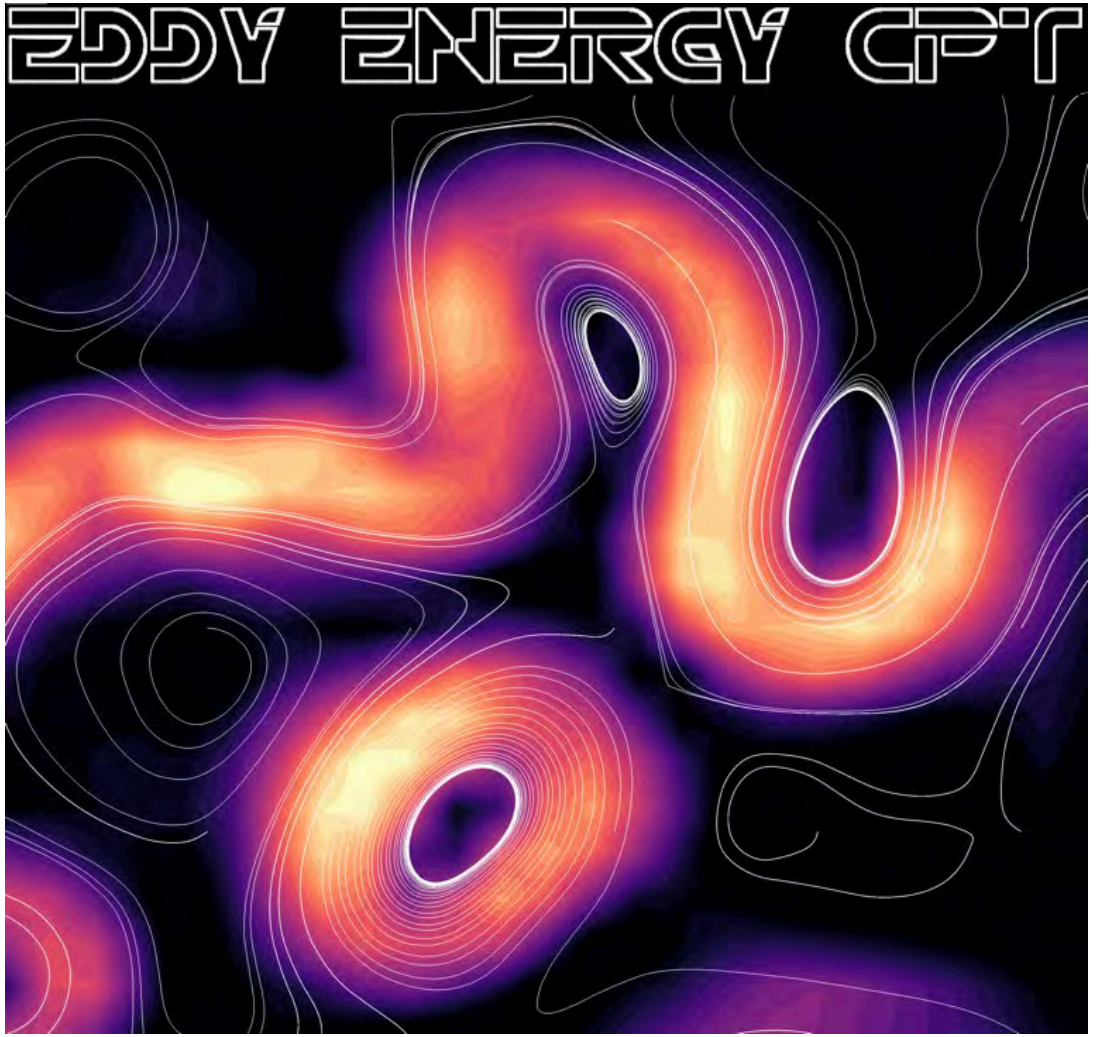
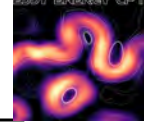
“Ocean Transport & Eddy Energy” Climate Process Team Updates

Scott Bachman, NCAR



Much of this presentation courtesy of Laure Zanna (NYU, Courant Institute)

Outline



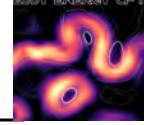
- Introduction/Motivation
- Aims of the CPT on Ocean Transport & Eddy Energy
- Research highlights of the CPT (led by early career researchers)

  ➞Evaluating current parameterizations of mesoscale eddies
  - **NeverWorld 2:** An idealized model for evaluating, implementing & testing eddy parameterizations.
  - **GCM-filter:** A software package to filter high resolution simulations.

  ➞ **Understanding the energy cycle in observations & models:** Scale-dependent EKE; evaluating the energy cycle; Vertical structure

  ➞**Development & implementation of novel closures**
  - GM + Backscatter + MEKE in idealized and global models
  - Emulating MEKE with machine learning
  - Near-surface lateral eddy diffusion
- Possible future work
- Concluding remarks & open questions

What is the Eddy Energy CPT?



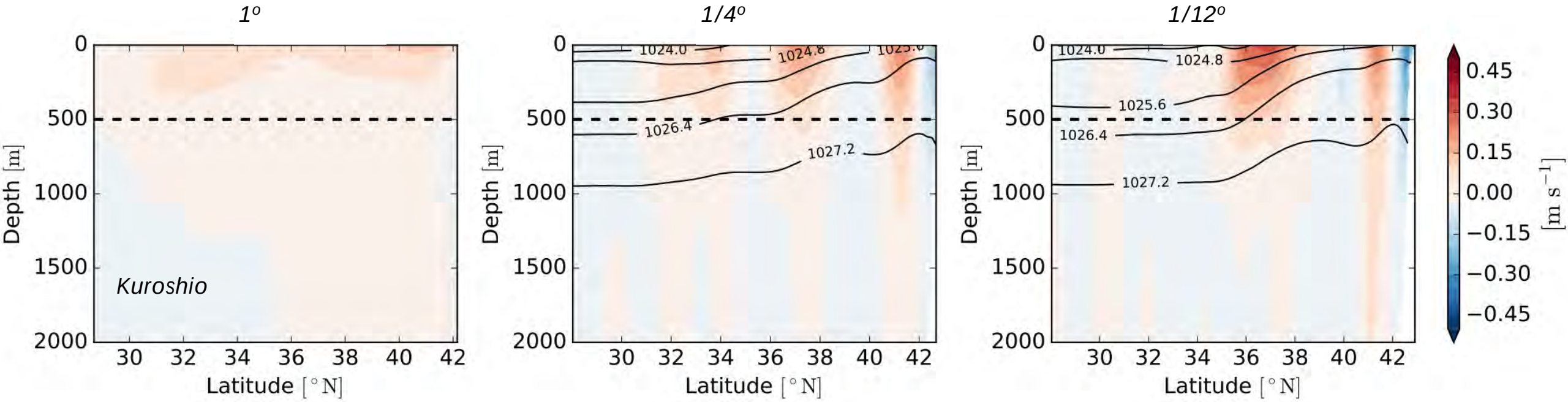
- NSF-NOAA- funded project in spring 2019 for 3 years
- 7 Research Institutions & 3 Modeling Centers

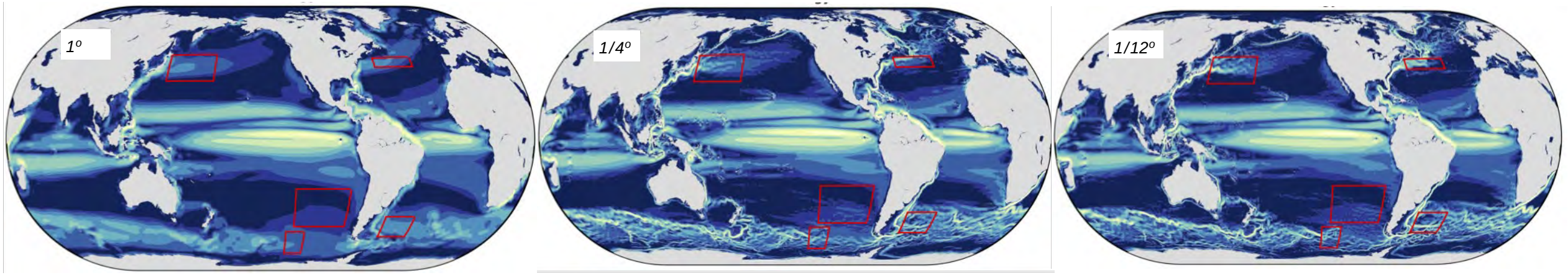
  The aim of this CPT is to improve, unify, and thoroughly vet scale- and flow-aware parameterizations of ocean sub-grid turbulent processes in climate models across a range of resolutions.

- PI kick-off meeting at NYU in Nov 2019 + Ocean Sciences Session in Feb 2020
- And then lockdown!

- Early Career Researchers (ECRs) started in Summer/Fall 2020.
- Applied for 2-year renewal, April 2022.

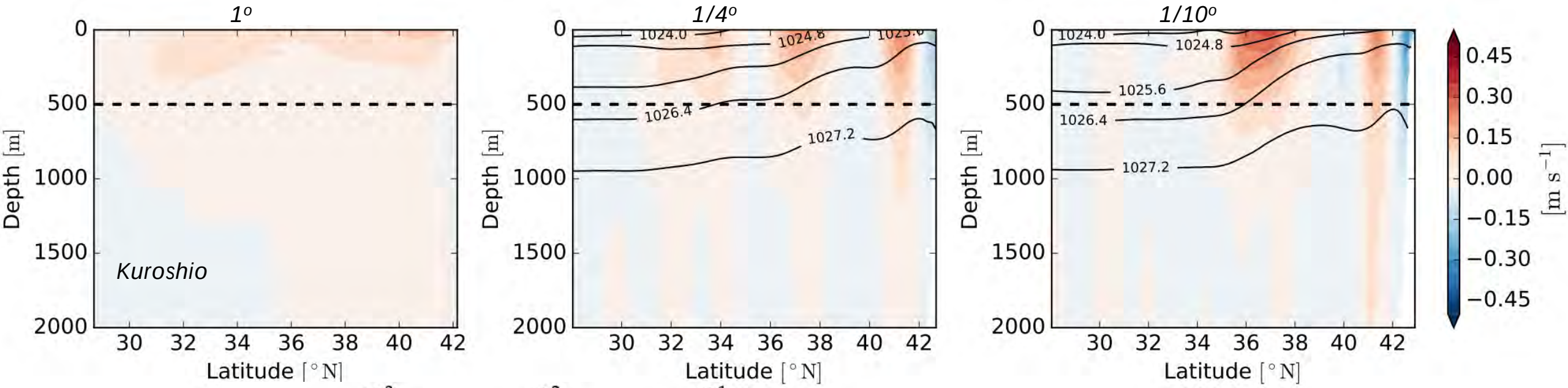
Ocean Transport in Global Models

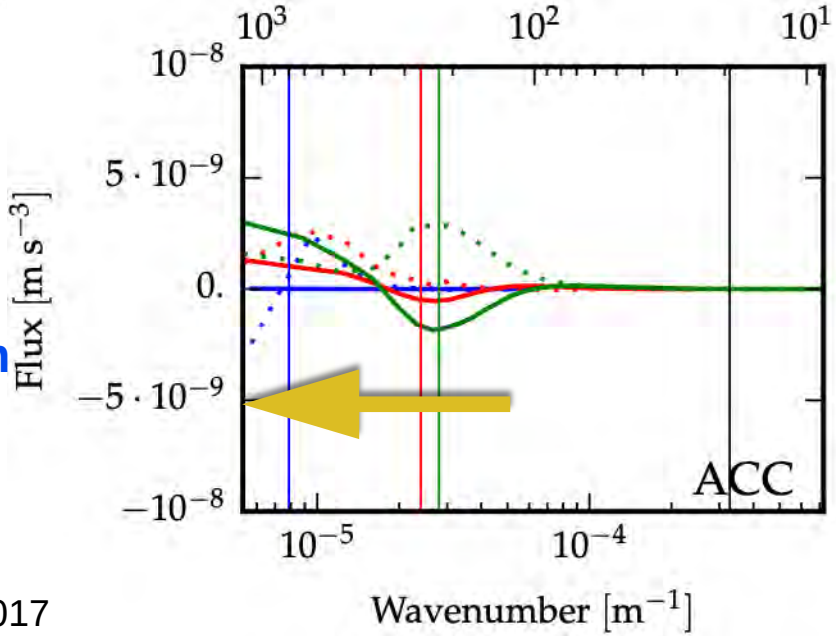




Kjellsson & Zanna, 2017

Ocean Transport in Global Models





~100km
~30km
~8km

Lack of kinetic energy at all scales

+

Weak energy conversions & fluxes

=

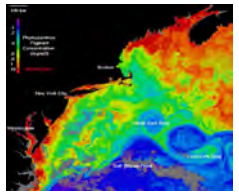
biases in horizontal & vertical transport in lower resolution GCMs

Kjellsson & Zanna, 2017
See also e.g., Jansen & Held, 2014

Energy Cycle & Model Biases

- **Mesoscale eddies are a major player in the energy cycle:**
  - ➞extract energy from the mean flow
  - ➞form the bulk of the kinetic energy in the ocean
  - ➞transfer of kinetic energy across scales

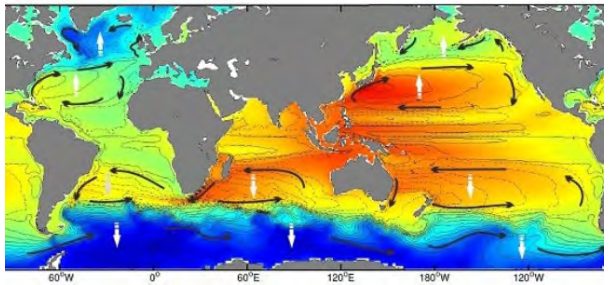
Submesoscales (1-10km)



Mesoscales (10-100 km)

Deformation Scale

Wind + Buoyancy Work



Large Scale (1000's kms)

Dissipation

Available Potential Energy

Baroclinic mode

Baroclinic Instability

Barotropic mode

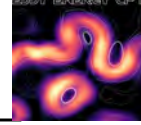
Kinetic Energy

Inverse cascade/Backscatter

Zanna, Bachman, Jansen et al. 2020

adapted from Salmon, 1998 & Vallis, 2006

Climate Process Team: Aims

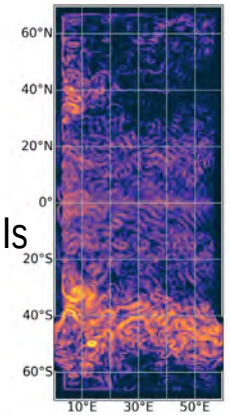


➞ Increase the fidelity of the large-scale transport representation in IPCC-class models by unifying energetics & mesoscale eddy closures of buoyancy & momentum for a robust resolution-, scale- & flow-aware implementation

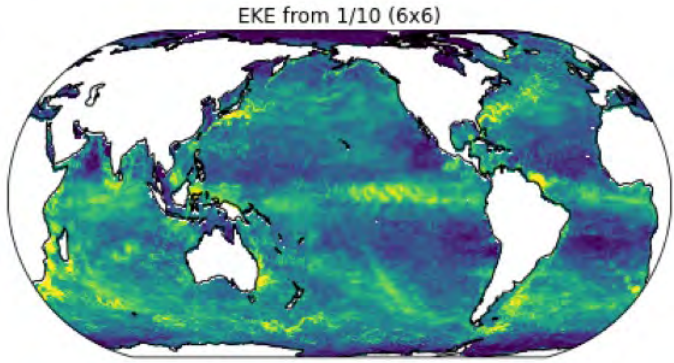
Our Objectives

- Evaluation of existing & novel parameterizations
- Unifying buoyancy & momentum parameterization via energetics
- Improving the large-scale flow & its vertical structure in ocean models

NeverWorld 2



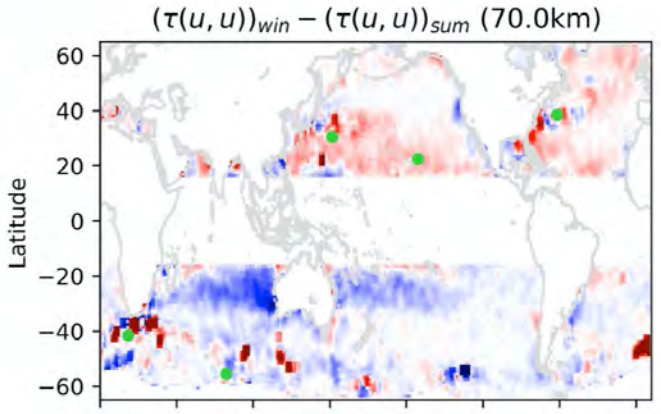
CESM OM4



Our strategy

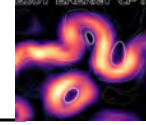
- Building tools that can be used by the team & the community
- Creating synergies across groups working on observations, theory and model development

Satellite Altimetry



Los Alamos NATIONAL LABORATORY · Columbia University · Columbia Climate School · Lamont-Doherty Earth Observatory · Princeton University · NYU · GFDL · The University of Chicago 1890 · University of Colorado Boulder · Brown · NCAR UCAR · Woods Hole Oceanographic Institution 1930

Outline



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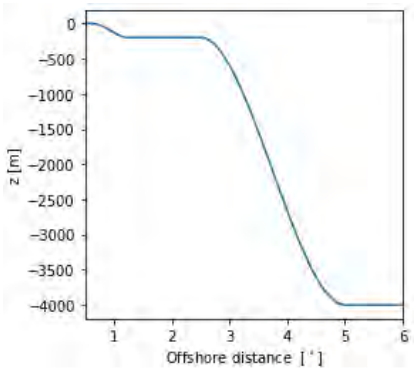
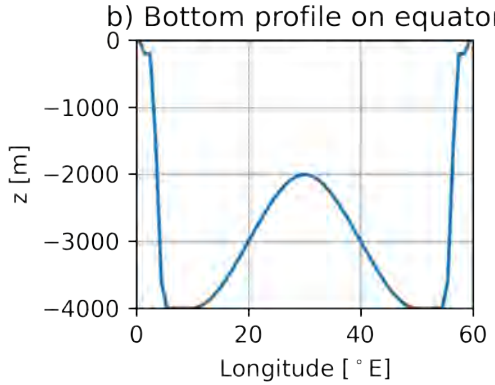
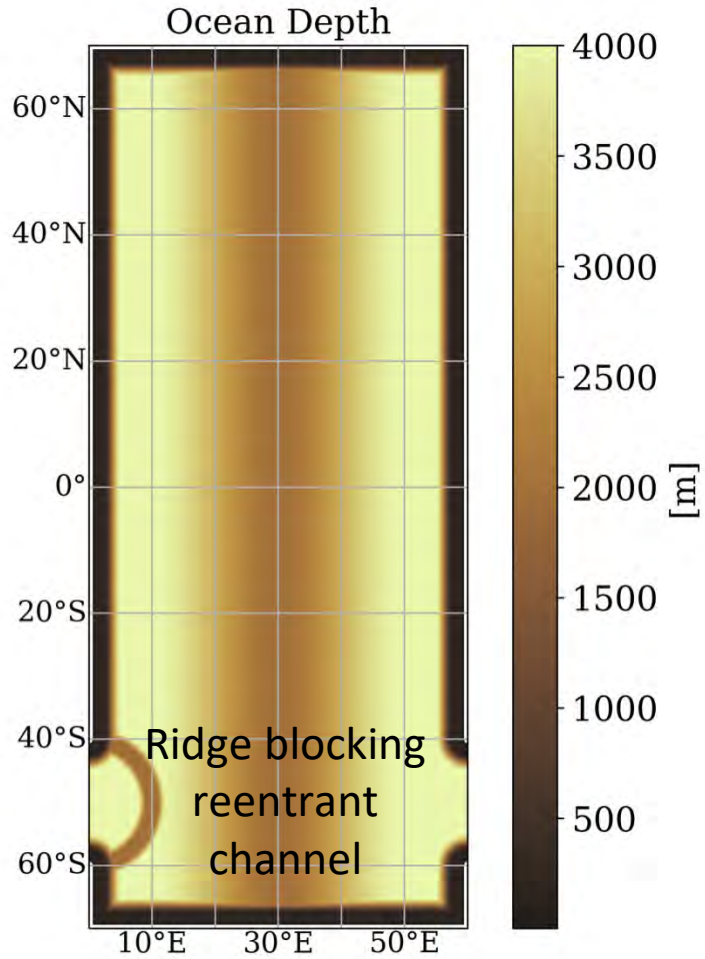
NeverWorld 2: Idealized Model for Testing

- Testbed for all implementation & evaluation of extant (and future) subgrid scale parameterizations
- Affordable high-resolution & extensive analysis + diagnostics

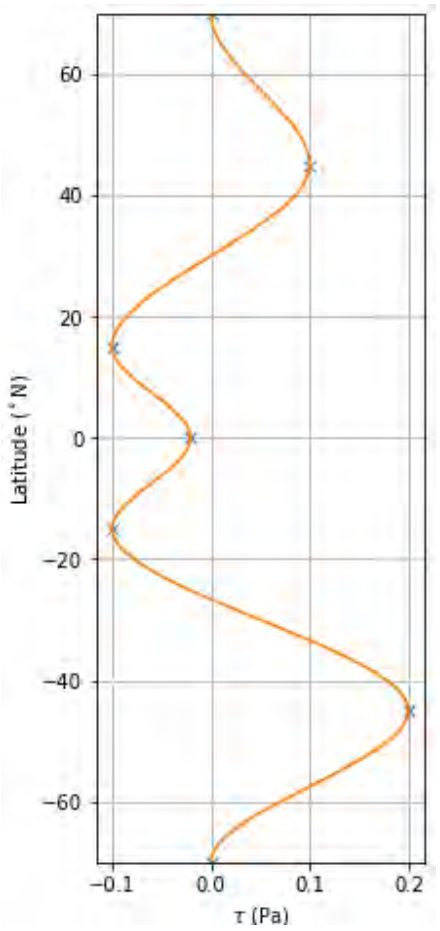
Coastal shelf and slope





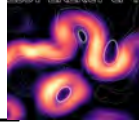


Fixed zonal winds



Marques et al. (2022): *Submitted to GMD, doi: 10.1002/essoar.10511043.1*

NeverWorld2 Stacked Shallow Water Model

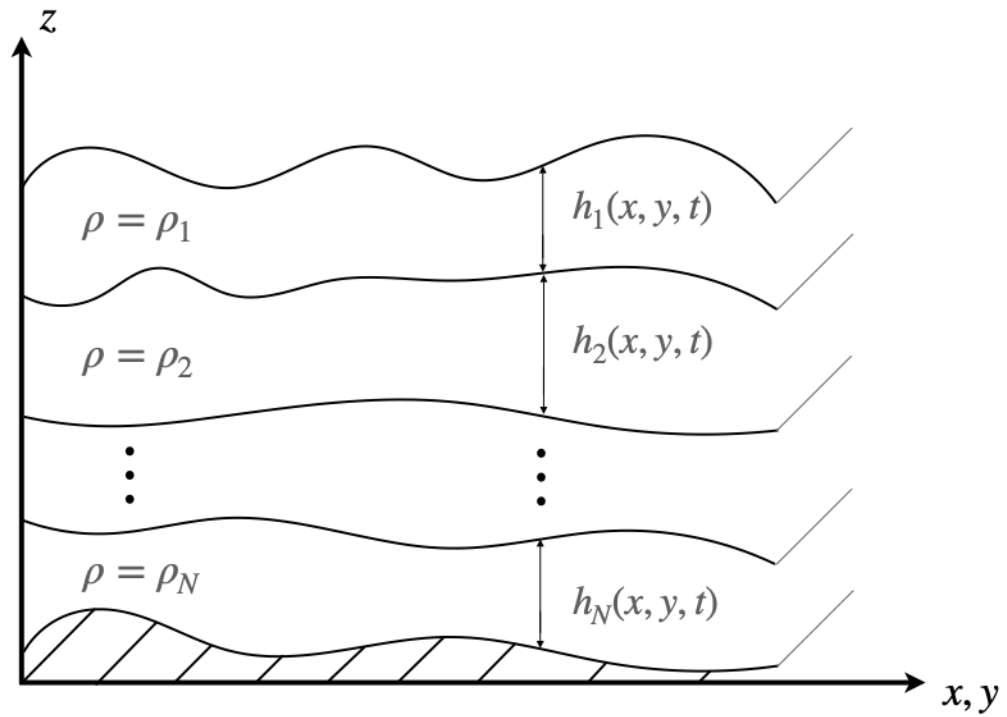


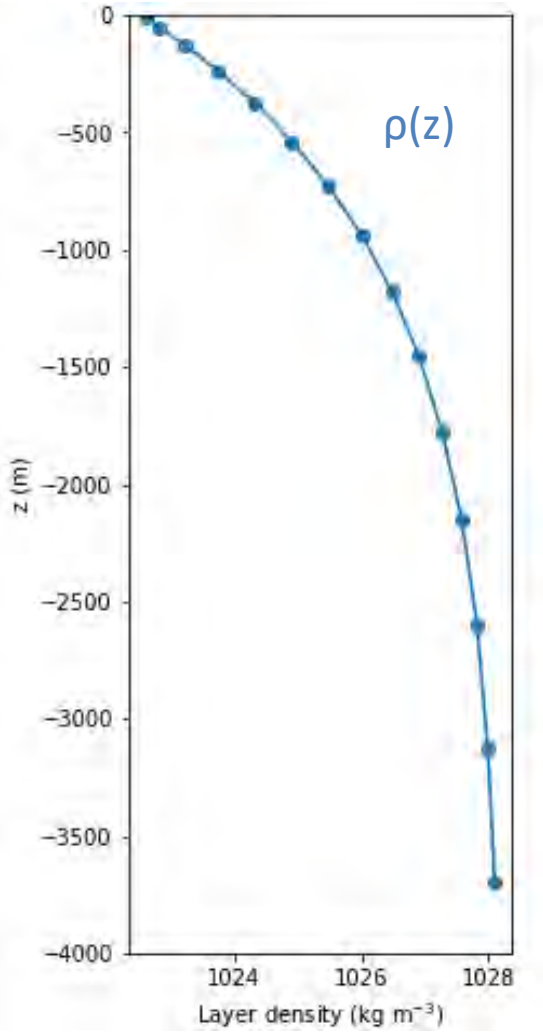
$$(\textbf{Continuity equation})_n \qquad \partial_t h_n = -\nabla \cdot (h_n \mathbf{u}_n)$$

$$(\textbf{Velocity equation})_n \qquad \partial_t \mathbf{u}_n + \mathbf{u}_n \cdot \nabla \mathbf{u}_n + \mathbf{f} \times \mathbf{u}_n = -\frac{1}{\rho_1} \nabla p_n + \mathbf{F}_n$$

- 15 layers, exponential stratification
- Adiabatic (no buoyancy forcing)

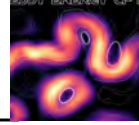
Stacked shallow water model





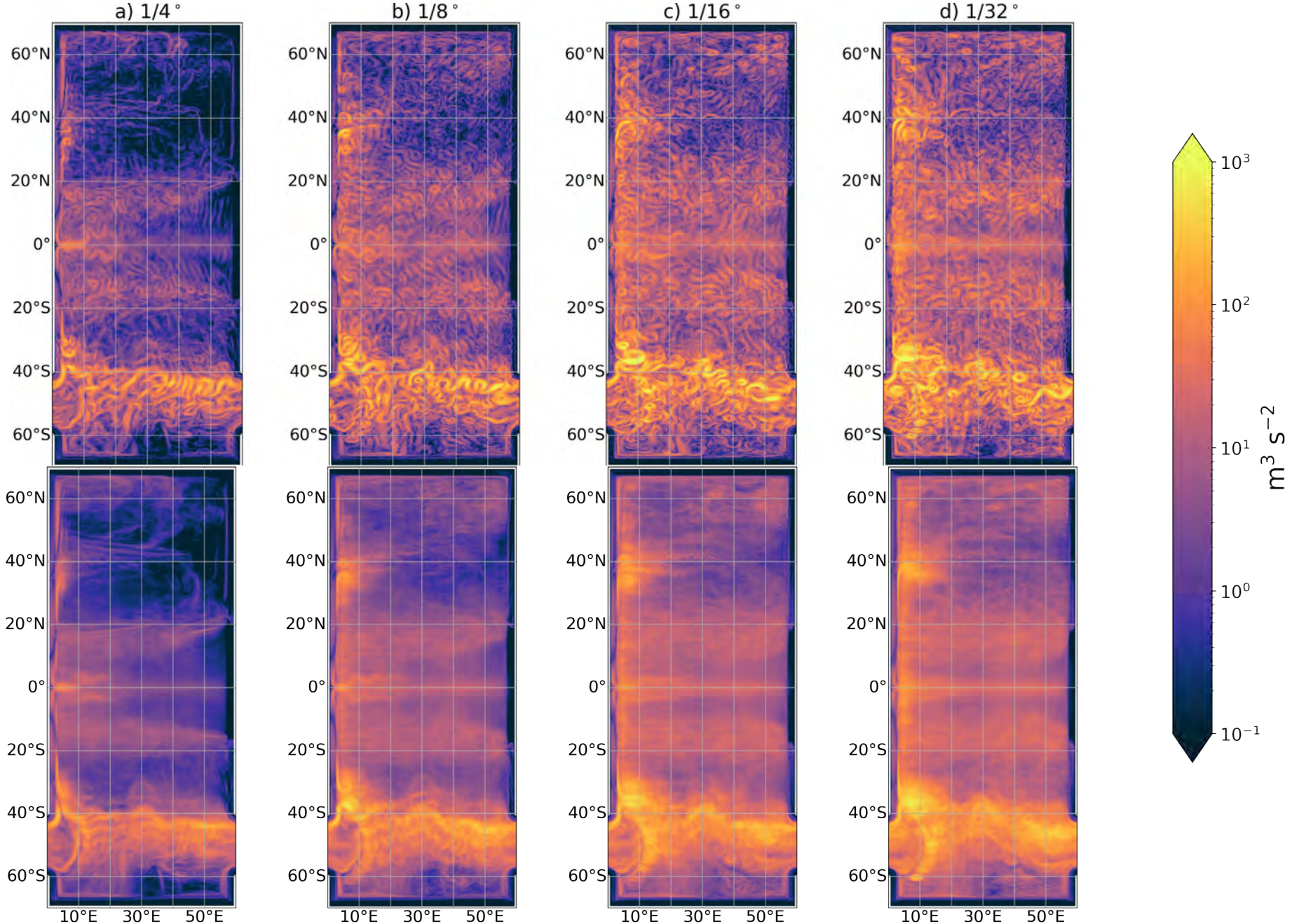
https://github.com/ocean-eddy-cpt/NeverWorld2

NeverWorld 2 Kinetic Energy

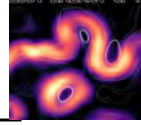


Snapshot

500-day average



NeverWorld 2: Evaluation of Parameterizations



➞ **Many Parameterizations: Old & New**

Parameterization of ocean eddies: Potential vorticity mixing, energetics and Arnold's first stability theorem

David P. Marshall [a,*], Alistair J. Adcroft [b]

Scale-aware deterministic and stochastic parametrizations of eddy-mean flow interaction

Laure Zanna [a,*], PierGianLuca Porta Mana [b], James Anstey [a], Tomos David [a], Thomas Bo

A scale-aware subgrid model for quasi-geostrophic turbulence

Scott D. Bachman[1], Baylor Fox-Kemper[2], and Brodie Pearson[2]

Effects of vertical variations of thickness diffusivity in an ocean general circulation model

Gokhan Danabasoglu [a,*], John Marshall [b]

Energy budget-based backscatter in an eddy permitting primitive equation model

Malte F. Jansen [a,b,c,*], Isaac M. Held [b,c], Alistair Adcroft [b,c], Robert Hallberg [b,c]

The GM+E closure: A framework for coupling backscatter with the Gent and McWilliams parameterization

Scott D. Bachman *

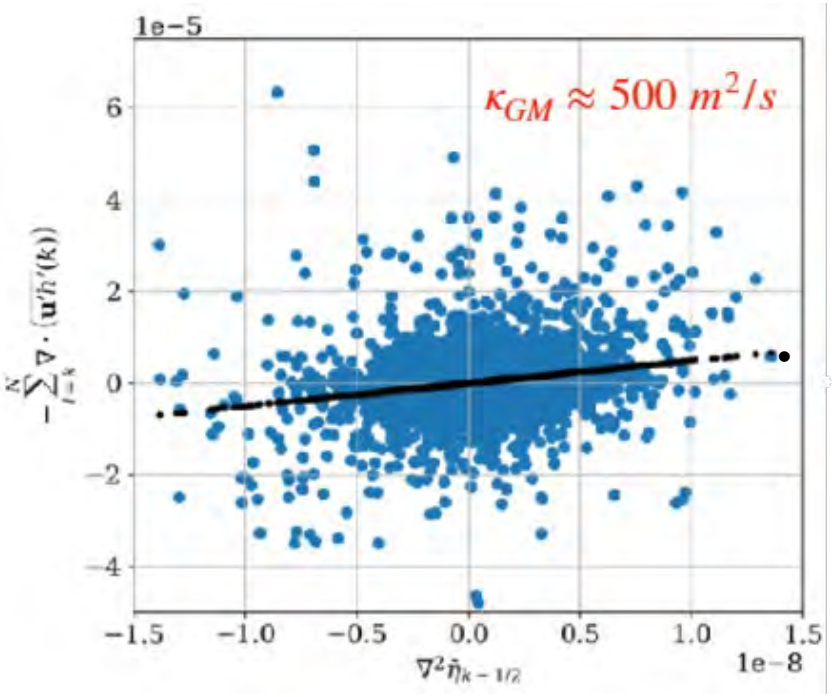
National Center for Atmospheric Research, Boulder, CO, USA

Implementation of a Geometrically Informed and Energetically Constrained Mesoscale Eddy Parameterization in an Ocean Circulation Model

J. MAK

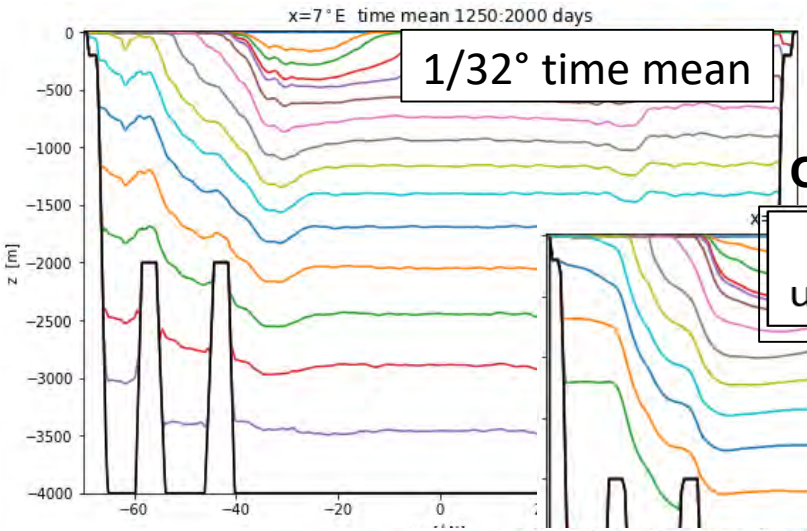
NeverWorld 2: Evaluation of existing parameterizations

- **Offline analysis of high-resolution data**
  - Filtering high-resolution simulations
  - Testing/optimization of free parameters in parameterizations
  - Derivation of new parameterizations

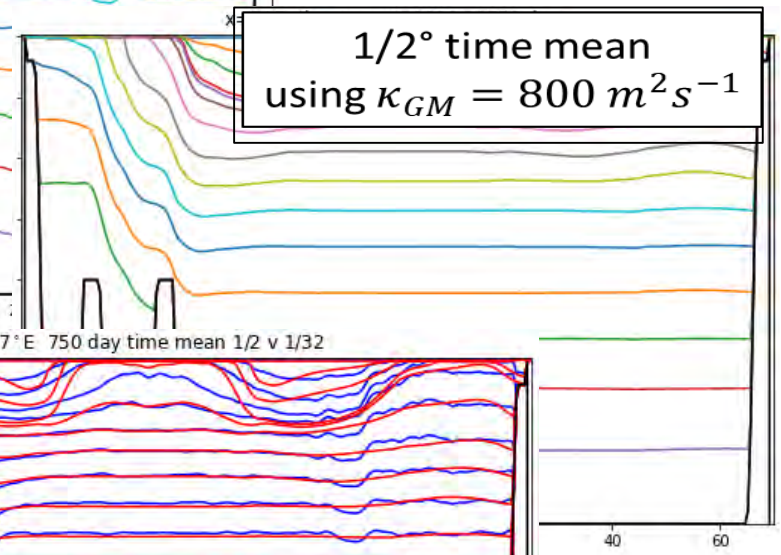


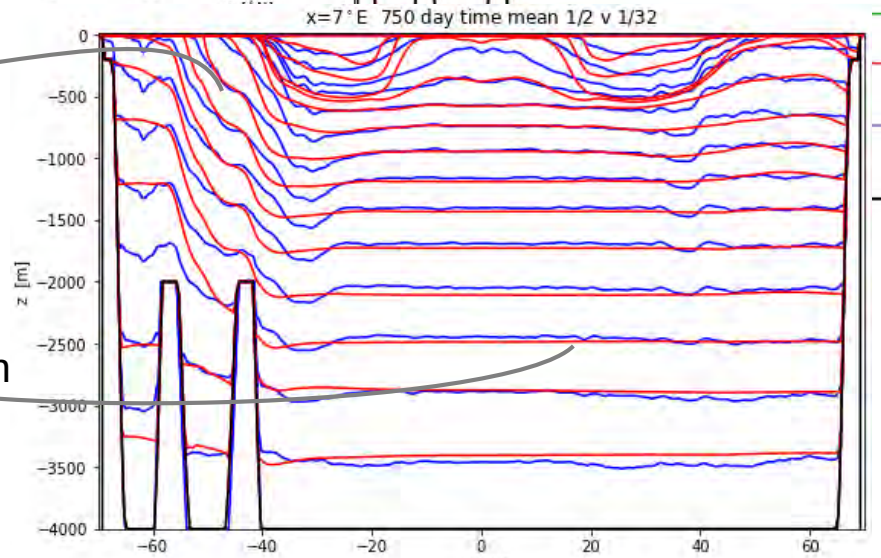
- **Online evaluation**
  - assumes correct form of parameterizations

Truth



Coarse-res + GM

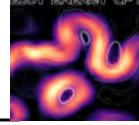




1/32° v 1/2°

Systematic biases
- near topography likely due to standing eddies
- Large scale biases in interior: deficiency of existing parameterization

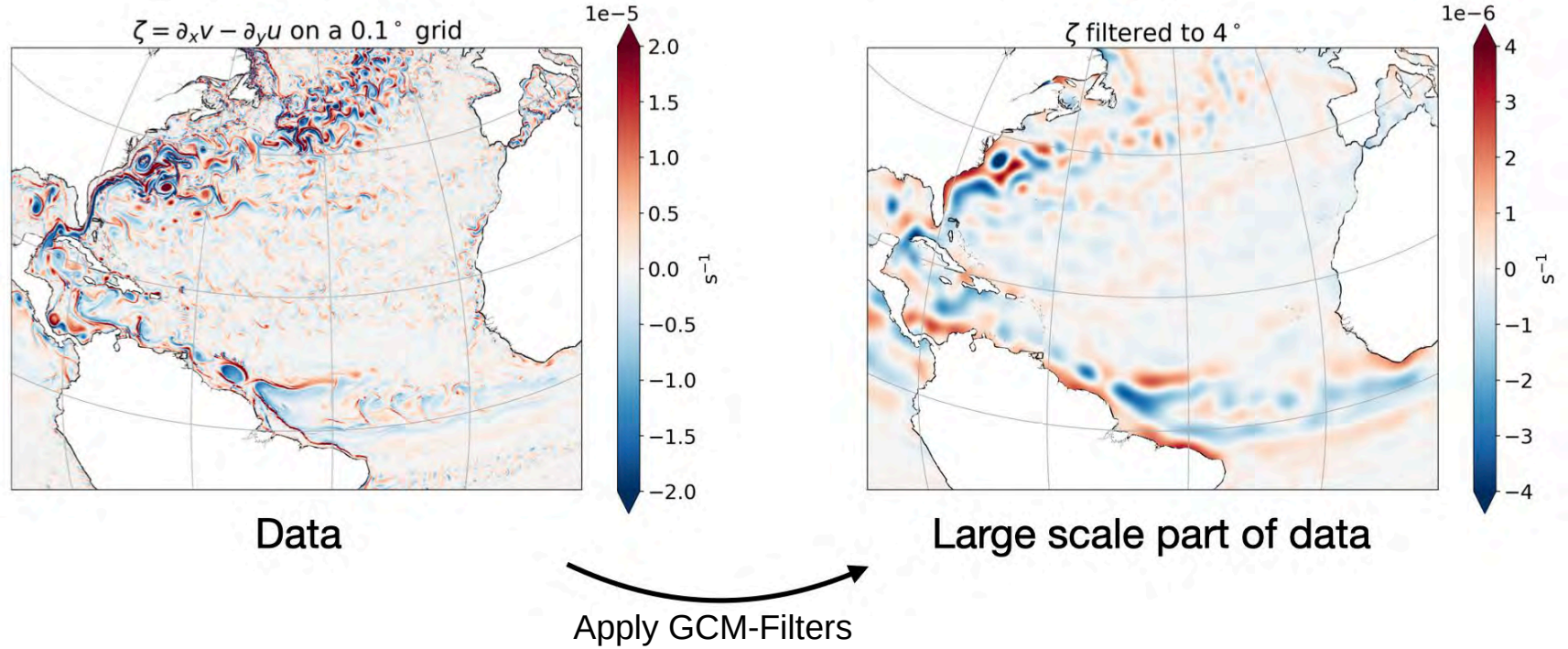
GCM-Filters: A CPT-developed Open-Source Python package for Spatial Filtering Analysis



Publications:

Grooms et al., 2021 (JAMES)

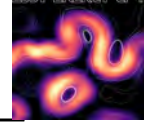
Loose et al., 2022 (Journal of Open Source Software)

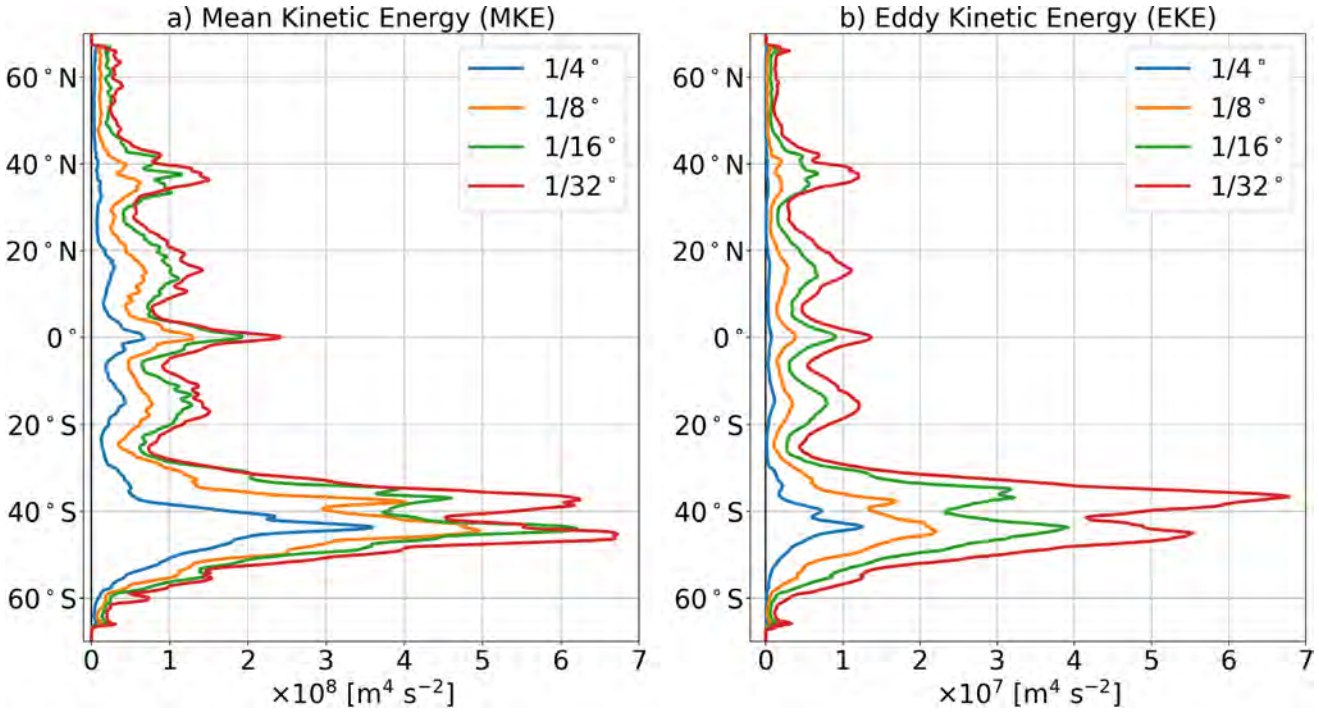


Applications:

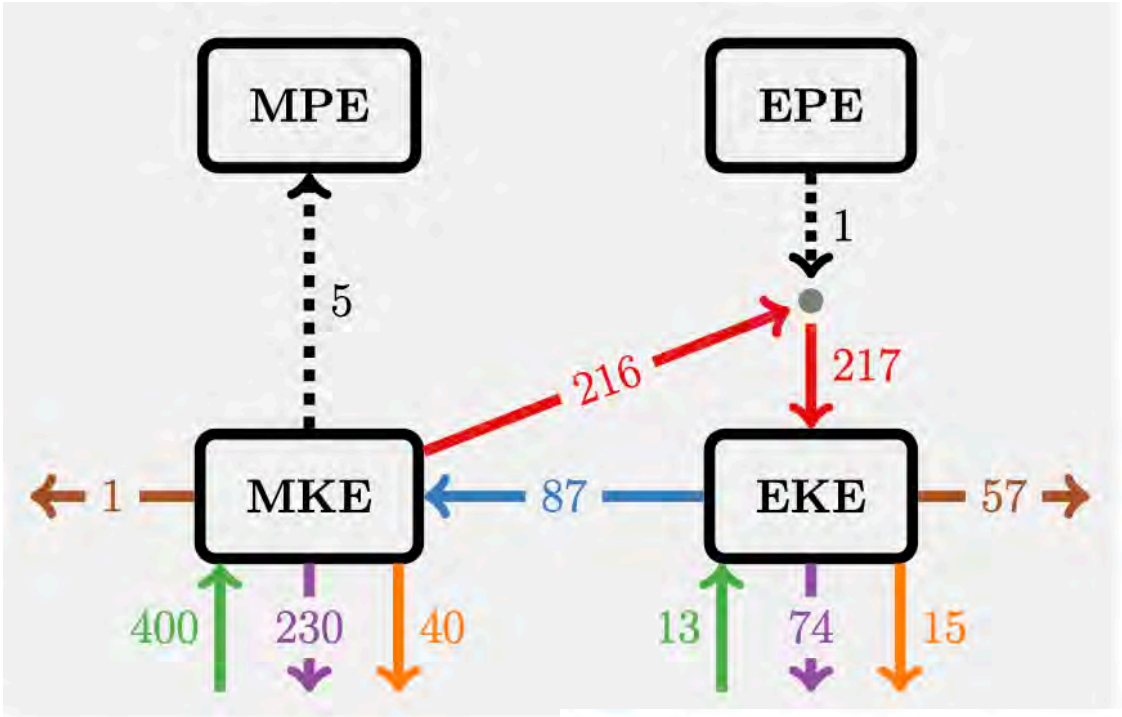
- Studying oceanic & atmospheric motions at different spatial scales
- Diagnosing eddy fluxes in high-resolution model output to identify parameterization requirements in coarse & eddy-permitting models

NeverWorld 2: Energetics as a function of Resolution





Marques et al., *Submitted to GMD*



Loose et al., *Submitted to JPO*

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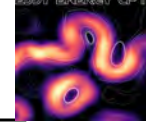

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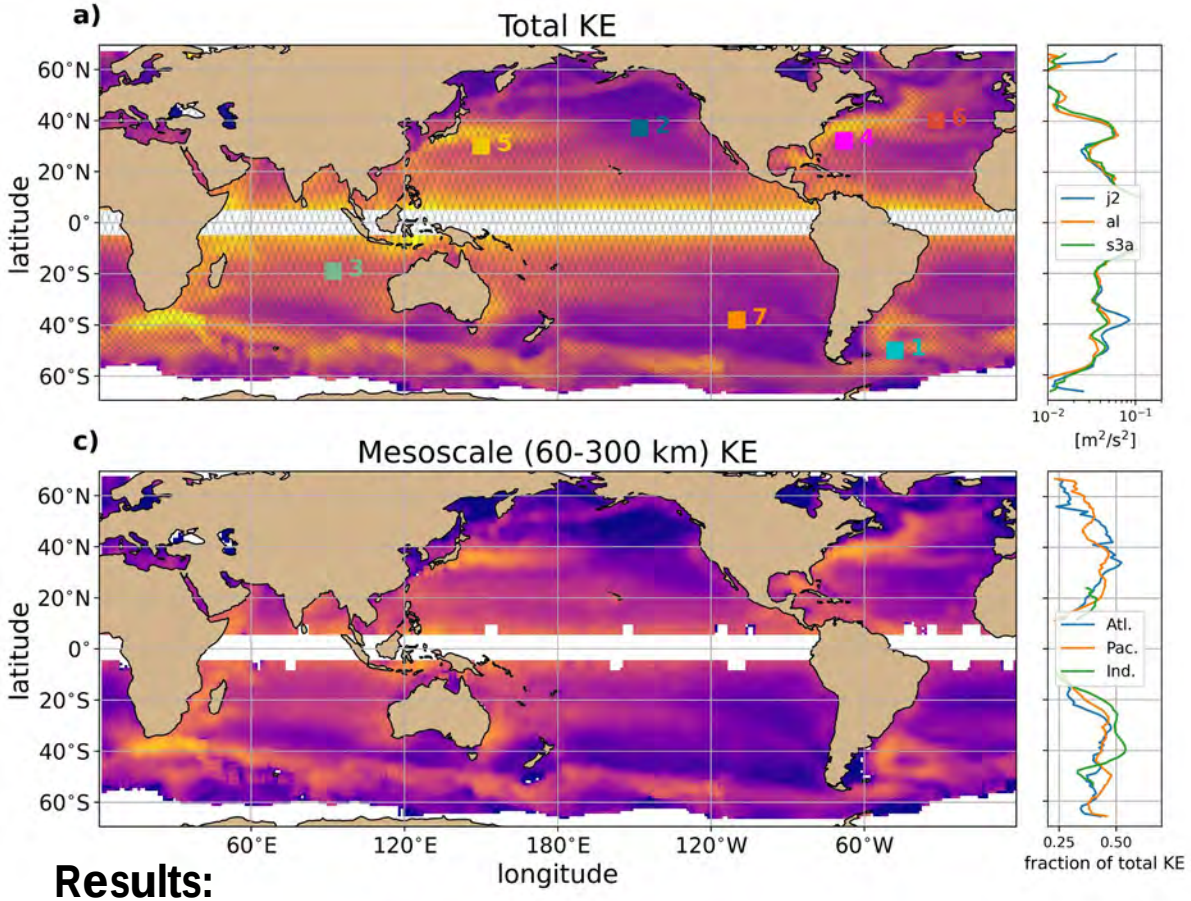
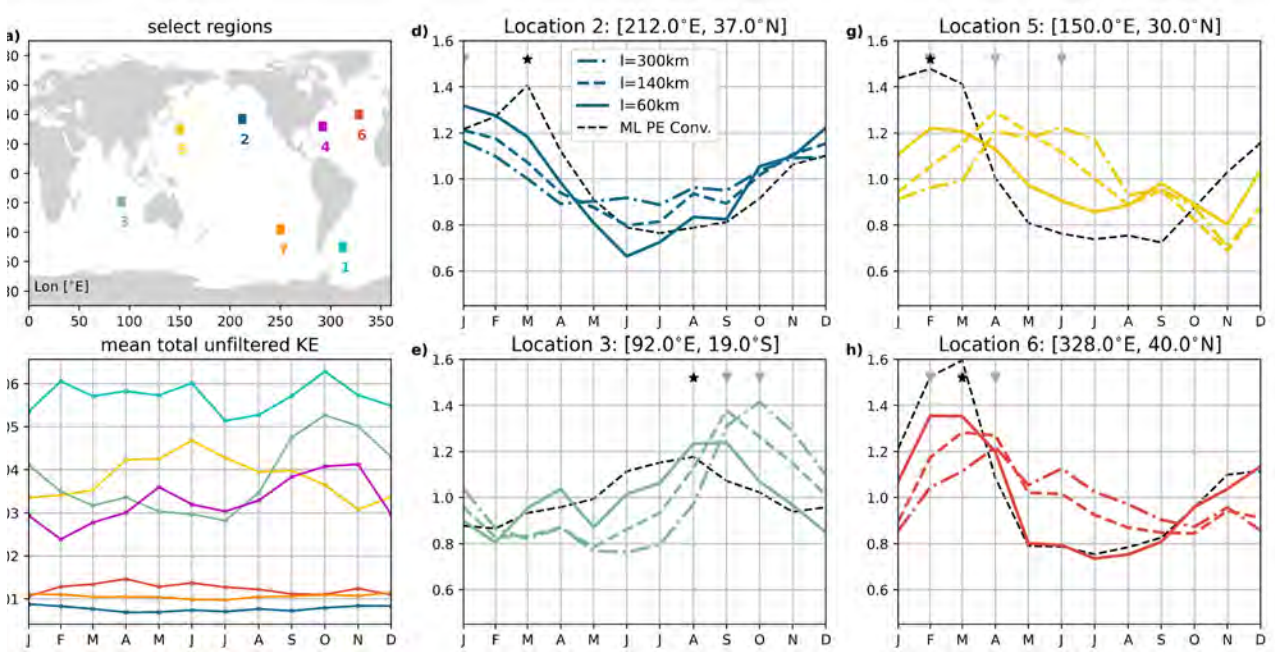
Timing of the inverse energy cascade

Scale-dependent EKE from along-track altimeter measurements





Tool: to generate EKE/MKE maps at desired scales (via sharp spatial filtering)

Results:

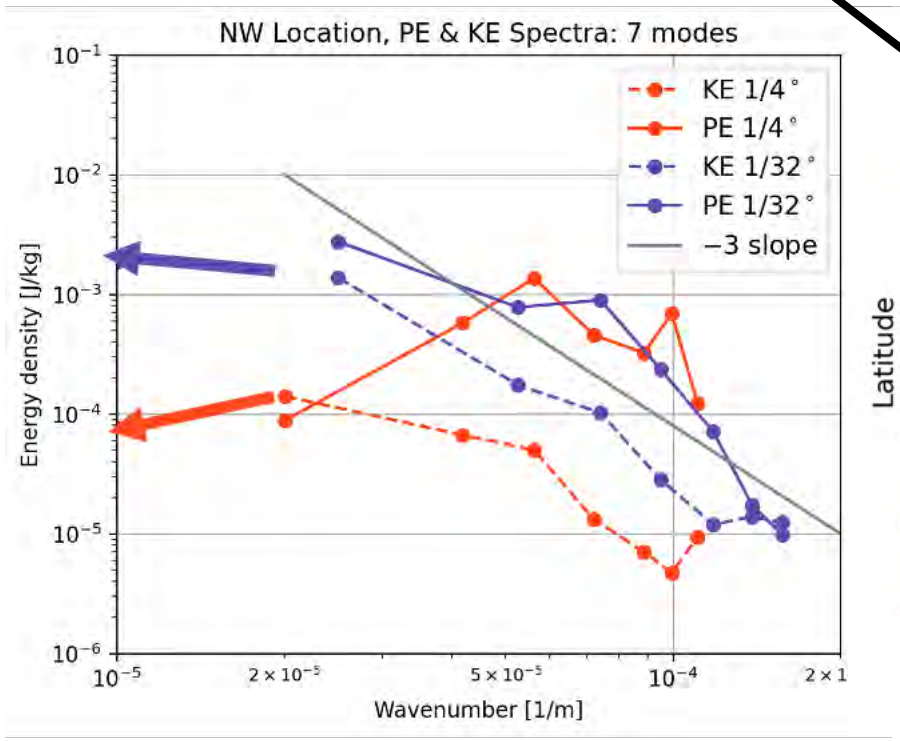
- Seasonal cycle in EKE that is a function of horizontal scale (< 60 km, < 140 km, < 300 km)
- Smaller scale EKE peaks earlier in the year than larger scale EKE
- This smaller scale peak coincides with EKE generation via mixed layer baroclinic instability (@ submesoscales)

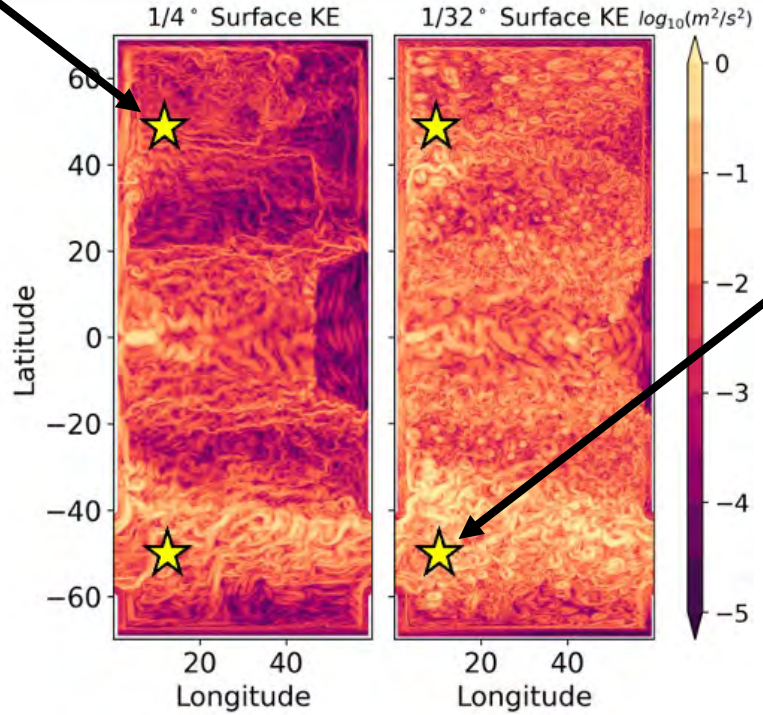
Steinberg et al. (2022), JPO

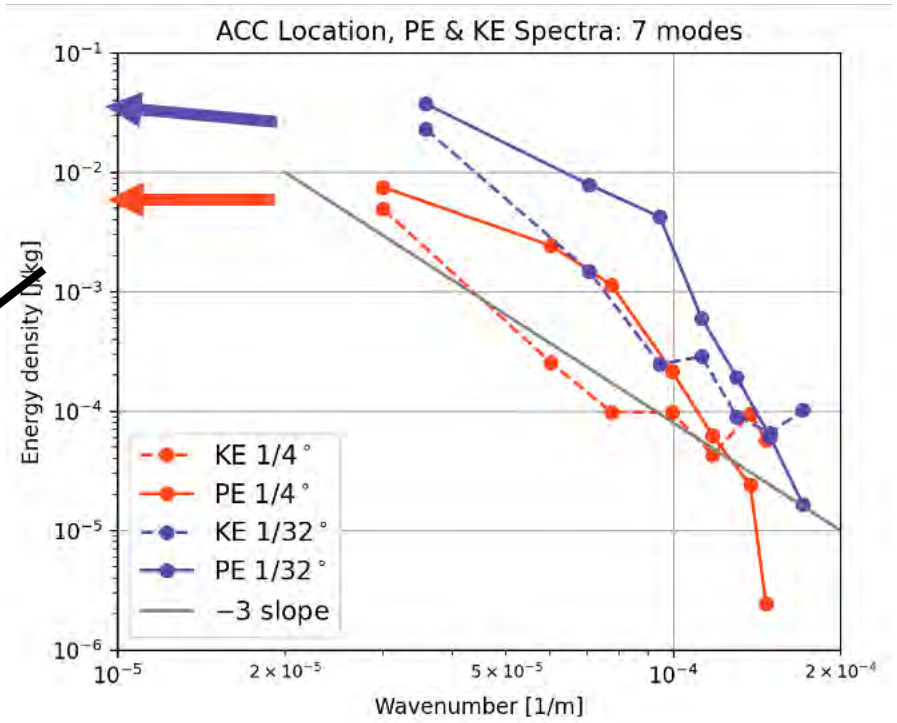
Eddies & Vertical Structure

Effects of resolution & dynamical regime on vertical structure **in idealized & global models**

- Weak mean flow
  - Increased resolution -> barotropization
  - When R_D is unresolved, PE & KE trapped in high vertical modes
- Strong, barotropic mean flow
  - Increased resolution -> increased energy
  - Vertical structure unchanged





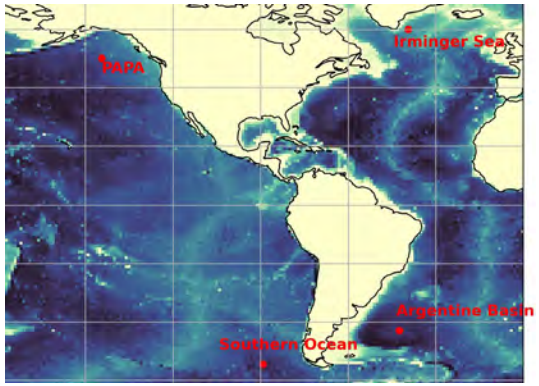


Yankovsky et al., To be Submitted to JAMES

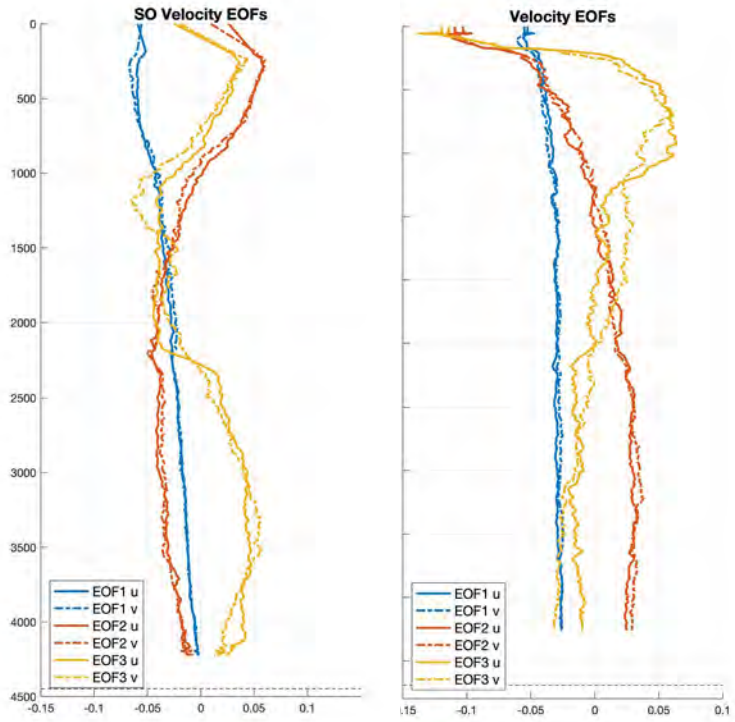
Eddies & Vertical Structure

How is the vertical partitioning of KE influenced by stratification, bottom slope, bottom roughness, and mean KE?

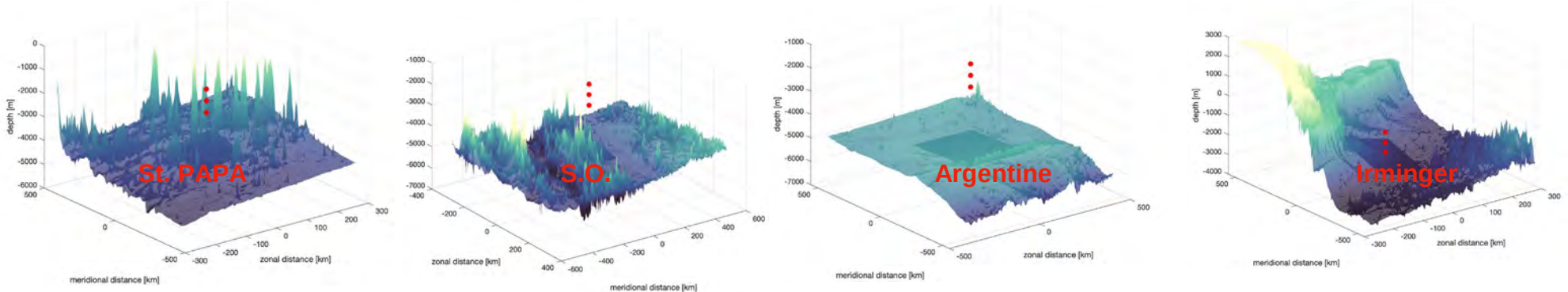
How do vertical structures of horizontal velocity (EOFs) compare to dynamical mode predictions (a function of ***bottom slope*** & ***roughness***)?



data:
multi-year full-depth horizontal velocity time series

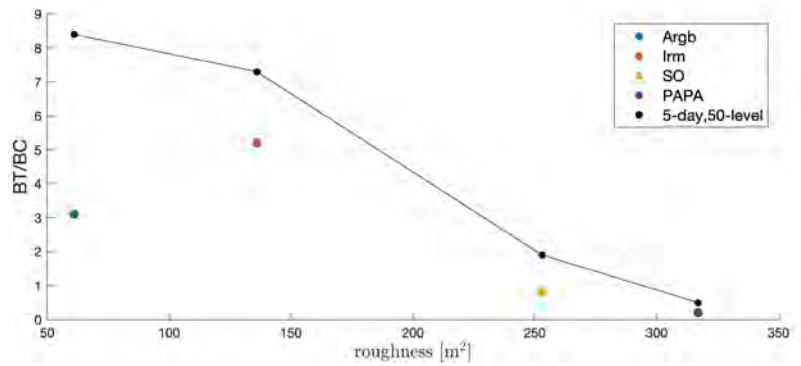


site bathymetry



initial results:

- no universal vertical structure
  - flat bottom modes match EOFs in flat regions
  - surface modes match EOFs in rough-bottom regions

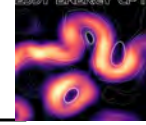


The ratio of barotropic to baroclinic KE decreases with increasing bottom roughness

continued work:

- how does vertical structure compare to model equivalents with variable horizontal resolution?
- increase # moorings analyzed
- test hypothesis in model (test against mean KE)

Outline



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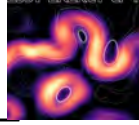
NeverWorld 2: Evaluation of Parameterizations



➞ **Many parameterizations in development**

Parameterization of ocean eddies: Potential vorticity mixing, energetics and Arnold's first stability theorem

David P. Marshall [a,*], Alistair J. Adcroft [b]

Scale-aware deterministic and stochastic parametrizations of eddy-mean flow interaction

Laure Zanna [a,*], PierGianLuca Porta Mana [b], James Anstey [a], Tomos David [a], Thomas Bo

A scale-aware subgrid model for quasi-geostrophic turbulence

Scott D. Bachman[1], Baylor Fox-Kemper[2], and Brodie Pearson[2]

Effects of vertical variations of thickness diffusivity in an ocean general circulation model

Gokhan Danabasoglu [a,*], John Marshall [b]

Energy budget-based backscatter in an eddy permitting primitive equation model

Malte F. Jansen [a,b,c,*], Isaac M. Held [b,c], Alistair Adcroft [b,c], Robert Hallberg [b,c]

The GM+E closure: A framework for coupling backscatter with the Gent and McWilliams parameterization

Scott D. Bachman *

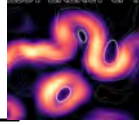
National Center for Atmospheric Research, Boulder, CO, USA

Implementation of a Geometrically Informed and Energetically Constrained Mesoscale Eddy Parameterization in an Ocean Circulation Model

J. MAK

Unified CPT-eddy energy parametrization (202?)

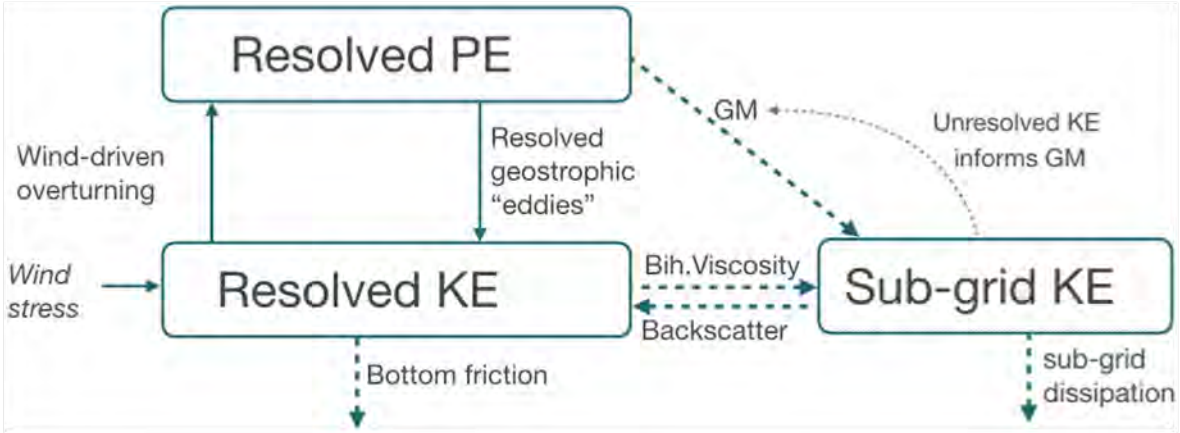
Prognostic Equation for Eddy Kinetic Energy



- Keeping track of eddy energy *using a prognostic equation for eddy energy*

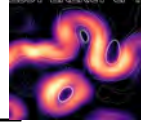
- 2D (depth-averaged) mesoscale eddy kinetic energy equation (MEKE) *(e.g., Cessi 2008; Eden & Greatbatch, 2009; Marshall & Adcroft 2010; Jansen et al 2019)*

$$\frac{\partial}{\partial t}\cdot \mathrm{EKE} = \text{Sources} - \text{Sinks} + \text{Transport}$$



Jansen et al. 2019

Prognostic Equation for Eddy Kinetic Energy



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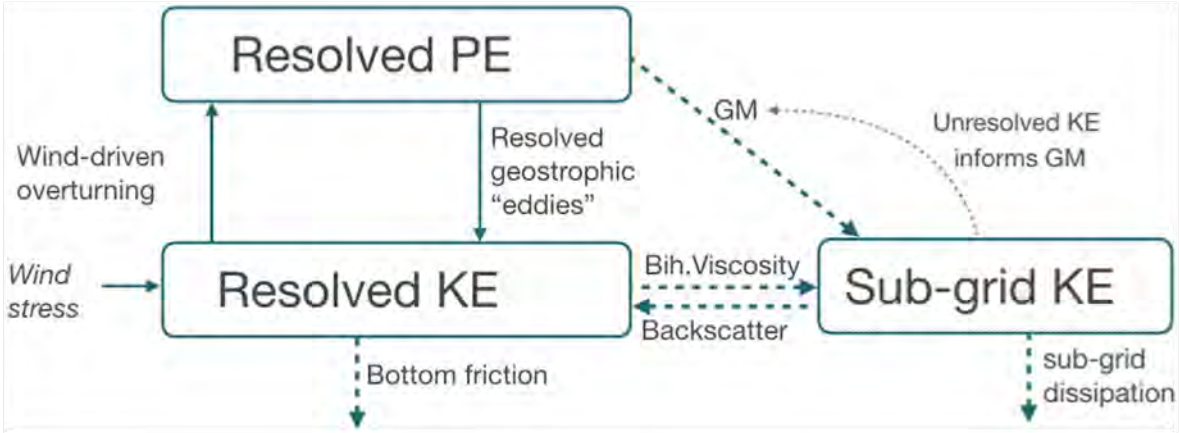

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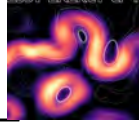

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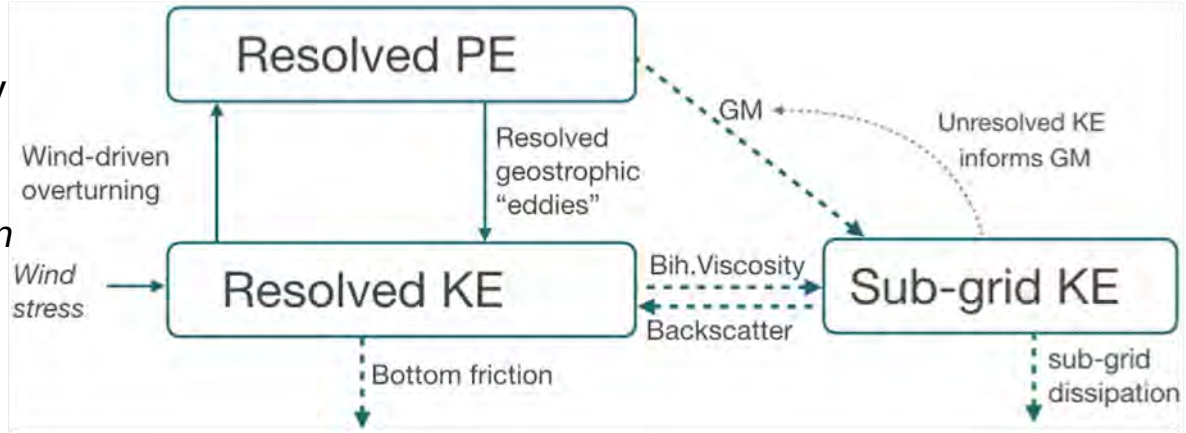
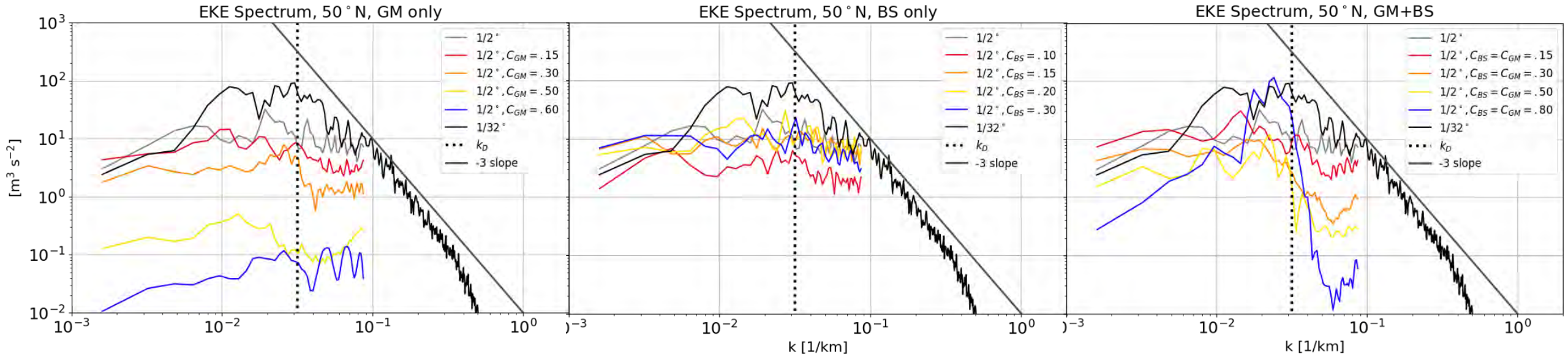
- New schemes which re-injects available potential energy removed by Gent-McWilliams or excess dissipation into resolved scales in the momentum equation *(e.g., Bachman 2019; Jansen et al 2019; Zanna et al. 2017)*



Jansen et al. 2019

Sensitivity of GM & Backscatter



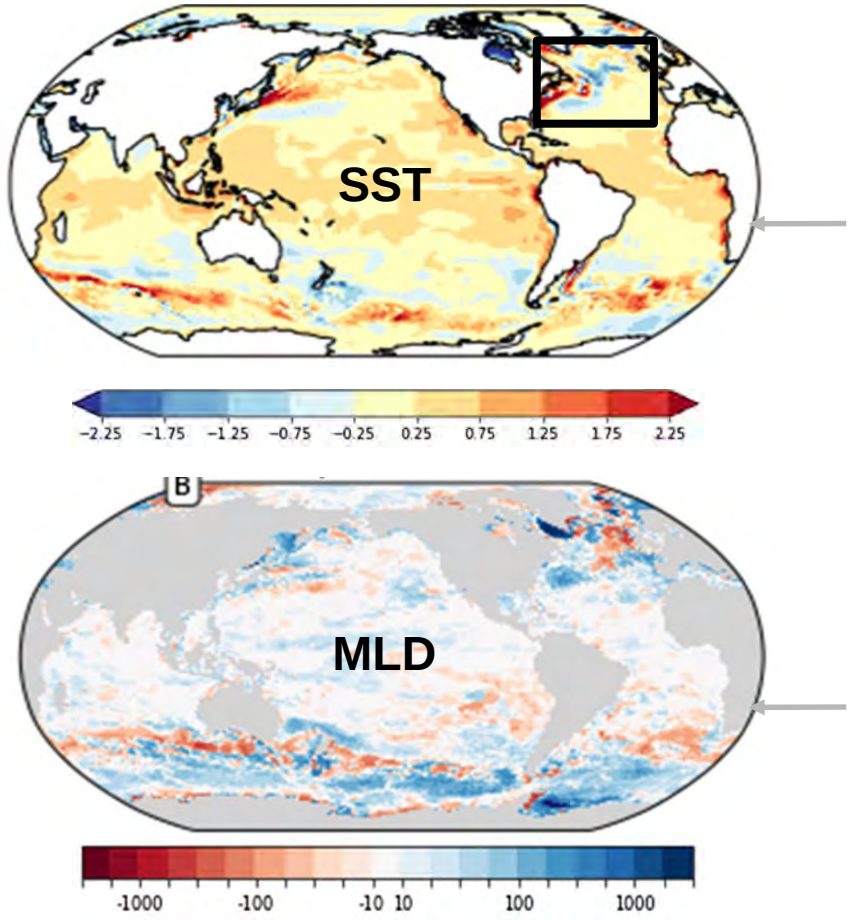
- GM: GM increases -> EKE decreases
- BackScatter: BS increases -> more EKE (& total KE increases ~150%)
- BS + GM: shape of spectrum changes, more energy near deformation scale R_D
- Can improve vertical structures but dependence on dynamical regimes

Yankovsky et al., in progress

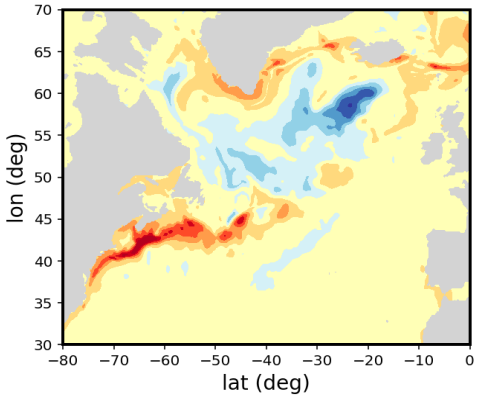
Gent-McWilliams & Backscatter in OM4

Adding MEKE points to both opportunities & challenges to reduce existing OM4 biases

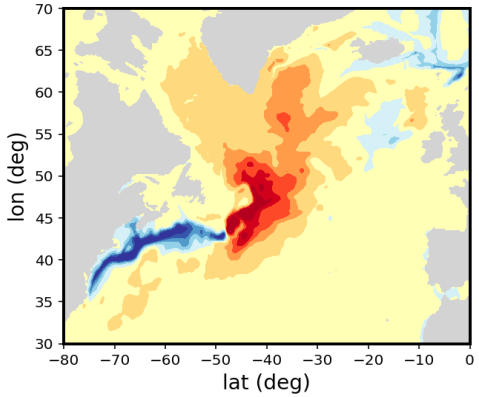
OM4p25 Biases [Adcroft et al. 2019]



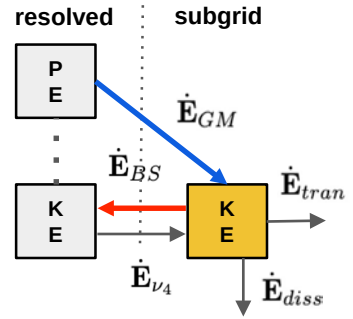
GM - CTL



BS - CTL



MEKE scheme [Jansen et al. 2019]



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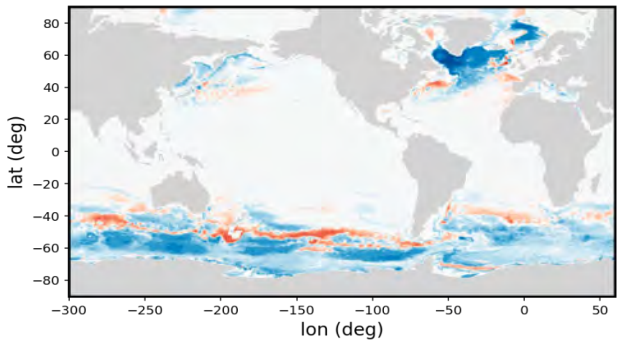

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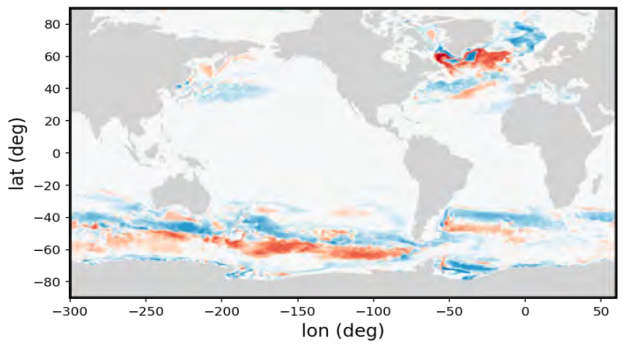
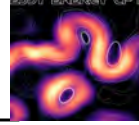


Weaker GM + stronger BS effect help reduce subpolar North Atlantic SST bias, but we see the opposite for the global MLD bias

Chang et al., in progress

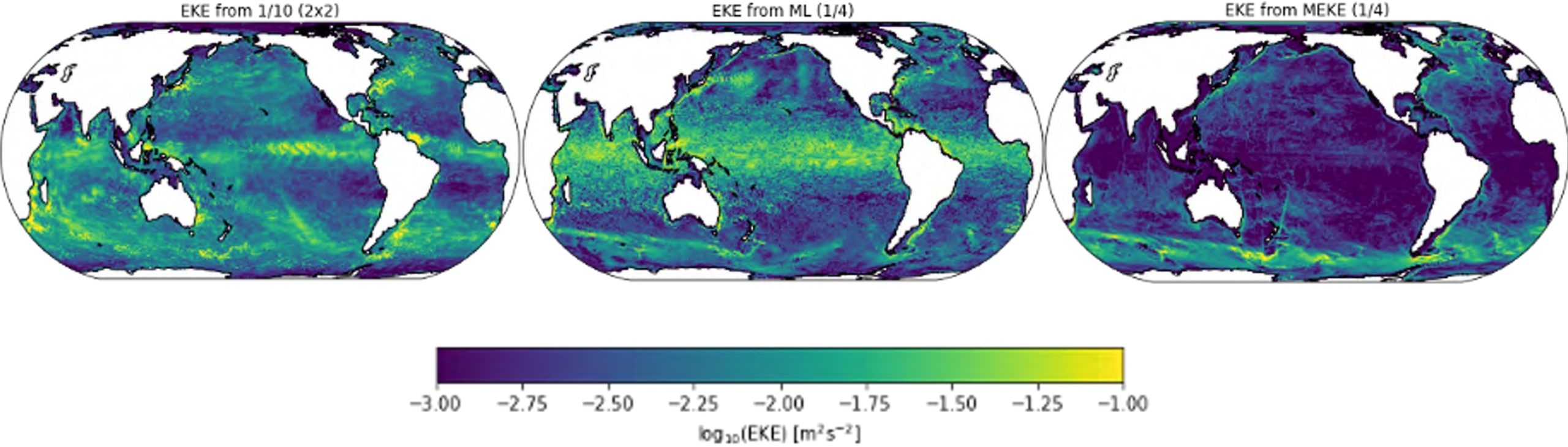
Inferring EKE using Machine Learning in GFDL's OM4 1/4º



"Truth" (1/10º)

Machine Learning

MEKE (Adcroft et al. 2019)

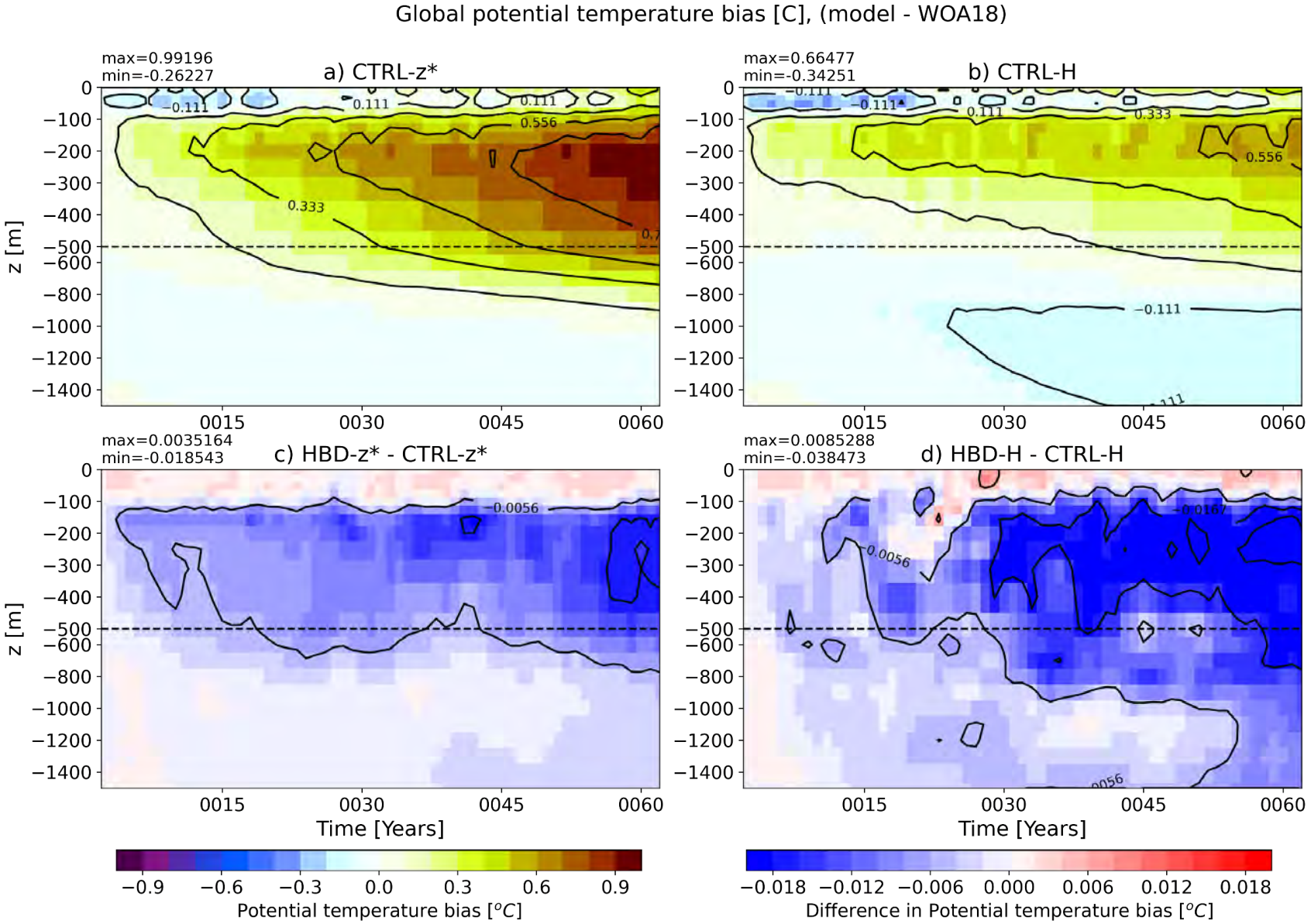


Marques et al., in progress

Novel Method for Applying Near-Surface Eddy Diffusion

➞ Bias reduction in temperature & salinity

Marques et al., in revision (JAMES)



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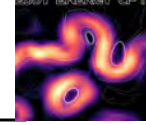

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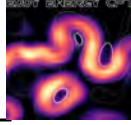
Possible Future Work



- Mixed Layer submesoscales contribute to the mesoscale energy budget & interact with the large scale flow
  - ➞*Appropriately accounting for meso-submeso energetics & its impact on the flow might prove important for global models*

- Regime- & topography dependent vertical structure & PE <—> KE conversion influences tracer mixing
  - ➞*How to use mesoscale eddy energy to constrain tracer mixing coefficients, anisotropy and vertical structure?*

- Subtleties in averaging and how it affects parameterization development
  - ➞*With a general vertical coordinate is one type of averaging superior or more natural than the rest? Does this automatically lead to superior parameterizations?*

- Backscatter: when, how, why?
  - ➞*What form should backscatter take (vertical structure, horizontal scale, numerical operators), and in what circumstances should it be used?*

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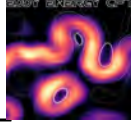
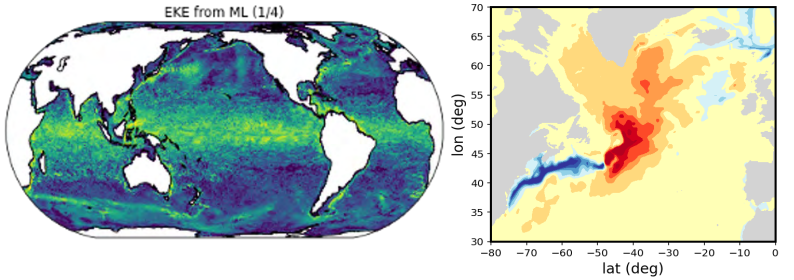


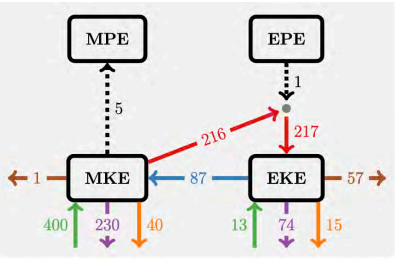
- Dissipation of energy: how should we think of it?
  - ➞*What rationale should we use to tune dissipative operators? e.g. cascades, numerical stability, internal wave breaking…?*
- Anisotropic tracer transport
  - ➞*Plenty of (not new) theory and some whispers that it can help, but no concrete implementation yet*
- Topography and its effects on energy and vertical structure
  - ➞*Baroclinic modal structure depends on the stratification and bottom slope, and eddy properties are clearly affected by the bathymetry*
- Unified parameterizations
  - ➞*Something we should aim for, or are we building a Tower of Babel?*

Concluding Thoughts & Open Questions

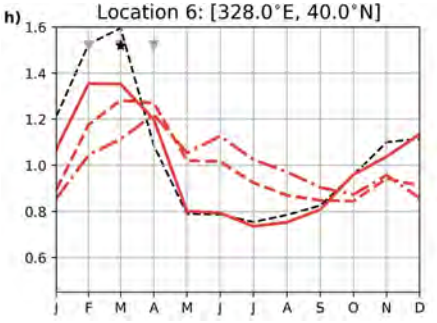
- Mesoscale eddy energy is key to ocean transport & parameterizing it lead to improved model physics & *bias reduction in **some** variables*



- Evaluation of parameterizations & energetics can serve as an important guide for global model implementation with versatile hybrid vertical coordinates
  → *Need for designing appropriate numerical/theoretical frameworks*



- Potential for broader collaboration with friends and partners abroad



- Concept of an energy/diffusivity duality should extend to other flow regimes, not just mesoscale; are we laying the groundwork for the foreseeable future?

- Does machine learning represent a different evolutionary branch, or will it end up synergizing with the eddy energy parameterization framework?