAL PACIFIC

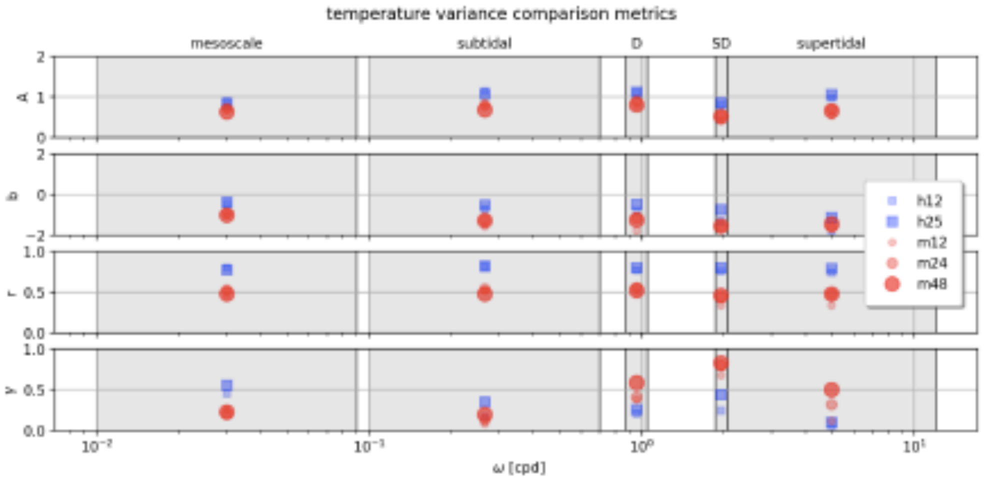
Buijsman et al., paper in preparation

(Carrère et. al.), another paper in preparation, shows that our HYCOM results also model internal tide phases well enough to be used as corrections in some regions.

More work remains to get them to a level comparable to those of the best empirical models.

Models vs. mooring archive (Luecke et al., in review)





Correlation coefficients, KE

Correlation coefficients, temperature variance

1/12.5° + 1/25° HYCOM (bluish symbols) has a higher spatial correlation with observations than
1/12° + 1/24° + 1/48° MITgcm (orange/red symbols),
across all frequency bands examined

Why?

Speculation: as an operational model, HYCOM has been tuned to accurately capture western boundary currents, stratification, etc.

Advantage of MITgcm lies in supertidal band—more realistic energy levels (consistent with Savage et al. 2017)