The many benefits (and a few drawbacks) of inserting tides into general circulation models

Brian K. Arbic, University of Michigan

Thanks to a very long list of collaborators, and to DOE and NOAA for additional funding.

Slide from Richard Ray's "100 years of tides" talk at Fall 2019 AGU meeting

General Circulation Models

Ignore tides – the source of largest variability in sea level; ~half the power for ocean mixing

Tide Models

Treat the ocean as a homogeneous fluid, unchanged by weather or climate

Ocean Modelling 32 (2010) 175–187

Contents lists available at ScienceDirect

Ocean Modelling

journal homepage: www.elsevier.com/locate/ocemod

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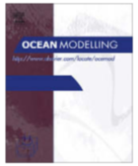

Concurrent simulation of the eddying general circulation and tides in a global ocean model

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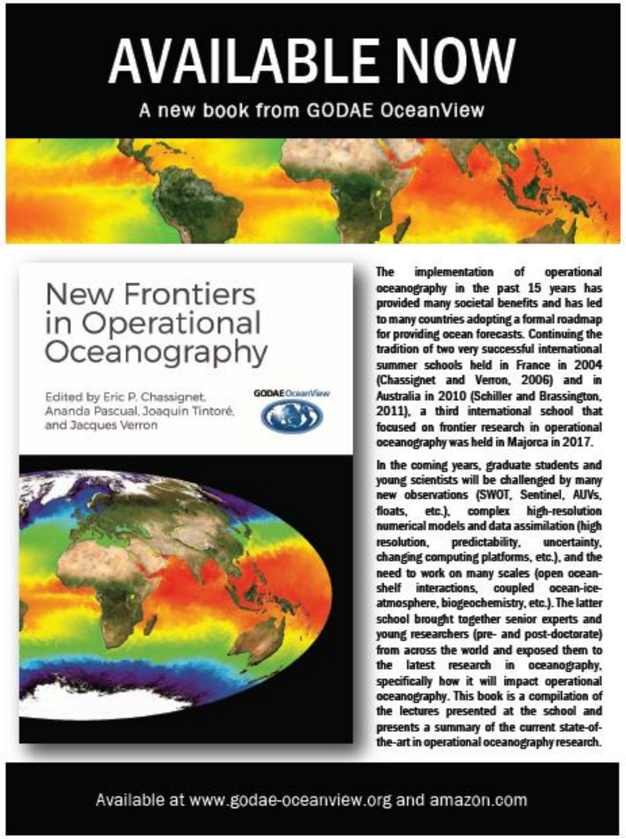
Insertion of tides in models

- My research group collaborates with the following groups to insert tides into ocean general circulation models
  - US Navy HYCOM global simulations
  - NASA MITgcm global simulations
  - UCLA ROMS and FSU HYCOM basin scale simulations
  - Italian effort (Federica Borile and Nadia Pinardi)
  - Australian effort (Callum Shakespeare, Andy McC. Hogg, and Adele Morrison)
  - Grenoble basin-scale NEMO simulation and Toulouse (Mercator) global NEMO simulation
  - NOAA operational modeling group
  - DOE E3SM group

Arbic 2022 review article



CHAPTER 13

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 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.

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Arbic et al. (2018) book chapter

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Review

Incorporating tides and internal gravity waves within global ocean general circulation models: A review

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ABSTRACT

Until recently, high-resolution global modeling of tides has been done separately from high-resolution global modeling of the atmospherically-forced oceanic general circulation. Here we review the emerging class of high-resolution global models that are simultaneously forced by both atmospheric fields and the astronomical tidal potential. Such models simulate barotropic (surface) tides, internal tides, near-inertial motions, the eddying general oceanic circulation, and a partially resolved internal gravity wave (IGW) continuum spectrum (Garrett-Munk spectrum) simultaneously. We review the technical aspects of such global models and their myriad applications, for example, in satellite oceanography, operational oceanography, boundary forcing of regional models, tidal-cryosphere interactions, and assessment of future coastal flooding hazards in a changing climate with altered tides.

1. Introduction

Tides have fascinated humankind for thousands of years (Cartwright, 1999). Accurate analysis and prediction of tides in ports and harbors has been practiced since the 1800s. The advent of the TOPEX/JASON satellite altimetry series (Fu & Cazenave, 2001; Stammer & Cazenave, 2017; International Altimetry Team, 2021) revolutionized physical oceanography by allowing for highly accurate global maps of surface tidal elevations (e.g., Le Provost, 2001; Egbert & Ray, 2017; Ray & Egbert, 2017) and other oceanic motions. The TOPEX/JASON tidal maps build upon work demonstrating the feasibility of tidal mapping with the earlier Seasat and Geosat altimeters (e.g., Cartwright, 1983; Mazzega, 1985; Woodworth & Cartwright, 1986; Cartwright & Ray, 1990). Despite the advent of accurate tidal maps from altimetry, many questions about tides remain, including the response of tides to climate change, the details of tide-cryosphere interactions and open-ocean tidal dissipation mechanisms, the predictability of internal tides, and the impact of tides on upcoming remote sensing missions. Some of these questions are addressable with global high-resolution simulations that incorporate tidal and atmospheric forcing simultaneously, a frontier direction in ocean modeling that is the subject of this paper.

1.1. Background and definition of terms

Tides are best known for effecting a periodic rise and fall of the sea surface height (SSH). The large-scale motions that dominate SSH are variously known as surface tides or barotropic tides. The surface tides are arguably weakly resonant in the open-ocean (e.g., Wunsch, 1972; Garrett & Greenberg, 1977; Heath, 1981; Arbic et al., 2009), because the spatial structures and frequencies of oceanic normal modes (e.g., Platzman et al., 1981; Platzman, 1991; Zahel & Müller, 2005; Müller, 2007) match those of the astronomical forcing reasonably well. The weakly resonant open-ocean tides drive strong tides in coastal regions (e.g., Hudson Strait, the Bay of Fundy, the Patagonian and Northwest European Shelves, and others) that are well-shaped for resonance (e.g., Garrett, 1972; Clarke, 1991; Cummins et al., 2010).

The barotropic SSH perturbations are driven by converging and diverging barotropic (depth-independent) flows. When barotropic tidal currents flow over topographic features they initiate vertical motions, which in a stratified fluid such as the ocean implies the existence of tidal oscillations along the interfaces between layers of different densities (e.g., Bell, 1975; Wunsch, 1975; Baines, 1982; St. Laurent & Garrett, 2002; Lahaye et al., 2020; amongst many). The heaving of interfaces below the sea surface at tidal frequencies, known as the internal or baroclinic tide, is associated with temperature perturbations, as we will show later in frequency spectra of temperature, and brings about a considerable baroclinic (depth-dependent) component in tidal velocities (see, for instance, Figs. 2 and 5 of Timko et al., 2013). Internal tides can be divided into stationary (also referred to as "coherent") components, which can be defined with a predictable amplitude and phase lag, and

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What is an internal gravity wave?

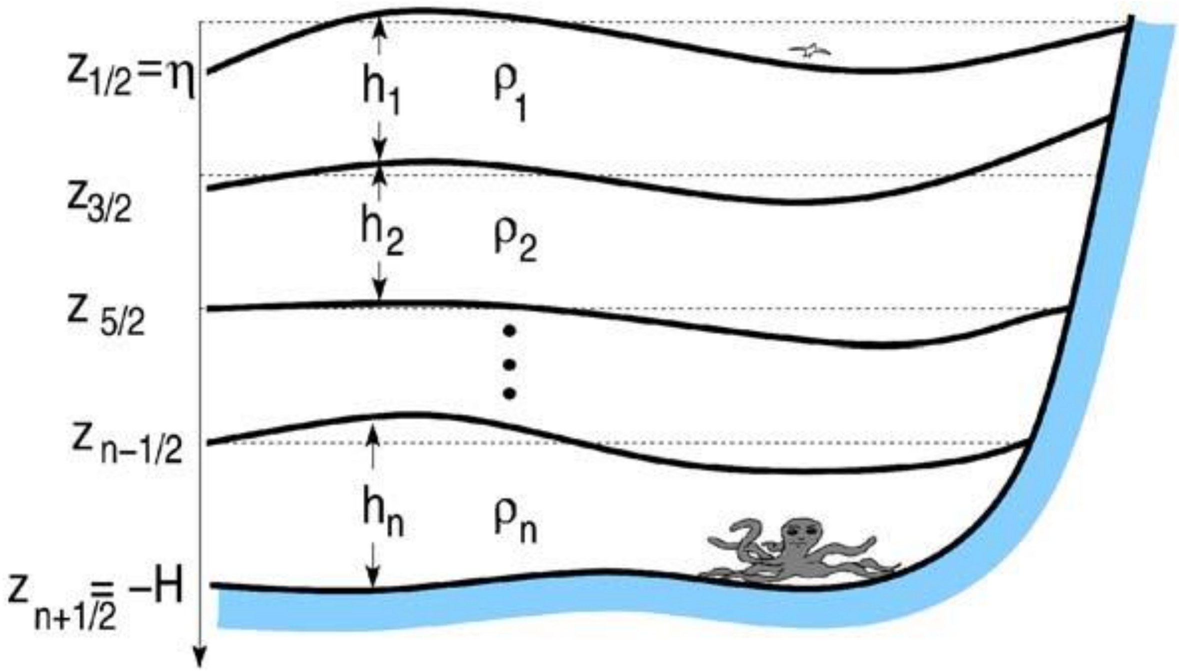
Internal gravity waves (IGWs) are gravity waves that are "internal" to the ocean

- Larger displacement signals are at depth

In a layered model, IGWs exist on the interfaces between layers.

Schematic for layered models

IGW undulations show up as temperature variance signals

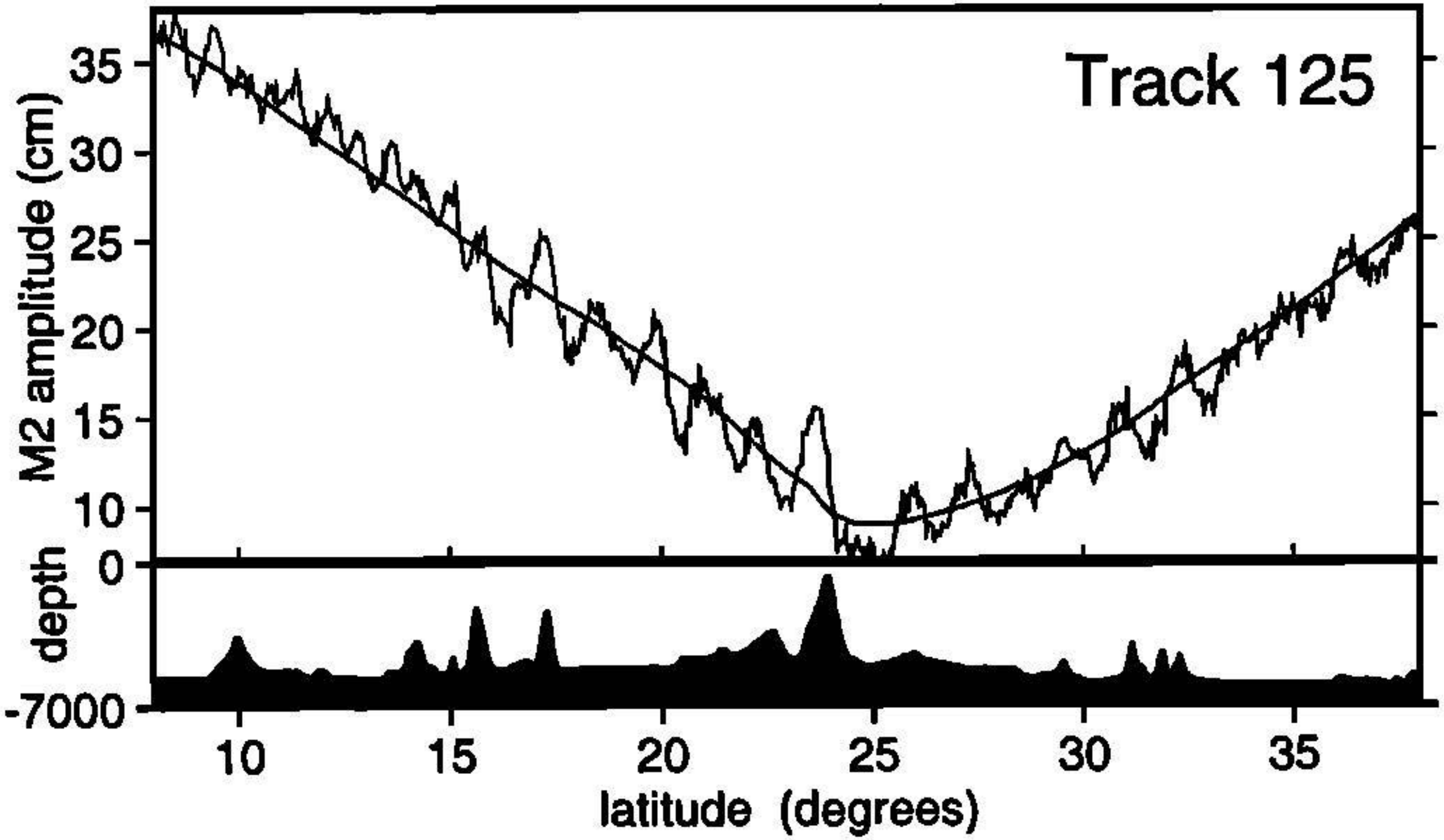


Simmons et al. (2004)

Motivating observational studies

Evidence for radiation of coherent low-mode internal tides over long distances from acoustic tomography (Dushaw et al. 1995) and altimetry (Ray and Mitchum 1996, 1997).

Evidence that 25%-30% of 3.5 TW total tidal dissipation takes place through internal tide generation over open-ocean rough topography (Egbert and Ray 2000).



Internal tides in altimetry

Ray and Mitchum (1996)

Show animations

Why add tides to high-resolution global circulation models?

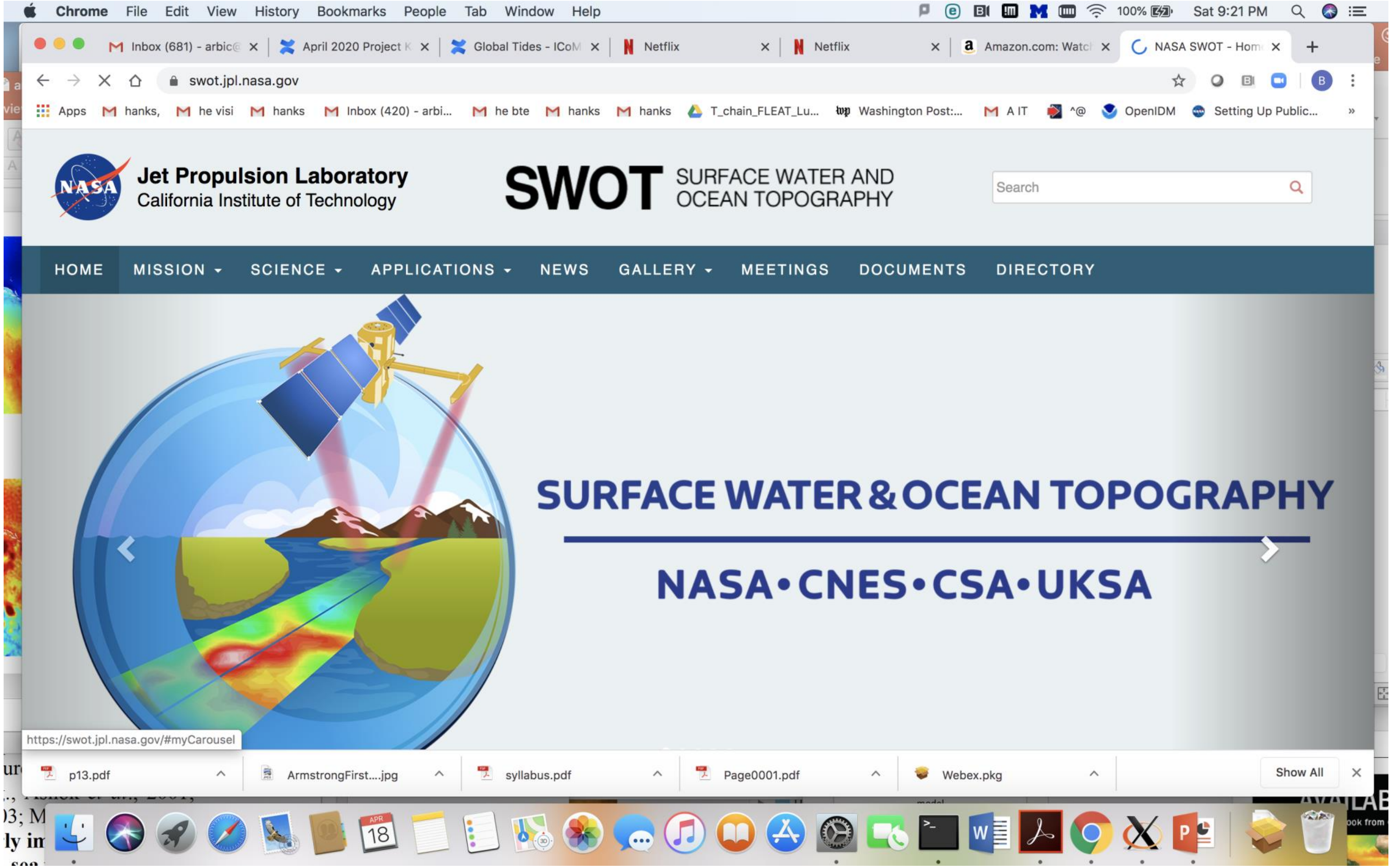
- Barotropic tidal flow over rough topography in a stratified fluid generates internal tides
- Internal tides propagate in an environment with changing stratification and eddies→yields a realistic internal tide non-stationarity (incoherence, non-phase-locking)
- Non-linear interactions between internal tides and wind-driven near-inertial waves yield a partially resolved supertidal internal gravity wave (IGW) continuum, or Garrett-Munk spectrum, as shown in Müller et al. 2015 (for US Navy HYCOM simulations), Rocha et al. 2016 (for NASA MITgcm simulations), and other papers
- Breaking IGWs drive mixing
  - can our models help us understand the space-time geography of ocean mixing?
- Internal waves impact ocean acoustics
- Remotely generated internal waves should be included in boundary conditions for regional models
- Tides interact with other components of the climate system (e.g., ice) and tides change in a changing climate
- Global internal wave models help us plan for and interpret SWOT

SWOT will measure surface water heights over oceans, lakes, and rivers→
Joint oceanography + hydrology mission

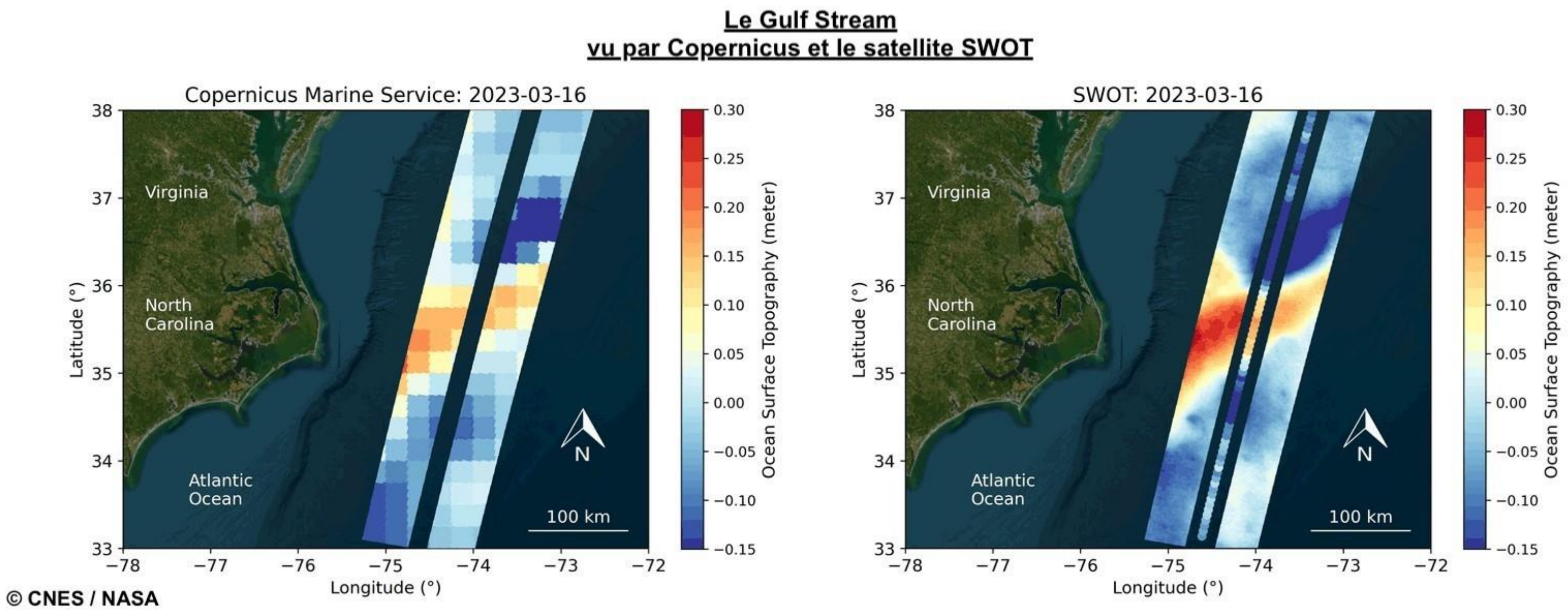
In contrast to current nadir altimeters, SWOT measurements will be in two-dimensional swaths rather than one-dimensional tracks

Feature resolution will be much higher

Launched in December 2022



First release of SWOT data on sea surface heights



Why do global internal wave models matter for SWOT?

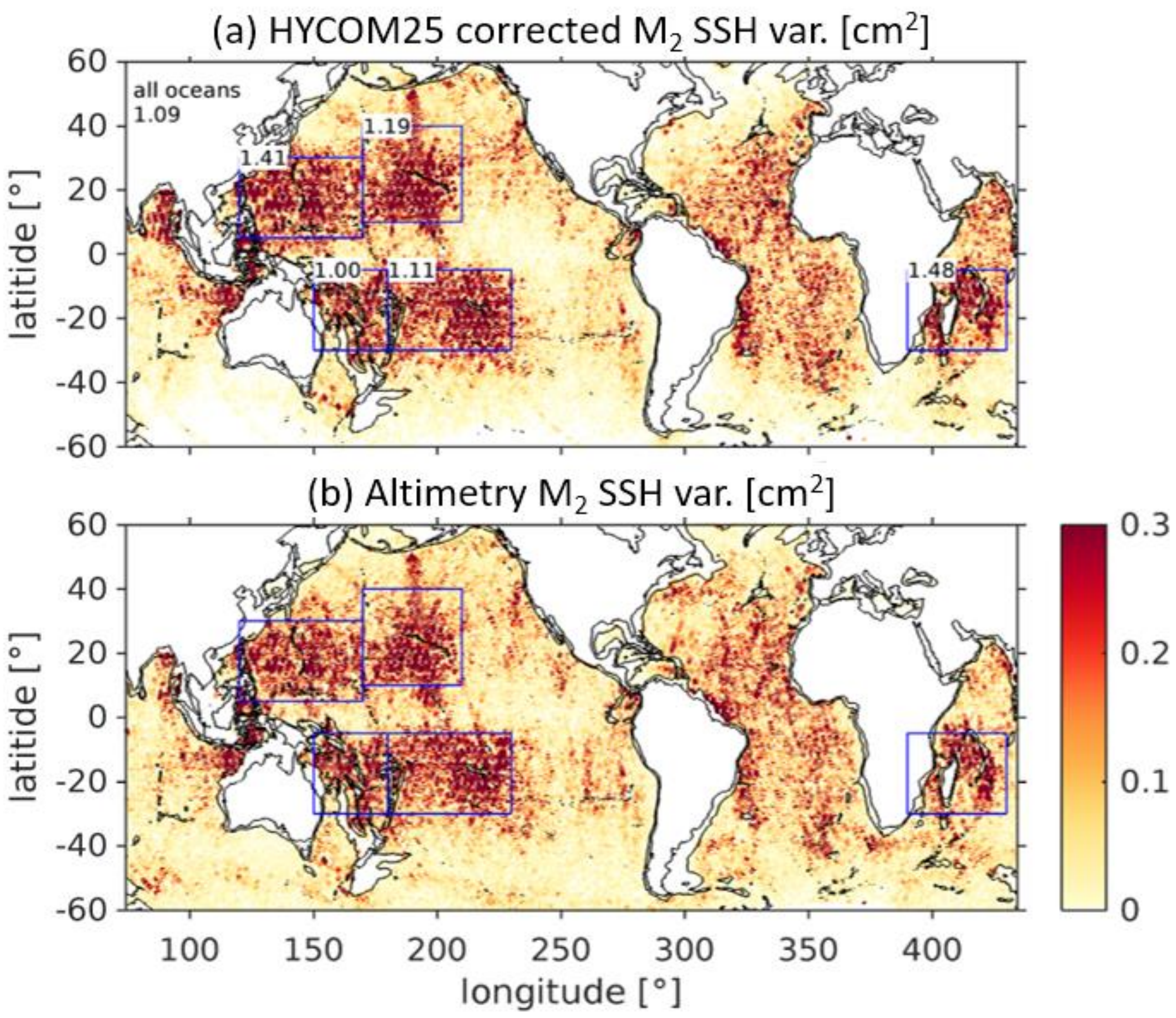
SWOT will measure sea surface heights at high resolution

Therefore, small-scale internal tides and waves will be measured, and will represent a “noise” from the point of view of someone who wants to study the eddies

Characterization vs. Correction

- The HYCOM group, and other modeling groups, have used global internal wave models to **characterize** the internal tide and internal wave fields.
- Recently we have raised the bar and shown that we can phase-predict internal tides and waves
  - HYCOM therefore could be used for internal wave **corrections** to SWOT and nadir altimetry
    - Tidal forcing yields phase-locked internal tides which then interact with eddies
    - Assimilation of altimetry data improves stratification and puts eddies in the correct locations

Characterization: phase-locked internal tides

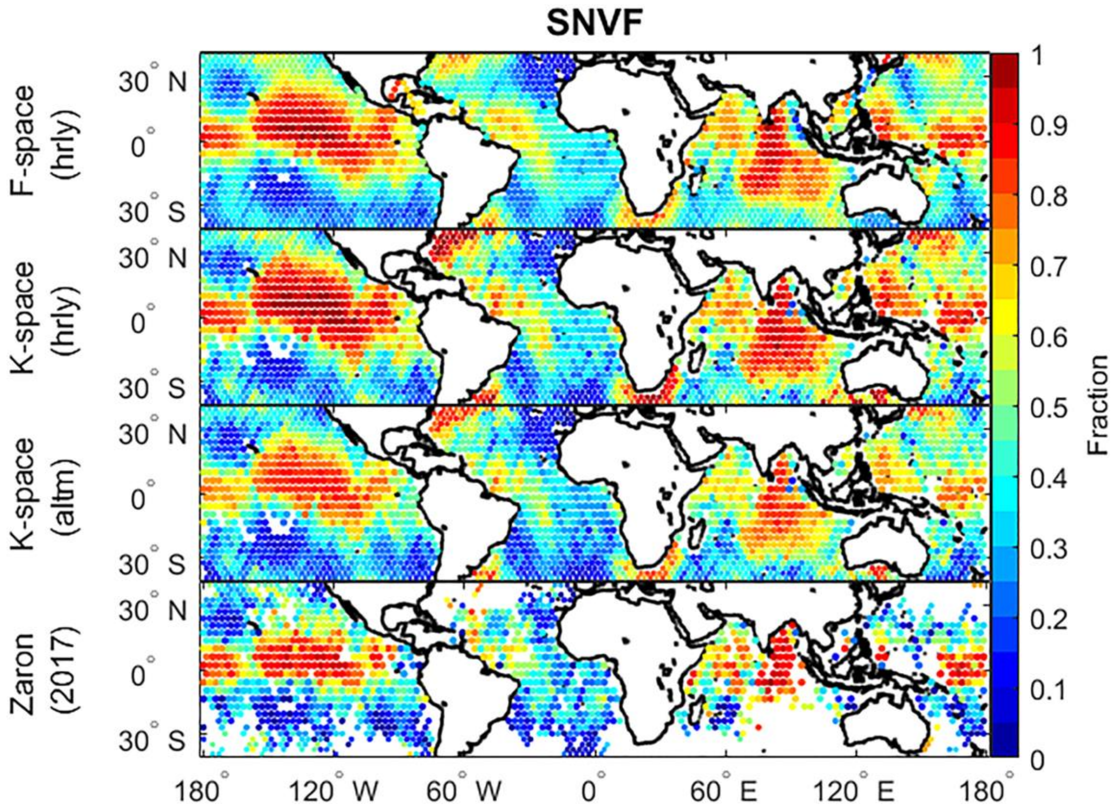


- Sea surface height (SSH) variance of the phase-locked principal lunar semidiurnal tide M_2 in **non-assimilative** HYCOM (top) and altimetry (bottom).
- The HYCOM variances have been corrected for the effects of the short duration of the model output record.
- Numbers represent the fraction of HYCOM variance to altimetry variance.
- Determined by spatially high-passing amplitudes of total tidal SSH (as in Ray and Mitchum 1996)

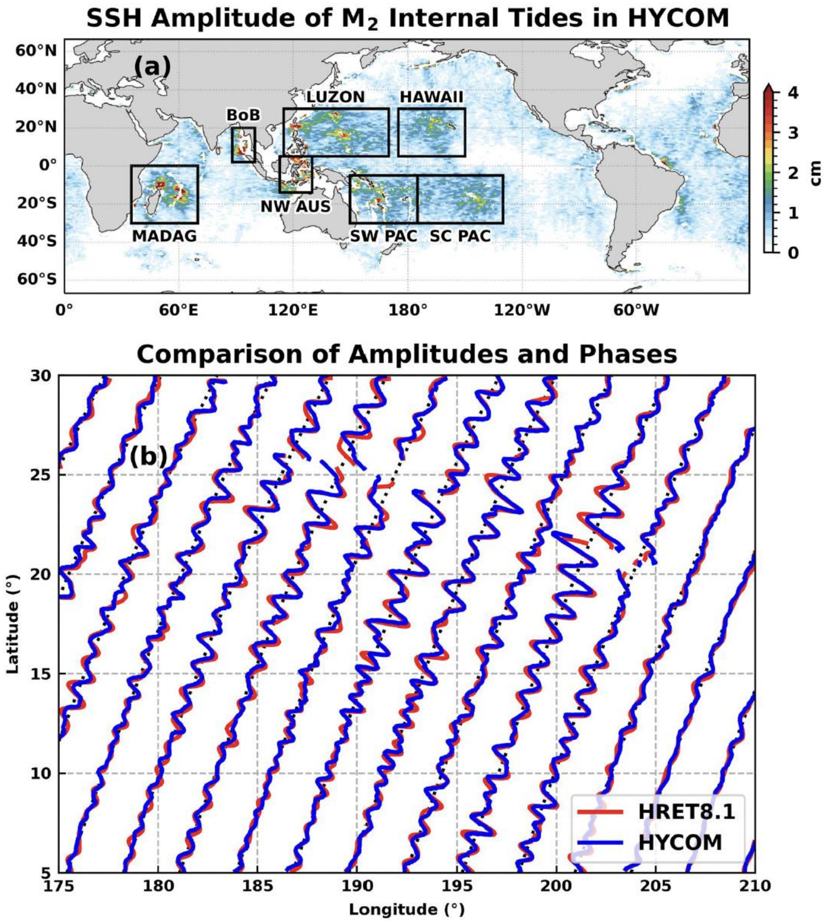
Buijsman et al., Ocean Modelling, 2020

Characterization: semi-diurnal non-phase-locked variance fraction (SNVF) in non-assimilative HYCOM vs. altimetry (Nelson et al., 2019)

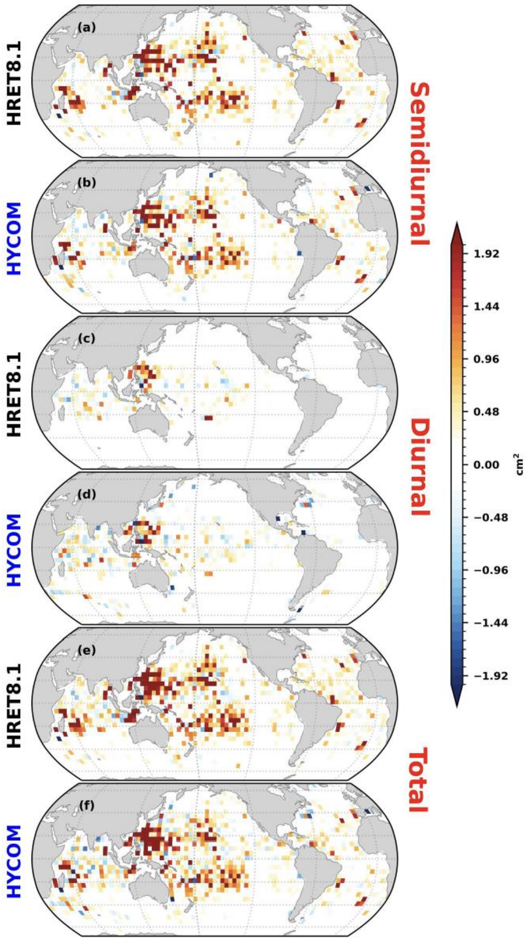
- Large non-stationarity in equatorial regions examined in detail in Buijsman et al. (2017)



Internal tide correction: Data assimilative system shows skill in phases



Bottom: amplitude * sin (phase)



Variance reduction from nadir altimetry

Yadidya et al. 2024

Internal tide correction: Data assimilative system shows skill in phases

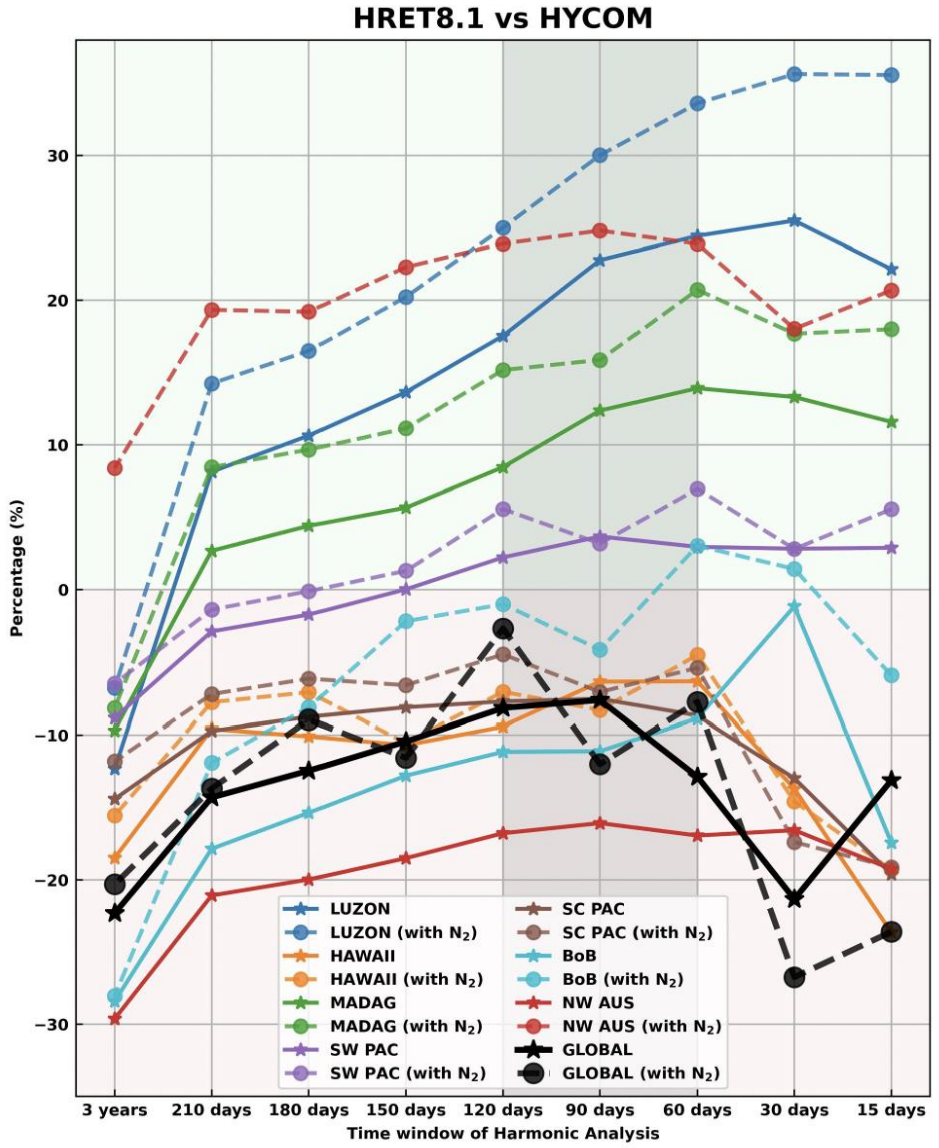


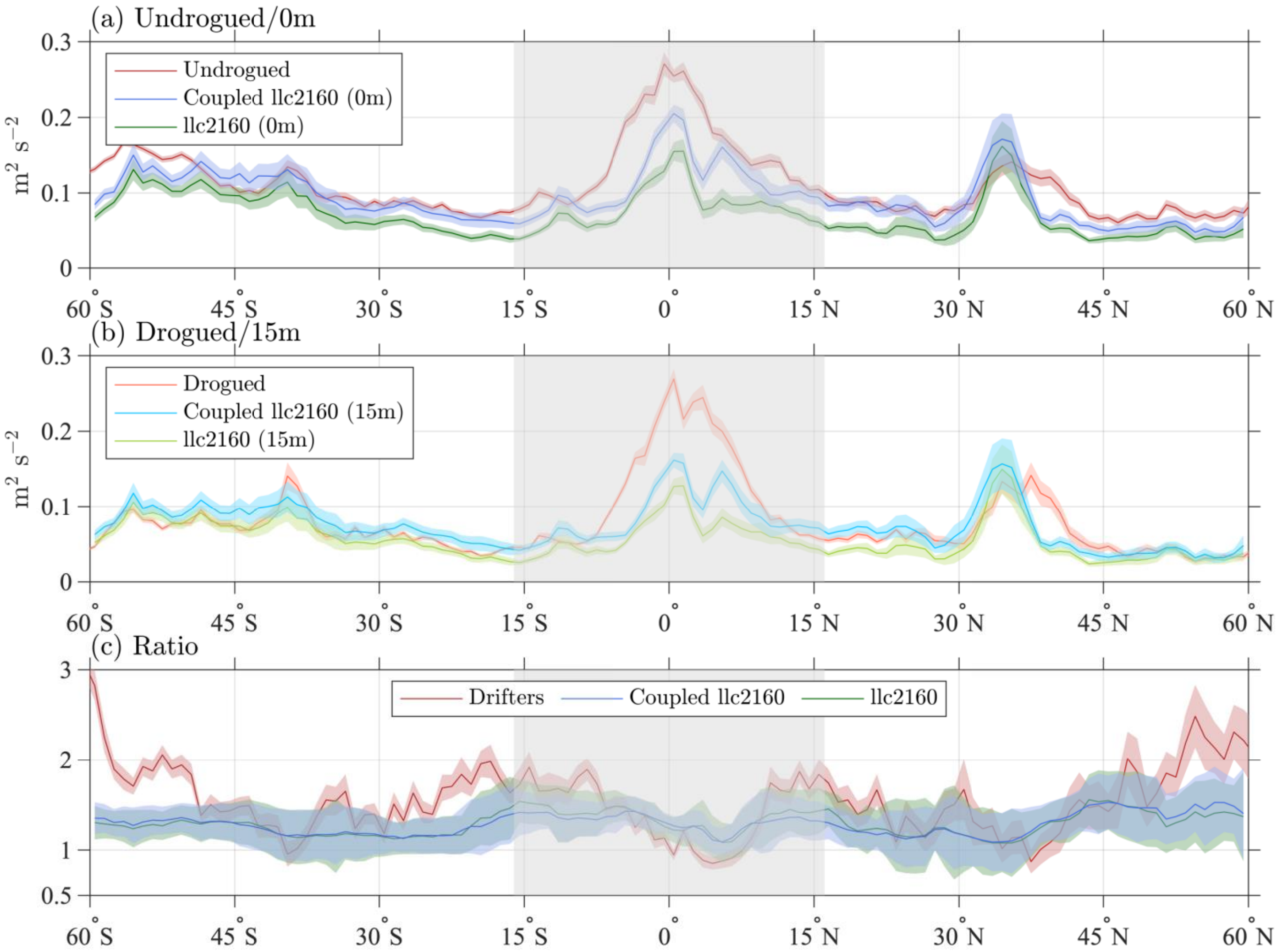
Figure 3. Comparison of variance reduction achieved in HYCOM versus HRET8.1, as a function of the time window of the HYCOM harmonic analysis, measured in percentages. Results are given for the regions of strong internal tide activity shown in Figure 1 as well as for the global average. Positive values imply that HYCOM reduced a larger amount of variance, while negative values imply that HYCOM reduced a smaller amount of variance. The results shown in this figure are computed over both semidiurnal and diurnal bands. Results are shown with and without the inclusion of the N_2 constituent in HYCOM.

Yadidya et al. 2024

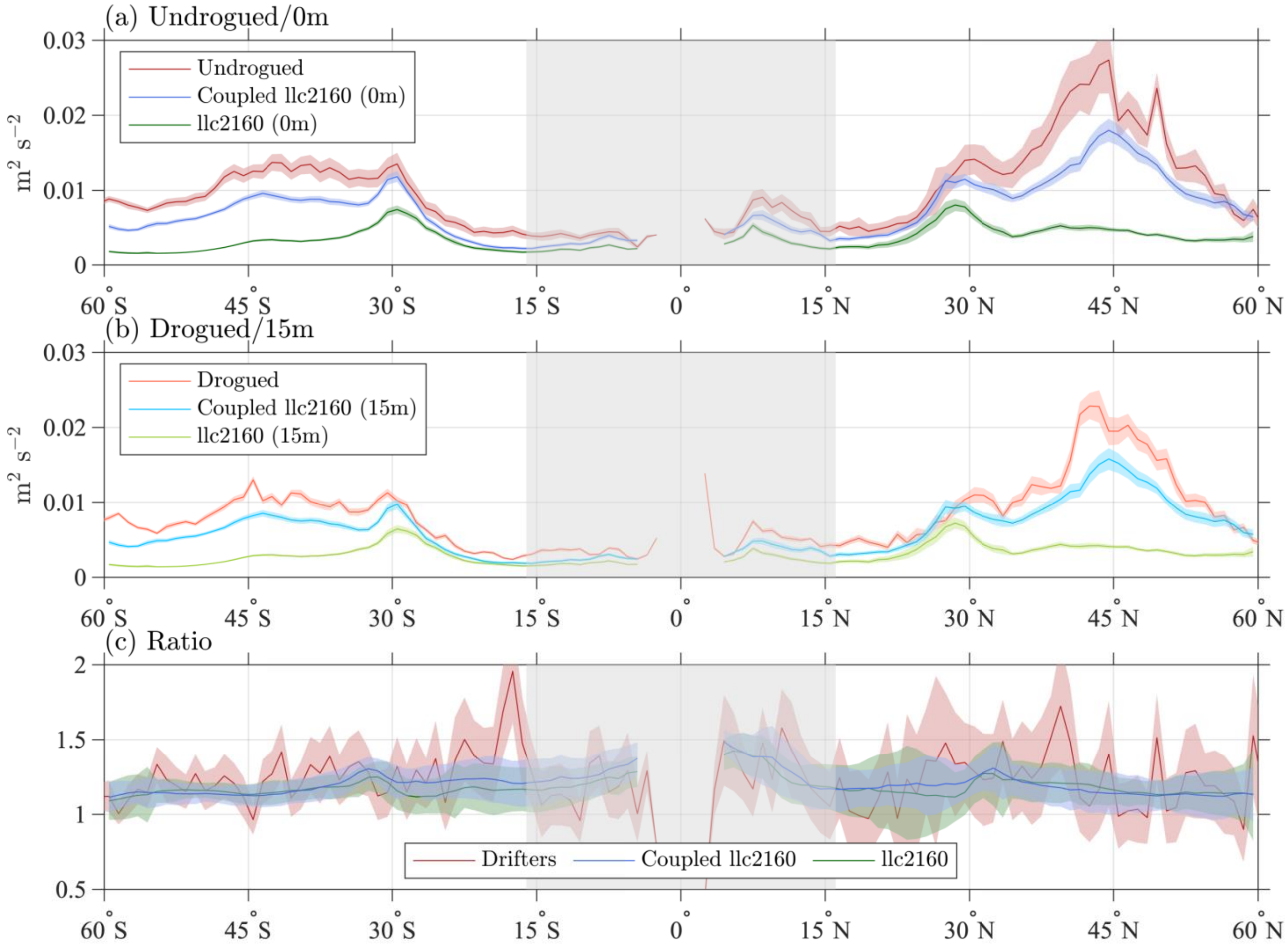
On to other topics

- Aside from the potential of using HYCOM for SWOT internal tide corrections, we continue to work on other SWOT-relevant topics, including:
  - Model – observational comparisons
    - Moorings (Ansong et al. 2017, Luecke et al. 2020, Nelson et al. 2020, Thakur et al. 2022)
    - Drifters (Arbic et al. 2022, Caspar-Cohen et al. in preparation, other ongoing work)
  - Boundary forcing regional models
  - Applications to mixing

Models vs. near-surface drifters: Low-frequency band (Arbic et al., 2022, Arbic new results)



Models vs. near-surface drifters: Near-inertial band (Arbic et al., 2022, Arbic new results)



Models vs. near-surface drifters: Semidiurnal band (Caspar-Cohen et al. in preparation)

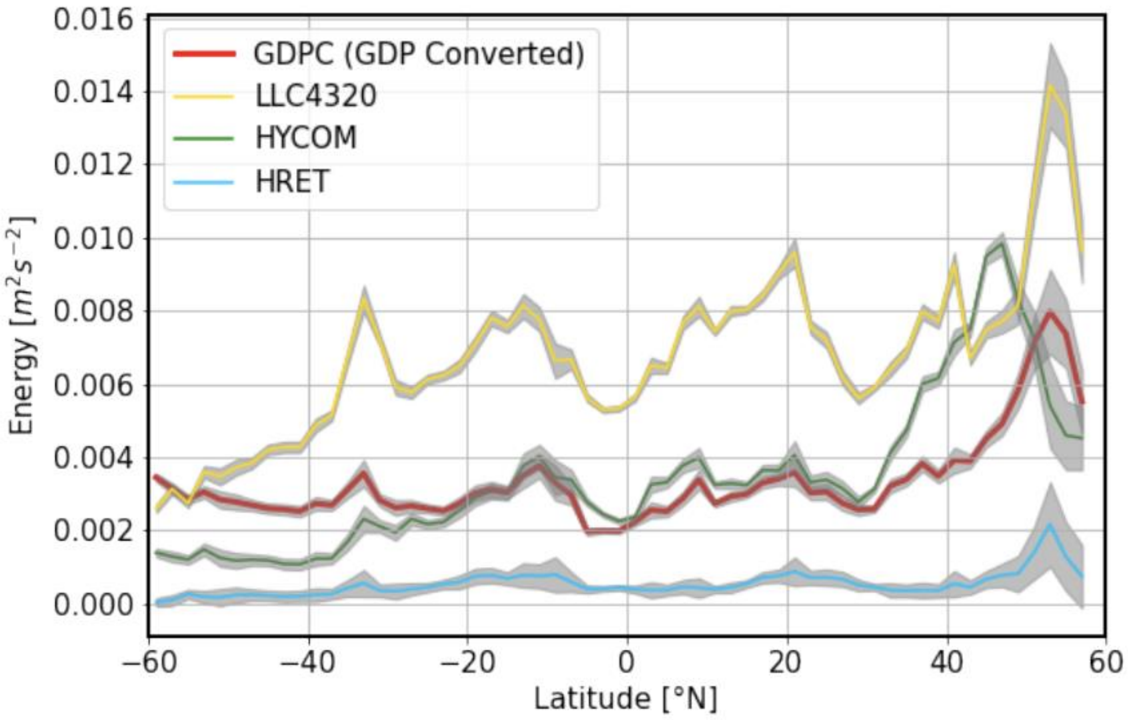


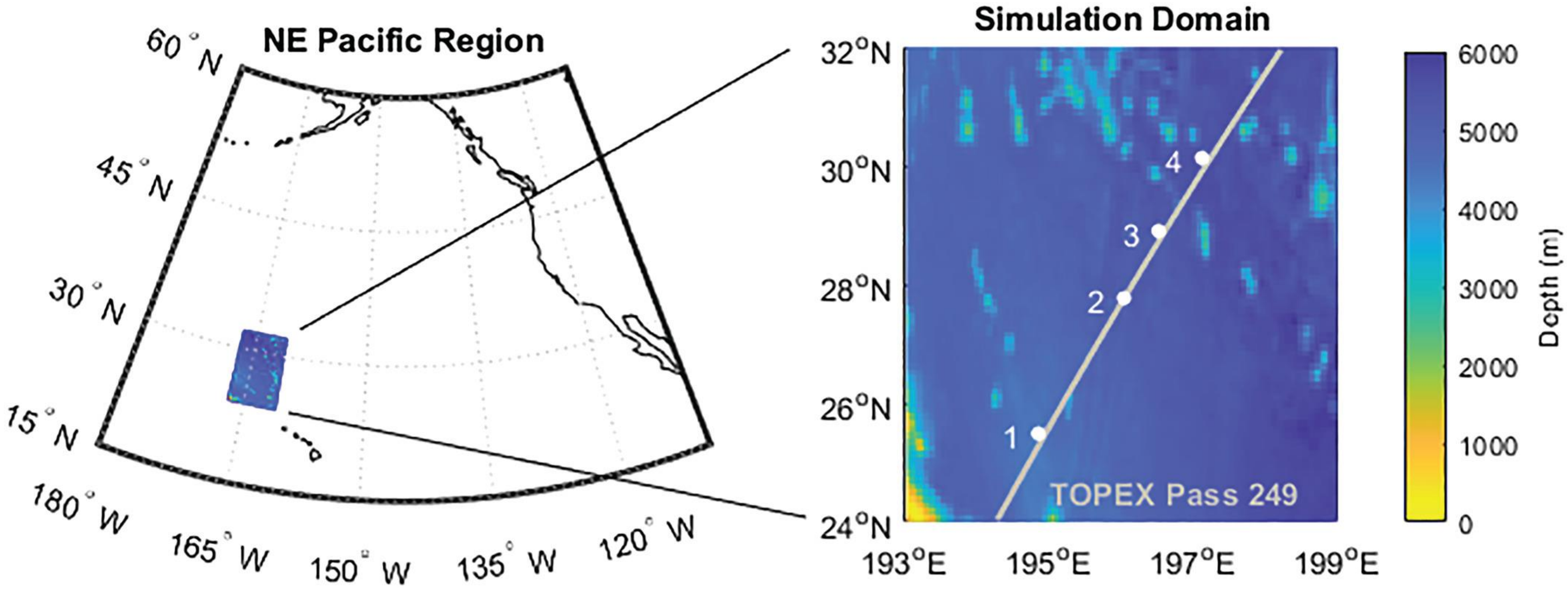
Figure 5: Zonal average of the surface semi-diurnal kinetic energy estimated from LLC4320, HYCOM, converted GDP and HRET. Grey shading correspond to error due to spatial sampling (i.e. standard deviation)

Boundary forcing very-high resolution regional simulations

- SWOT mission motivates running regional models at the highest possible resolutions
- ”Pilot” project in collaboration with Dimitris Menemenlis, Dick Peltier (University of Toronto) and others.
- Another Dimitris Menemenlis “hero run”, done on Canadian supercomputer Niagara (courtesy of collaboration with Dick Peltier).
- Use Dimitris’ global 1/48° MITgcm simulation to boundary force a 6° by 8° MITgcm patch near Hawai’i, with 8X higher horizontal and 3X higher vertical resolutions (Nelson et al. 2020, Pan et al. 2020)

- Alternatively, can use same resolution in regional domain as in global domain to explore parameter sensitivities in much cheaper regional domain (Thakur et al. 2022, Skitka et al., Momeni et al. in review).

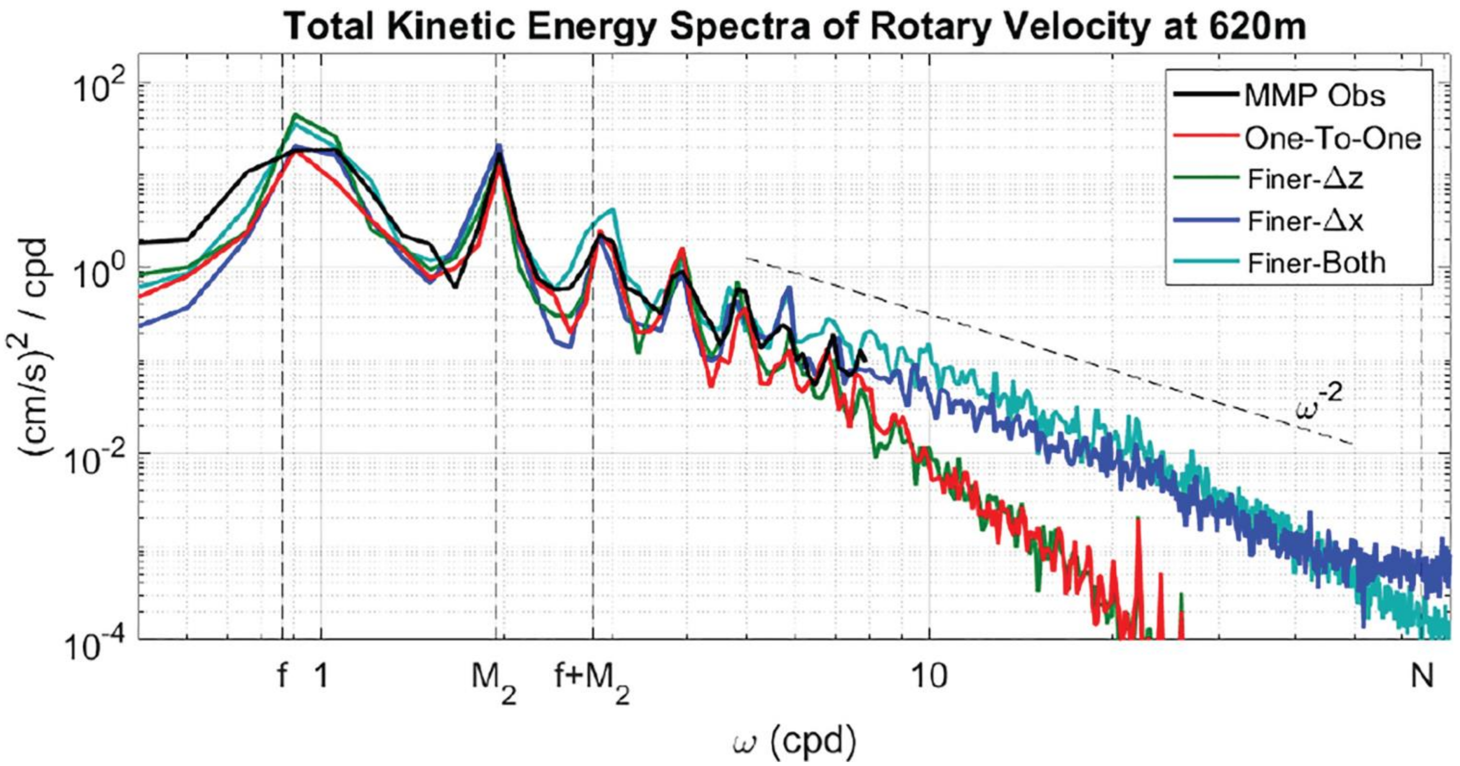
Model domain, high-resolution regional simulation (Nelson et al., 2020)



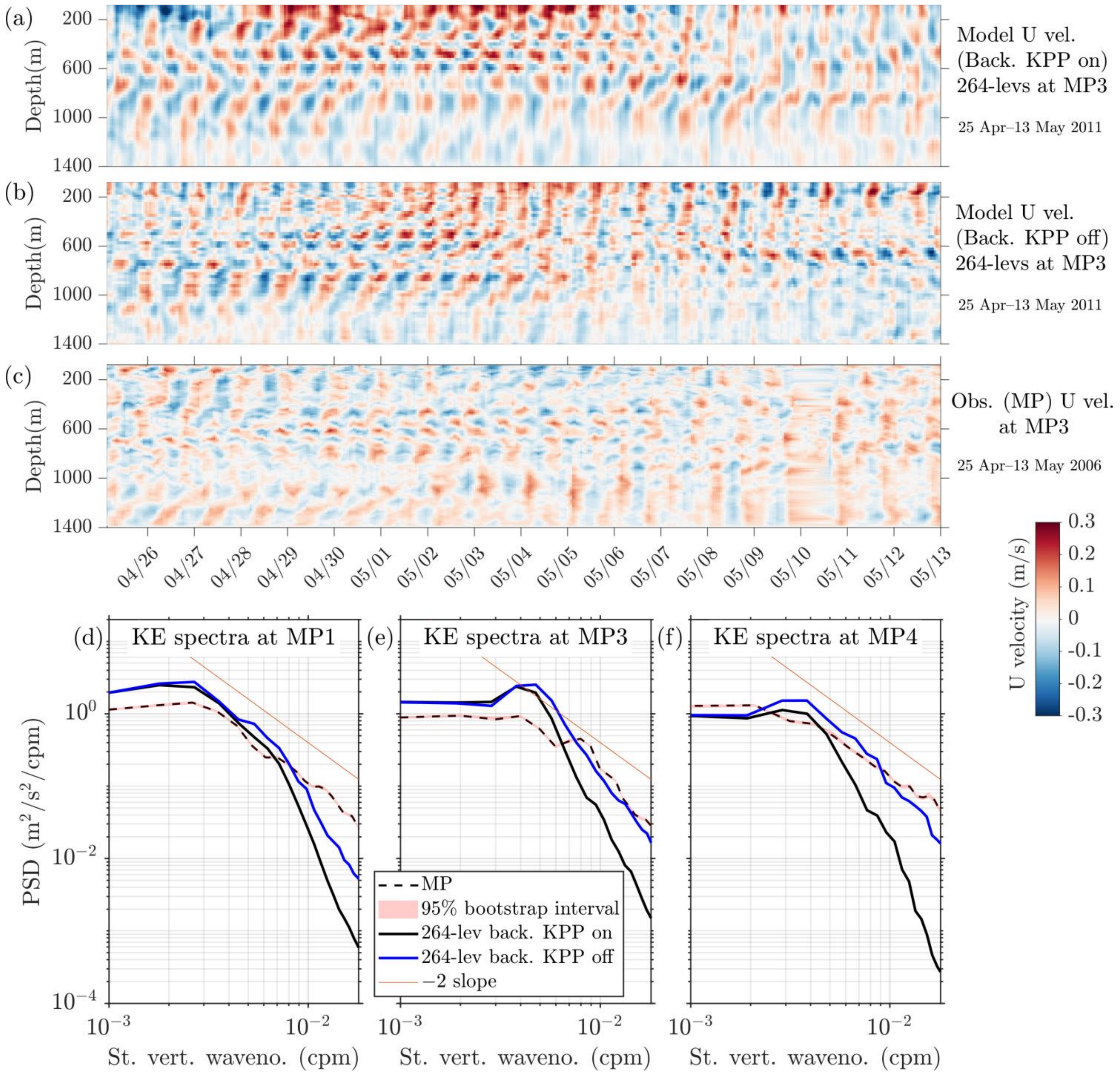
Improved IGW frequency spectra in a regional model forced by the global MITgcm simulation (Nelson et al., 2020)

- Mazloff et al.: w/o internal tide boundary conditions, a regional model has an insufficiently energetic IGW spectrum

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



Improved IGW vertical wavenumber spectra in a regional model forced by the global MITgcm simulation (Thakur et al., in review)



KPP was developed for models that do not resolve internal waves

In models that partially resolve internal waves, turning off the KPP background yields a vertical structure that agrees more closely with observations

Vertical profile of IGW dissipation (Skitka et al., in review)

The model damping operators are dissipating energy at rates that are comparable to those seen in observations.

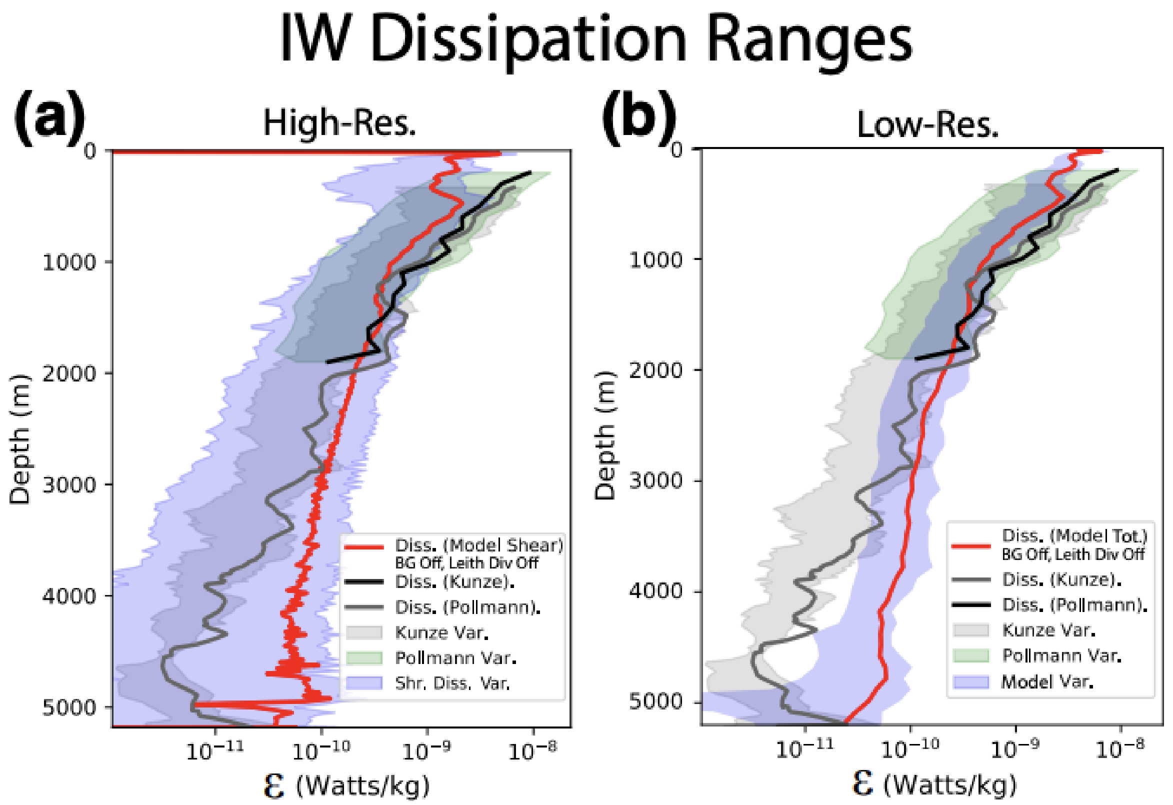


Figure 4. Dissipation profiles with the 16th - 84th percentile highlighted around the mean for high- and low- resolution KPP-BG-off/Leith-div.-off cases. In the high-resolution case, we choose to display the shear term from the model output as it exhibits better agreement with observations.

ROMS simulation in California Current region
Lateral boundary condition: global HYCOM

Papers

Siyanbola et al. 2023, Delpech et al. 2023, 2024

In review: Siyanbola et al. 2024

Collaborators

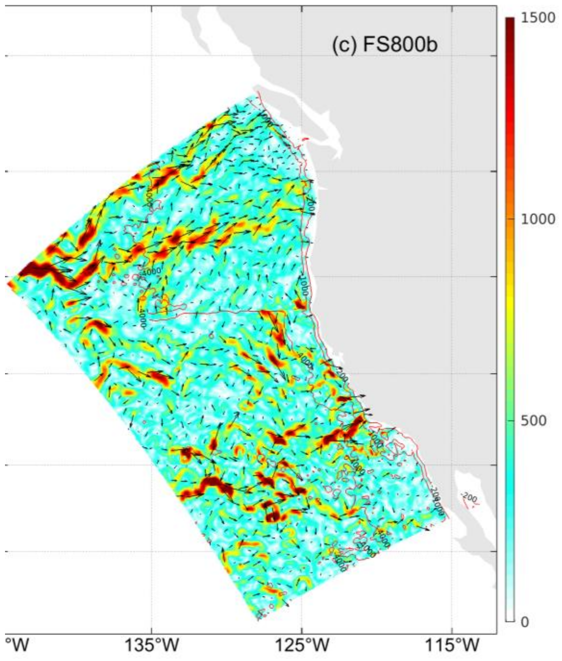
Maarten Buijsman, Oladeji Siyanbola: U-Southern Mississippi

Roy Barkan, Audrey Delpech, Jim McWilliams: UCLA (Roy also at Tel Aviv U)

Brian Arbic, Ritabrata Thakur: U-Michigan

Jay Shriver: NRL Stennis Space Center

Lionel Renault: LEGOS



Comparisons with SWOT observations

SWOT/global model comparison: Kuroshio region

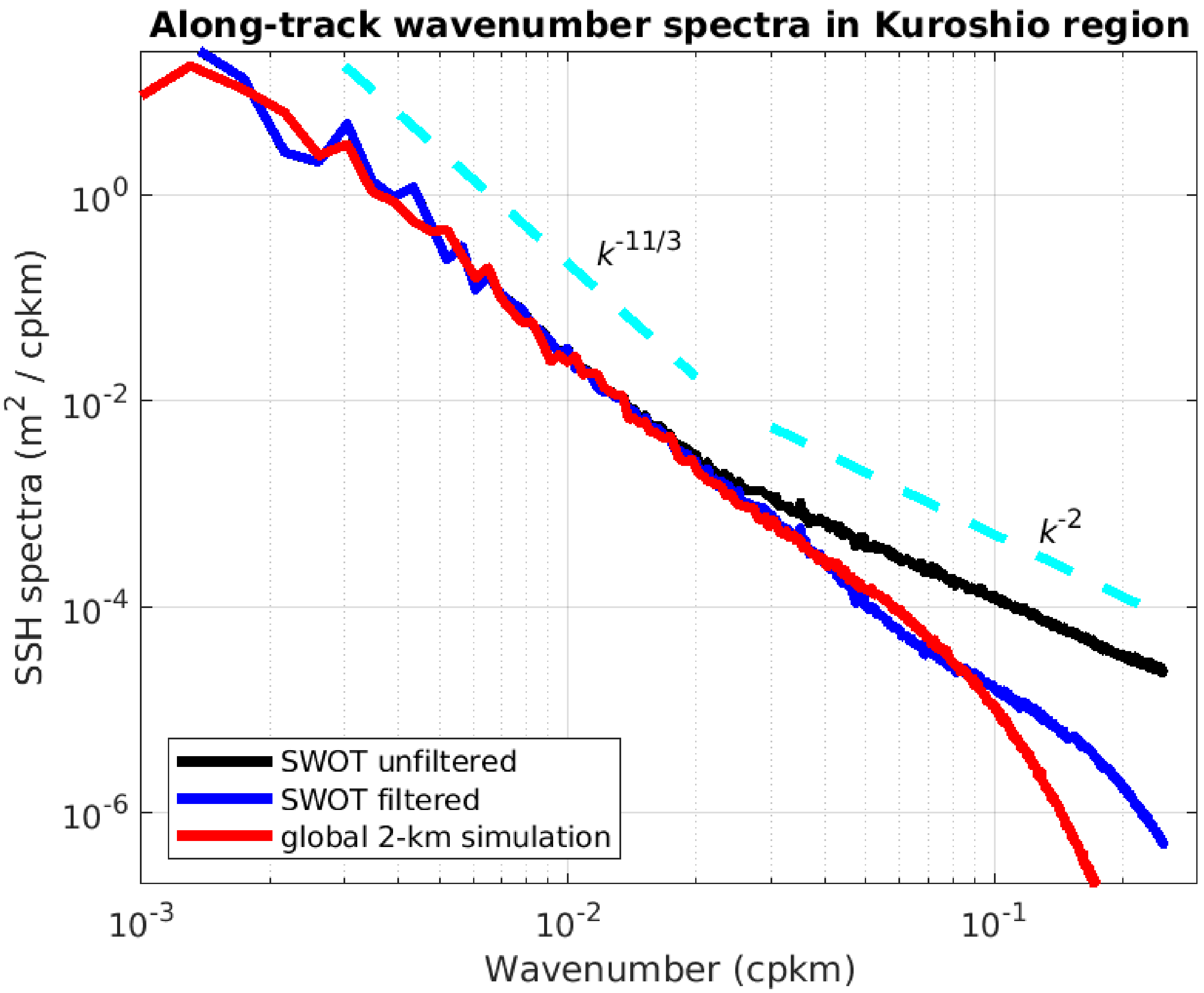
SSH wavenumber spectra from 1-day phase in Kuroshio region

--SWOT Level 3 (L3) 1-day repeat phase

--Calibrated (Unfiltered)

--Filtered

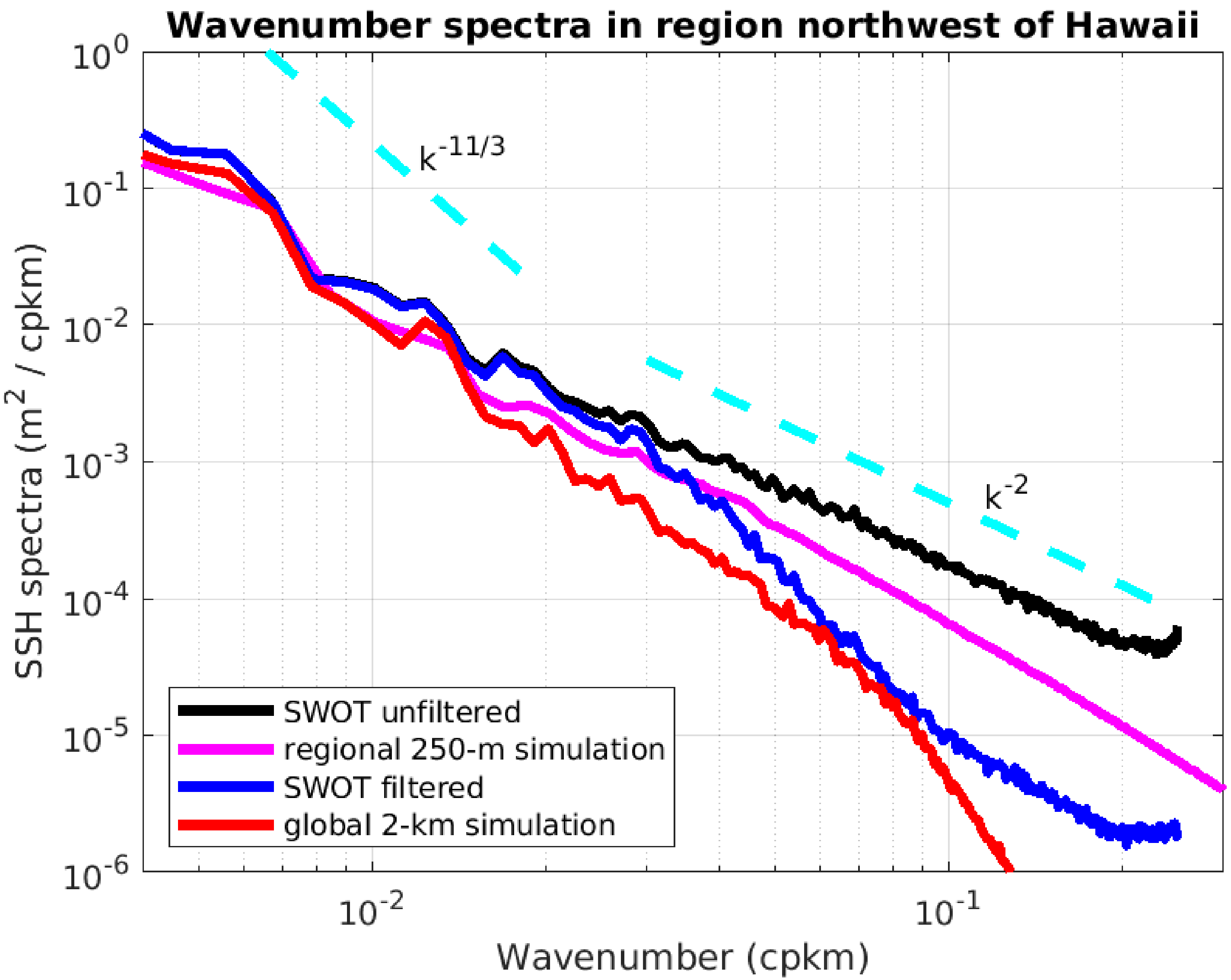
--2km global LLC4320 simulation



SWOT + global model + regional model comparison: Hawai'i region

- SSH wavenumber spectra in Hawai'i region from

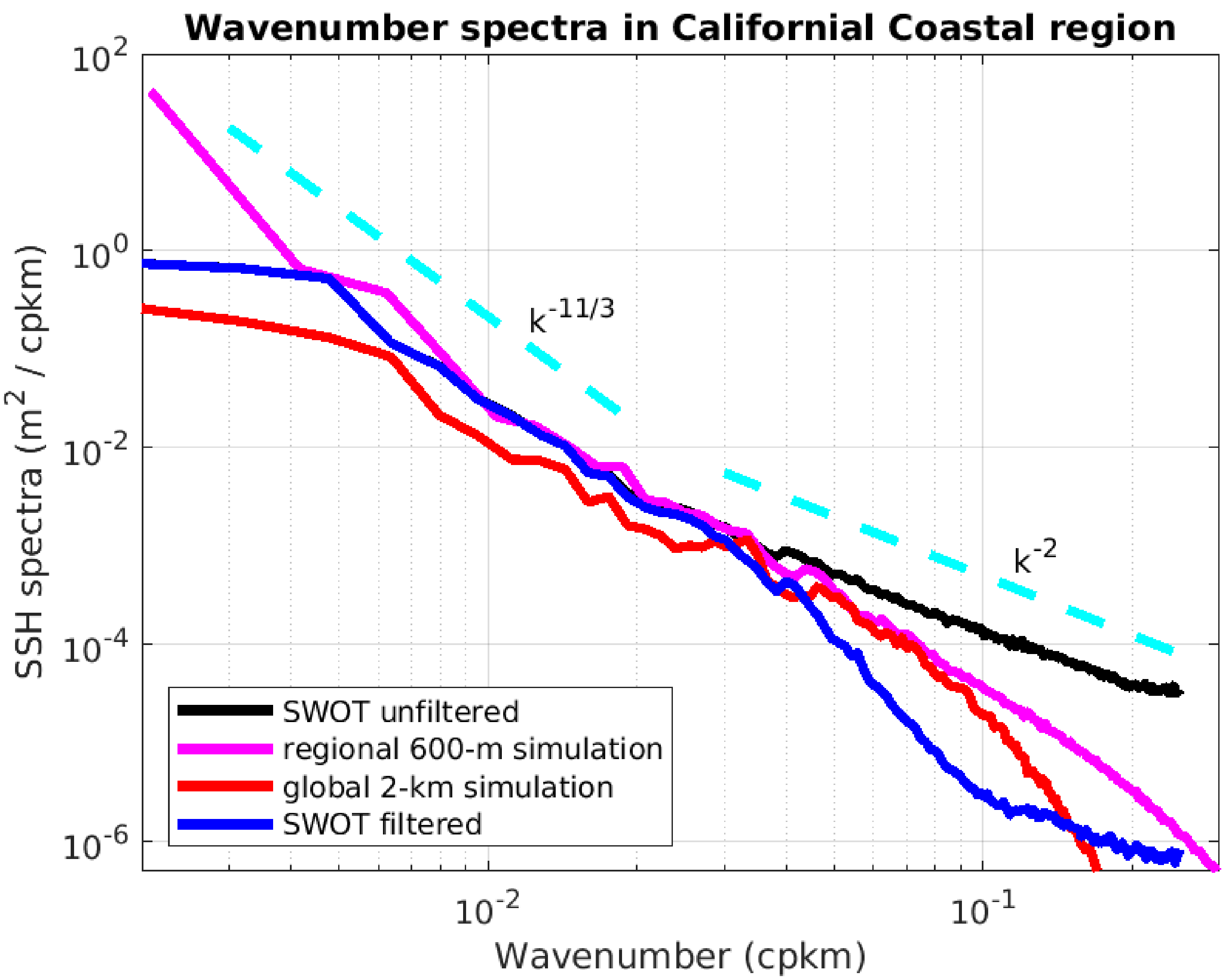
- --SWOT Level 3 (L3) science phase
- --Calibrated (Unftiltered)
- --Filtered
- --250 m regional MITgcm simulation
- --2km global LLC4320 simulation



SWOT + global model + regional model comparison: California Current region

- SSH wavenumber spectra in California Current region from

- --SWOT Level 3 (L3) science phase
- --Calibrated (Unfitered)
- --Filtered
- --600 m regional ROMS simulation
- --2km global LLC4320 simulation

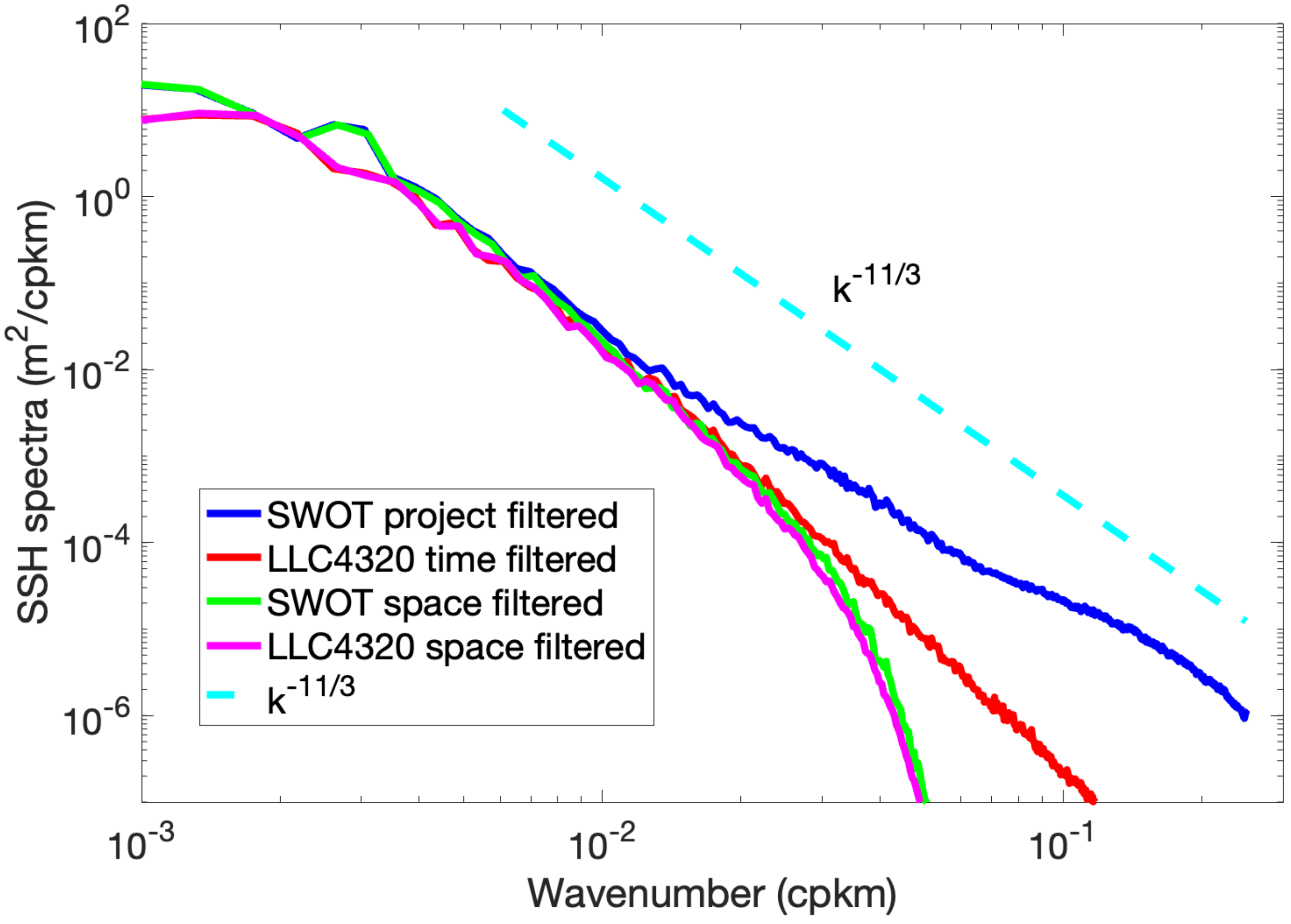


Can space or time filtering provide us with geostrophic SSH?

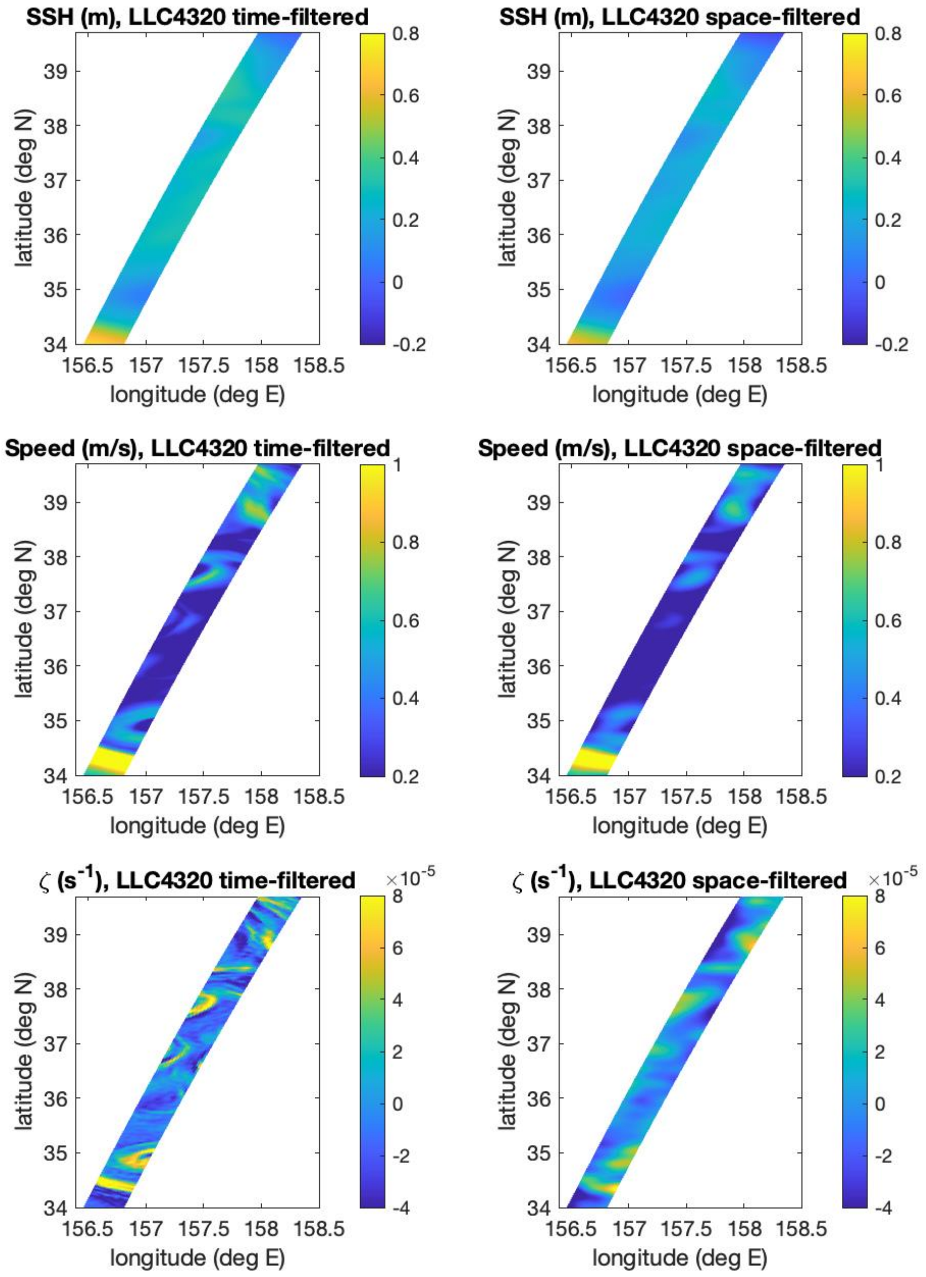
Pass 19 of 1-day phase,
Kuroshio region

Space filter: Blackman filter going to zero 11 grid points away from center

Time filter: 3-day low-pass fourth-order Butterworth filter

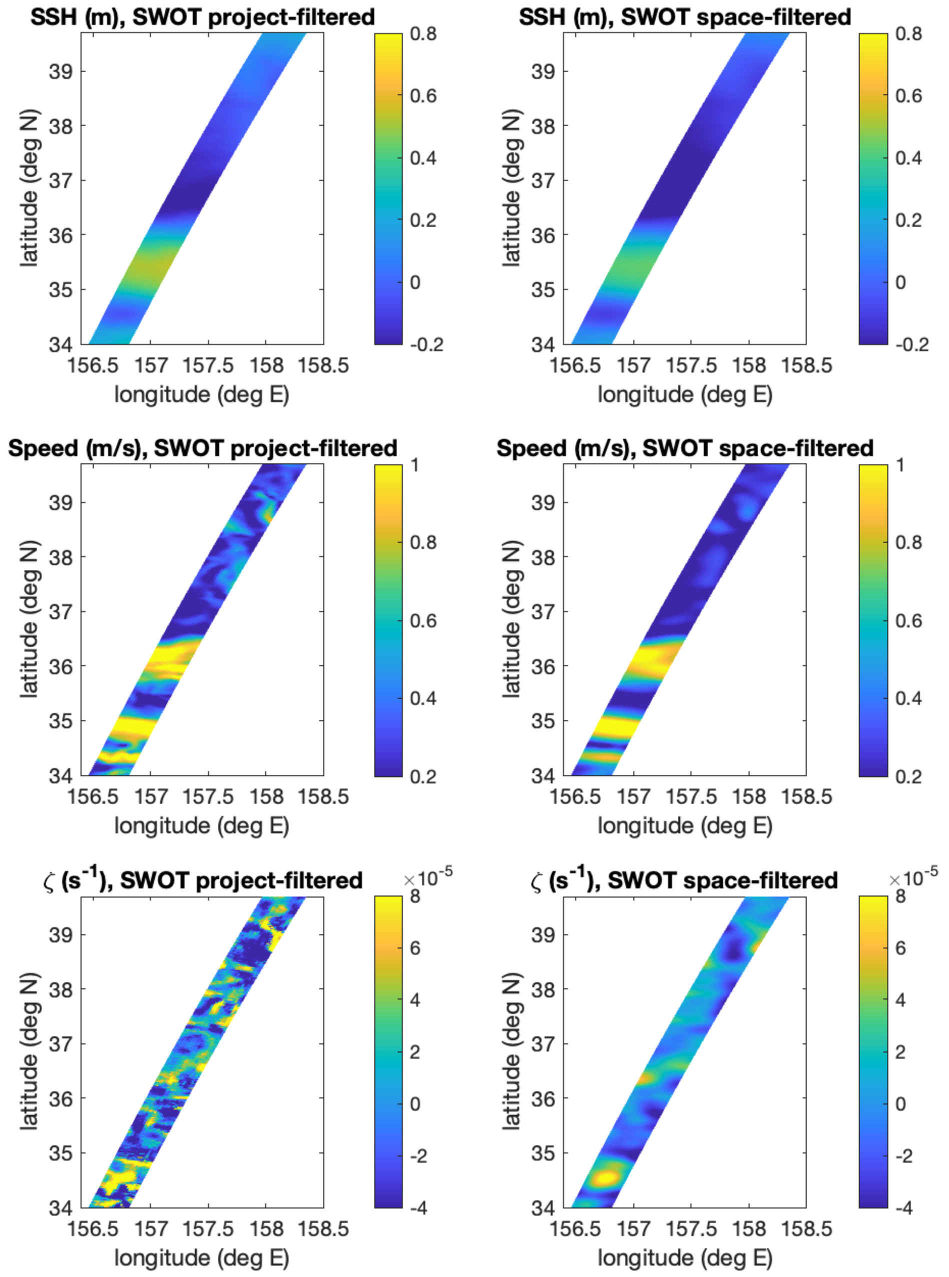


Visualization: Effects of differentiation



LLC4320 snapshots

SWOT snapshots



Impact of climate change on tides (Barton et al. in preparation)

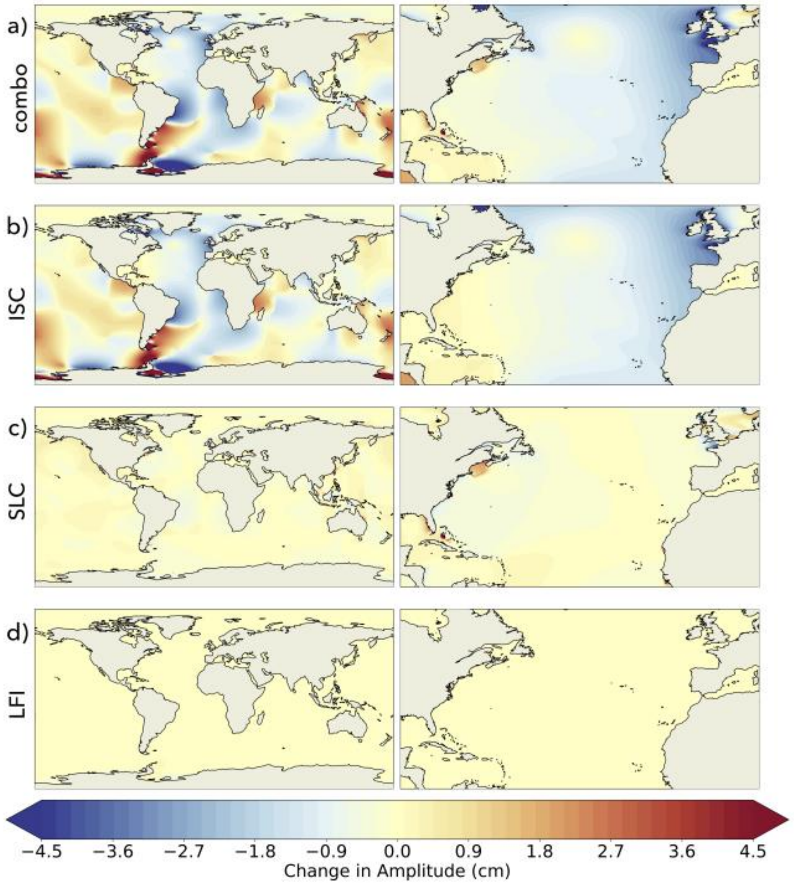


Figure 1: Change in M_2 amplitude (cm) at 2100 using AE03 ice sheet data due to a) combination of SLC, ISC changes, and LFI reduction; b) ISC changes only; c) SLC only; d) LFI reduction only. SLC impacts the coastal areas, but the ice-shelf cavity changes have much larger amplitude changes in the open-ocean. The left four plots show the global changes, while the right four plots focus on the North Atlantic region, demonstrating the spatially smaller-scale influence on coastal tides from sea level.

Disadvantages of including tides in OGCMs

- Need for high-frequency output
  - BUT note that there are other reasons to analyze high frequencies (e.g., diurnal cycle, high frequencies in precipitation)

- Analysis of low-frequency motions is “contaminated” by high-frequency motions

- Need some additional expertise to analyze high-frequency motions

Summary

Global internal wave models continue to progress and will be useful for many reasons

Lots of work left to do

Extra slides

Task Force Ocean (TFO) and NOPP projects

We have two relatively new ONR projects:

Task Force Ocean (TFO) project on impact of internal waves on basin-scale propagation of acoustic waves

NOPP project to test global internal wave models with arrays of in-situ instruments (and altimetry)

HYCOM/ROMS regional modeling effort in California Current region (Siyanbola et al. 2023)

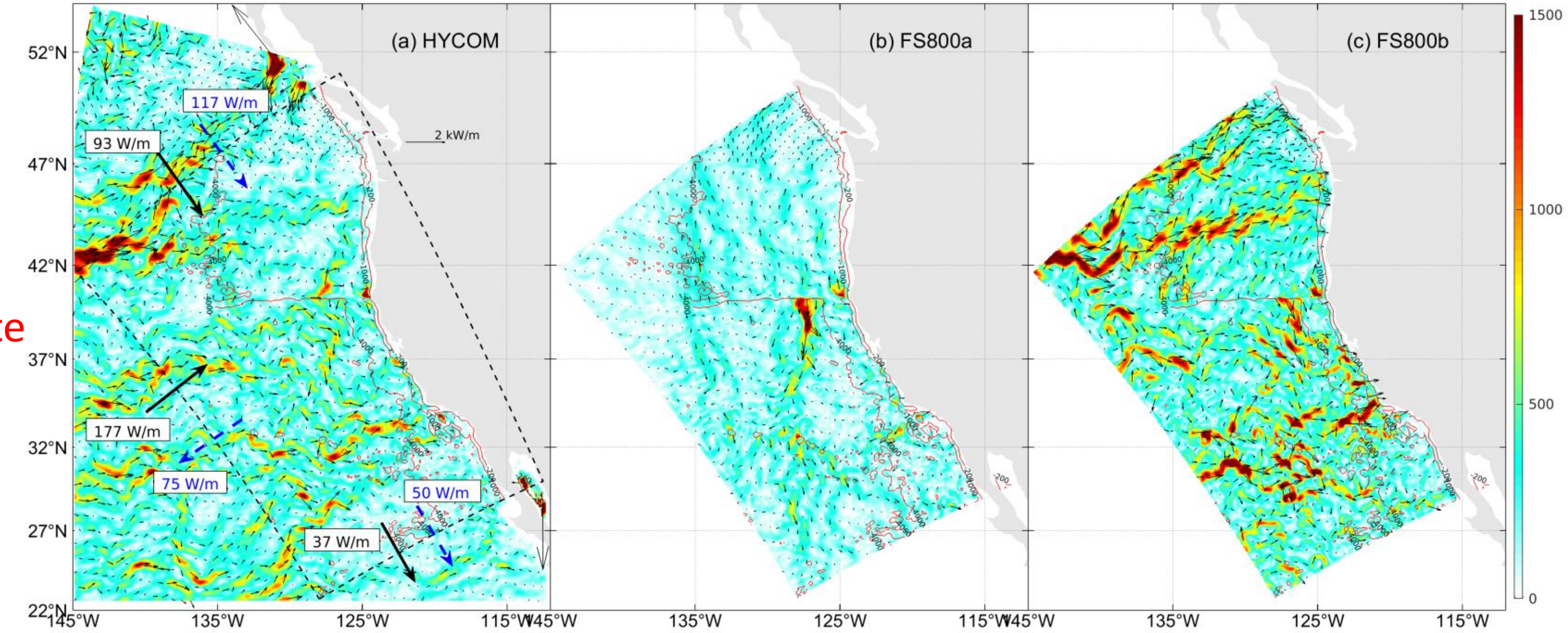
Left: depth-integrated semidiurnal fluxes for HYCOM

Middle: FS800a - ROMS run without remote internal wave forcing from HYCOM

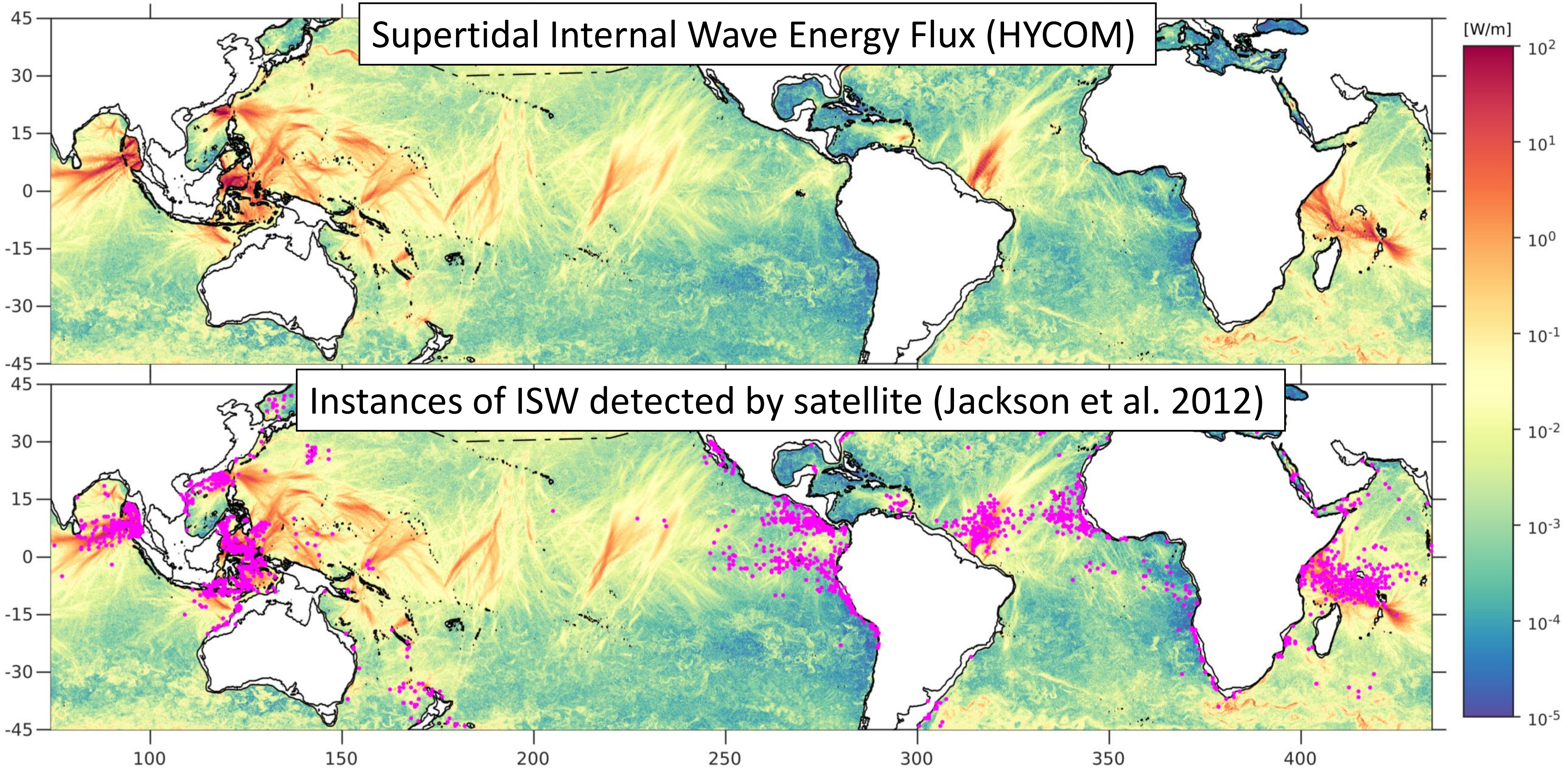
Right: FS800b - ROMS run with remote internal wave forcing from HYCOM.

Our domain gets more energetic with the inclusion of high-frequency baroclinic forcings at the open boundaries.

See also Delpech et al. 2023, 2024

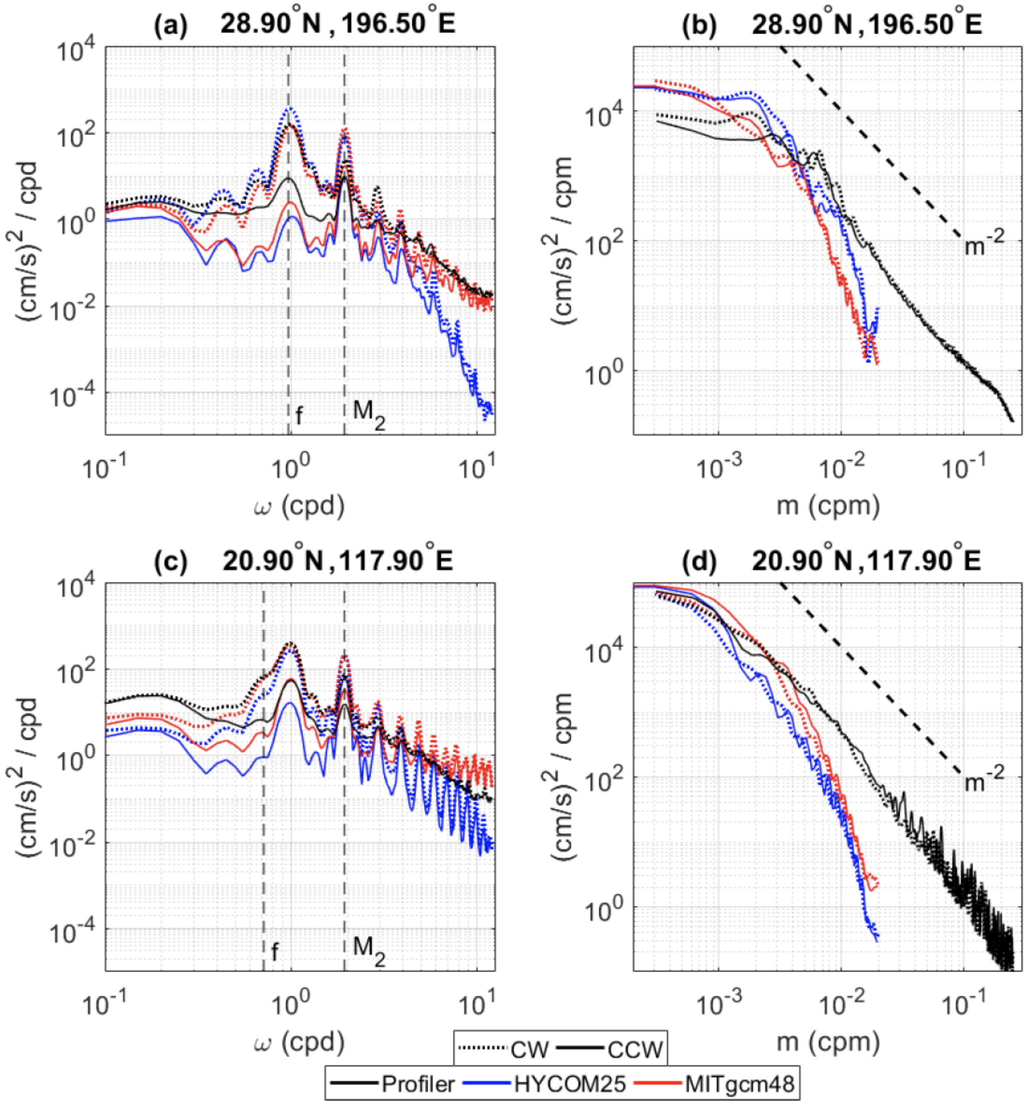


Internal Solitary Waves (ISW)



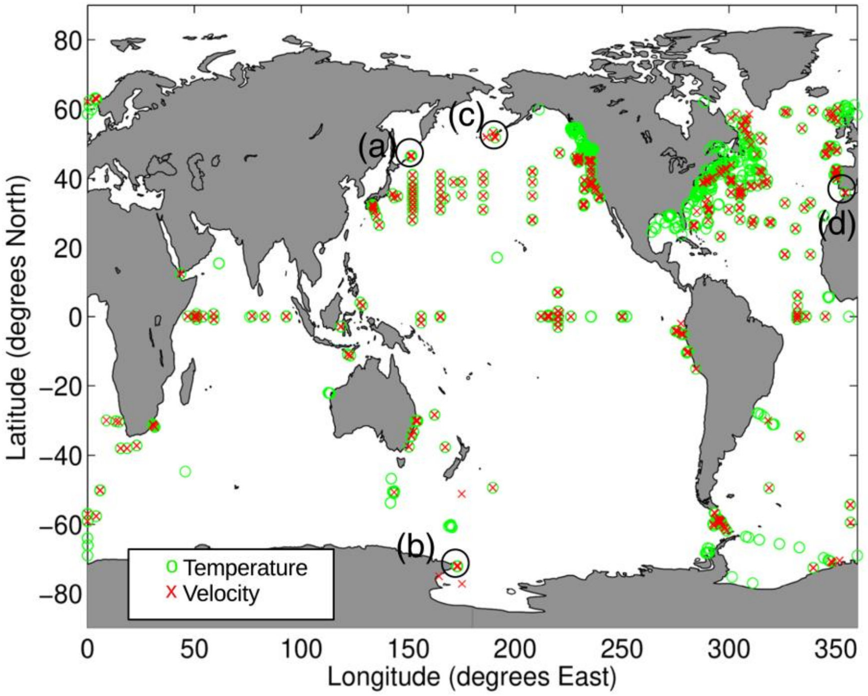
Models vs. McLane profilers (Ansong et al., in preparation)

Global MITgcm outperforms global HYCOM in the frequency domain

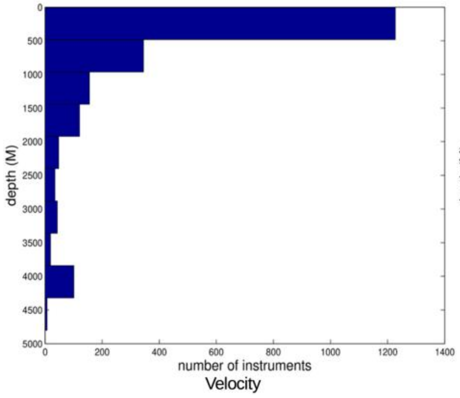


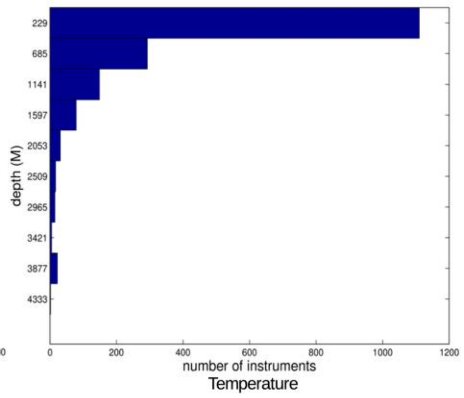
The global models are more similar to each other in the vertical wavenumber domain and are both deficient

Models vs. historical mooring archive (Luecke et al., 2020)



Geographical distribution





Vertical distribution

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

Integrate across bands of interest:
--mesoscale
--subtidal
--diurnal
--near-inertial (KE only)
--semidiurnal
--supertidal

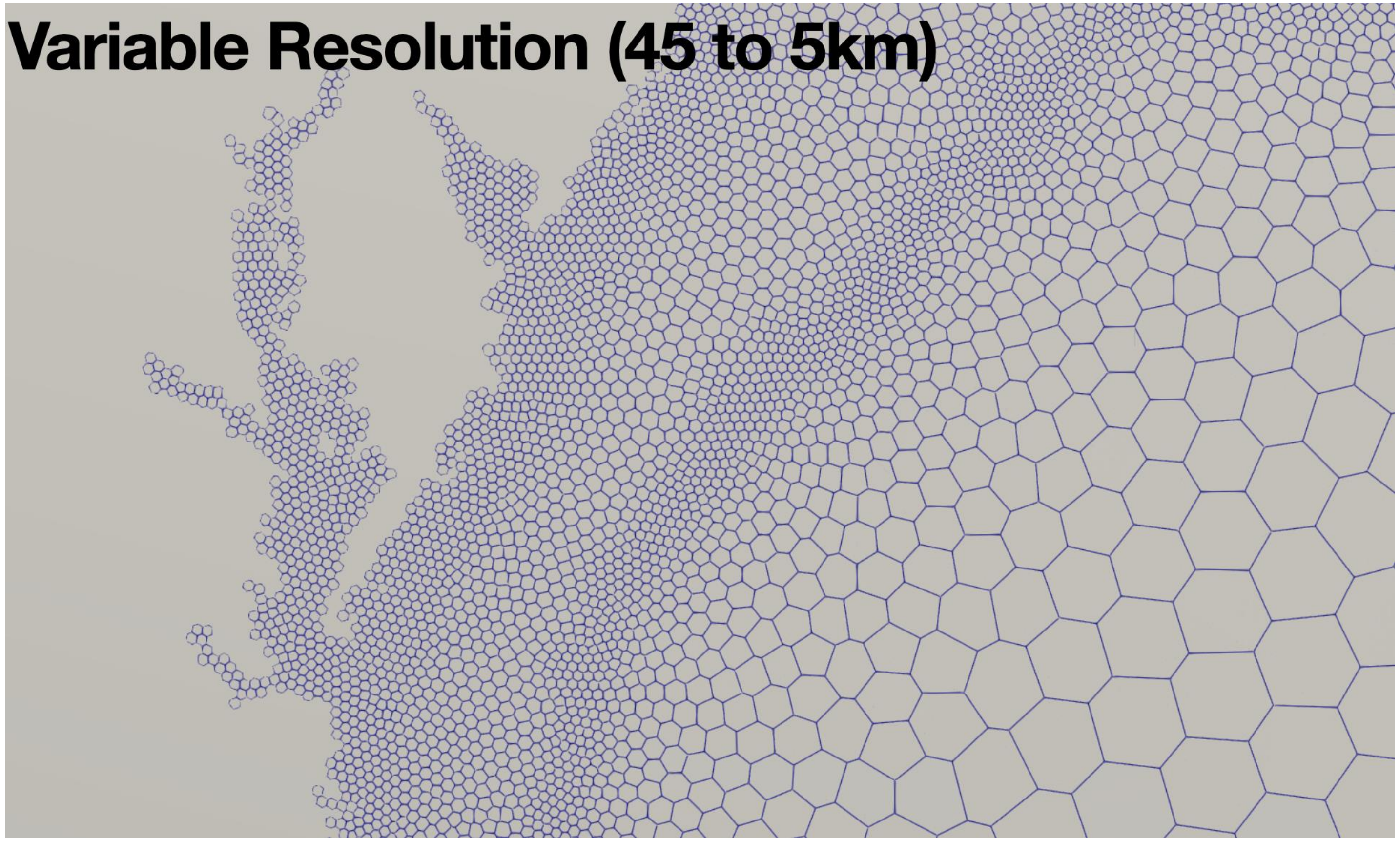
Make scatterplots, compute correlation coefficients and other statistics

MITgcm closer to observed energies in supertidal band

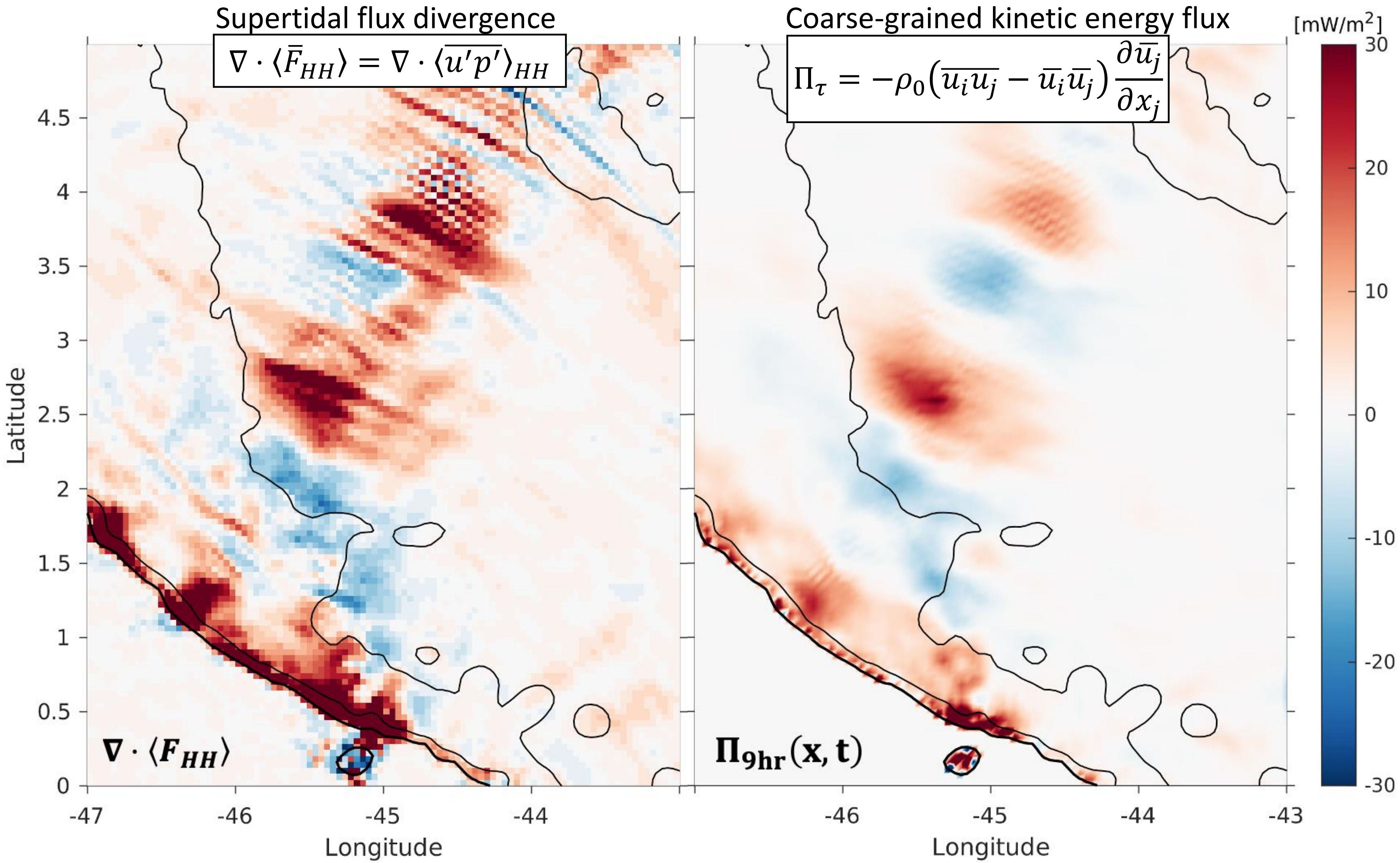
HYCOM shows better spatial correlations, in all bands

A repository of the QC'ed observational datasets from the archive is available, as part of the paper publication, for anyone to use.

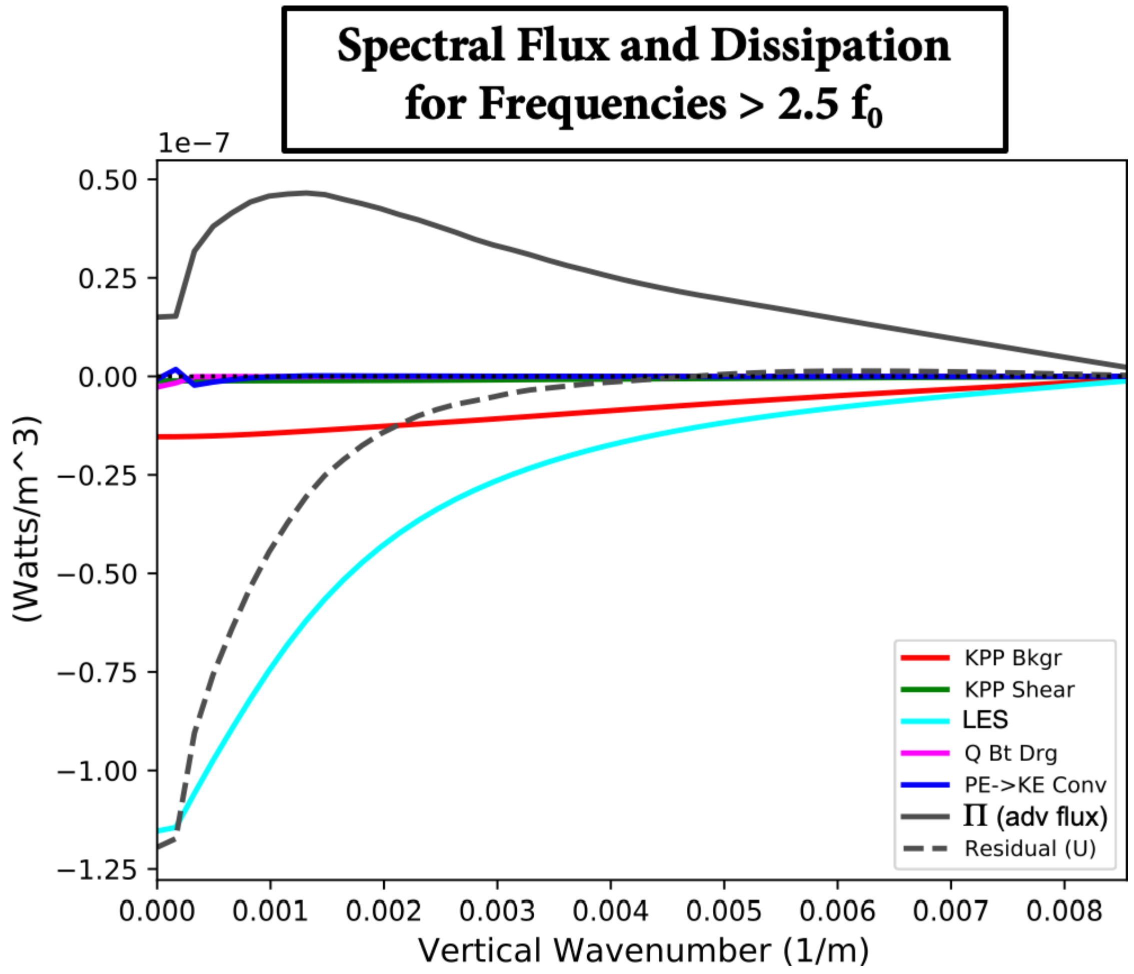
Unstructured grid used in DOE MPAS-O model (Barton et al. 2022)



Energy Cascade to Higher-Harmonics



Spectral energy flux budget in vertical wavenumber domain (Skitka et al., in review)



The forward cascade is balanced primarily by Leith horizontal eddy viscosity in regional runs with same resolution as global model.

Will this picture change as resolution increases?

Model comparison vs. drifters

- Arbic et al. (2022): Comparison of kinetic energy in global HYCOM and MITgcm LLC4320 to surface drifters
- HYCOM lies closer to the drifters in the near-inertial band than LLC4320 does, due to more frequent atmospheric forcing.
- HYCOM lies closer to the drifters in the semi-diurnal tidal band than LLC4320 does, probably due to the presence of a parameterized topographic wave drag.
- Both models display skill in simulating vertical structure of kinetic energy

Can we phase-predict the non-phase-locked internal tides using HYCOM?

- Egbert and Erofeeva, 2021: can use HYCOM output in a PCA (principal component analysis) approach that seems promising
- What about brute force methods? (i.e., straight-up comparison of model vs. altimeter time series)
- Yadidya Badarvada will perform variance reduction tests on nadir altimeter SSH using phase-locked and band-passed internal tides from HYCOM.
  - Will HYCOM remove more SSH variance using the band-passed results, which include non-phase-locked internal tides?
  - Reasons for optimism: data-assimilative system yields accurate phase-locked internal tides, accurately placed eddies
  - Reasons for pessimism: HYCOM data-assimilation system designed for eddies, produces spurious internal waves (we are trying to fix this)

HYCOM as a correction model

HYCOM could offer a hydrodynamical correction model for phase-locked internal tides, to complement empirical models derived from analysis of nadir and SWOT altimetry.

Can HYCOM do even more? E.g., phase-predict the non-phase-locked internal tides?

First, characterize whether HYCOM has the right geographical patterns of non-phase-locked internal tides…

Intercomparison of 4 hydrodynamical global internal tide models with altimetry (Ansong et al., in preparation)

- Stationary M_2 internal tides in altimetry vs.
  - 1/12° HYCOM with different wave drag strengths
  - 1/12° and 1/36° Mercator/NEMO (no wave drag)
  - 1/12° MOM6 (no wave drag)
  - 1/12° MITgcm (no wave drag)
  - 1/48° MITgcm (no wave drag)
- Main results (not shown for sake of brevity):
  - Internal tides too strong in all models, unless wave drag is brought in
  - Internal tides in 1/48° MITgcm slightly weaker than in 1/12° MITgcm→speculate this is due to loss of energy in cascade to IGW continuum
  - Differences between 1/12° simulations without wave drag (why? numerics?)
  - MITgcm tidal forcing had errors
    - omission of SAL
    - astronomical forcing 11% too large
  - Barotropic tide model used to estimate corrections for MITgcm kinetic energies

More on the spurious internal waves

The spurious internal waves produced by assimilation of nadir altimetry in the current HYCOM system are broadband.

They leak into internal tide as well as near-inertial bands (Raja et al., in preparation).

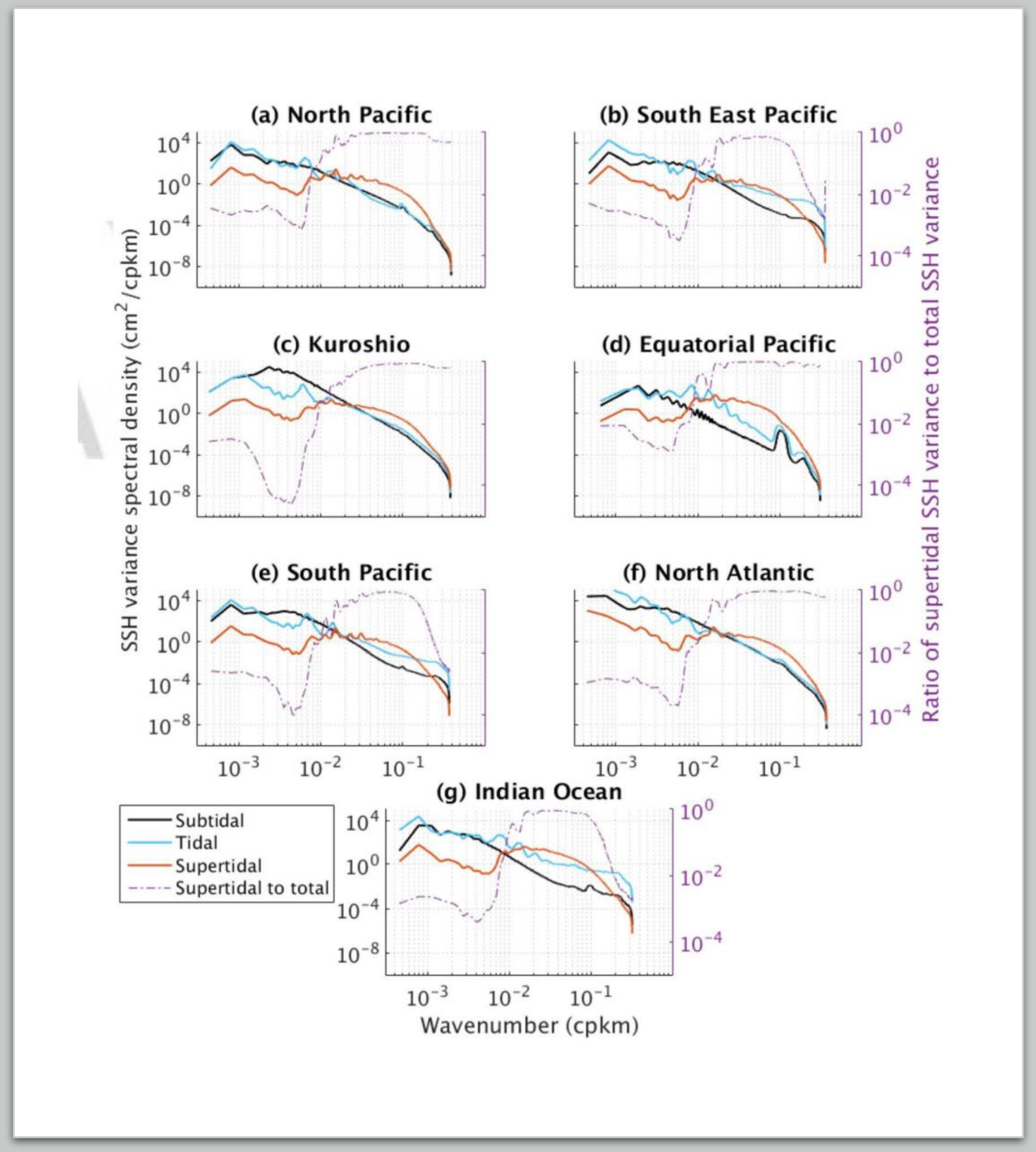
Spurious internal gravity waves are a first-order problem that affects the ability of HYCOM to estimate internal wave corrections for SWOT and to provide accurate boundary conditions of high-frequency internal wave motions for regional models. Raja et al. has come up with a possible solution to the problem.

Band-integrated SSH wavenumber spectra over different regions
in 1/48° MITgcm (Savage et al. 2017b)

- At the high wavenumbers of interest for SWOT, the tidal and supertidal frequencies can dominate in some regions.

- See also Richman et al. (2012) and many others, including:

- Callies and Ferrari (2013),Bühler et al. (2014), Rocha et al. (2016a,b), Qiu et al. (2018, 2020), Torres et al. (2018,2019), Wang et al. (2019), Klein et al. (2019), Cao et al. (2020), others

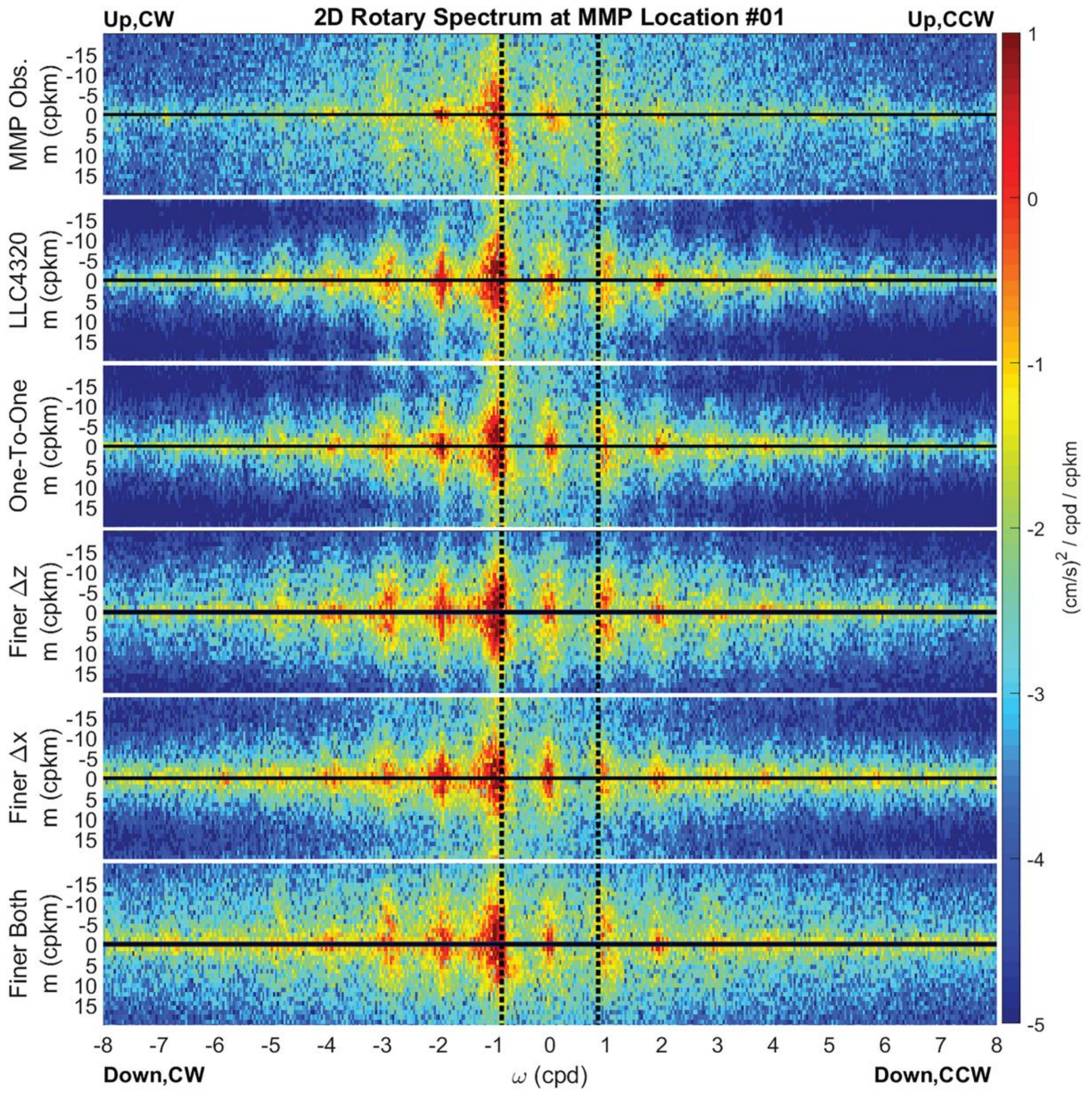


Turning to a few other topics:

New ONR projects

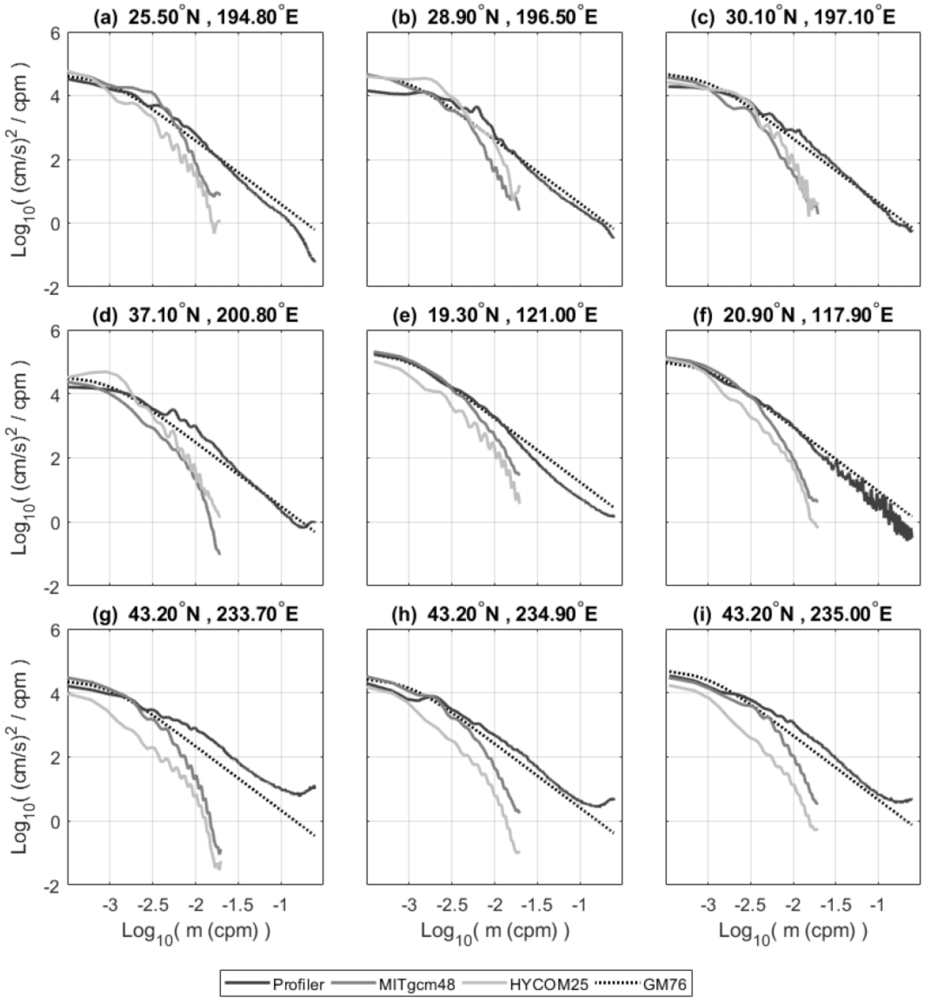
Insertion of tides into OGCMs run by other groups

Rotary spectra (Nelson et al., 2020)



Vertical wavenumber spectra across all 9 McLane profilers (Ansong et al., in preparation)

- Both models deficient at high vertical wavenumbers



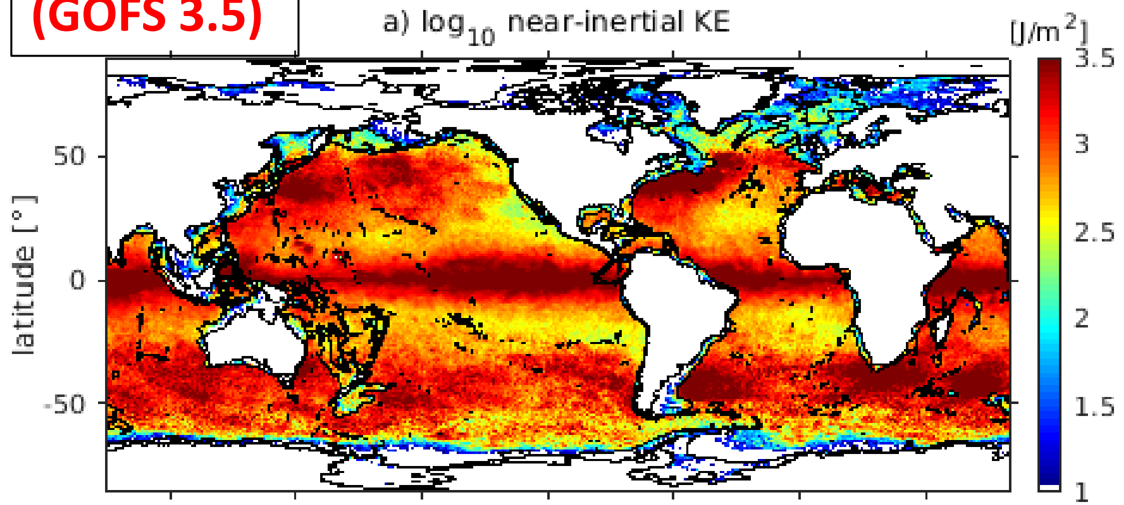
Can we reduce the spurious internal waves?

- Will ingestion of SWOT data itself help?
  - SWOT is two-dimensional, provides more information than one-dimensional nadir altimeter tracks
  - NRL group, like others in the community, has shown that assimilating SWOT data will improve forecasts of ocean eddies
- Would a 4DVar system produce less spurious noise than a sequential system?
  - A NOPP proposal led by Eric Chassignet and Hans Ngodock will address this problem

Near-Inertial Wave Kinetic Energy (NIW KE)

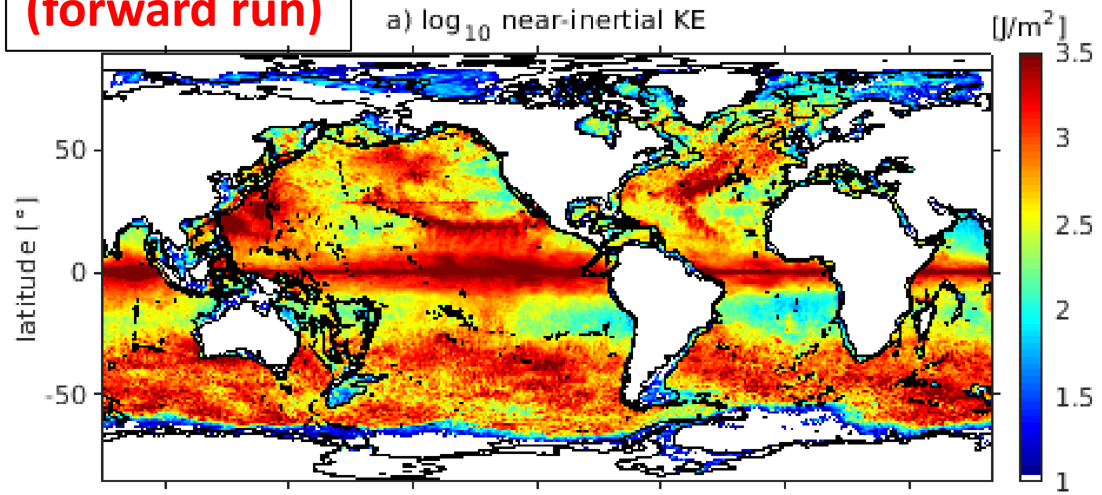
Expt 21.6
(GOFS 3.5)

With DA
May-June 2019
1-way atmospheric coupling



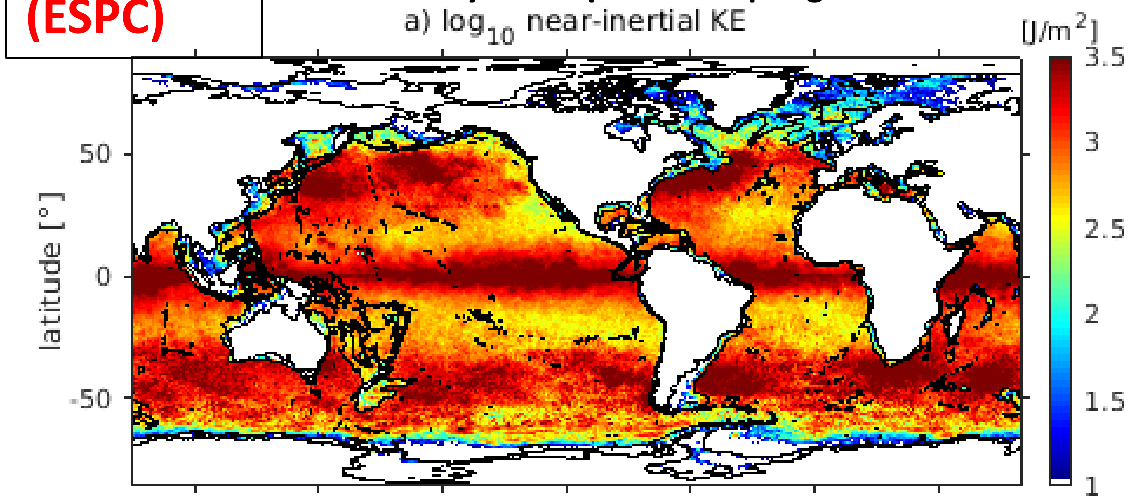
Expt 22.1
(forward run)

Without DA
September 2016



Expt 10.0
(ESPC)

2-way atmospheric coupling



Forward simulation has much less NIW energy

Global NIW KE abs(latitude)>10

Expt 21.6 (DA, 1-way)	289.31 PJ
Expt 10.0 (DA, 2-way)	306.12 PJ
Expt 22.1 (Without DA)	190.15 PJ

Global M2 KE = 84.2 PJ

Keshav Raja et al., in preparation

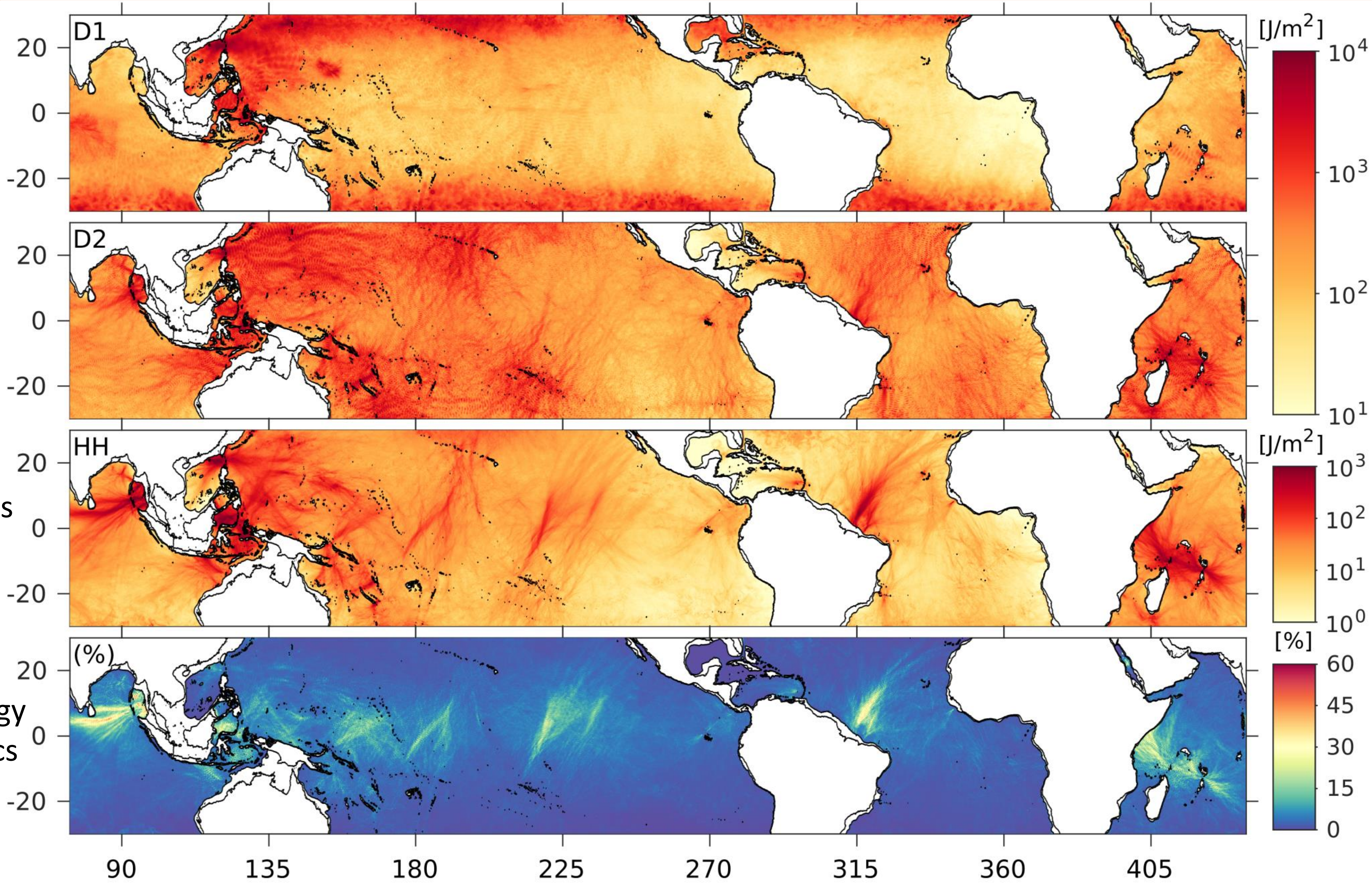
Primary and Higher-Harmonic KE

Diurnal
(0.8-1.2)

Semidiurnal
(1.6-2.67cpd)

Higher-Harmonics
(>2.67cpd)

(%) of Kinetic Energy
in higher-harmonics



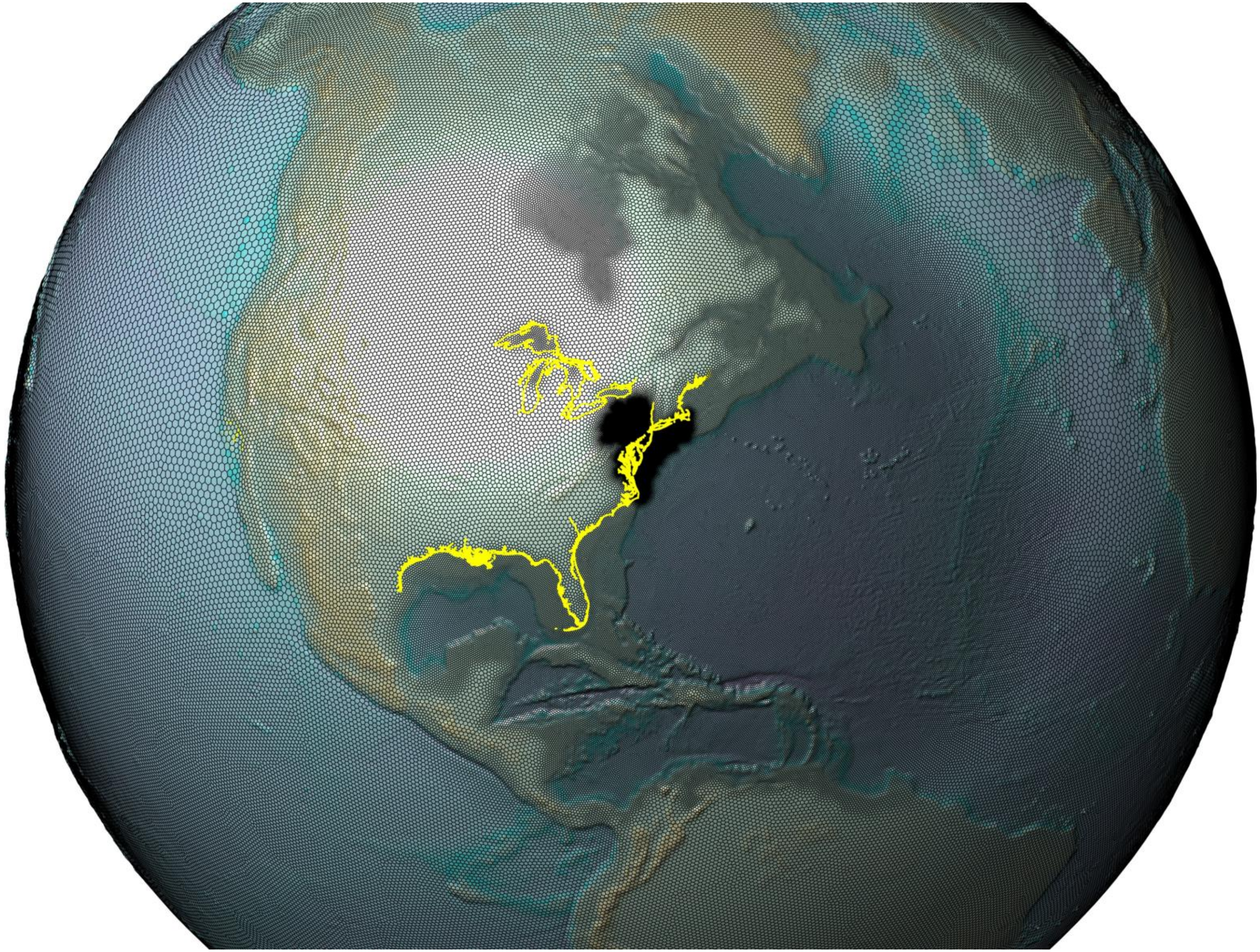
THE UNIVERSITY OF SOUTHERN MISSISSIPPI

Last slides before summary

Sample DOE MPAS-O grid

For ICOM project

Courtesy Darren Engwirda



Last slides before summary

Sample DOE MPAS-O grid

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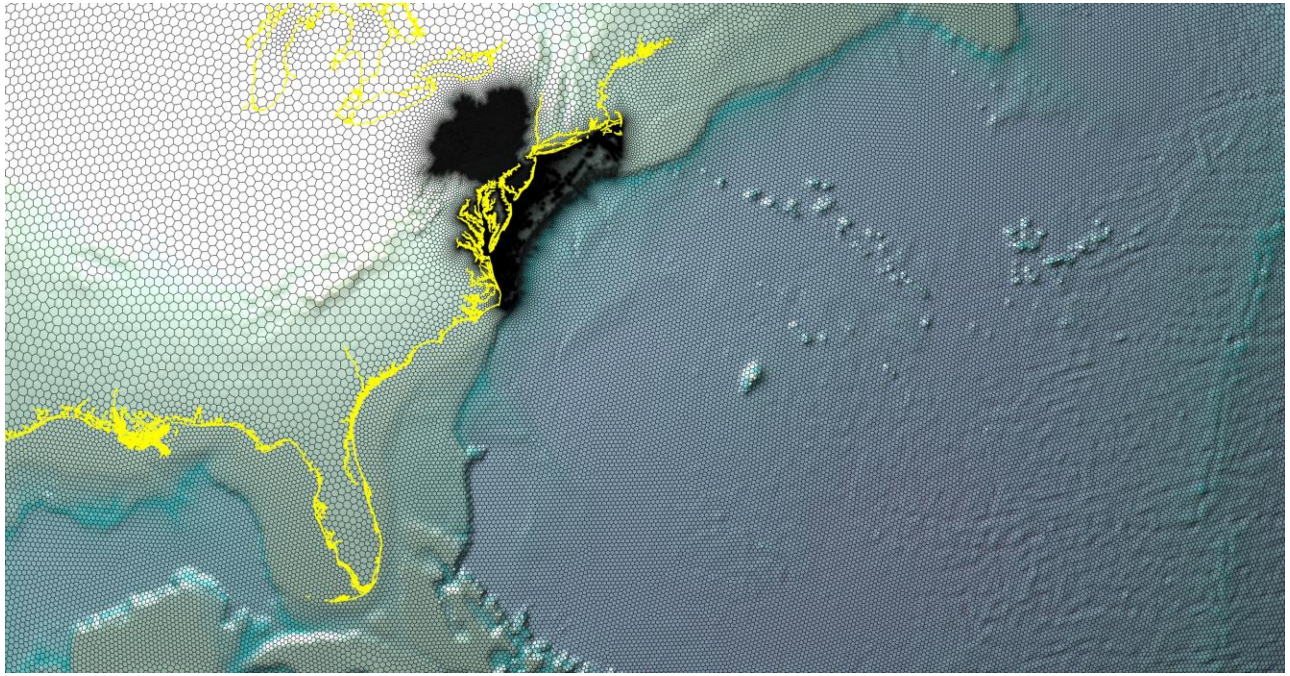
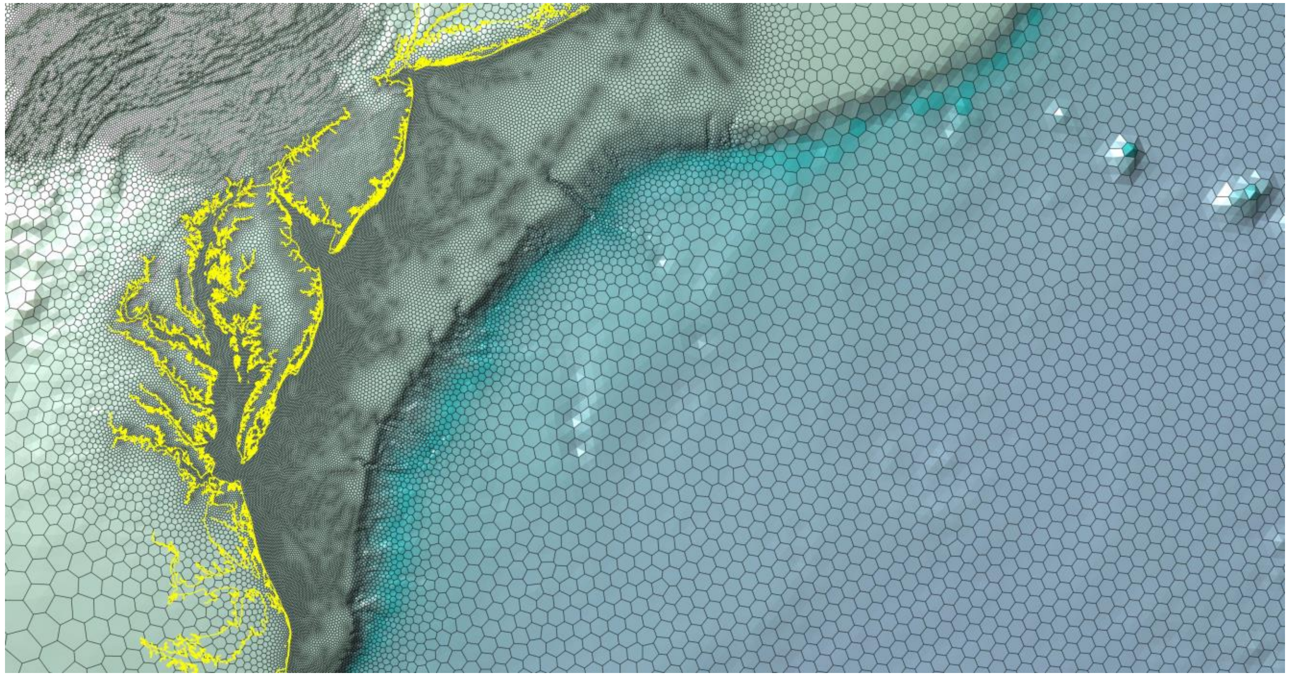




Bathymetry—an old favorite

- One factor in the accuracy of the internal tides is the accuracy of the barotropic tides.

- Barotropic tide accuracy is affected by bathymetry.

- Sandwell (SIO), Smith, and collaborators continue to churn out improvements in global bathymetric datasets.

- Can we use these in OGCMs to (hopefully) get improved tides?

Providing HYCOM output for SWOT (and S-MODE) team

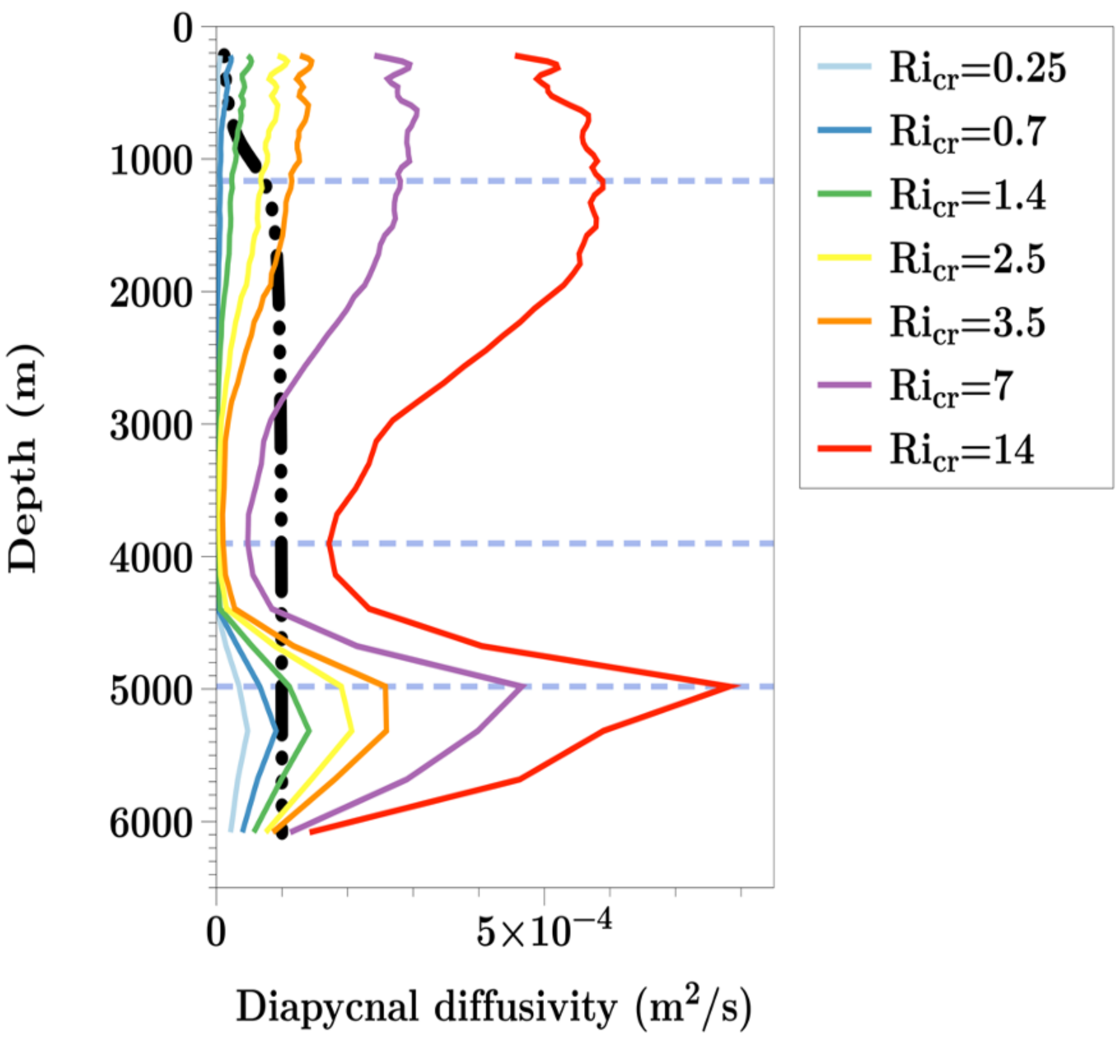
- We are providing 3-D output in the SWOT Cal/Val region, and global SSH, from operational HYCOM, to the SWOT (and S-MODE) teams.

- Two-week delay to satisfy Navy security requirements.

Sensitivity of diffusivity to critical Richardson number (Momeni et al., in preparation)

Vertical profiles of diffusivity at a location within the regional domain.

Shear component of KPP triggers more often when critical Richardson number is increased.



Frequencies of IGWs

- Classical linear internal wave theory→ $|f|<\omega<N$
  - f: Coriolis (inertial) frequency
  - ω: frequency of IGW
  - N: buoyancy frequency
- IGWs near f are called near-inertial waves
  - Driven primarily by rapidly changing winds
- IGWs of tidal frequency are called internal (baroclinic) tides
  - Driven by barotropic (depth-averaged) tidal flow over topography
- At supertidal frequencies there is an IGW continuum (Garrett and Munk 1972, 1975)
  - Thought to arise from nonlinear interactions between near-inertial waves and tides.

Preliminary results: near-inertial and tidal currents in HYCOM vs. drifters

Jonathan Brasch, Shane Elipot, Aurélien Ponte, Xiaolong Yu, and others in conjunction with HYCOM team

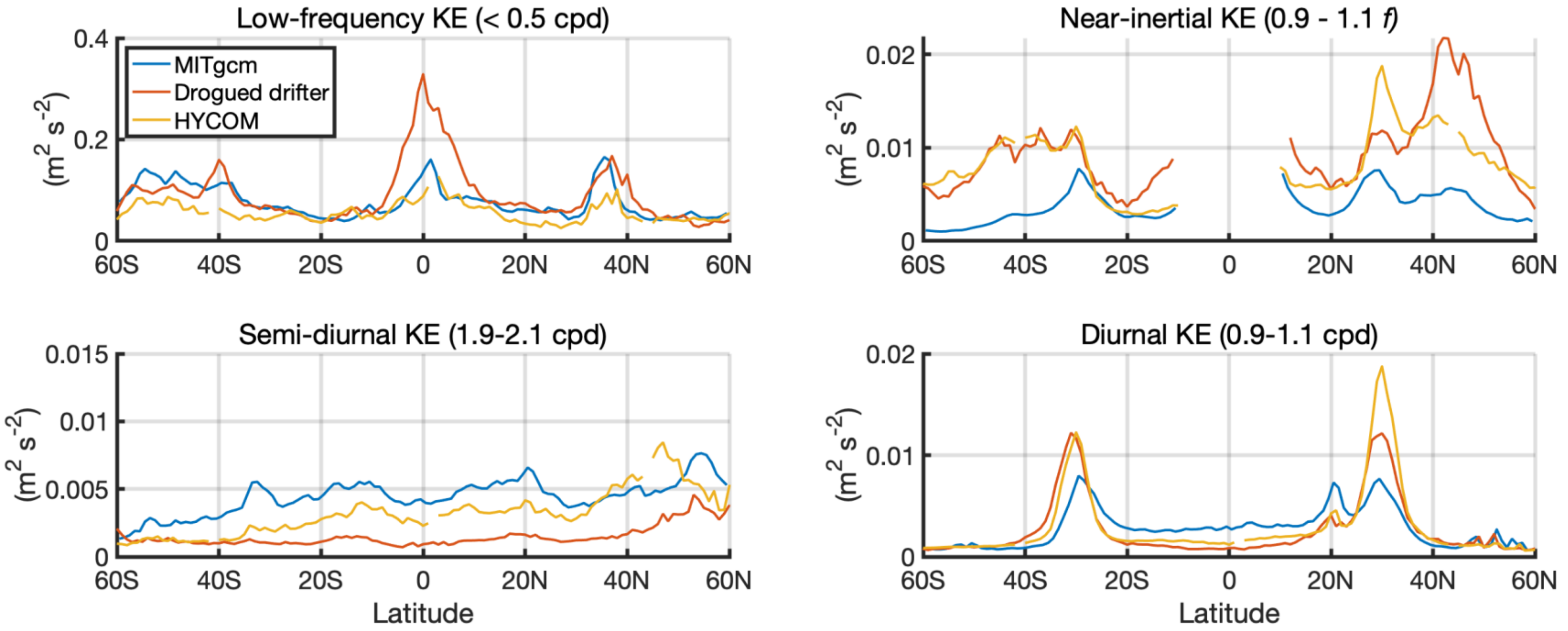
- Yu et al. (2019) compared surface velocities in MITgcm to drifters
- Here we add HYCOM into the comparison

Zonal average surface kinetic energy, 1/25° HYCOM and 1/48° MITgcm vs. drifters

Note that these HYCOM runs are non-assimilative

In low-frequency band, MITgcm performs better, but this contradicts some of our other results—more checks needed.

In near-inertial band, HYCOM lies closer to drifters than MITgcm, due to more frequently updated wind fields.



In semi-diurnal band, MITgcm is too high, due to lack of wave drag and mistake in tidal forcing. HYCOM also too high, but closer to drifters over most latitudes.

In diurnal band, HYCOM lies closer to drifters over most latitudes, especially ~40°S to 25°N. Diurnal band overlaps with near-inertial band near ~30°.

Internal gravity waves (IGWs) in global high-resolution “atmosphere plus tide” models

- Atmospheric forcing
  - ”Fast winds” generate near-inertial waves
  - “Slow winds” and buoyancy forcing, together with mixing, control background stratification
- Tidal forcing
  - Barotropic tidal flow over rough topography in a stratified environment generates internal tides
- High resolution
  - High vertical and horizontal resolution allows for nonlinear interactions to generate supertidal internal gravity wave (IGW) continuum (Garrett-Munk spectrum)

Tides in OGCMs run at modeling centers

- Navy: Collaboration since 2006 to insert tides into operational HYCOM simulations. Navy is interested in impacts of internal tides on ocean acoustics, ocean mixing, regional ocean modeling.

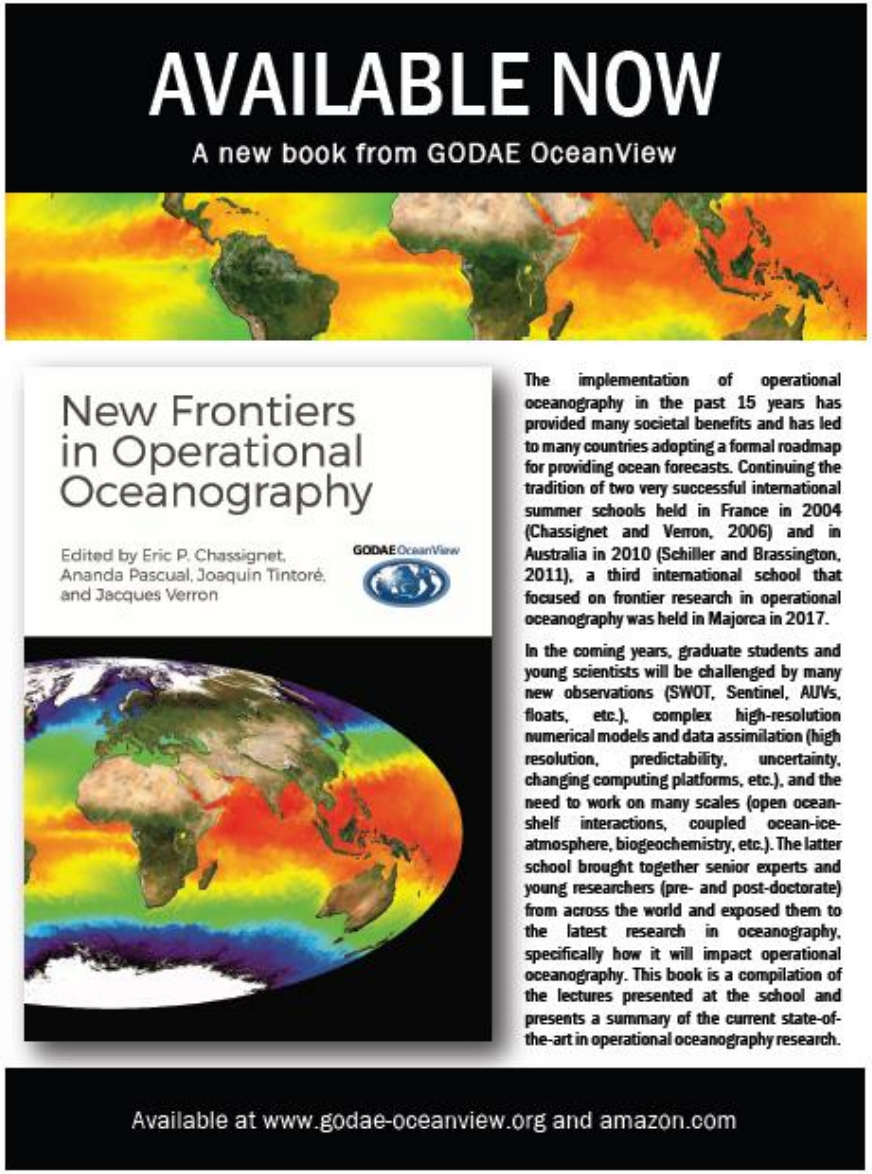
- NOAA: NOAA, like the Navy, is interested in operational ocean modeling, but with MOM6 instead of HYCOM.

- NASA: Runs MITgcm at highest resolutions ever performed in global model. Global internal tide and wave models are critical to the success of the Surface Water Ocean Topography (SWOT) mission.

- DOE: Work just begun. DOE is interested in tide-ice interactions and tidal changes with climate, using an unstructured grid to focus in on coastal areas.

DOE has very big computers!

Thus far, our group and our collaborators have published 27 journal articles and one book chapter on embedding tides within OGCMs. Many more are in preparation, and one is in-press for JGR-O.



CHAPTER 13

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]

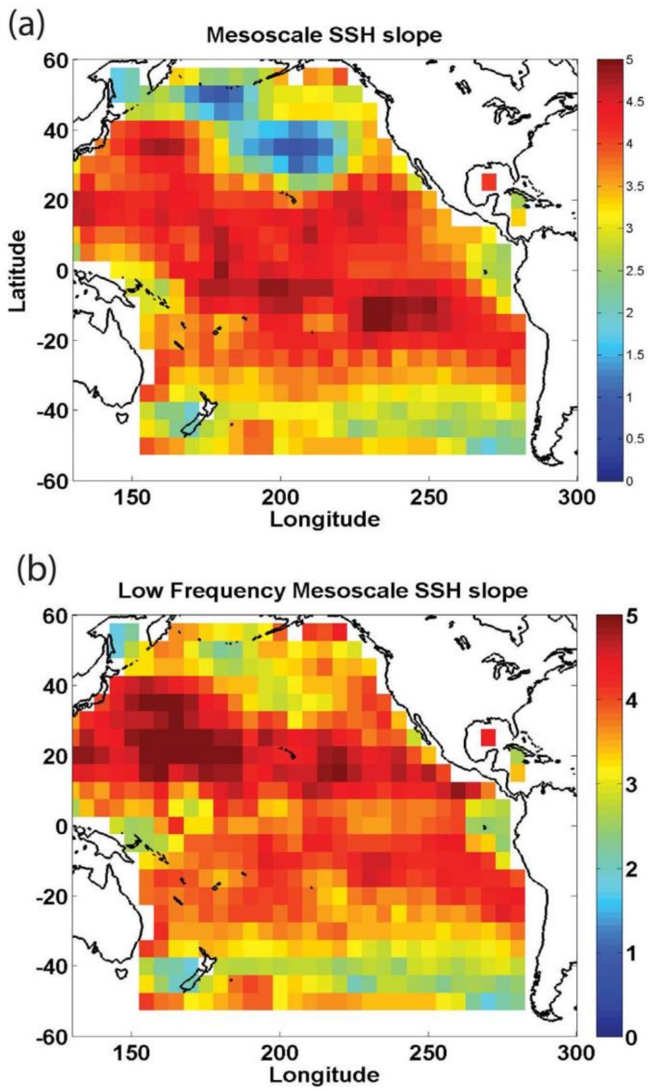
[1]University of Michigan, Ann Arbor, Michigan, USA; [2]Currently on sabbatical at Institut des Géosciences de L'Environnement (IGE), Grenoble, France, and Laboratoire des Etudes en Géophysique et Océanographie Spatiale (LEGOS), Toulouse, France; [3]University of California San Diego, La Jolla, California, 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.

Summarizes our papers on tides in Navy HYCOM simulations through 2018

Also summarizes tides in even higher-resolution MITgcm simulations performed by NASA



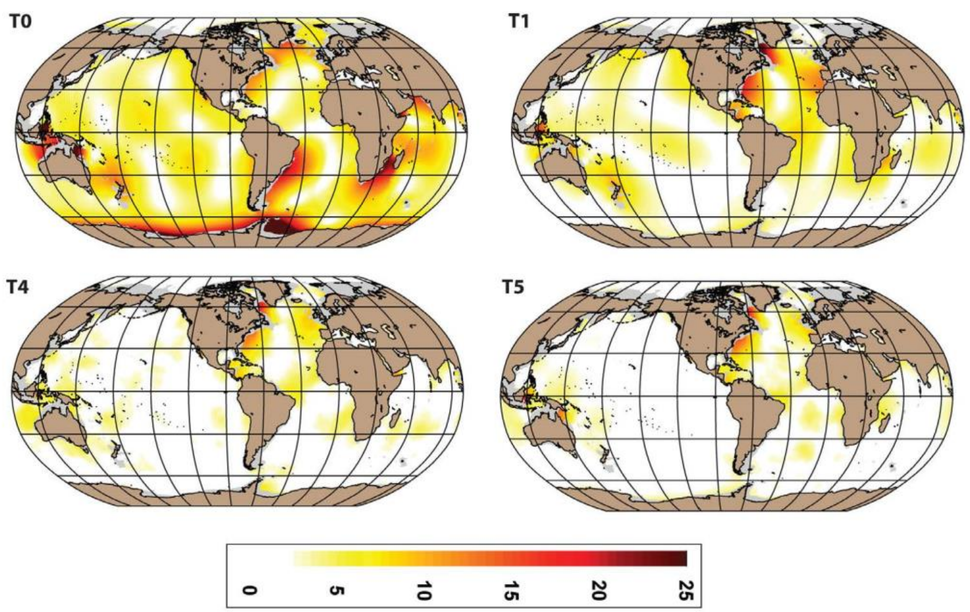
The slope of the wavenumber spectrum is flatter with internal waves (k^{-2}) present.

→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)

Improvement of HYCOM barotropic tides over time



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).

ASEnKF used perturbations with large horizontal scales typical of open-ocean barotropic tides

Ngodock et al. (2016)

Shriver et al. in preparation→adding smaller-horizontal scale perturbations in coastal areas shaves more off the error

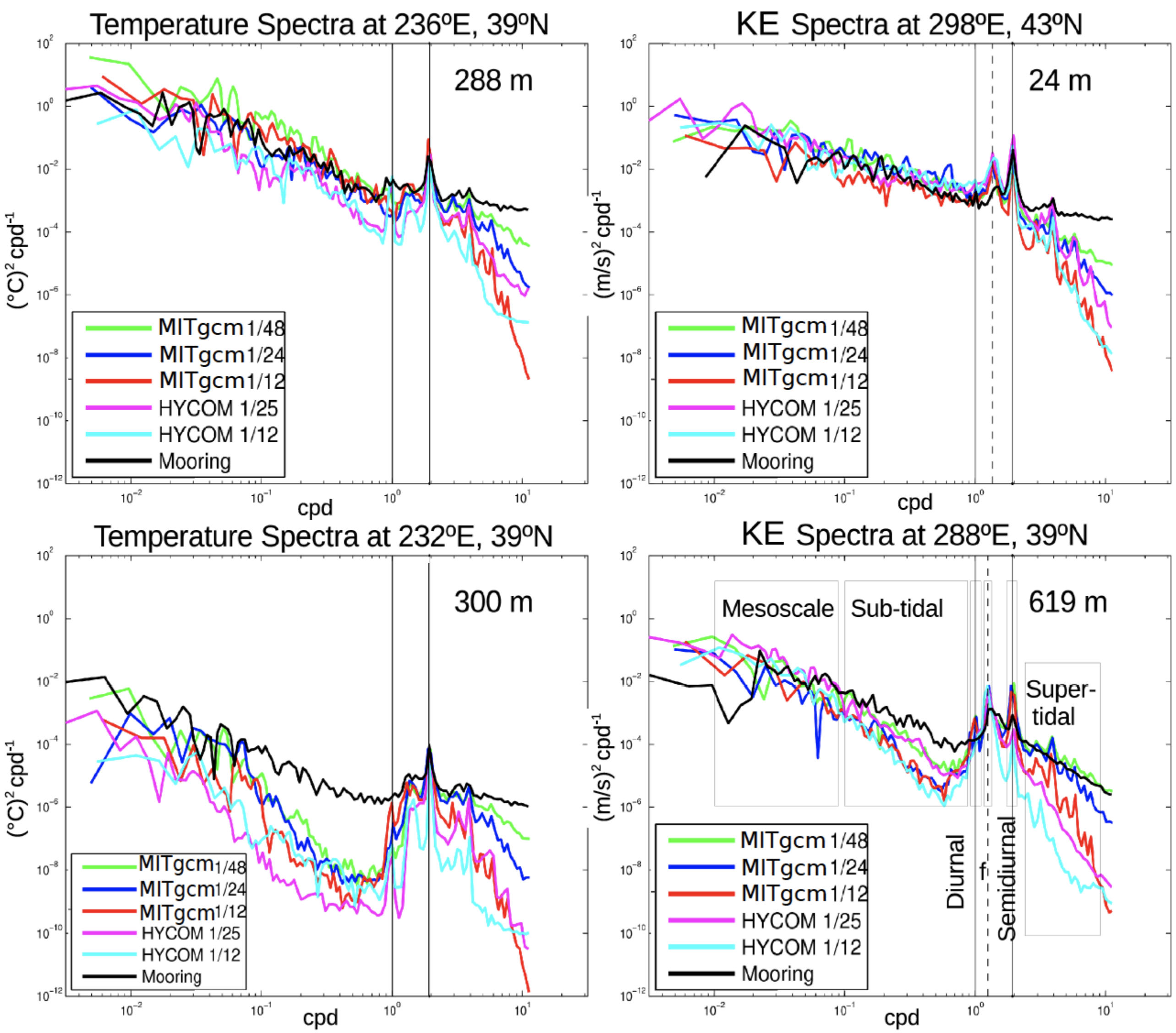
What about improving the underlying bathymetry?

Model-mooring comparisons

- Moored observational records can provide time series and frequency spectra

- Historically, moorings have a few instruments at selected depths.
- McLane profilers crawl up and down in the vertical direction.
- In “high-frequency mode”, McLane profiler data can be interpolated in time and depth to produce a record with high resolution in both time and depth.
- On the other hand, we’re only using 9 McLane profilers.
- There are a few thousand historical moorings that we can use.

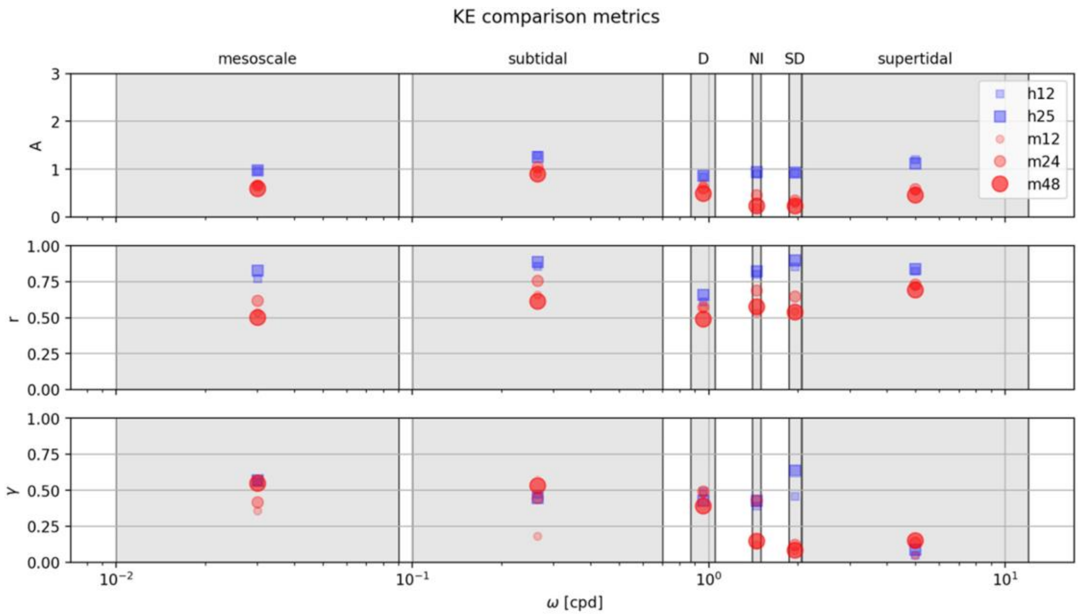
Models vs. historical mooring archive (Luecke et al., in press)

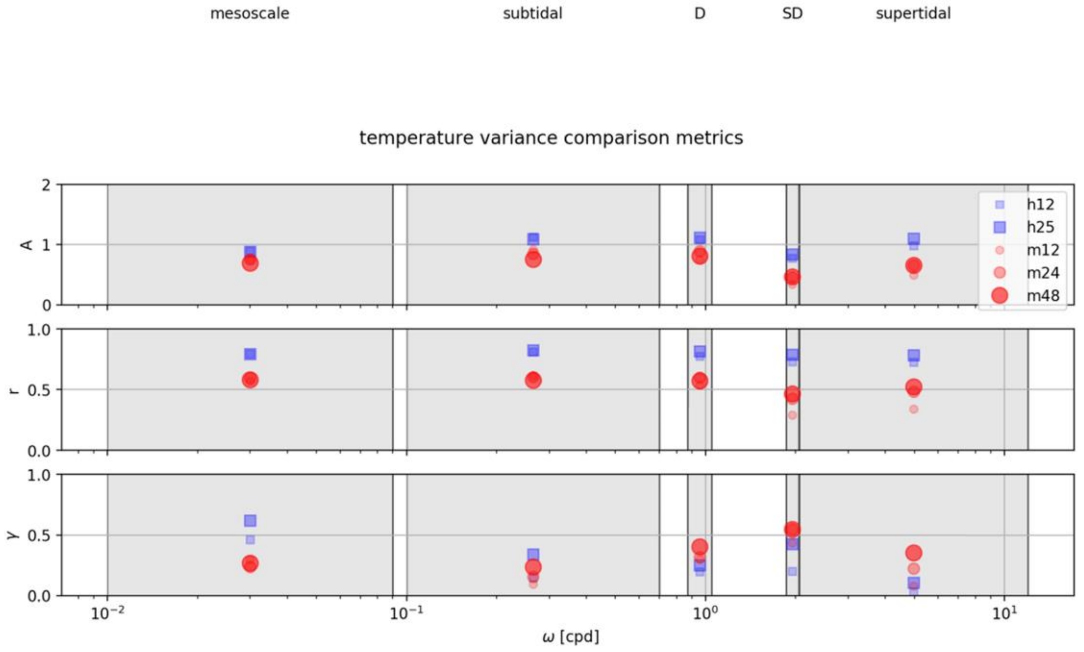


Example frequency spectra

Summary of results in Luecke et al. 2020

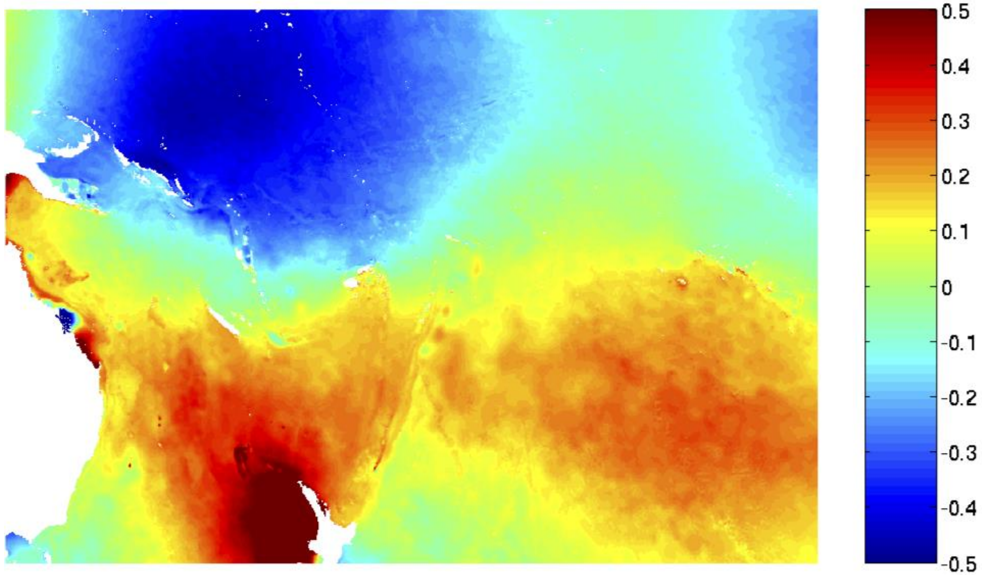
Over all frequency bands,
For both KE and temperature variance, the spatial correlations in HYCOM (blue) are higher than those in MITgcm (red)





Animations of steric and non-steric SSH in HYCOM

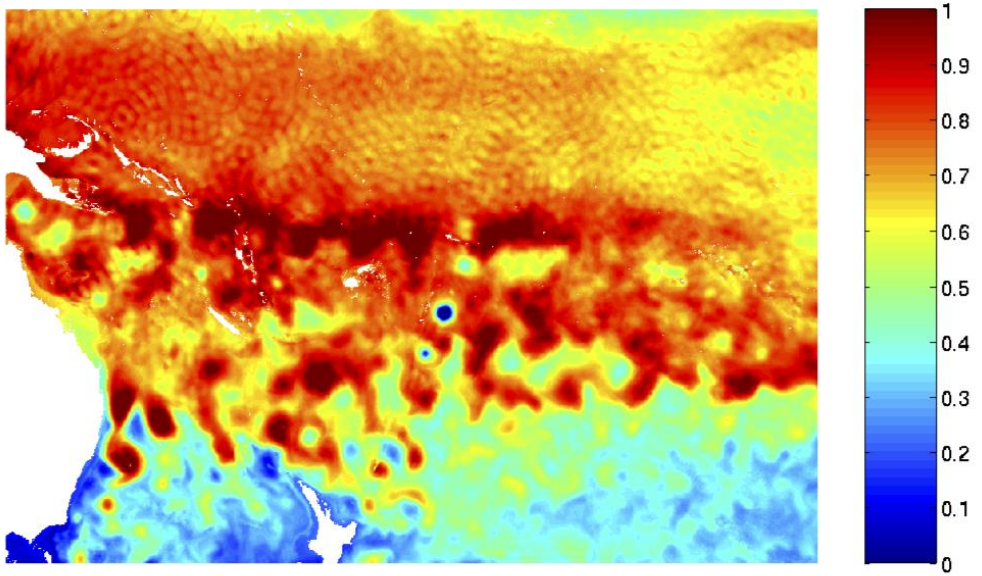
(a)



Separation of Southwest Pacific SSH snapshot into non-steric (a) and steric (b) components

←Non-steric SSH is dominated by barotropic tides

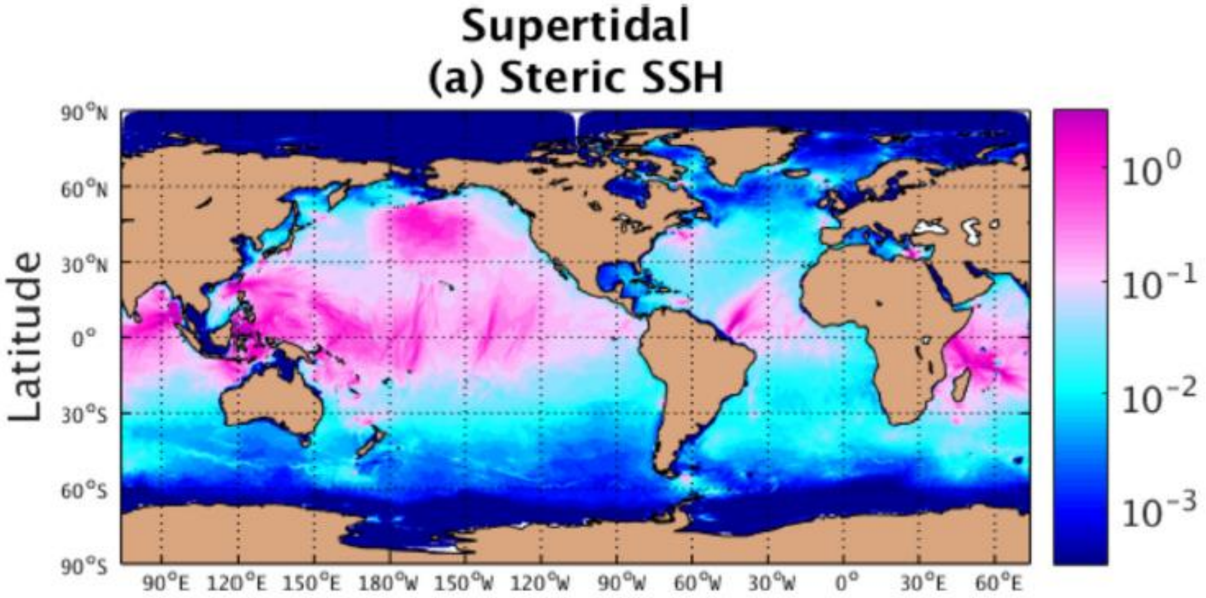
(b)



←Steric SSH is dominated by low-frequency mesoscale eddies and high-frequency internal tides

Arbic et al. (2010)

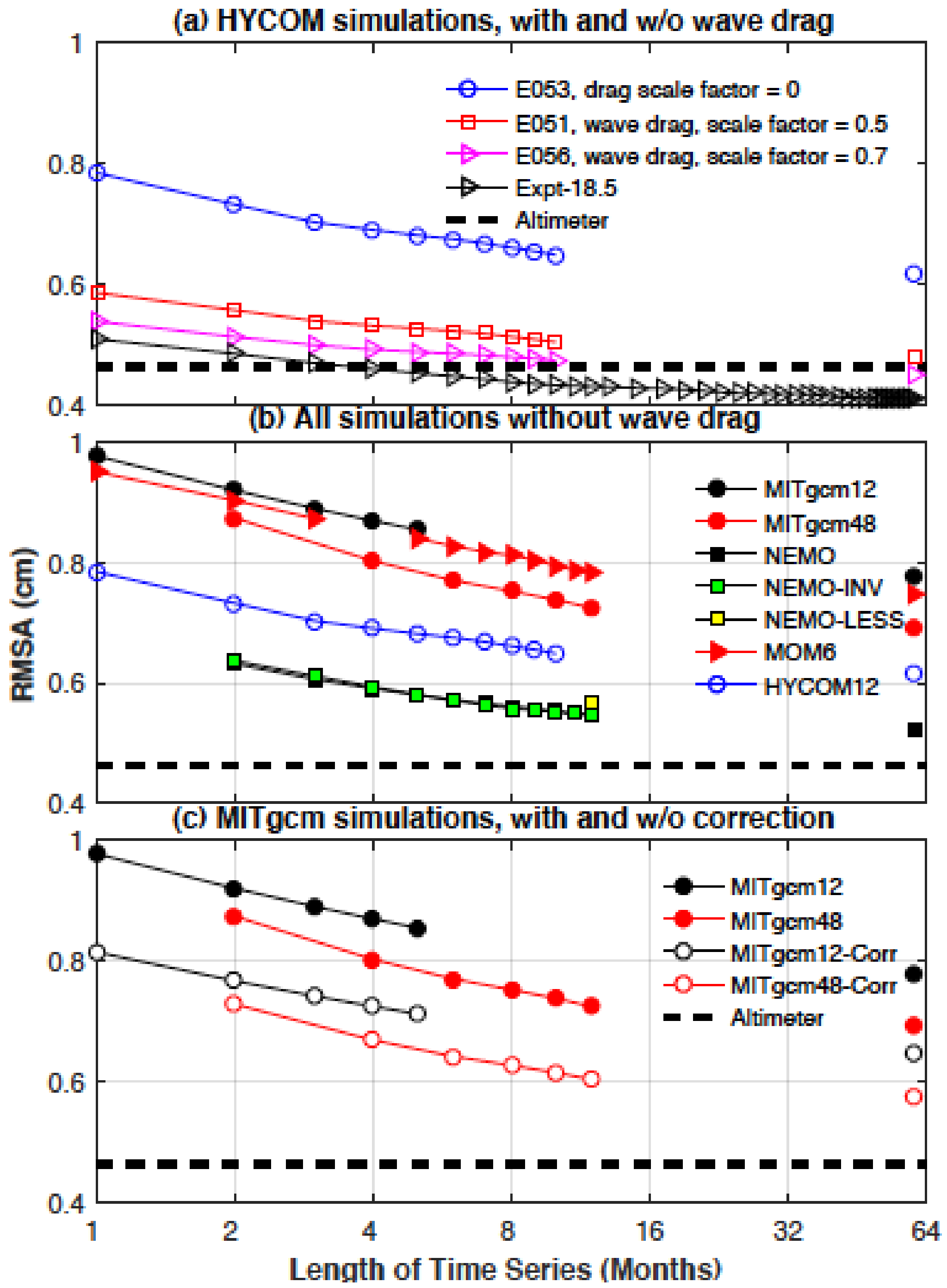
Supertidal internal gravity wave continuum SSH variance (cm^2) in HYCOM (Savage et al., 2017a)



How can we validate this map?

Compare with subsurface Argo estimates of internal waves? (e.g. Hennon et al. 2014, Pollmann et al. 2017)

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 barotropic and internal 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)
- We used a shallow-water (barotropic) tide model with correct astronomical forcing vs. forcing like that used in the MITgcm runs, in order to make the corrections shown on the previous page.
- New MITgcm runs, being planned now, will implement a correct astronomical forcing.