Progress toward NOAA/GFDL's OM5 Global Ocean Configuration

and Related MOM6 Ocean Model Development

Presented by Robert Hallberg (NOAA/GFDL)

with contributions from numerous members of the OM5 / MOM6 Development Teams

MOM6 is available via https://github.com/NOAA-GFDL/MOM6-examples
or at https://github.com/mom-ocean/MOM6

New GFDL Global Models to Address NOAA Mission Objectives across Timescales

	SHiELD (2020 & onward) Weather to Seasonal Data-Initialized Physical Prediction	SPEAR (2020 & onward) Seasonal to Multi-decadal Data-Initialized Physical Prediction	ESM4.5 (2025) Decadal to Century Full Earth System Projection	CM5 (2026, 2028) Decadal to Century Physical Climate Sea Level
FV3 dycore Atmosphere	**SHiELD** 3 to 13 km; 91 Level	**AM4** 25 to 100 km; 33 Level	**AM4.5** 100 km; 49 Level	**AM5** 25 or 100 km; 65 Level
Atmospheric Chemistry	Simple Aerosols	Simple Chemistry & Aerosols	Full Chemistry & Aerosols	Simple Chemistry & Aerosols
LM4 Land	**NOAH LSM** (Initialized **LM4.2i** planned)	**LM4.0/LM4.2** Ecosystems	**LM4.5** Ecosystems, Fire, Snow	**LM4+** Orography Aware
MOM6 / SIS2 Ocean / sea-ice	**Mixed Layer** (**OM5** planned)	**OM4**-derived 1° to $^{1}/_{12}$°; 75 Layer	**OM5** ¼°; 75 Layer	**OM5** (non-Boussinesq) ¼° to $^{1}/_{12}$°; 75 Layer
FMS Coupler & Infrastructure	**Atmospheric Ensemble Data Assimilation**	**Ensemble Data Assimilation**	**COBALTv3 Ocean Ecosystems**	**Interactive Dynamic Ice Sheets**

Regional MOM6/SIS2 Earth System Configurations

GFDL and partners are deploying MOM6 in 5 large-regional marine systems as a part of NOAA's Climate Ecosystem Fisheries Initiative (CEFI)

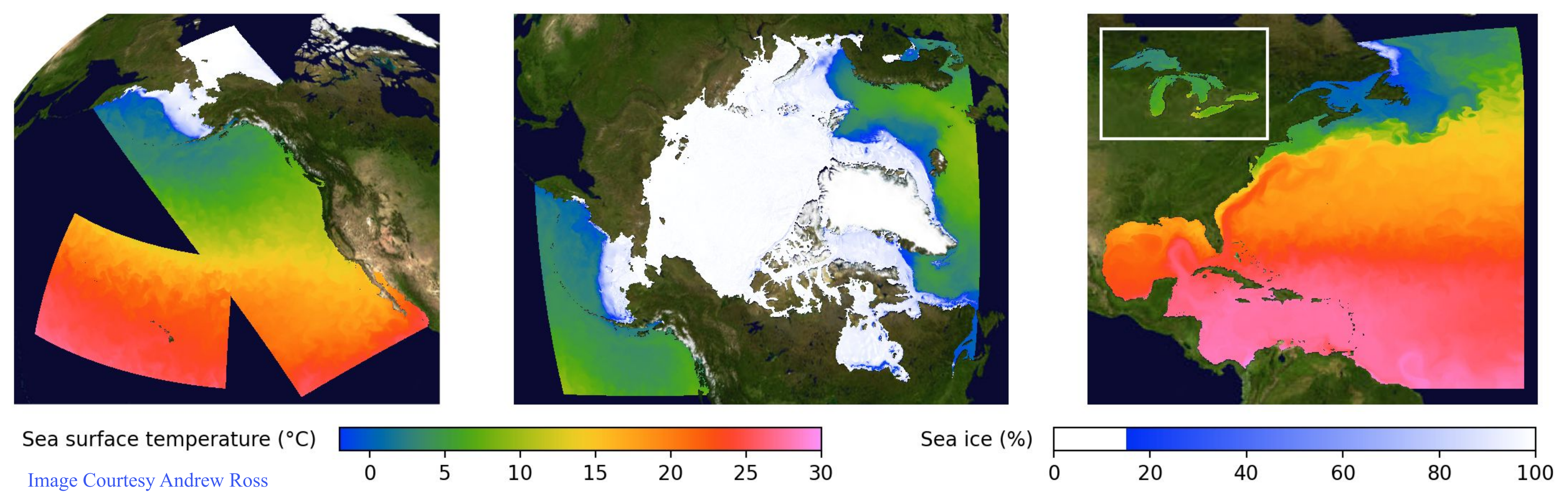
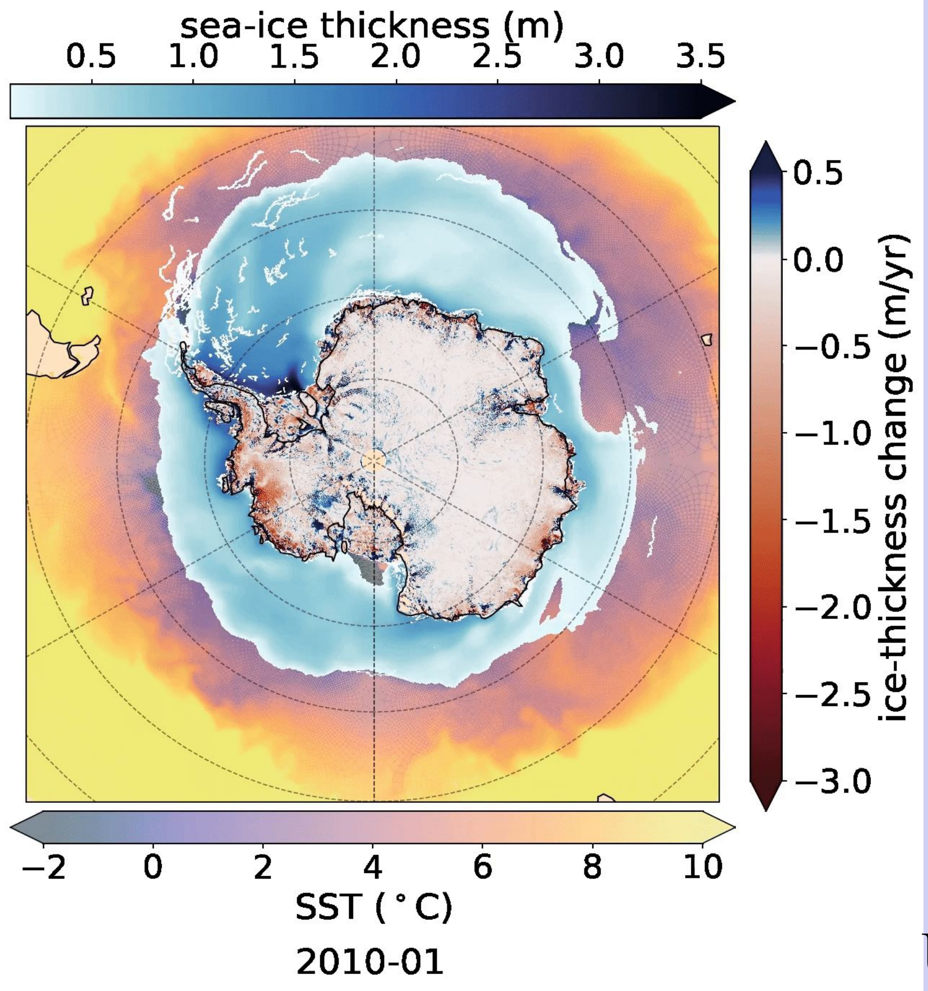


Image Courtesy Andrew Ross

Other regional MOM6 configurations in use: Northwest Pacific (Korean Inst. Ocean Sci. & Tech. & K-MUG)
Southern Hemisphere (Australian Centre of Excellence & COSIMA) ; Tropical Atlantic (Brazil)
Indian Ocean (L. Resplandy group at Princeton)

Synchronously Coupled Global Ocean-Cryosphere Model

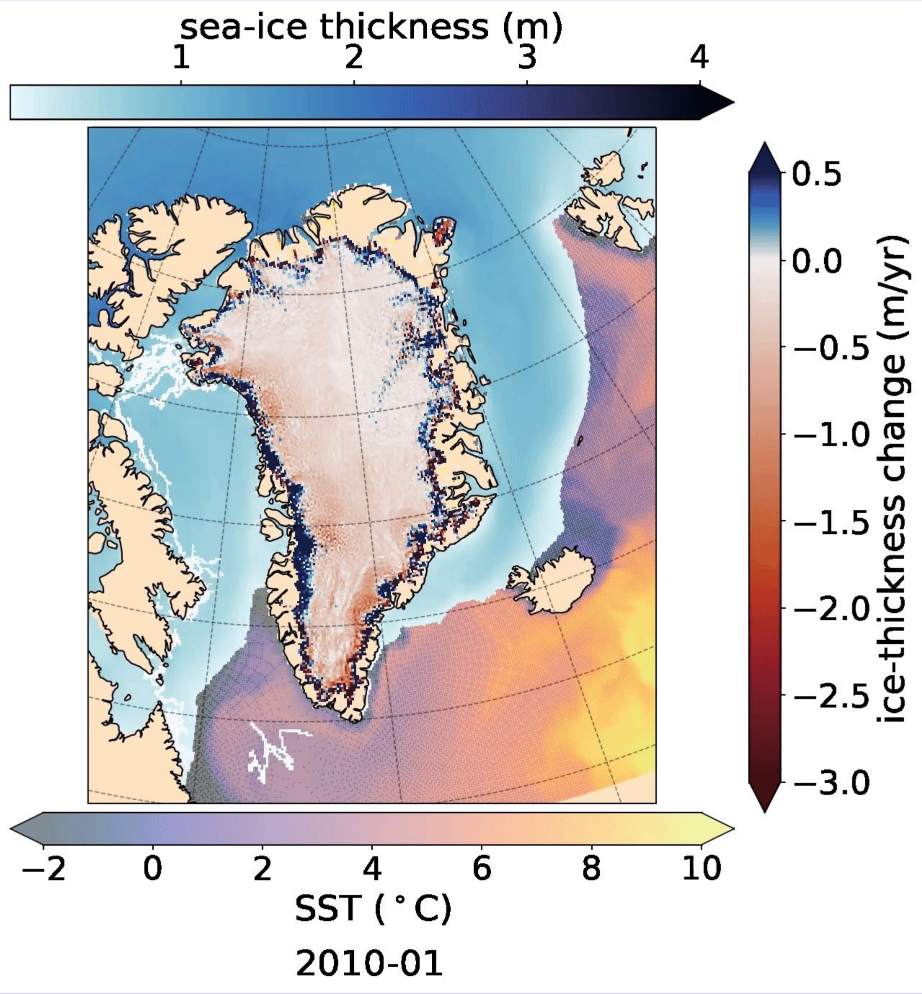


MOM6
ocean

MOM6-IS
ice sheet

SIS2
sea ice

KID
icebergs



Sergienko et al. (*in prep.*)

Unique features

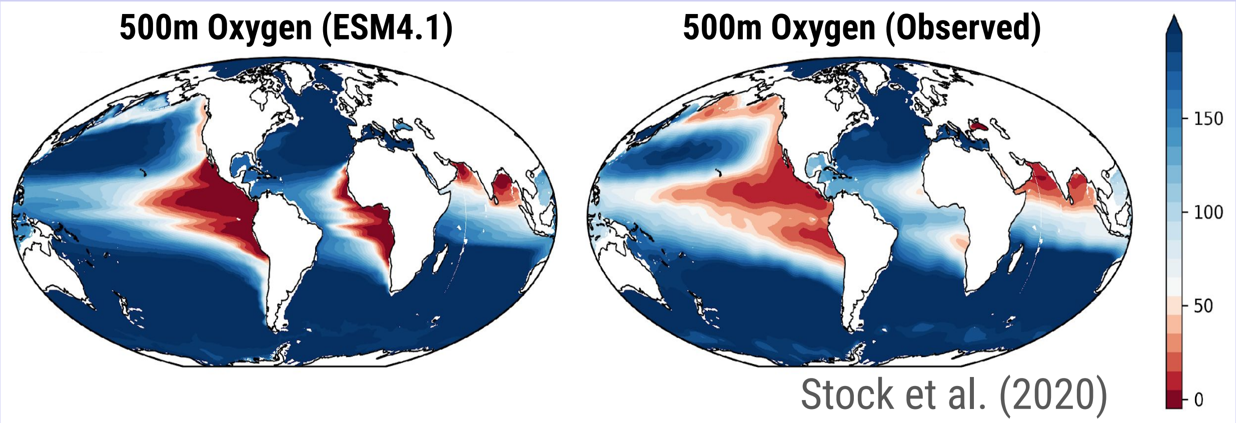
- Synchronous coupling between the dynamic ice sheets and the ocean
- Both ice sheets are coupled simultaneously

New ocean modeling capabilities to fill ESM4 gaps

Gap: Biases in chlorophyll and biogeochemical cycles

- Photoacclimation scheme improves chlorophyll
- Variable N:P stoichiometry improves P-limitation
- Fast sinking detritus, anammox reduces oxygen minimum zone biases
- River runoff carbon improves coastal CO_2

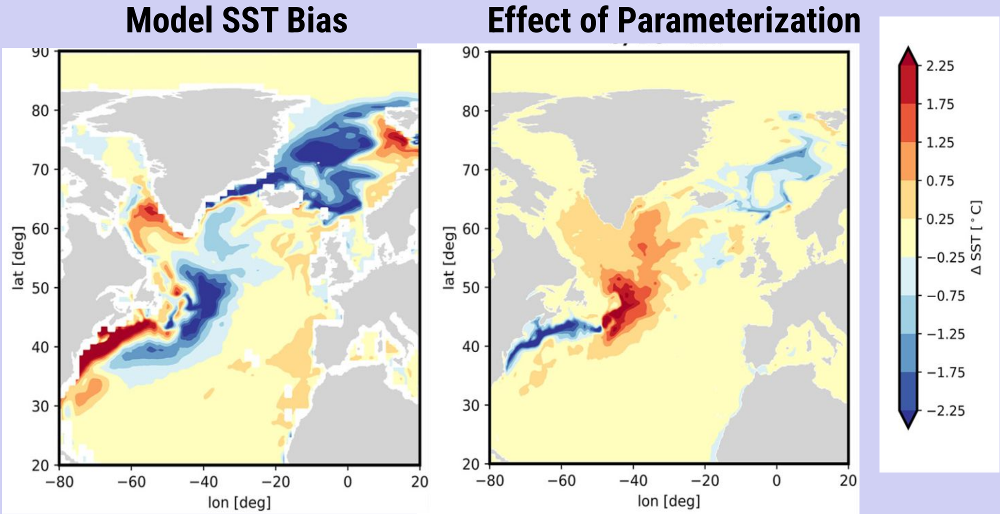
Oxygen minimum zone biases in ESM4.1



Gap: Effects of under-resolved mesoscale eddies

- Increased ocean resolution in ESMs
- Energetically consistent eddy parameterizations

Impact of eddy backscatter parameterization on SST bias in OM5



Chang et al. (2023)

These capabilities will be deployed in GFDL's new ESM4.5 Earth System Model.

New ocean & cryosphere modeling capabilities to fill CM4 gaps

Gap: Direct simulation of sea level and regional patterns
- Interactive ice sheets
- Non-Boussinesq formulation
- Explicit tides with on-line gravitational self-attraction and solid-earth loading
- Improved representation of grid-scale bathymetry

Gap: Mixing-related tropical and mid-latitude biases and static (climate-invariant) mixing rates
- Boundary layer mixing improvements
- AI/ML mixing parameterization refinements
- Energetically constrained mixing
- Improved shear-driven mixing

Gap: Polar ocean and sea-ice biases
- Sea-ice physics improvements
- Numerically stable ice-ocean coupling
- More realistic icebergs
- Latitude-dependent internal gravity wave mixing

Gap: Biases in deep ocean overflows & ocean overturning circulation
- Improved vertical coordinates
- Improved representation of bathymetry
- Bottom boundary layer mixing processes
- Improved shear-driven mixing

Gap: Great Lake circulation impacts U.S. climate
- Explicitly coupled Great Lakes in OM5
- Hydraulic control (waterfalls) in ocean model

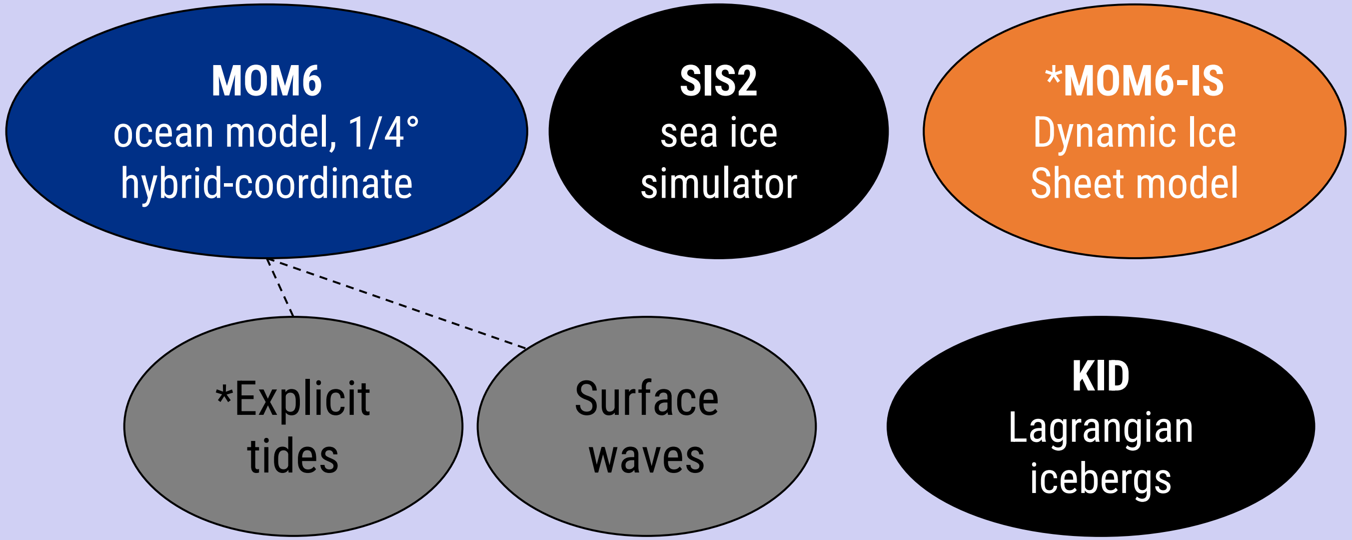
Many of these capabilities will be deployed in GFDL's new OM5 Ocean Model & CM5 Coupled Model.

OM5 Mission

The next generation of GFDL's world-leading ocean and cryosphere models that will advance GFDL scientific interests and NOAA's mission

OM5 Goals

A. Simulate regional-to-global patterns and trends of sea level
B. Reduce polar ocean and cryosphere biases
C. Reduce tropical & mid-latitude ocean stratification biases
D. Improve representation of deep ocean circulation



**New Features beyond OM4*

MOM6 development activities are supporting OM5's goals

A. Simulate regional-to-global Sea Level

- Non-Boussinesq implementation
- Explicit tides
- On-line self-attraction and loading
- **Modern equation of state**

B. Reduce Polar Biases

- Ocean sea-ice coupling & numerical stability
- Improved sea-ice physics
- double-diffusive mixing
- Internal gravity wave mixing
- Brine rejection distributed as plumes

C. Reduce Tropical & Mid-latitude Ocean Biases

- Boundary layer mixing improvements
- Shear mixing improvements
- Implementing tidally-driven diffusivity
- Mesoscale & mixed layer eddy parameterizations

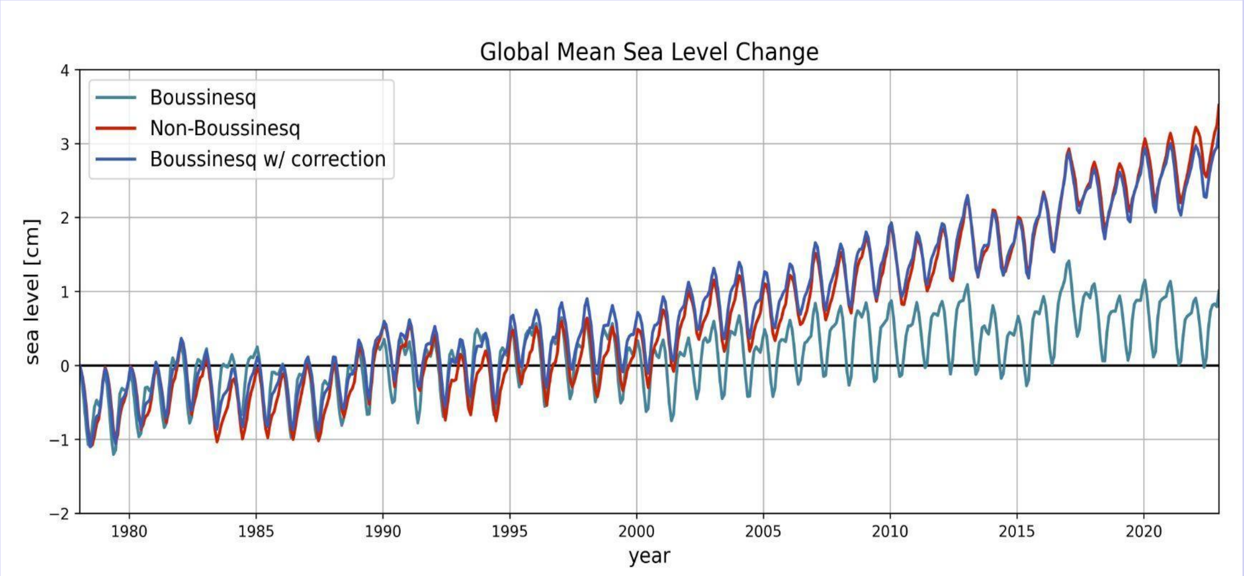
D. Improve Deep Ocean Circulation

- Porous barrier & porous medium topography
- Vertical coordinate development
- Updated bathymetry and horizontal grids

Under the MOM6 open development paradigm, all of these capabilities are freely available.
OM4 is the basis of the UFS GFS v.17 ocean; OM5 will be available as a template for future versions of UFS

MOM6 algorithm and formulation improvements being deployed in OM5

- Non-Boussinesq version of MOM6 [goal A]
- Improved vertical coordinate algorithms [goal D]
- Improved various numerical aspects [goal A,D]
- “Porous” representation of bathymetry [goal D]
- Modern Equation of state [goals A,B,C,D]
- Surface wave-averaged equations [goals A,B,C]
- Explicit simulation of global tides [goal A]
- Add Great Lakes and waterfalls [goal A]
- Add support of evolving ice-sheet geometry [goal A,B]

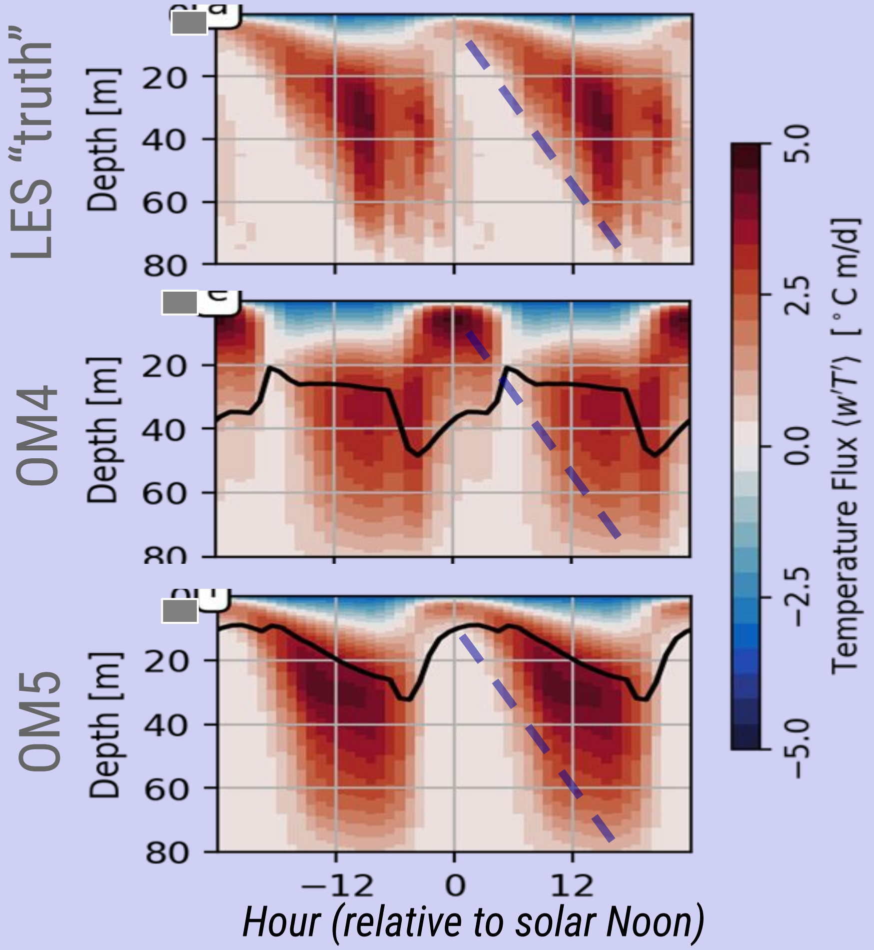


OM5 w/ non-Boussinesq version of MOM6 can explicitly simulate the thermal contraction (by cooling) and expansion (by warming) of sea level in the recent historical epoch.

Energetics Based Boundary Layer Parameterizations

- Upgrade surface mixing scheme (ePBL)[1,11,12]
  - *Improves mixed layer depths and diurnal cycle [goal A,B,C,D]*
- Include surface wave driven fluxes and mixing[2,3,4,5,6,8,10,16,17]
  - *Improves mixed layer depths and air-sea fluxes [goal A,B,C]*
- New submesoscale parameterization[10,15]
  - *Physically consistent frontal length scale in tropics [goal B,C,D]*
- Improve BBL mixing[12,14]
  - *Improves bottom water from coastal regions to deep overflows [goal D]*
- Machine learn ePBL enhancements[9,13]
  - *Further improves stratification and mixed layer depths [goal A,B,C,D]*
- New energetic mixed layer depth metrics and observations[7]
  - *Improves model bias diagnosis and process understanding*

Improve Diurnal "Deep Cycle" Equatorial Mixing via Adjusted ePBL & Background Viscosity



Comparing diurnal cycle of turbulent vertical heat flux at 0N, 140W using Large Eddy Simulation ("truth") with OM4 ePBL vs OM5 ePBL and background viscosity settings (Reichl et al., 2024)

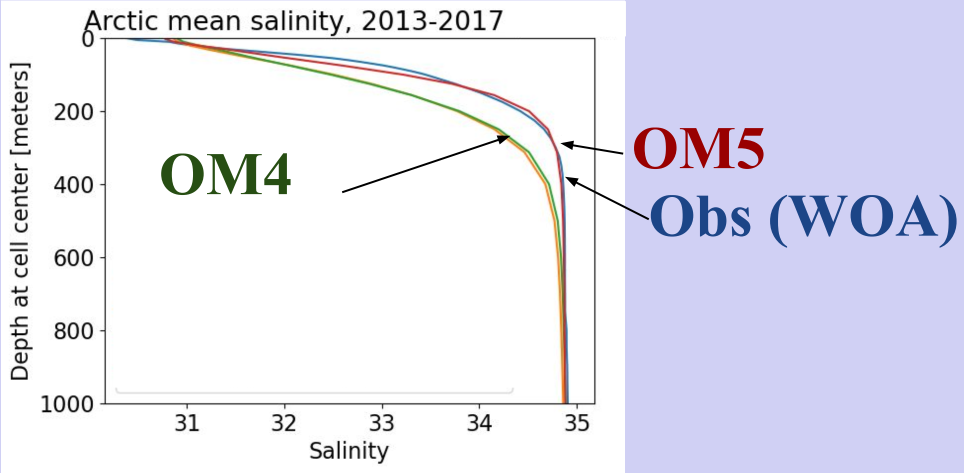
[1]Reichl and Hallberg (2018) [2]Li et al. (2019) [3]Reichl and Li (2019) [4]Reichl & Deike (2020) [5]Deike et al. (2022) [6]Kim et al. (2022) [7]Reichl et al. (2022) [8]Zhou et al. (2022) [9]Sane et al. (2023) [10]Zhou et al. (2023) [11]Reichl et al. (2024)[12]Griffies et al. (in review) [13]Sane et al. (in prep) [14]Hallberg et al. (in prep) [15]Uchida et al. (in prep) [16]Rustogi et al. (in review) [17]Deike et al. (in review)

Physically Consistent Interior Mixing Parameterizations

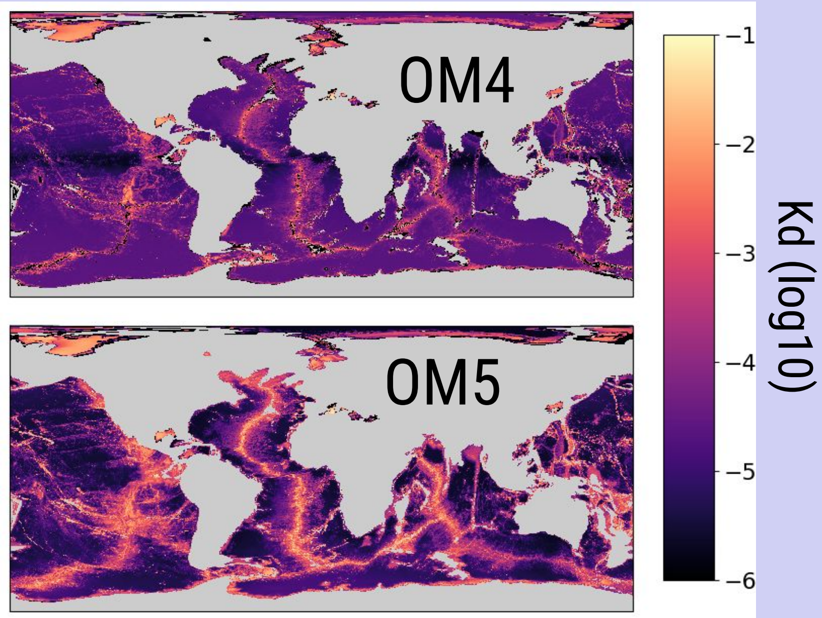
- More realistic (reduced) background viscosity[2]
  - *Improves mean shear and thermocline bias [goal C]*
- Improve tidal mixing physics[1]
  - *Major improvement to Arctic salinity bias [goal B]*
- Add double diffusive vertical mixing
  - Include mixing by salt fingers & diffusive convection [goal A,B,C]
- Improved interior shear driven mixing[3]
  - *Reduces numerical sensitivity of induced mixing [goal B,C,D]*
- Ray-tracing internal tide energy for mixing[5]
  - *Propagate energy and convert to turbulent mixing [goal B,C,D]*
- Implicit energetics-based full-column mixing[4]
  - *More robust & consistent mixing algorithms [goal A,B,C,D]*

[1]Harrison & Hallberg (2008) [2]Reichl et al. (2024) [3]Griffies et al. (in review) [4]Hallberg et al. (in prep) [5]Dussin et al. in prep

Arctic mean Salinity profiles in OM4 & OM5 vs world ocean atlas



Log10 of mean diffusivity at 1000m depth in OM4 vs OM5 w/ ray tracing scheme



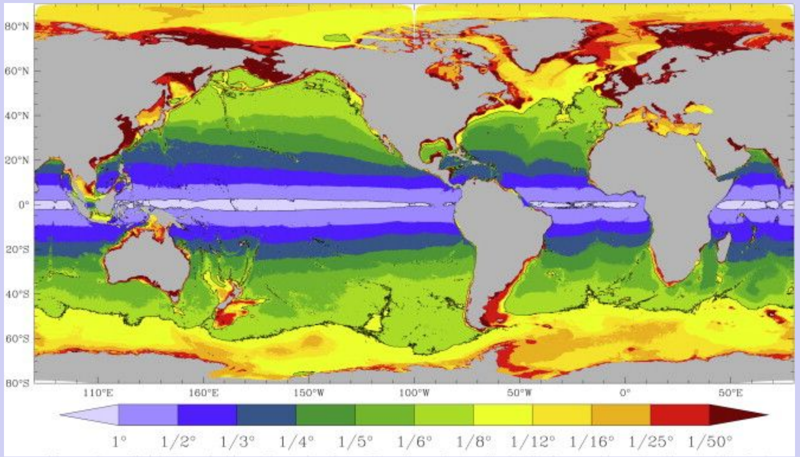
Mesoscale Eddy Mixing Parameterization Development

OM5's ¼° resolution is insufficient to resolve all mesoscale eddies

GFDL plays a critical role in eddy parameterization development

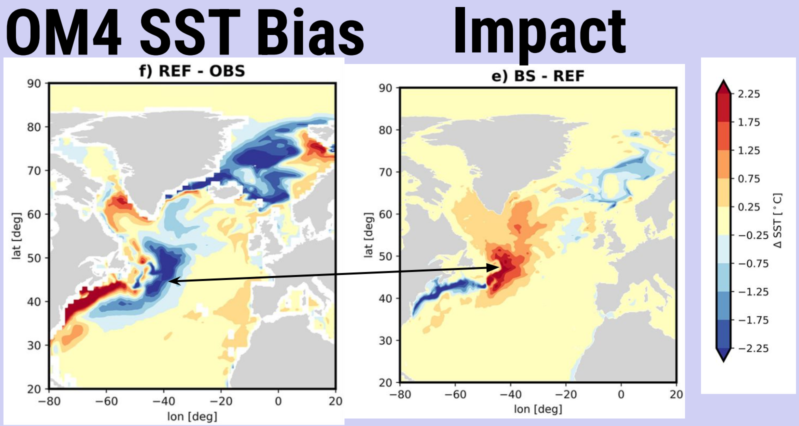
- Progress to understand and simulate processes, energetics, and scales of the ocean's mesoscale eddy field[1,4,5,7,8,9,10,18]
- Progress to develop energetically constrained eddy parameterizations with realistic vertical structures
  - *Improving resolved eddy characteristics[13] [goal C]*
  - *Improving sub-grid energy models[11,12,15] [goal B,C]*
  - *Improving algorithms and approaches[2,3,6,14,17,20,21] [goal A,B,C,D]*
- Progress in machine learning parameterizations[16,19]

[1]Naveira Garabato et al. (2019) [2]Shao et al. (2020) [3]Stanley et al. (2020) [4]Khatri et al. (2021) [5]Aluie et al. (2022) [6]Kenigson et al. (2022) [7]Marques et al. (2022) [8]Naveira Garabato et al. (2022) [9,10]Yassin & Griffies (2022a,2022b) [11]Storer et al. (2022) [12]Buzzicotti et al., 2023 [13]Chang et al. (2023) [14]Loose et al. (2023) [15]Storer et al. (2023) [16]C. Zhang et al. (2023) [17]Jansen et al. (2024) [18]Lobo et al. (2024) [19]Perezhogin et al. (2024) [20]W. Zhang & Wolfe (2024) [21]W. Zhang et al. (2024)



Hallberg (2013)

Fig 1: Simulation horizontal resolution requirement to resolve mesoscale eddy effects in global ocean model



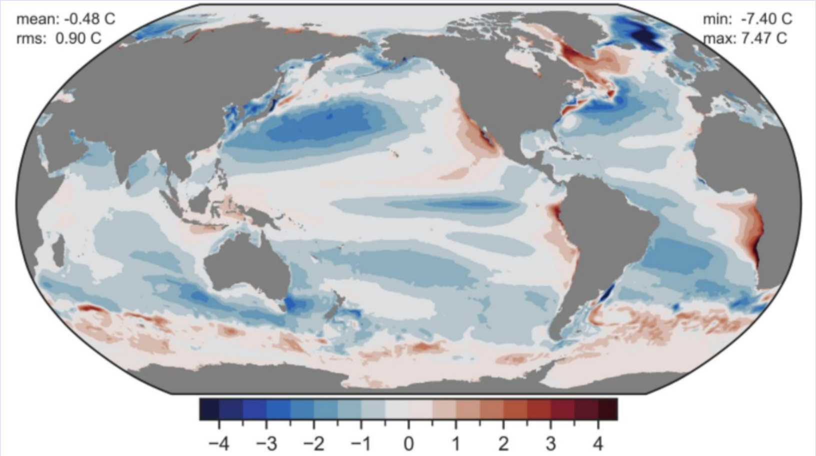
Chang et al. (2023)

Fig 2: Impact of eddy backscatter parameterization on SST bias in OM5 prototype model

Preliminary results from a prototype CM5 simulation (SST, ENSO)

SST bias (CM4-obs)

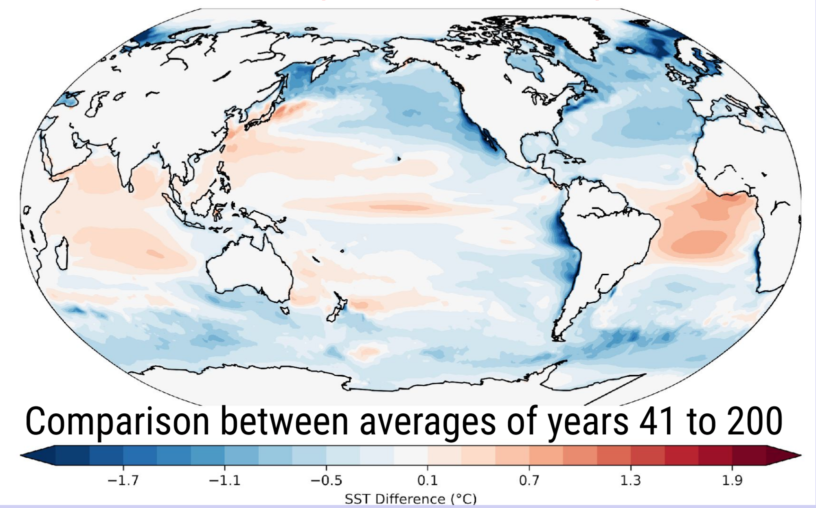
CM4
(100 km AM4 atmos;
25 km OM4 ocean)

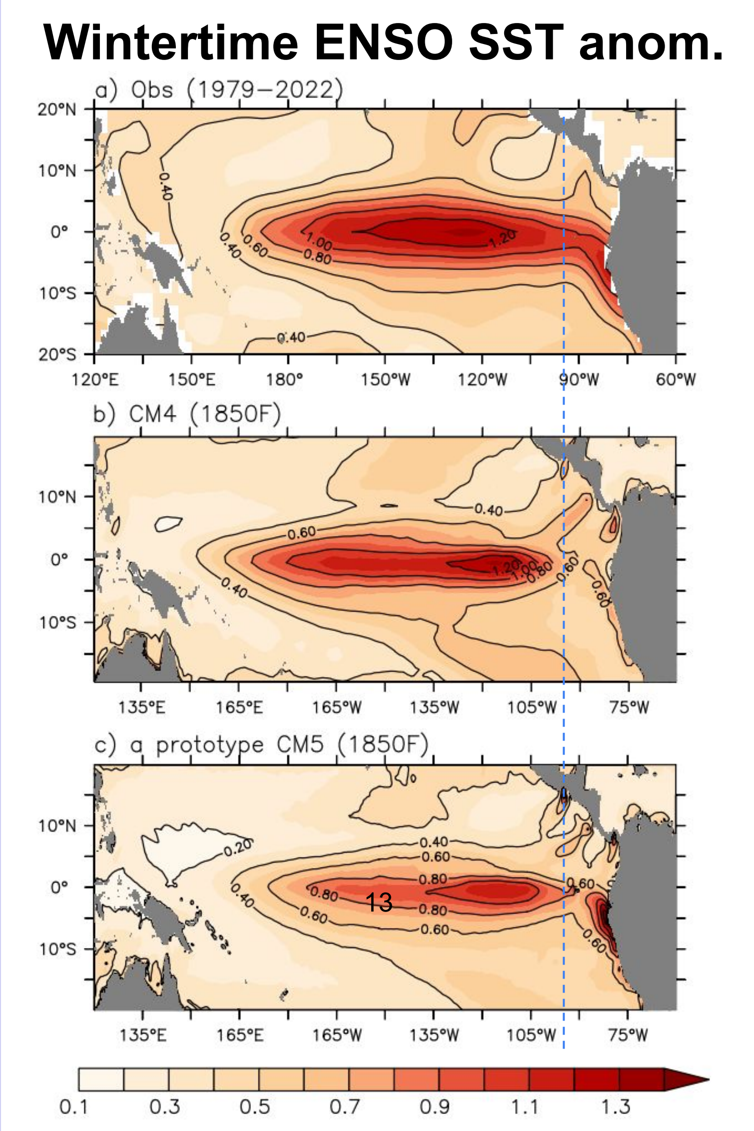


Held et al. 2019; Griffies et al. 2024

SST difference (CM5 – CM4) (1850 Forcing)

Prototype CM5-HR
(25 km AM5 atmos;
25 km OM5 ocean)





Obs

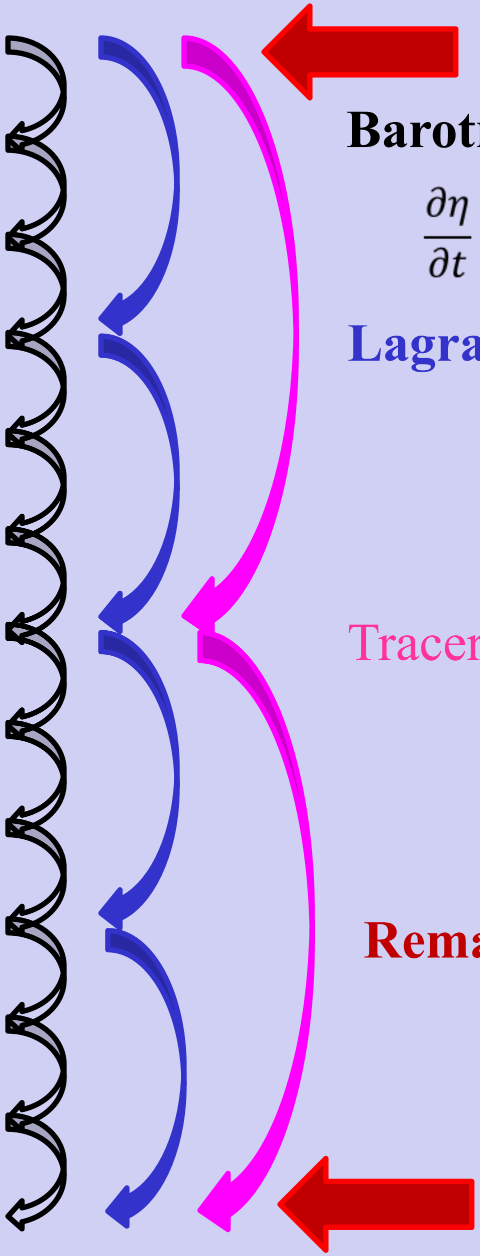
CM4

Prototype CM5-HR

Prototype CM5 simulations are looking very good, but there is still room for improvement, including an unexpectedly large sensitivity to the ocean timesteps.

4 Time Stepping Cycles in MOM6

(CM4 timesteps)



Barotropic (2-d linear momentum, integrated continuity) **(Δt ~20 *s*)**

$$\frac{\partial \eta}{\partial t} + \nabla \cdot \left((D + \eta) \bar{u}_{BT} \right) = P - E \qquad \frac{\partial \bar{u}_{BT}}{\partial t} = -g \nabla \eta - f \hat{z} \times \bar{u}_{BT} + \bar{F}_{BT}$$

Lagrangian dynamics (3-d Stacked Shallow Water Eqns) **(Δt = 900 s)**

$$\frac{\partial \vec{u}_k}{\partial t} + (f + \nabla_s \times \vec{u}_k) \hat{z} \times \vec{u}_k = -\frac{\nabla_s p_k}{\rho} - \nabla_s \left(\phi_k + \tfrac{1}{2} \| \vec{u}_k \|^2 \right) + \frac{\nabla \cdot \tilde{\tilde{\tau}}_k}{\rho}$$

$$\frac{\partial h_k}{\partial t} + \nabla_s \cdot (\vec{u} h_k) = 0$$

Tracer Advection, **Thermodynamics** and Mixing **(Δt = 7200 s)**

$$\frac{\partial h_k}{\partial t} = (P - E)_k$$

$$\frac{\partial}{\partial t}(h_k \theta_k) + \nabla_s \cdot (\vec{u} h_k \theta_k) = Q_k^{\theta} h_k + \Delta \left(\kappa \frac{\partial \theta}{\partial z} \right) + \nabla_s (h_k K \nabla_s \theta)$$

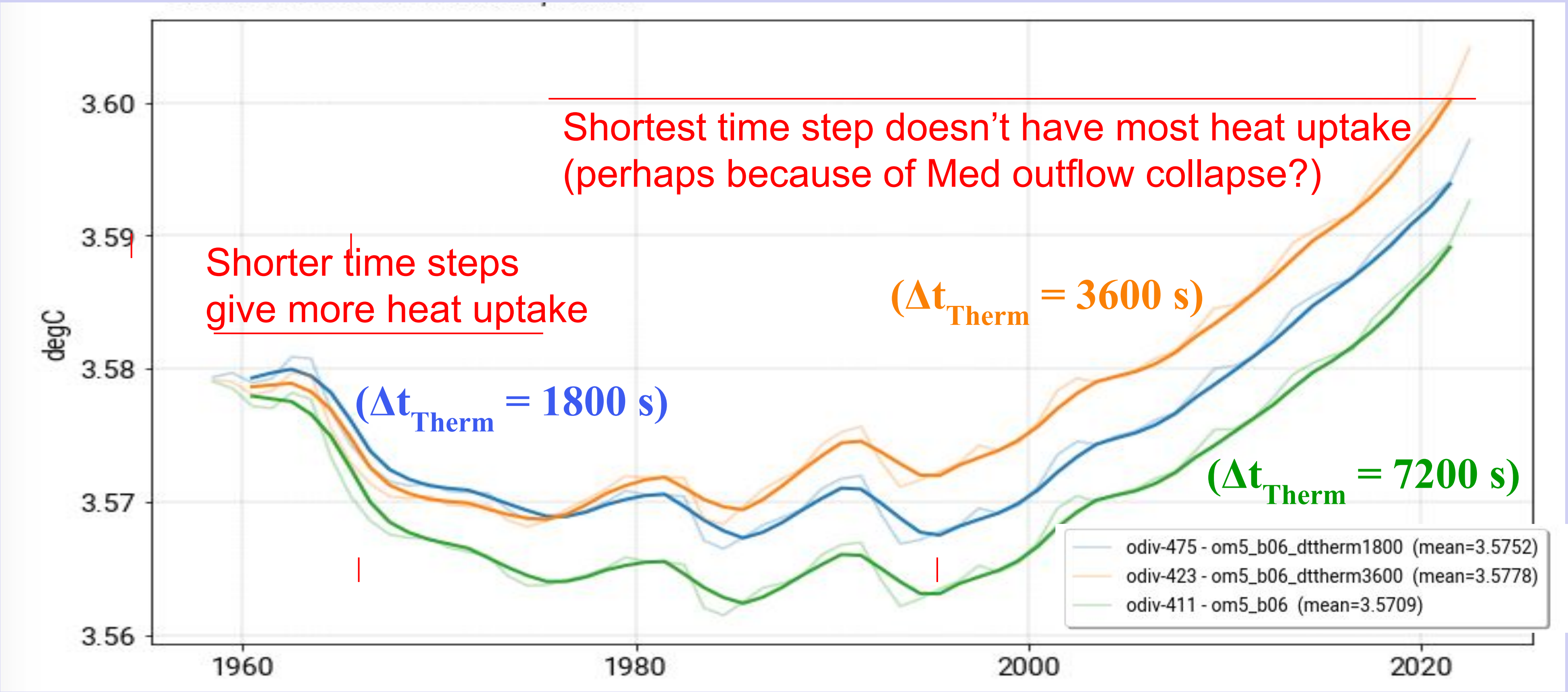
Remapping and coordinate restoration **(Δt = 7200 s)**

$$h_k^{new} = \Delta_k z_{Coord} \qquad \sum h_k^{new} = \sum h_k^{old}$$

$$\vec{u}_k^{new} = \frac{1}{h_k} \int_{z_{k-1/2}}^{z_{k+1/2}+h_k} \vec{u}^{old}(z') dz' \qquad \theta_k^{new} = \frac{1}{h_k} \int_{z_{k-1/2}}^{z_{k+1/2}+h_k} \theta(z') dz'$$

Thermodynamic Time Stepping Sensitivity in OM5

Global Mean Ocean Potential Temperature in JRA55do Forced OM5 Ice-Ocean Simulations

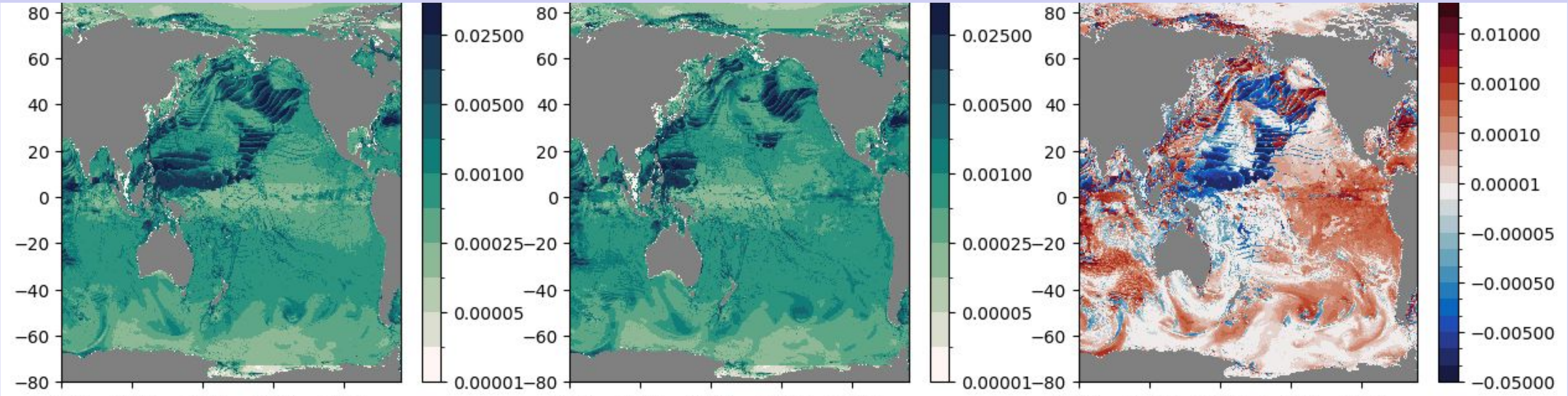


Time stepping sensitivity from shear mixing

Column-Integrated Diffusive Work ($\int \kappa N^2 dz$)

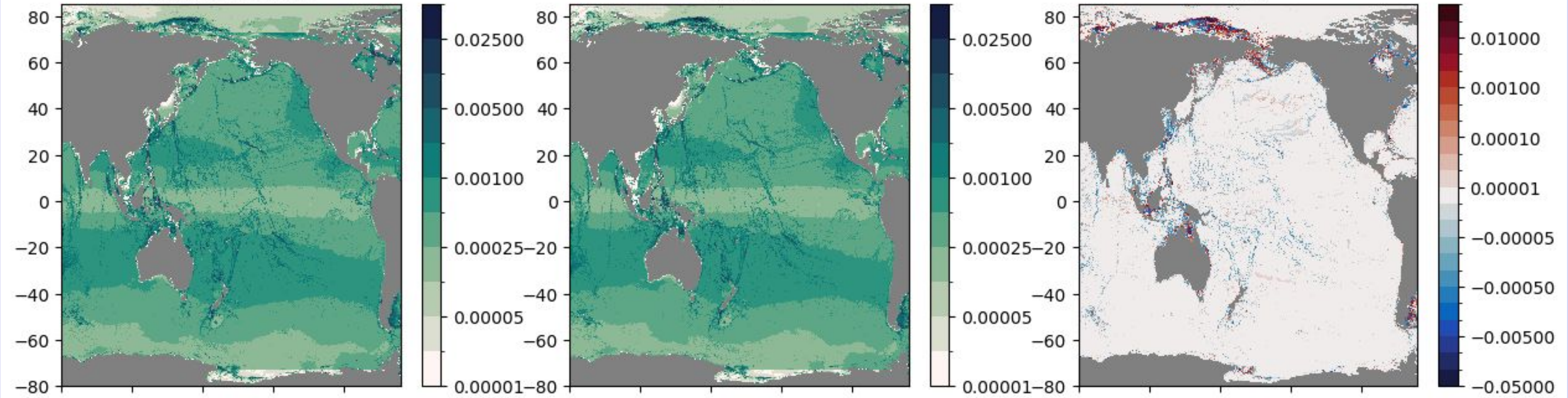
(Δt_{Therm} = 7200 s) (Δt_{Therm} = 300 s) Difference (B – A)

With Jackson et al (2008) κ-shear Param



Without Jackson et al (2008) κ-shear Param

2/1/1958 snapshots of JRA55do forced runs



What controls the thermodynamic time step sensitivity of OM5?

OM5 has a strong time step sensitivity due to the Jackson et al. (2008) shear vertical mixing parameterization

Can we reduce this?

a) Shorter dt_therm
(No…too expensive)

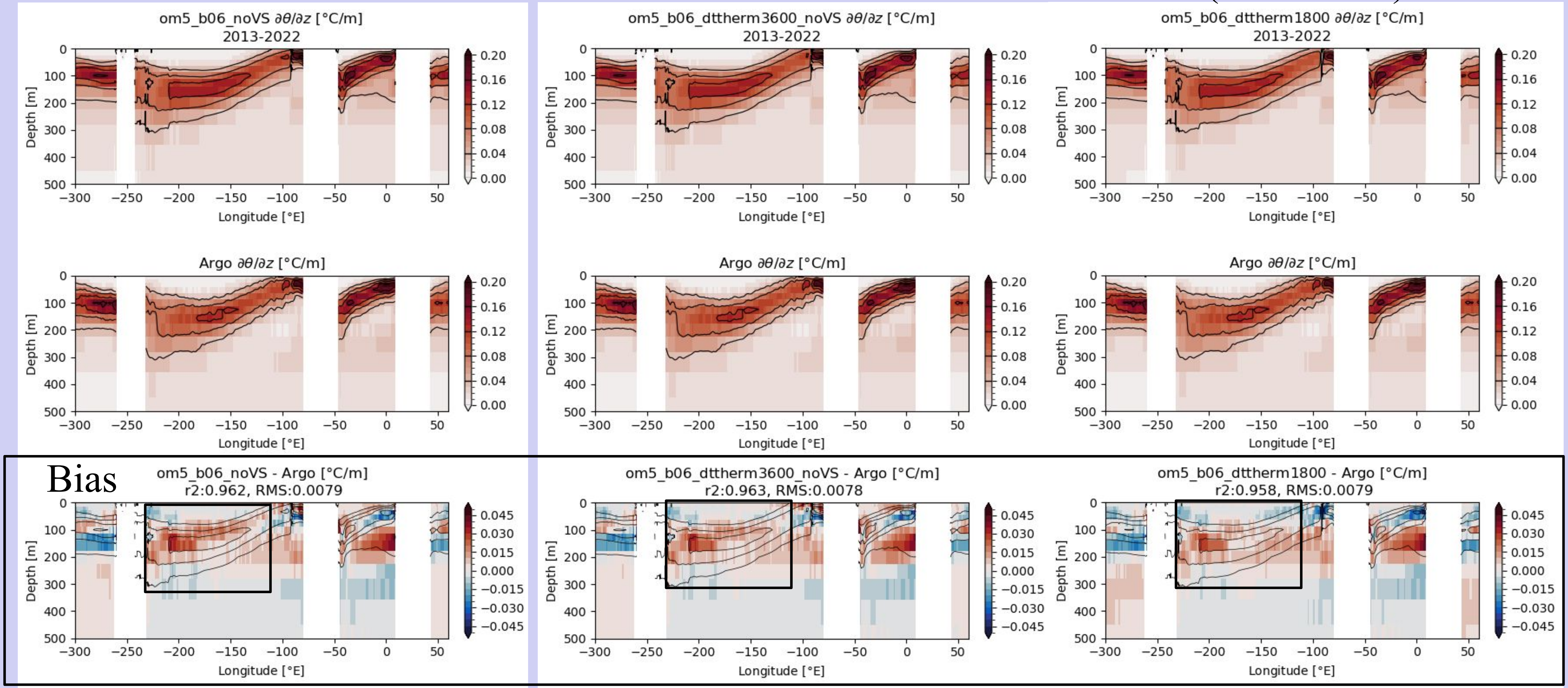
b) Add forcing into kappa shear solver?
(We think we know how)

Smaller dt_therm deepens the west equatorial Pacific (1S:1N) thermocline!

No VS, dttherm7200

No VS, dttherm3600

Orig VS, dttherm1800
(*weird run)



The Jackson et al. (2008, *JPO*) Parameterization of Shear Instability

$$\frac{\partial}{\partial z}\left((\kappa + \nu_o)\frac{\partial Q}{\partial z}\right) + \kappa\|S\|^2 - \kappa N^2 - \left(c_N N + c_S\|S\|\right)Q = 0 \quad \left(= \frac{DQ}{Dt}\right)$$

$$\frac{\kappa}{L_D^2} - \frac{\partial^2 \kappa}{\partial z^2} = 2\|S\| F(Ri)$$

κ: Turbulent diapycnal diffusivity and viscosity $[\mathrm{m^2\,s^{-1}}]$

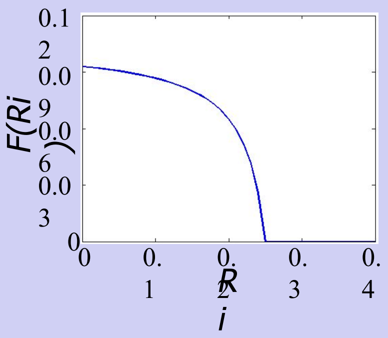
Q: TKE per unit mass $[\mathrm{m^2\,s^{-2}}]$

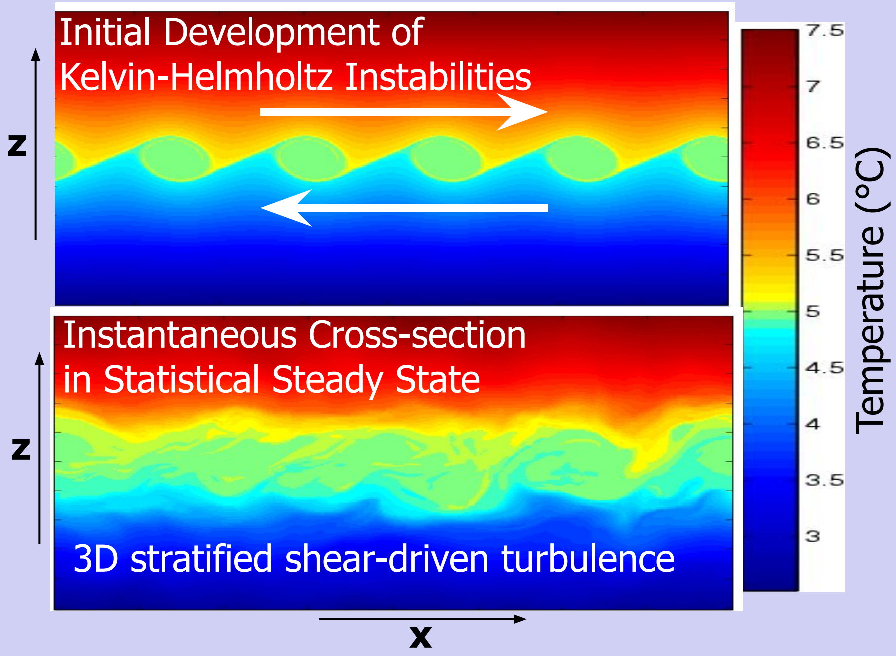
$$\|S\|^2 = \left(\frac{\partial u}{\partial z}\right)^2 + \left(\frac{\partial v}{\partial z}\right)^2 \qquad N^2 = -\frac{g}{\rho_0}\frac{\partial \rho}{\partial z}$$

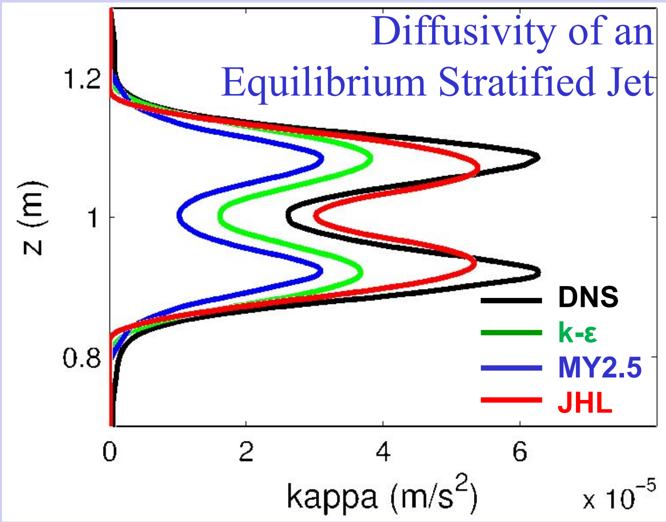
$$L_D^{-2} = \frac{N^2}{\lambda^2 Q} + \frac{f^2}{Q} + \frac{\left(z_{Top} + z_{Bot}\right)^2}{z_{Top}^2\, z_{Bot}^2} \approx \frac{N^2}{\lambda^2 Q}$$

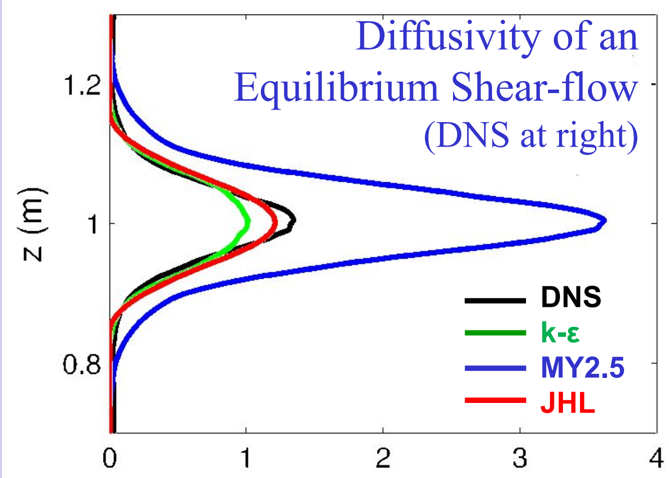
$$Ri = \frac{N^2}{S^2}$$

λ, c_N, c_S, Pr: Dimensionless constants









DNS – Results of 3-D DNS

k-ε – GOTM standard (~2008) k-ε closure (untuned)

MY – Mellor Yamada level 2.5 closure (untuned)

JHL –Jackson, et al, 2008 parameterization (tuned)

Implicit Solver for Jackson Shear Mixing Parameterization

As implemented in MOM6, the Jackson et al. shear mixing parameterization implicitly solves ~5 equations simultaneously for TKE (Q) and diffusivity (κ):

$$\frac{\kappa}{L_D^2} - \frac{\partial^2 \kappa}{\partial z^2} = 2\|\widetilde{Sh}\| F(\widetilde{Ri})$$

$$\frac{\partial}{\partial z}\left((\kappa + \kappa_0)\frac{\partial Q}{\partial z}\right) + \kappa\|\widetilde{Sh}\|^2 - \kappa\tilde{N}^2 - \left(c_N\tilde{N} + c_S\|\widetilde{Sh}\|\right)Q = 0$$

$$\tilde{u} = u^n + \Delta t\frac{\partial}{\partial z}\left(P_r\kappa\frac{\partial\tilde{u}}{\partial z}\right) + (\boldsymbol{Missing\ forcing\ terms})$$

$$\tilde{v} = v^n + \Delta t\frac{\partial}{\partial z}\left(P_r\kappa\frac{\partial\tilde{v}}{\partial z}\right) + (\boldsymbol{Missing\ forcing\ terms})$$

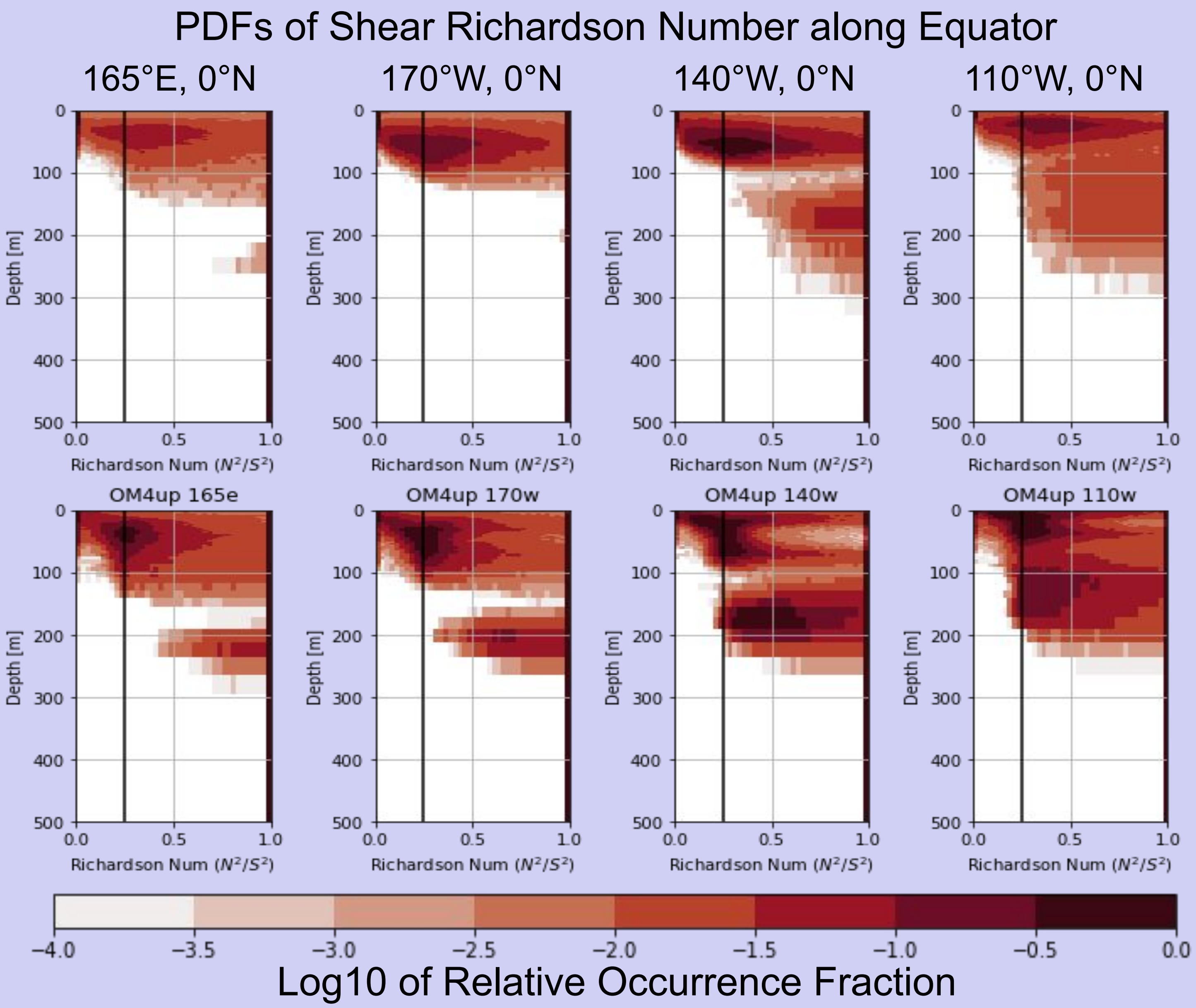
$$\tilde{\rho} = \rho^n + \Delta t\frac{\partial}{\partial z}\left(\kappa\frac{\partial\tilde{\rho}}{\partial z}\right) + (Missing\ terms)$$

with auxiliary equations:

$$\widetilde{Ri} = \frac{\tilde{N}^2}{\|\widetilde{Sh}\|^2} \qquad L_D^{-2} = \widetilde{Ri} = \frac{\tilde{N}^2}{\lambda^2 Q} + \frac{f^2}{Q} + \frac{(z_{Top}+z_{Bot})^2}{z_{Top}^2 z_{Bot}^2}$$

$$\|\widetilde{Sh}\|^2 = \left(\frac{\partial\tilde{u}}{\partial z}\right)^2 + \left(\frac{\partial\tilde{v}}{\partial z}\right)^2 \qquad \tilde{N}^2 = -\frac{g}{\rho_0}\frac{\partial\tilde{\rho}}{\partial z}$$

Background Viscosity dependence of Equatorial Undercurrent Mixing



Kv_{Back} = 10^{-4} m^2 s^{-1}
m^*_{Epbl} ≤ 10
Prandtl_turb = 1.25

Kv_{Back} = 10^{-6} m^2 s^{-1}
m^*_{Epbl} ≤ 1.25
Prandtl_turb = 1.25

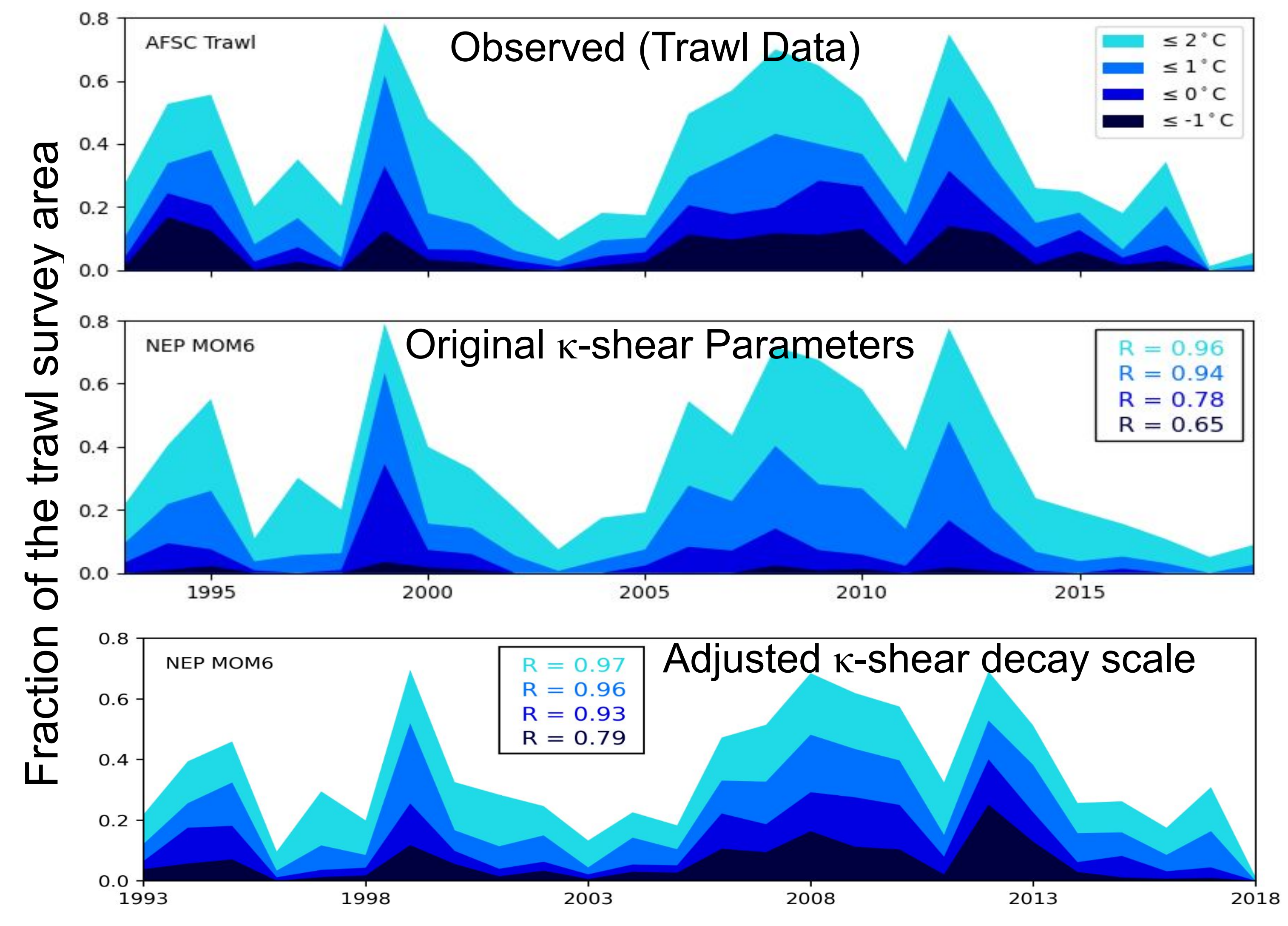
Reichl et al. (2024)

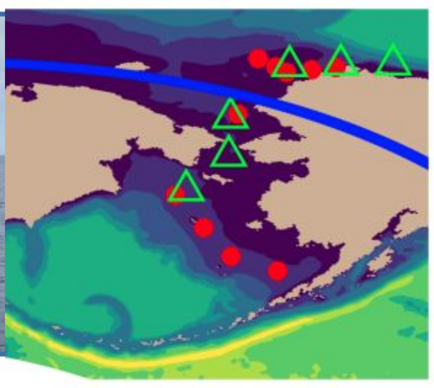
Shear Mixing in the Bering Sea Cold Pool

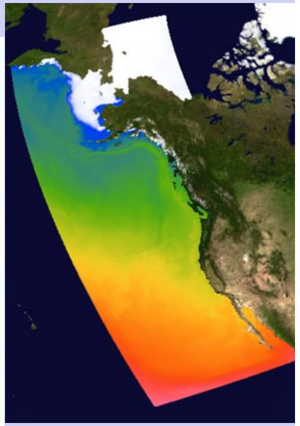
With original Jackson et al. (2008) parameters, strong tidal shears on the shelf were leading to excessive mixing

Adjusting a nondimensional turbulence decay scale greatly improves agreement with Obs.

Jackson et al. assumes equilibrium turbulence, but tidal shears vary on a comparable timescale to large-scale 3-d turbulence.







Drenkard et al. (Submitted)

Thanks to the Regional MOM6 Forum, especially Vivek Seelanki, Wei Cheng, Liz Drenkard, Kelly Kearney, Al Hermann, Theresa Cordero and Charlie Stock

OM5 and future ocean modeling at GFDL

- OM5 continues GFDL's role in systematically advancing the state of global and regional ocean and cryosphere modeling
- GFDL is addressing gaps in ocean and cryosphere modeling capabilities to address NOAA's mission objectives
  - Ocean - Ice-sheet coupling for better sea-level rise projections
  - Improved representation of physical processes for better forecasts and projections across a broad range of timescales and more insightful research
  - Adding Great Lakes to global climate models to improve regional U.S. climate
  - Explicit tides and self-attraction and loading for better regional circulation and changes
- OM5 ¼° developments lay the foundation for higher ocean resolutions
- All new capabilities for OM5 are publicly available via MOM6
  - The GFDL ocean and cryosphere modeling team looks forward to continuing our fruitful collaborations with the CESM Ocean Working Group and our MOM6 development partners

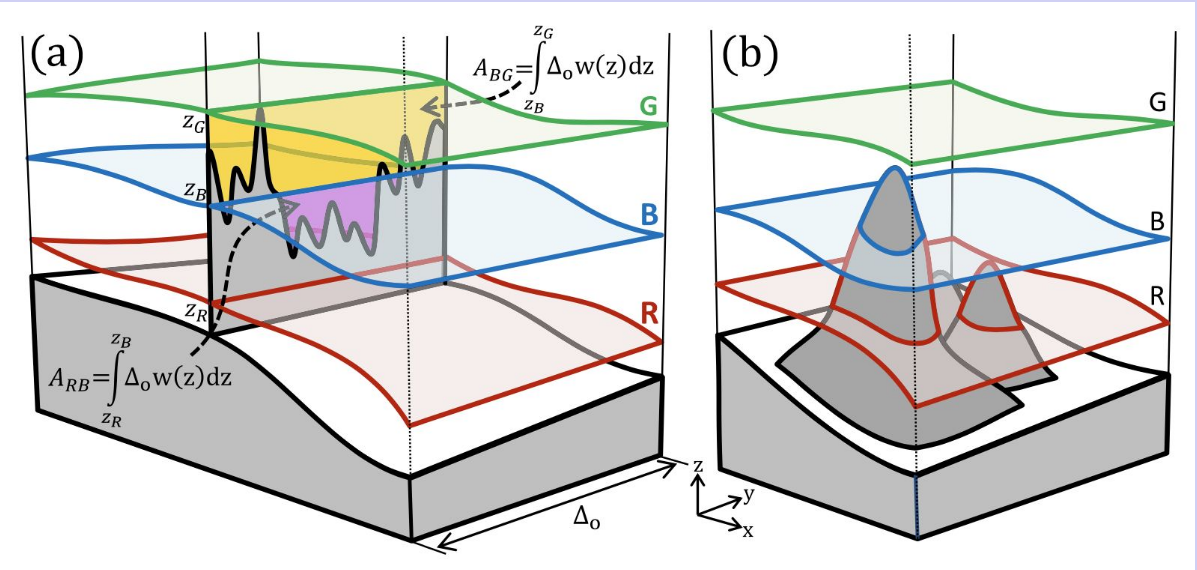
Backup Slides

POROUS BARRIERS AND TIDES

Porous barrier sub-grid scale topography (Adcroft 2013)

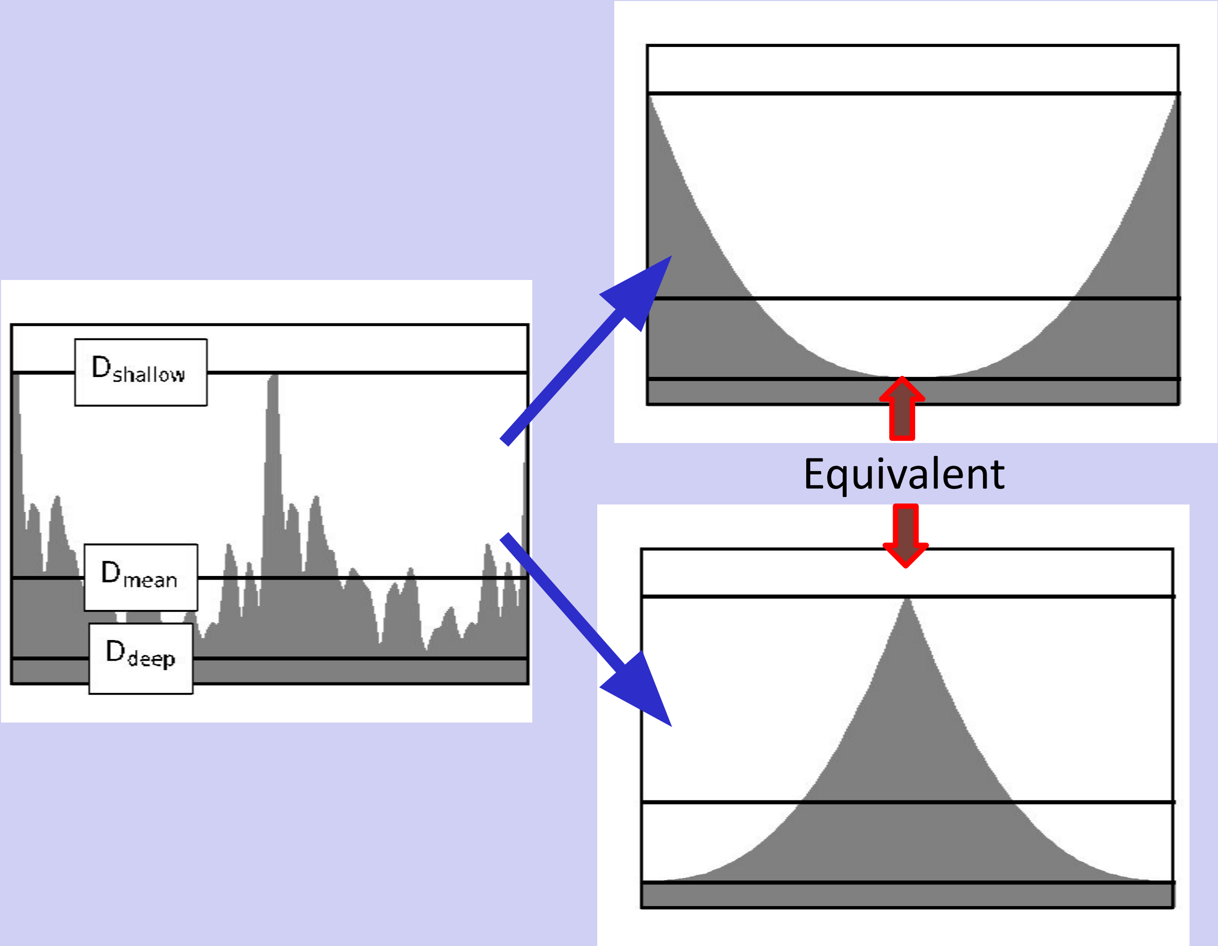
- Represent the missing geometric effects from unresolved bathymetric features in the model, using the statistics of the sub-grid scale depths to construct an idealized vertical profile of open area as a function of depth

Porous barrier　　　　Porous media



- Apply constraints on cross-cell-face transports (porous barriers) and cell integrated capacity (porous media)

Porous barriers

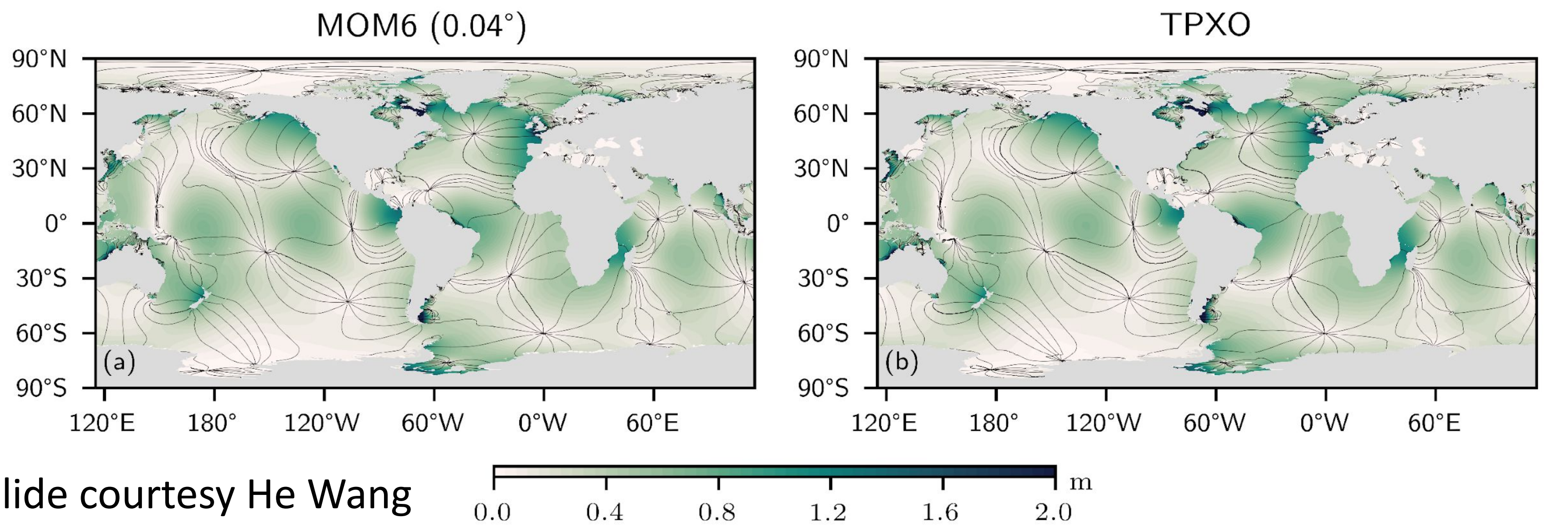


A schematic of the construction and effect of porous barriers

Wang et al. (2024)

Explicit global barotropic tides in MOM6

- Single-layer, 1/25° horizontal resolution
- Forced by M2 astronomical tidal potential
- Self-attraction and loading via fully inline spherical harmonics transforms
- Dissipation via quadratic bottom drag + parameterized internal wave drag

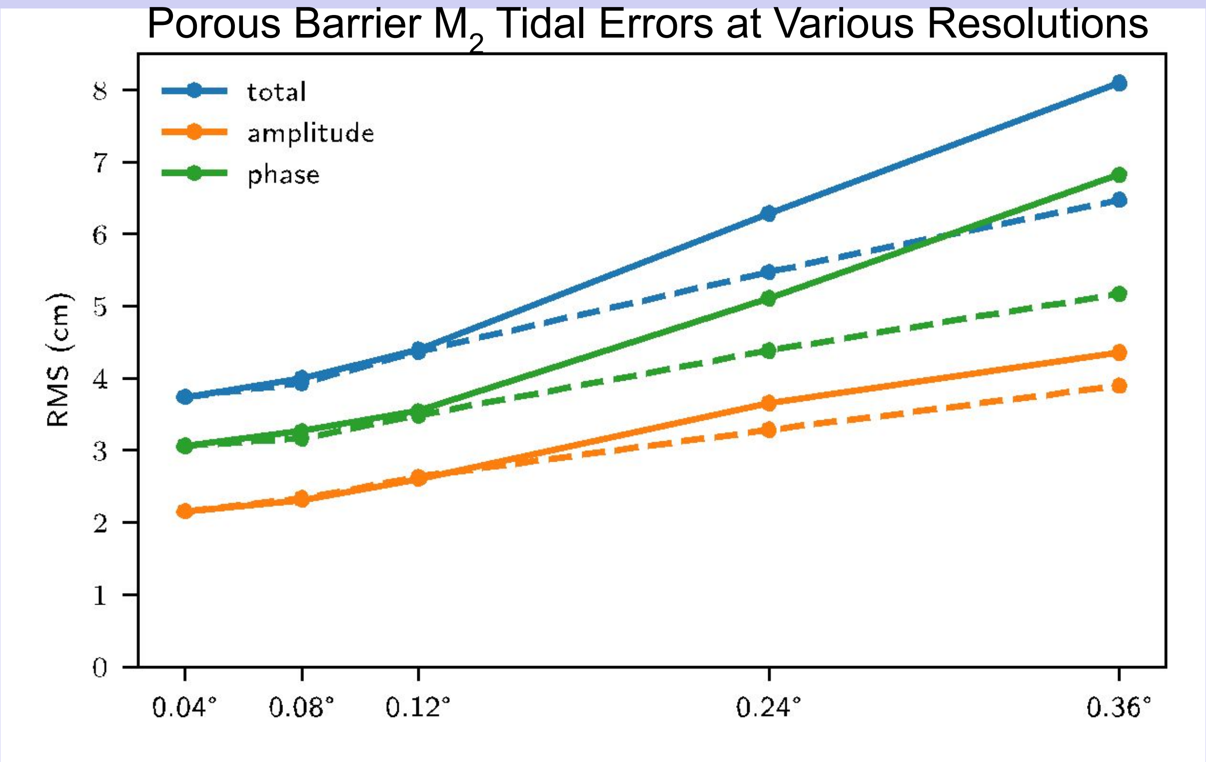


Slide courtesy He Wang

Wang et al. (2024)

Explicit M_2 global barotropic tides in MOM6

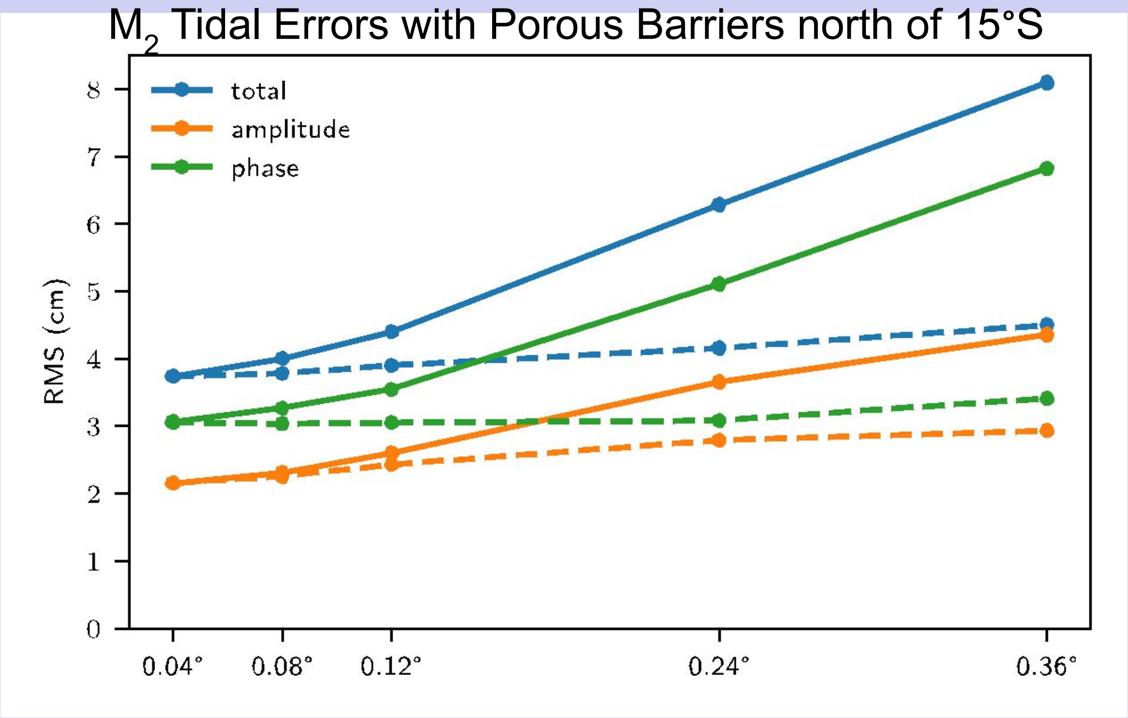
- Open ocean tidal errors (referenced to TPXO) depend on horizontal resolutions (solid lines)
- Porous barriers constructed from the finest resolution case reduce the errors in the coarse resolution cases (dashed lines)



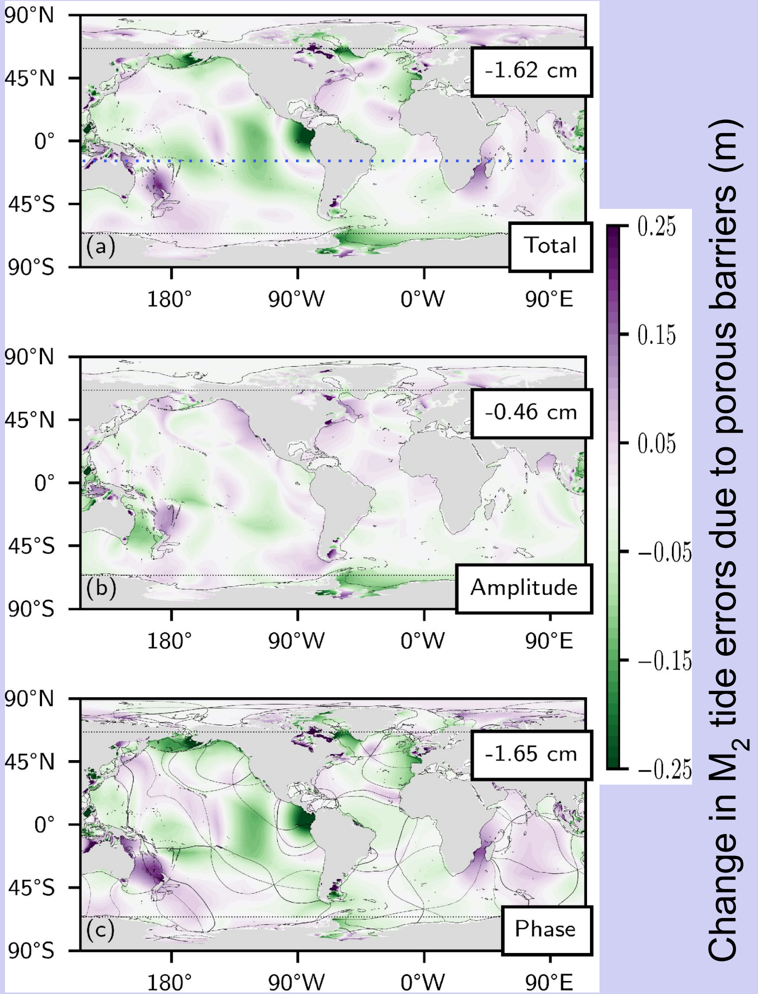
Wang et al. (2024)

Explicit M_2 global barotropic tides in MOM6

Limiting porous barrier implementation only north of 15°S leads to even better tides. (We suspect regional topography biases.)

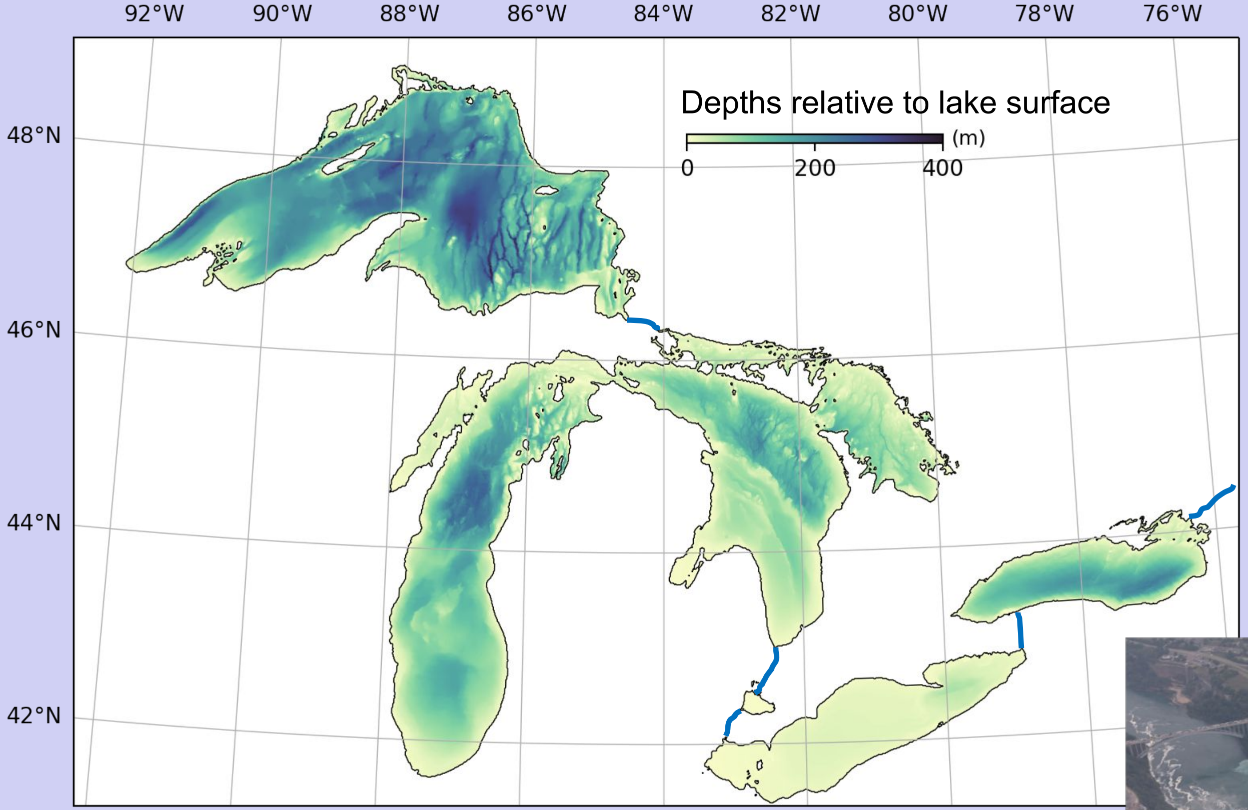


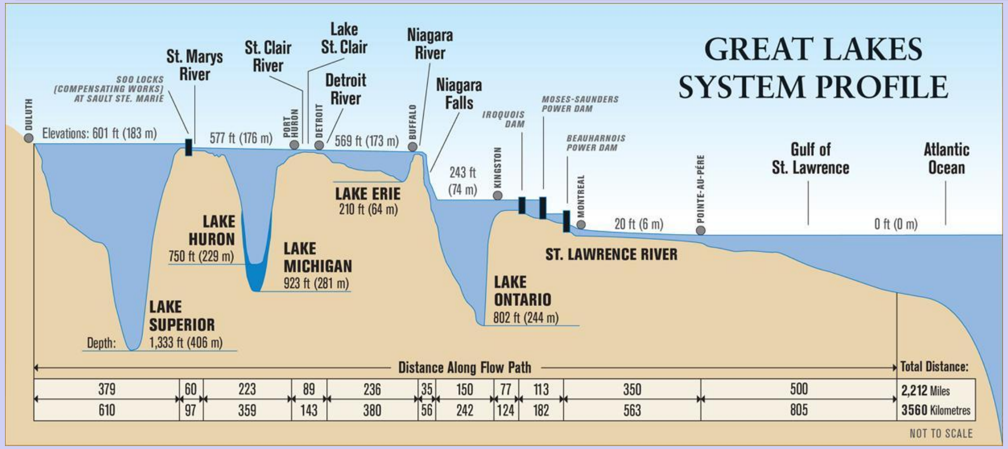
Tidal error differences due to porous barriers at 0.36°



Wang et al. (2024)

Interactive Great Lakes in OM5?






Niagara Falls, C. M. Highsmith 2018

Slide Courtesy He Wang