Improved upper ocean vertical mixing parameterization for simulating the tropical Pacific Ocean in climate models

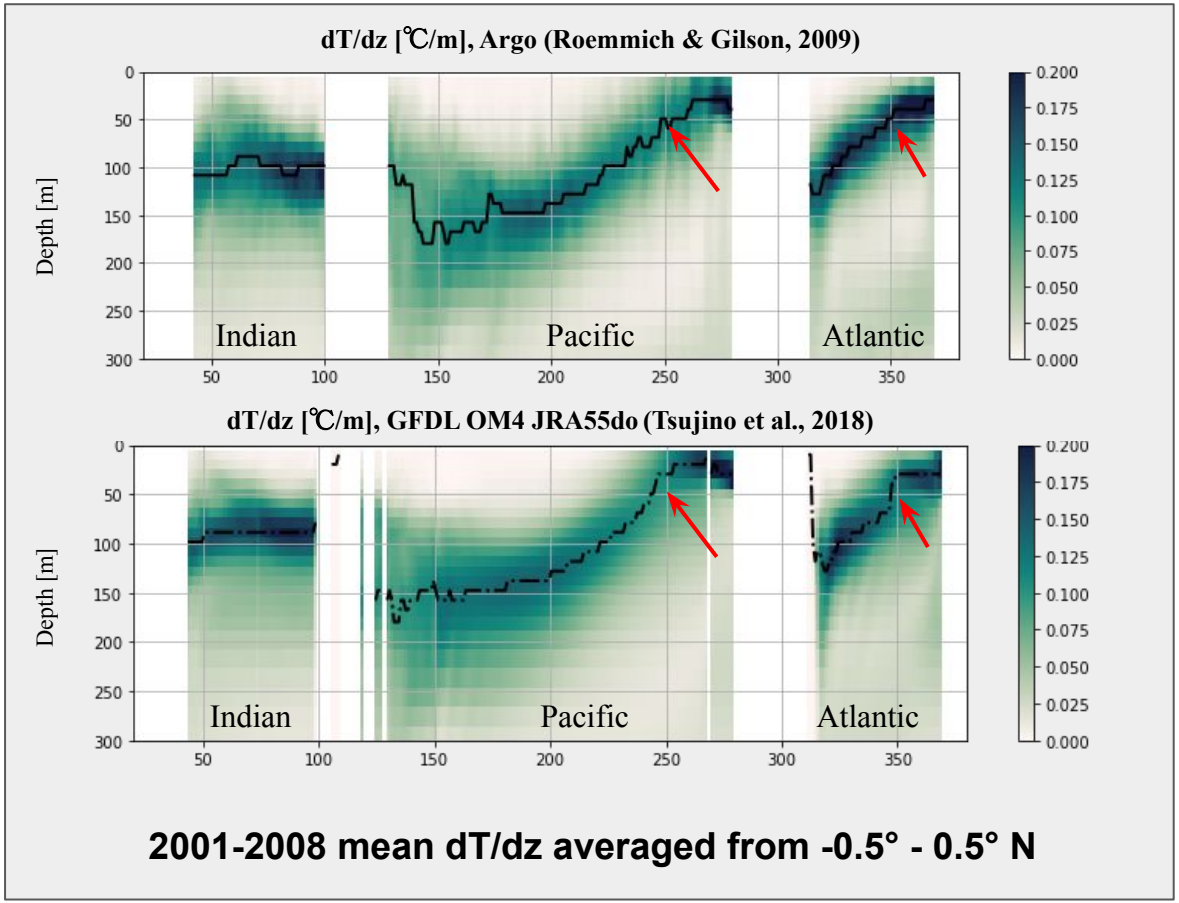
Brandon Reichl
A. Wittenberg, S. Griffies, A. Adcroft

NOAA/GFDL,
Princeton, NJ

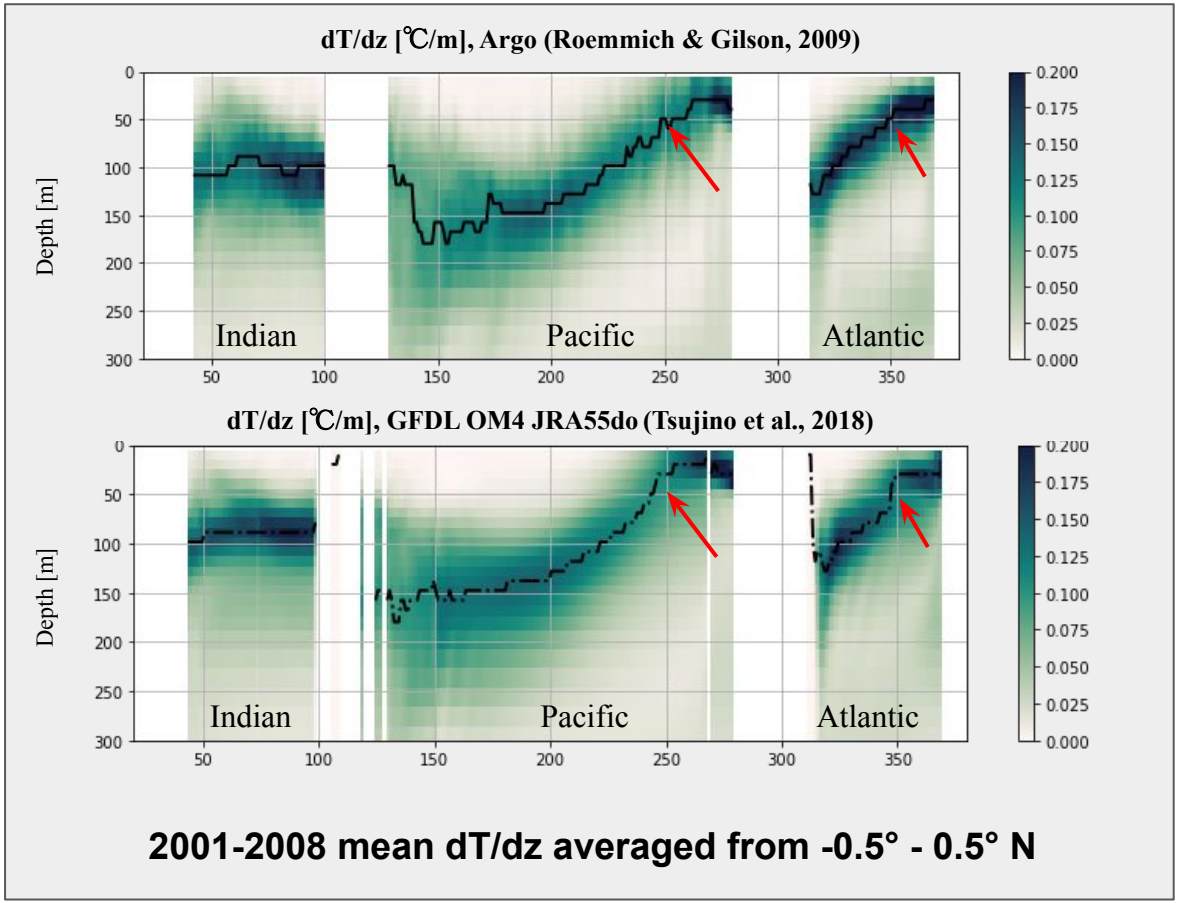
CESM OMWG 2023
February 10, 2023

NOAA
Geophysical Fluid Dynamics Laboratory

NOAA/GFDL's climate model ocean simulations exhibit a common "steppy" thermocline bias



NOAA/GFDL's climate model ocean simulations exhibit a common "steppy" thermocline bias



Goals

1. Diagnose cause of shallow/strong stratification bias in eastern tropical basins.
2. Test fidelity of OM4 vertical mixing parameterizations in tropics.
3. Test sensitivity of tropical thermocline and circulation to parameterization choices.

Investigated here w/ two strategies

1. **Large Eddy Simulation vs 1d model**
2. **OGCM simulations**

(Brief) Review of Vertical Mixing in the Tropics

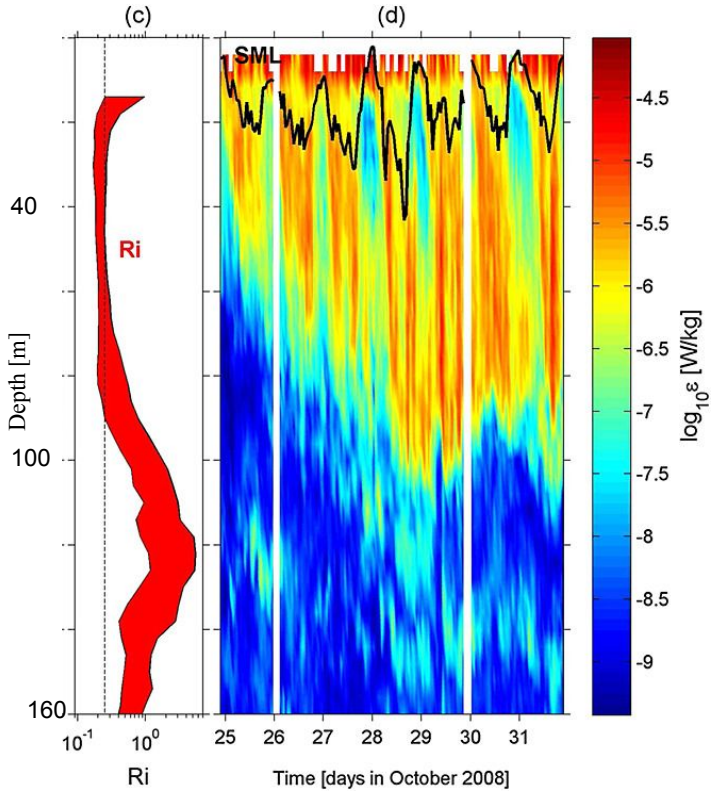
Vertical mixing in tropics is characterized by large diurnal swings in stability and turbulence associated with daily cycle of solar heating.

Diurnal patterns of turbulence in the tropics have been well studied observationally (e.g., Gregg et al., 1985, Moum et al., 1989, Smyth and Moum, 2013) **and from process models** (e.g., Wang et al., 1998, Pham et al., 2013, Whitt et al., 2022).

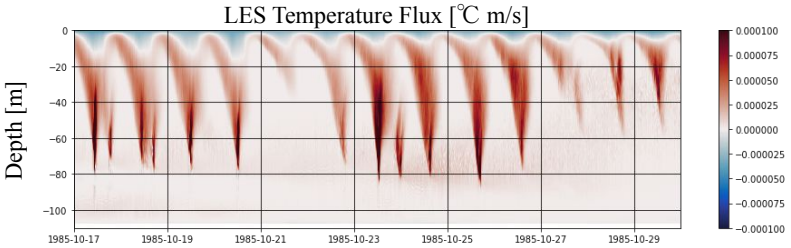
- **Daytime heating** restratifies the upper ocean and shoals the boundary layer.
- **Nighttime cooling** destratifies the upper ocean and rapidly deepens the boundary layer (deep-cycle turbulence).
- The **nighttime mixing** is strengthened when it taps into the strong shear at depth associated with the Equatorial undercurrent.

This diurnal variability should be captured by mixing parameterizations in ocean models (Pei et al., 2020**).**

Figure from Smyth and Moum, 2013



Part 1: How do OM4's vertical heat fluxes compare w/ Large Eddy Simulations?



LES output from Whitt et al. (2022)

Reference LES output
~30 day simulations w/ prescribed JRA55 atmospheric fields & "large-scale" horizontal forcing from regional model

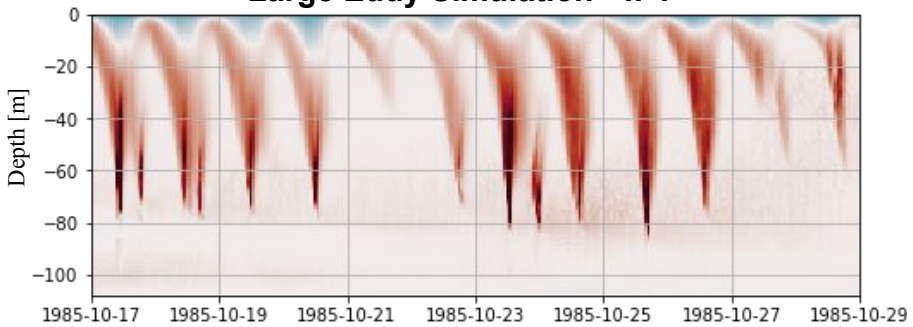
MOM6-1D: Column Modular Ocean Model 6 w/ identical fluxes/forcing to LES

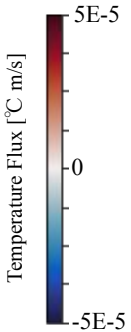
OM4-based mixing
- ePBL: boundary layer mixing (Reichl & Hallberg, 2018; Reichl & Li, 2019)
- JHL: resolved stratified shear mixing (Jackson, Hallberg, and Legg, 2008)
- Also have options to use GOTM (second moment closures) and CVMix/KPP

Can the OM4 mixing parameterizations reproduce the LES Heat Fluxes?

Time Series (colorbar lims +/-1.e-4)

Large Eddy Simulation <w'T'>

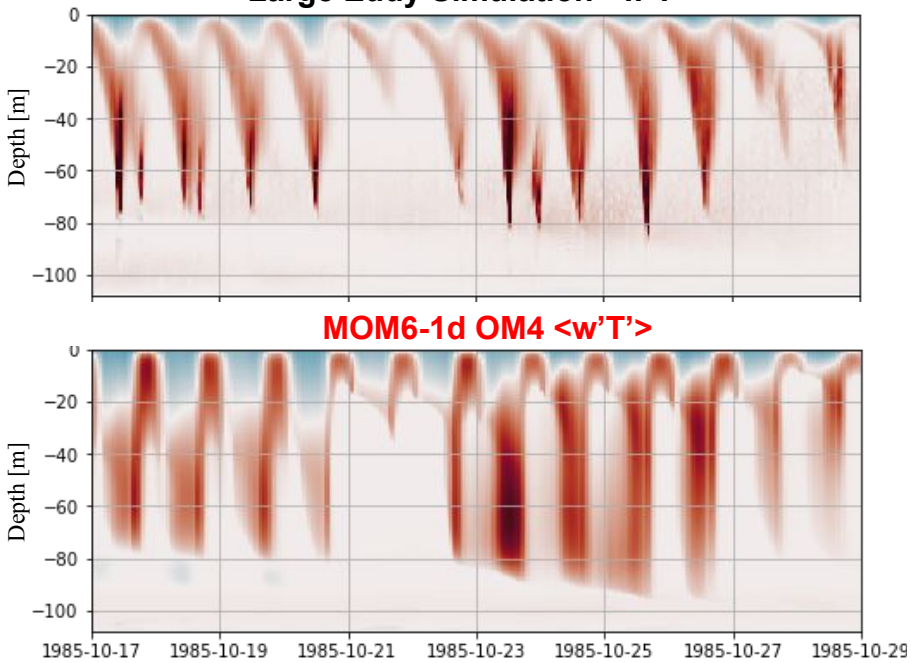


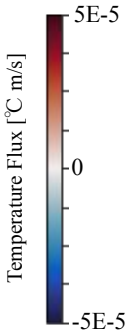


Can the OM4 mixing parameterizations reproduce the LES Heat Fluxes?

Time Series (colorbar lims +/-1.e-4)

Large Eddy Simulation <w'T'>

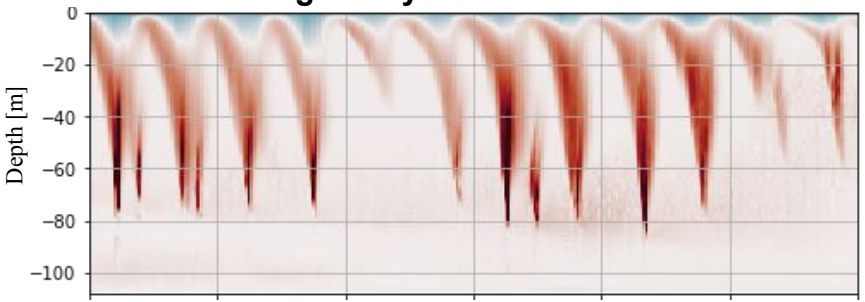




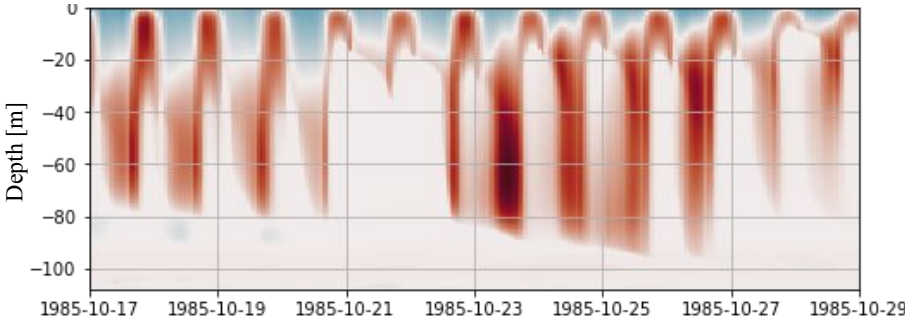
Can the OM4 mixing parameterizations reproduce the LES Heat Fluxes?

Time Series (colorbar lims +/-1.e-4)

Large Eddy Simulation <w'T'>

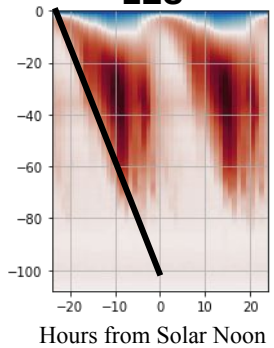


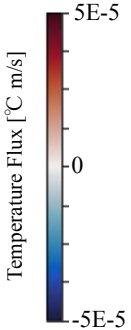
MOM6-1d OM4 <w'T'>



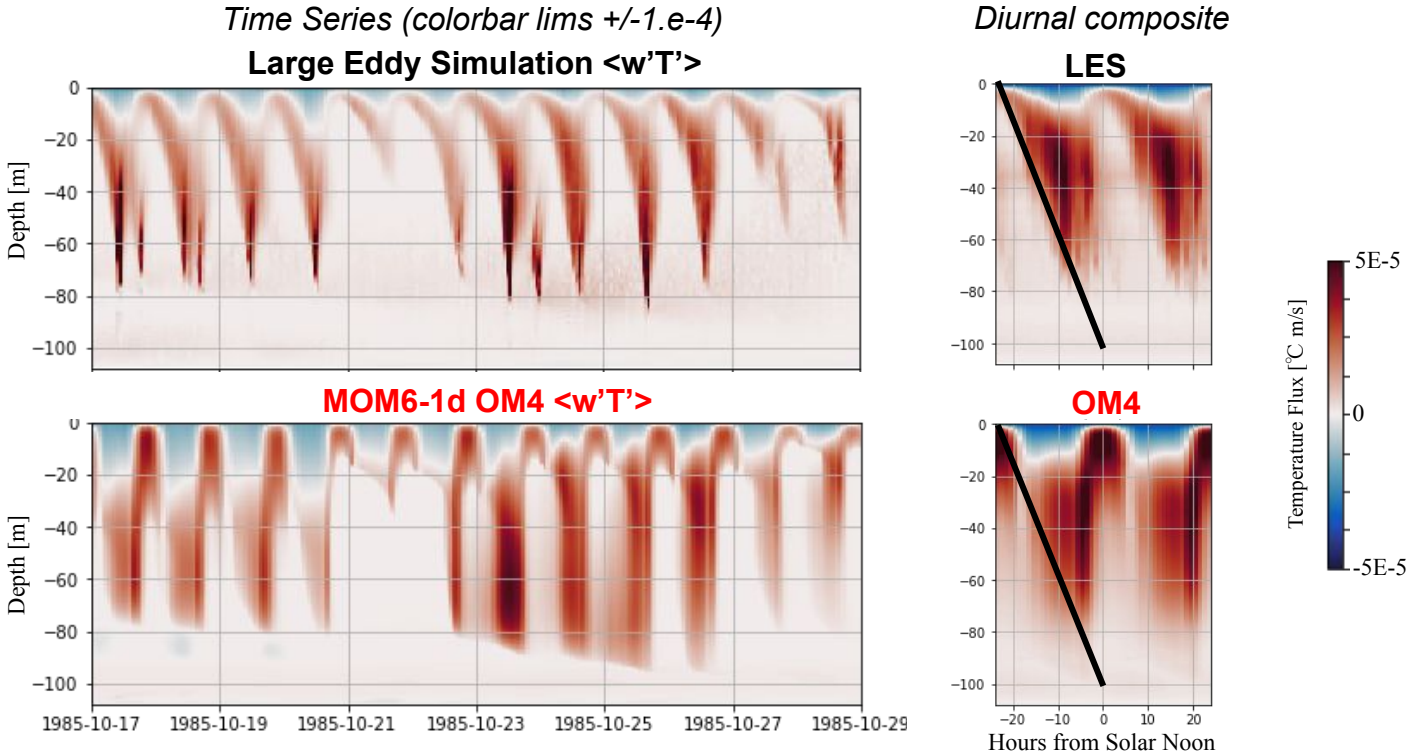
Diurnal composite

LES



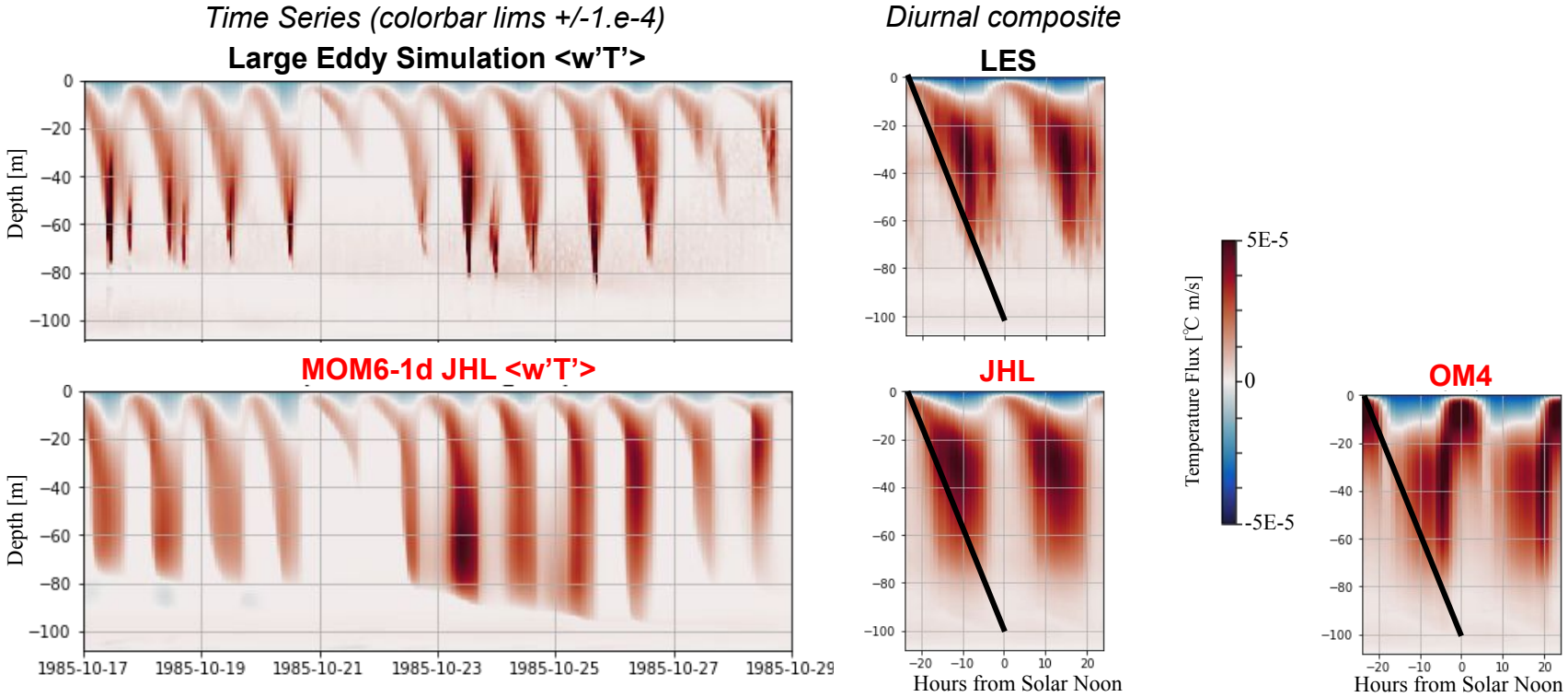


Can the OM4 mixing parameterizations reproduce the LES Heat Fluxes? (No)



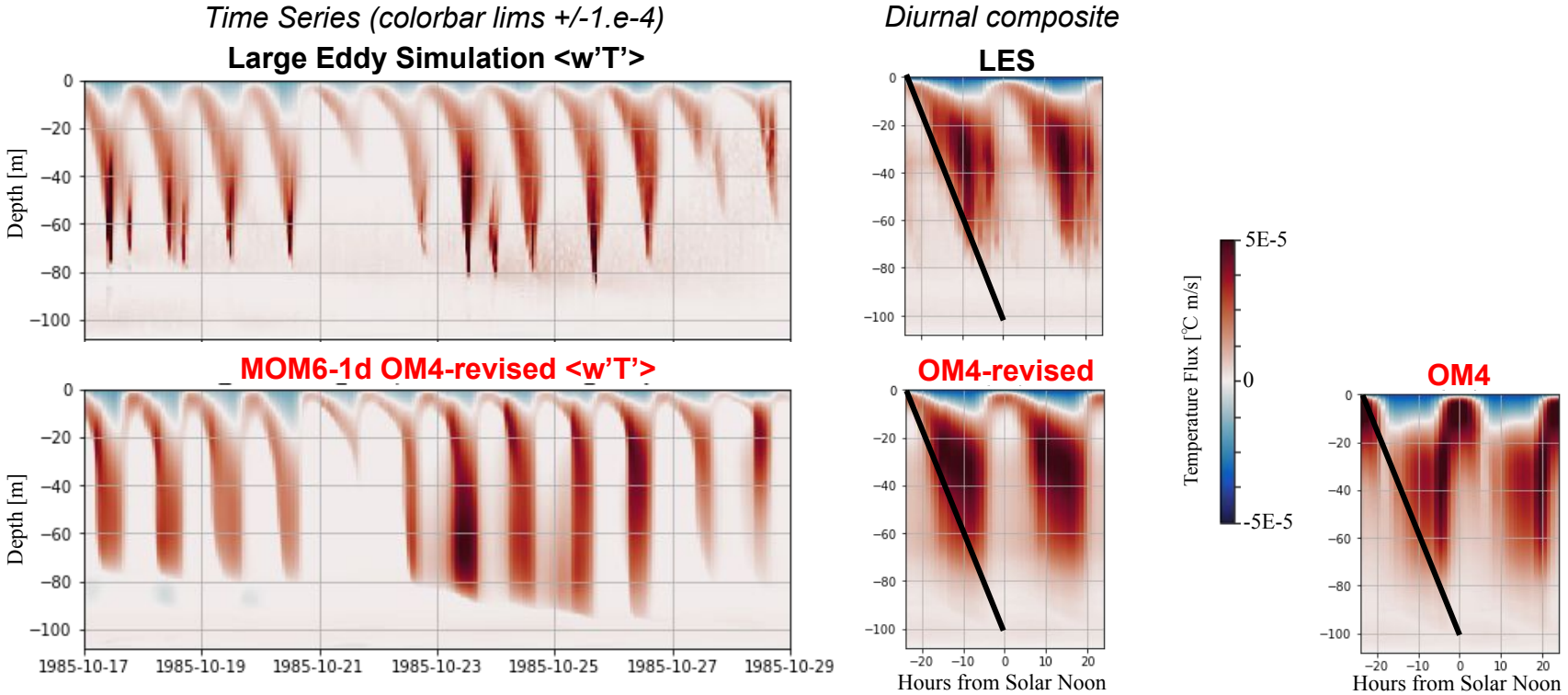
- Significant bias in heat flux phase & magnitude (too much downward heatflux in day, too rapid deepening in night).
- Conditions of OM4's ePBL stable forcing constraints failed due to large variability of deep-cycle mixing.
  - ePBL would need a new constraint for when mixing is energized by pre-existing turbulence.

Does the Jackson, Hallberg, Legg (2008) shear mixing parameterization alone do better? (Yes)



- JHL mixing scheme is already implemented for interior stratified shear mixing in MOM6/OM4.
- Improved representation of heat flux phase & magnitude compared to OM4 with ePBL.
- There is rapid downward propagation of <w'T'> in evening due to neglecting time tendency of TKE (future work).

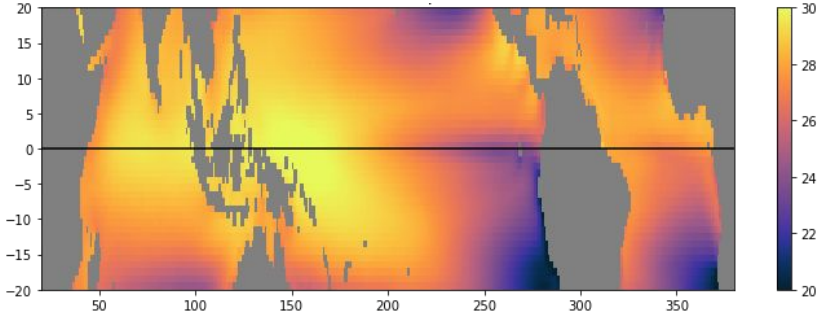
A revised ePBL/OM4 scaling to improve agreement with LES



- ePBL/OM4 is revised to relax equilibrium assumption between column turbulence and surface fluxes.
- The Jackson, Hallberg, Legg (2008) shear mixing now provides the interior heat flux estimates.
- The full model calibrates better to deep-cycle turbulence in the tropics.

How do parameterizations contribute to thermocline variability in models?

Forced OGCM (GFDL OM4) setup



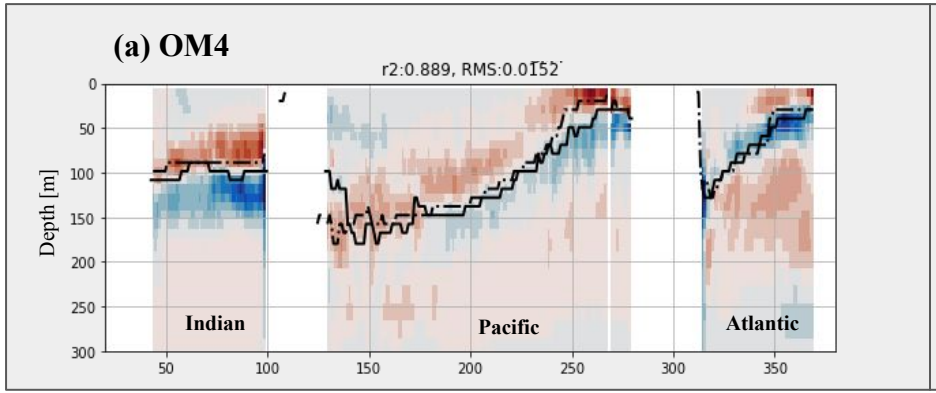
OGCM: Global ice-ocean ¼° simulations forced with JRA55do reanalysis (1999-2008)

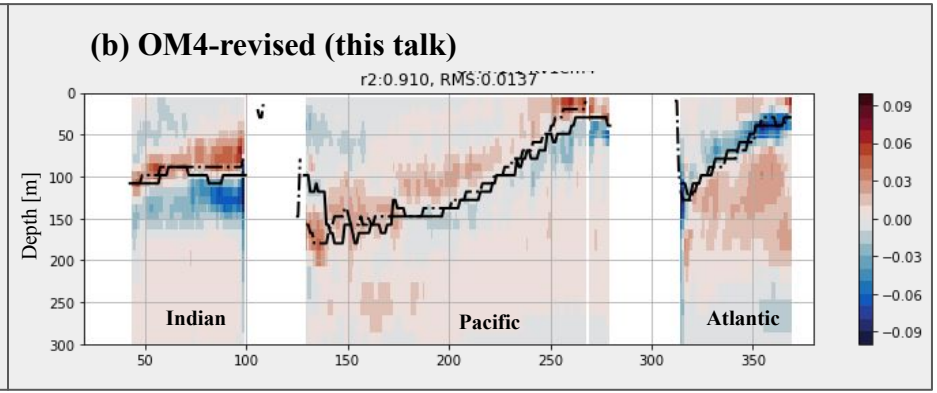
Relevant model factors:

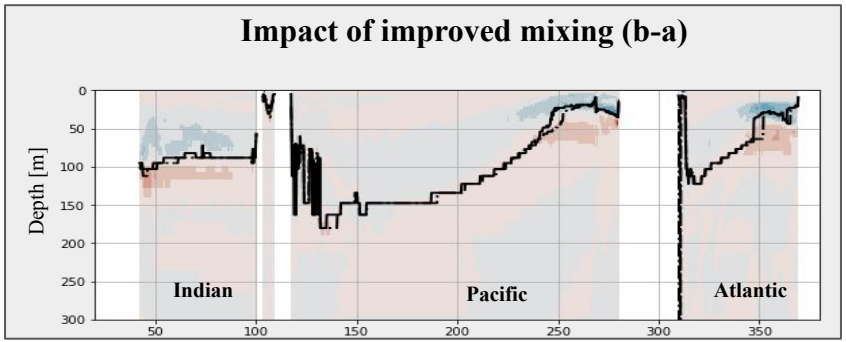
- Boundary layer/shear mixing schemes (this talk)
- Background mixing (this talk)
- Restratification parameterizations (not discussed)
- Resolution, vertical coordinate, etc (not discussed)

Result 1: Improved mixing parameterization slightly improves climatological dT/dz bias

Bias from argo, dT/dz [℃/m]

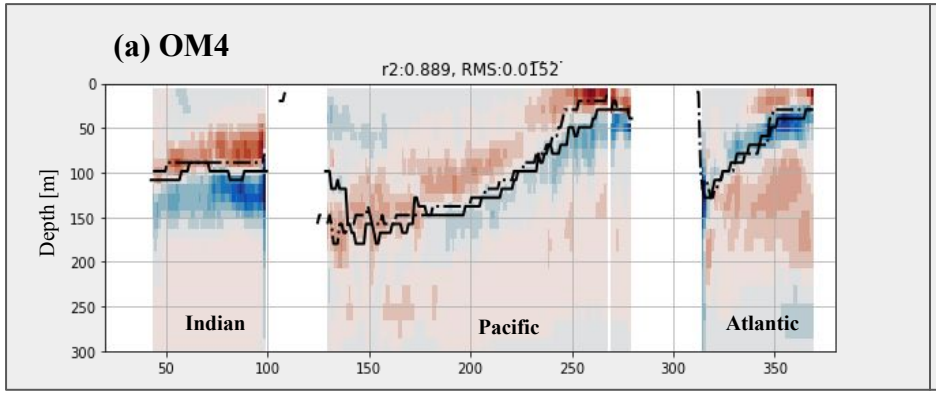


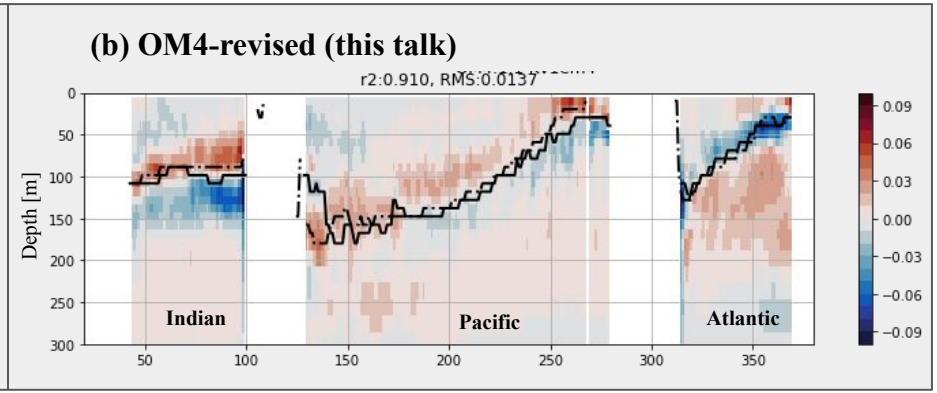


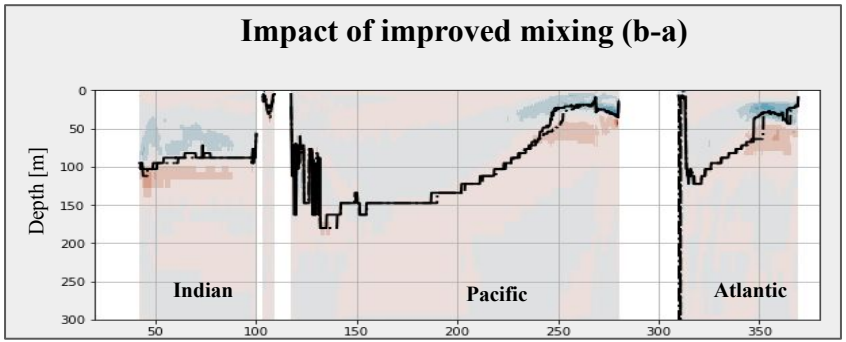


Result 1: Improved mixing parameterization slightly improves climatological dT/dz bias

Bias from argo, dT/dz [℃/m]



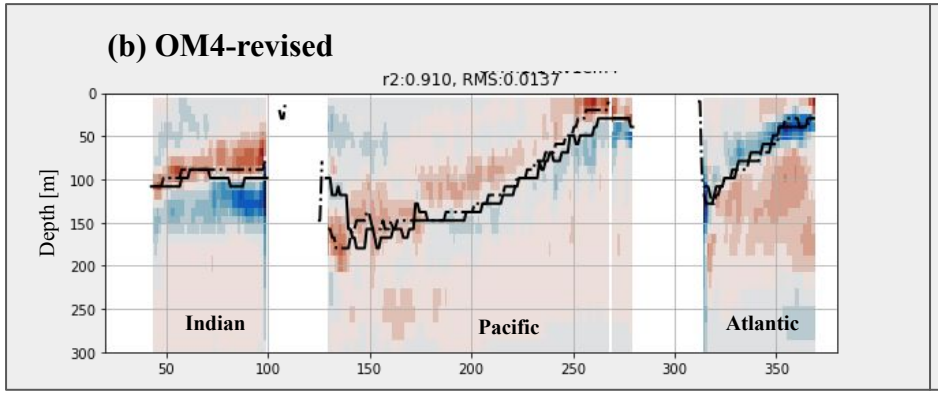


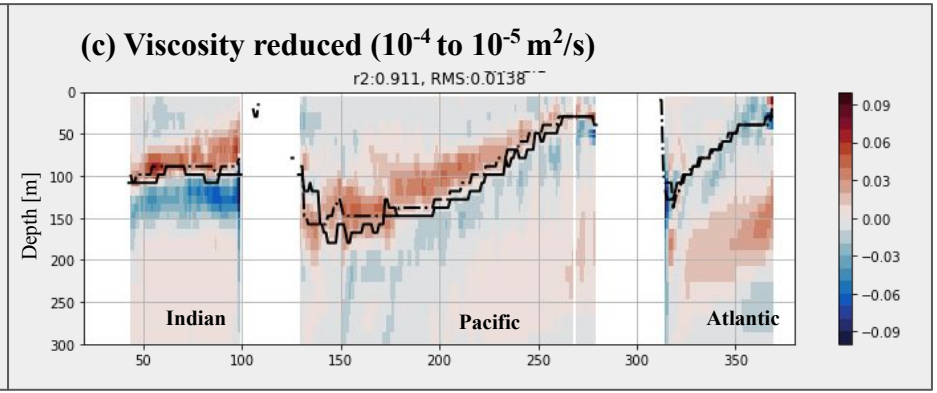


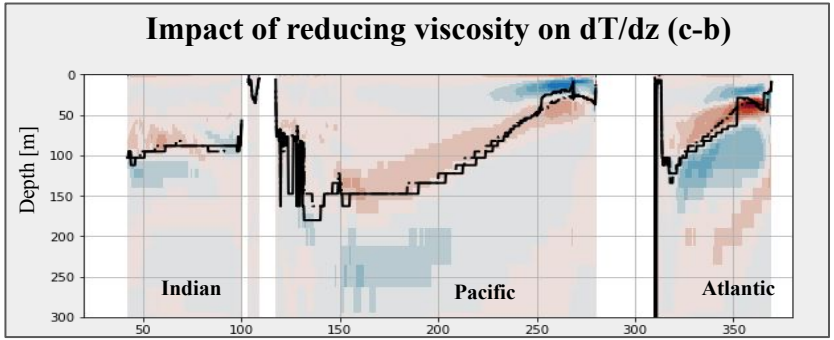
Tested sensitivity to many other factors (e.g., vertical coordinate, vertical resolution, submesoscale parameterization) in similar simulations, the most impactful model setting was…

Result 2: Reducing background viscosity improves the shallow eastern stratification!

Bias from argo, dT/dz [℃/m]



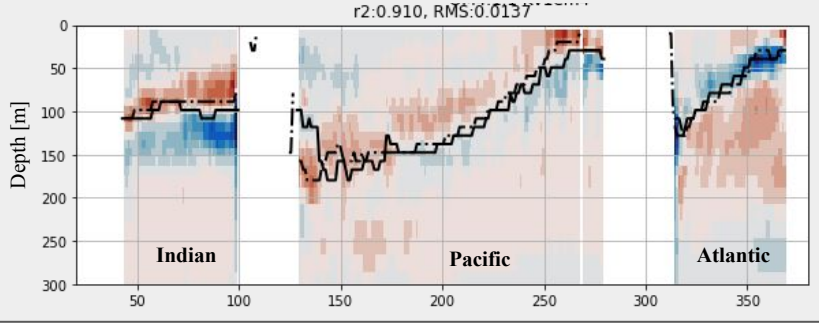




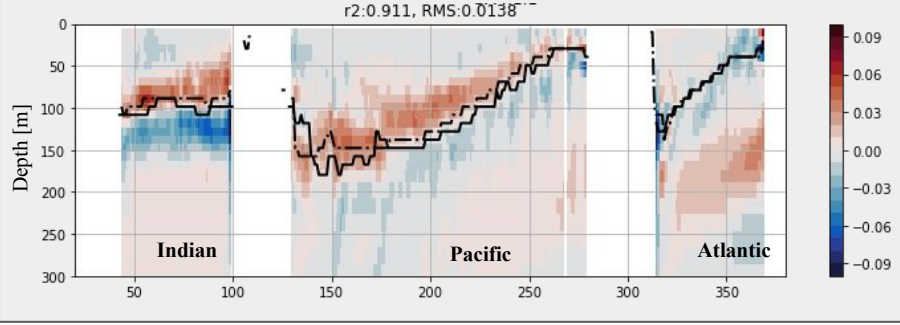
Result 2: Reducing background viscosity improves the shallow eastern stratification!

Bias from argo, dT/dz [℃/m]

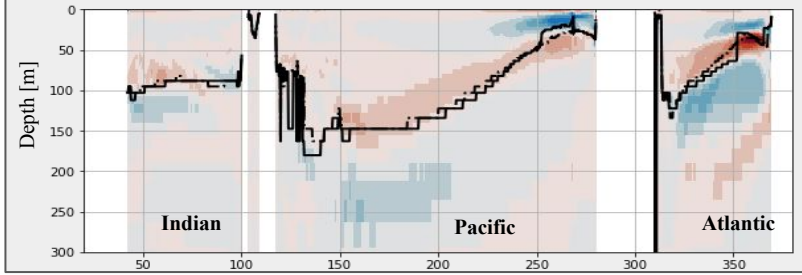
(b) OM4-revised



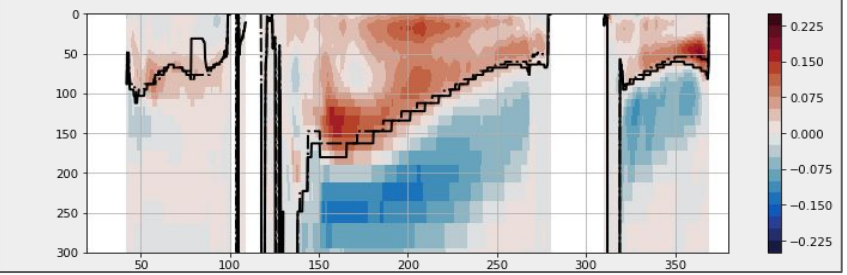
(c) Viscosity reduced (10^{-4} to 10^{-5} m^2/s)



Impact of reducing viscosity on dT/dz (c-b)

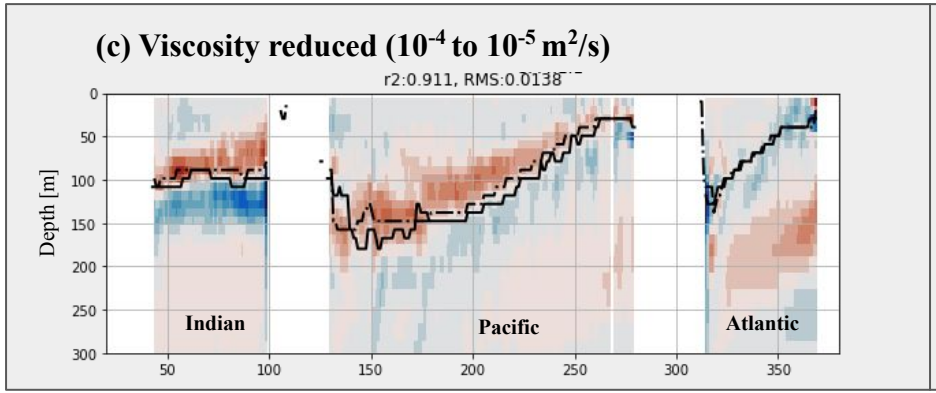


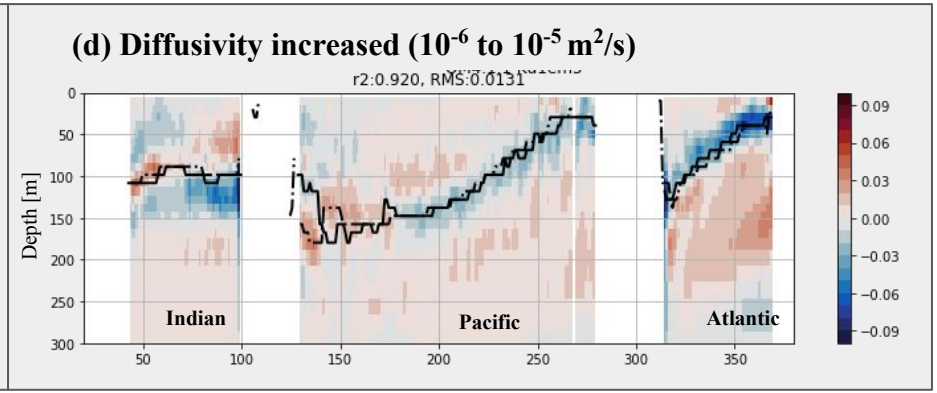
Impact of reducing viscosity on eastward current (m/s)

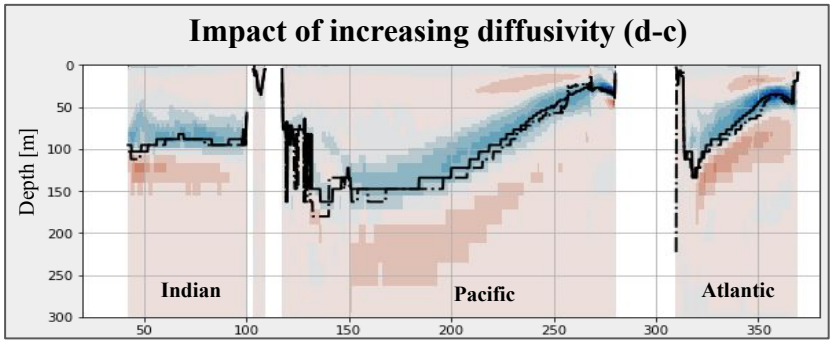


Result 3: Increasing background diffusivity reduces overall biases in stratification!

Bias from argo, dT/dz [℃/m]



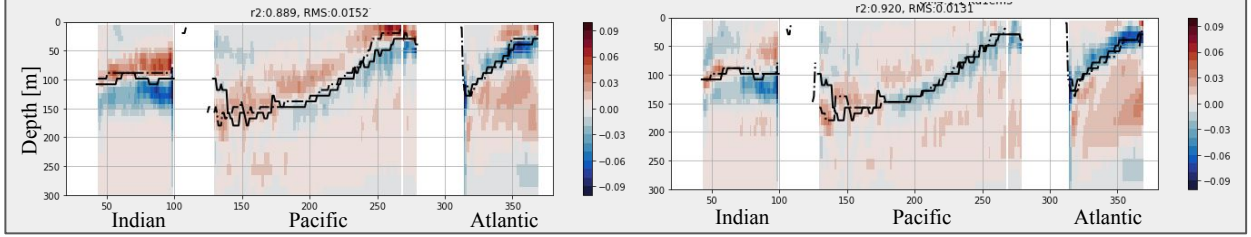




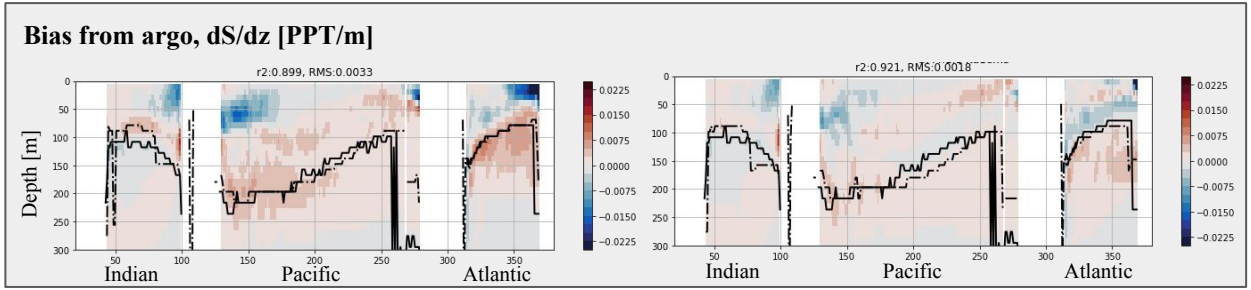
Temperature & Salinity shows significant improvement, currents are less conclusive.

OM4 | **OM4-revised, all changes**

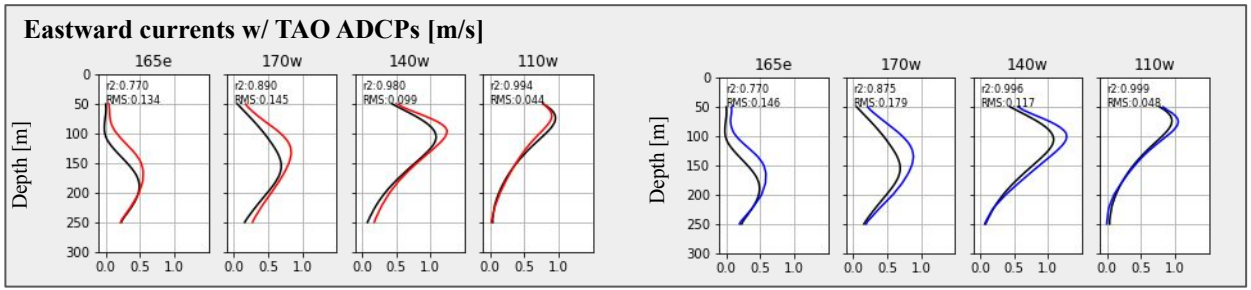
Bias from argo, dT/dz [℃/m]



Bias from argo, dS/dz [PPT/m]

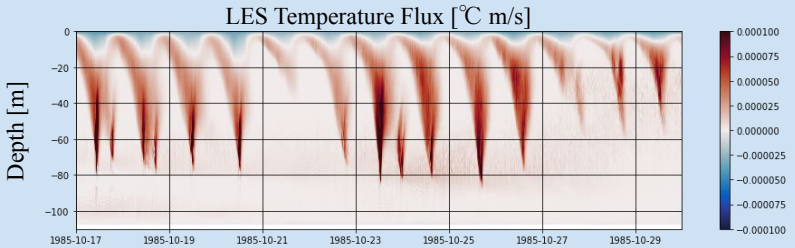


Eastward currents w/ TAO ADCPs [m/s]



Take Home Messages

LES approach allows testing the physics/process representation.

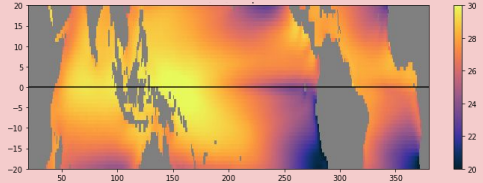


Does OM4's mixing capture accurate tropical mixing?

- The original OM4 mixing schemes are unable to capture diurnal/deep-cycle turbulence
- A revised OM4 mixing parameterizations simulates reasonable diurnal pattern of heat fluxes.

- A phase-shift of the downward heat flux propagation remains and is likely due to neglecting the turbulence time tendency (future work).

Forced OGCM approach suggests additional poor/missing process representation



How does mixing affect tropical currents/stratification?

- Improved OM4/ePBL only minorly helps stratification.
- Reducing background viscosity (10^{-4} to 10^{-5} m^2/s) and increased diffusivity (10^{-6} to $5x10^{-6}$ m^2/s) can further improve stratification and thermocline structure.
- These results clarify the role of the OM4 vertical mixing parameterization and guide future improvement efforts.

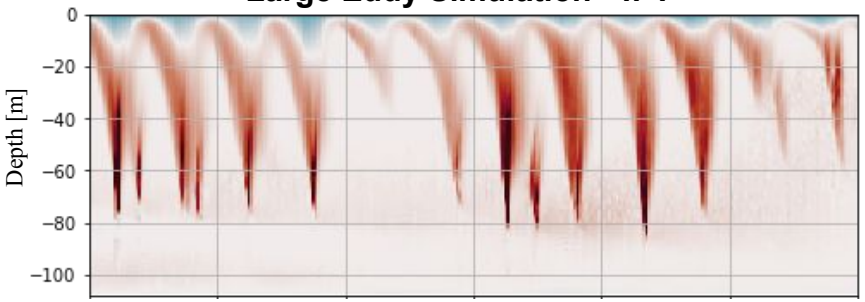
- Constant background mixing is only a proxy for better process representation (future work).
- Coupled simulations are needed to assess the impact of improved ePBL on atmosphere-ocean processes.

We are extremely grateful to the Argo program, TAO project, and GFDL model development teams who make these analysis possible!

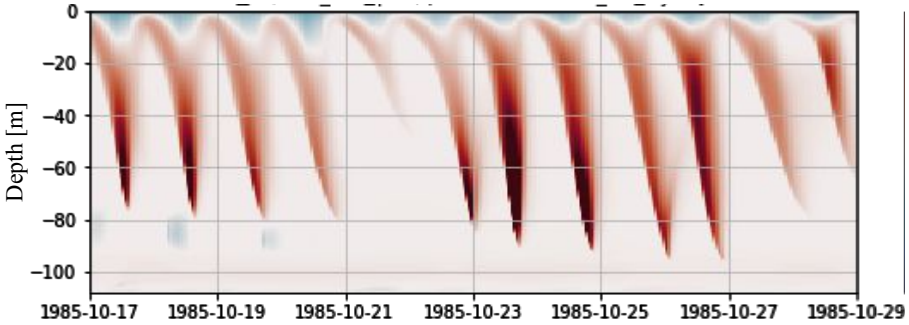
MOM6-1d with GLS/SMC?

Time Series (colorbar lims +/-1.e-4)

Large Eddy Simulation <w'T'>

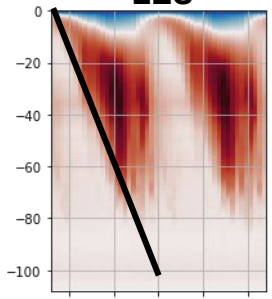


MOM6-1d SMC <w'T'>

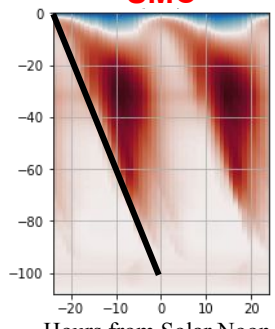


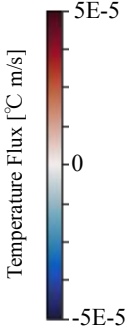
Diurnal composite

LES



SMC





OM4