Climate modeling in a mesoscale dominant regime

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Presentation given at NYU/Courant/CAOS
16 October 2024

Griffies from Southern Ocean, 2017

Thesis of this talk

- Stirring and mixing of ocean tracers (focus here on temperature) are central to how the natural and numerical ocean works.
- Most stirring happens via quasi-geostrophic mesoscale eddies (Ro<<1 with scales 10s to 100s km).
- Most mixing occurs via breaking internal gravity waves (Ro >> 1 at scales 10s of meters).
- Ocean climate models must respect the incredibly small interior mixing to preserve (over 100s-1000s mesoscale eddy turnover times) the ocean stratification.
- Respecting the stratification requires high fidelity representation and/or parameterization of stirring/mixing as well as negligible spurious mixing.
- We propose that models respecting the above thermally equilibrate far sooner (100s years rather than 1000s) for pre-industrial (1850) climate (as per CMIP).
- We refer to such models as ``mesoscale dominant'', since it is the mesoscale that dominates the piControl thermal equilibration time.

Outline of this talk

- Ocean stirring and mixing and role of the mesoscale
- Spurious sources for ocean model mixing
- Vertical Lagrangian remapping for ocean climate models (such as MOM6)
- Evidence that GFDL/CM4X-p125 represents an approximate mesoscale dominant ocean
- Some speculations on prospects for fine grid spacing climate models.

- Caveat 1: this work moves from the rigorous to the speculative, with much work remaining to fully explore the manner in which tracer transport processes affect thermal equilibration.
- Caveat 2: We focus on the role of the ocean in climate model equilibration. There is also a huge role for the atmosphere here. Yet the CM4X climate model design only changes one thing in the ocean: the grid spacing, so that we can focus on the ocean's role.

Ocean stirring and mixing

AN ANALYSIS OF THE STIRRING AND MIXING PROCESSES IN INCOMPRESSIBLE FLUIDS

By

CARL ECKART

Scripps Institution of Oceanography[1]
University of California
La Jolla, California

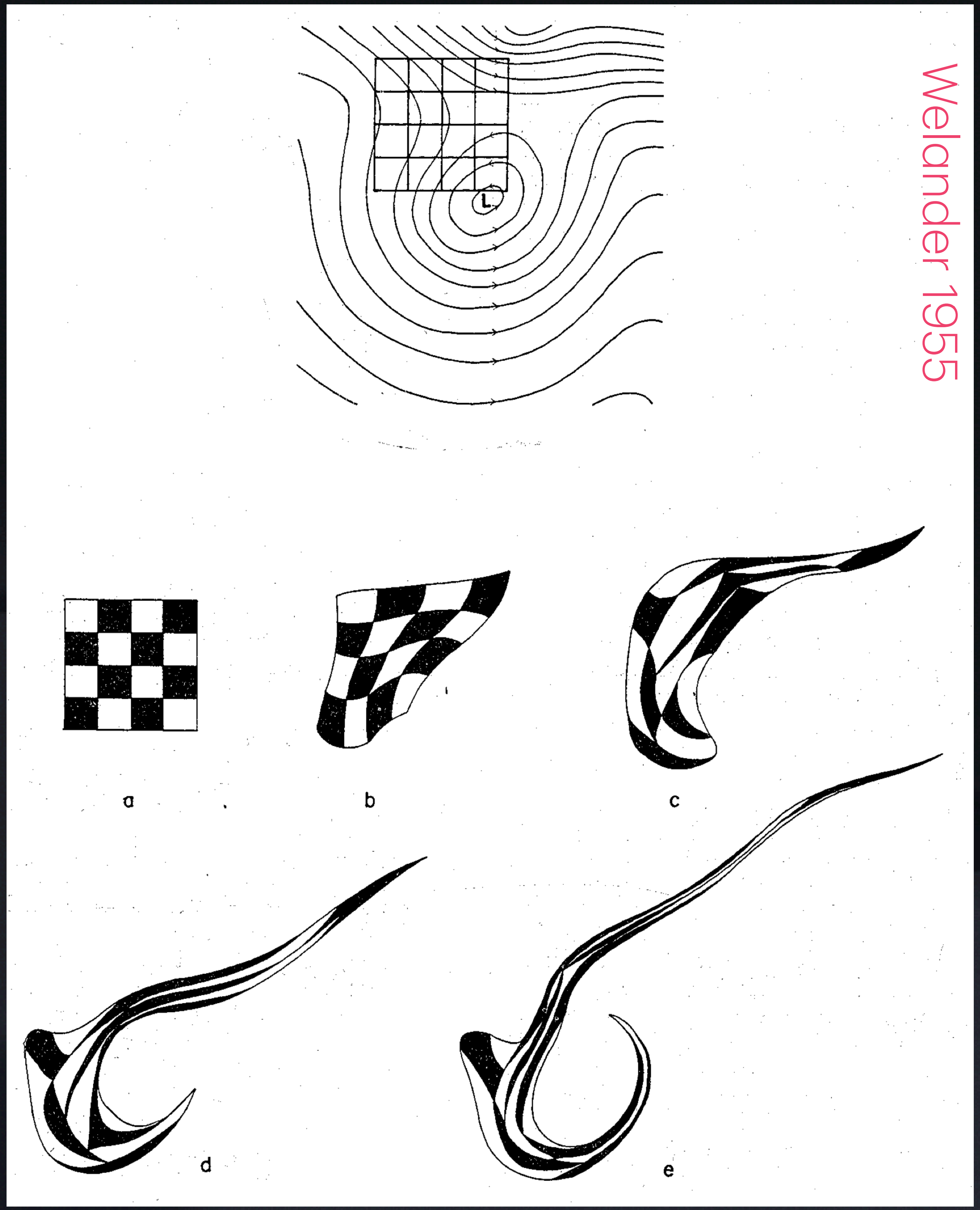
Tellus 1948

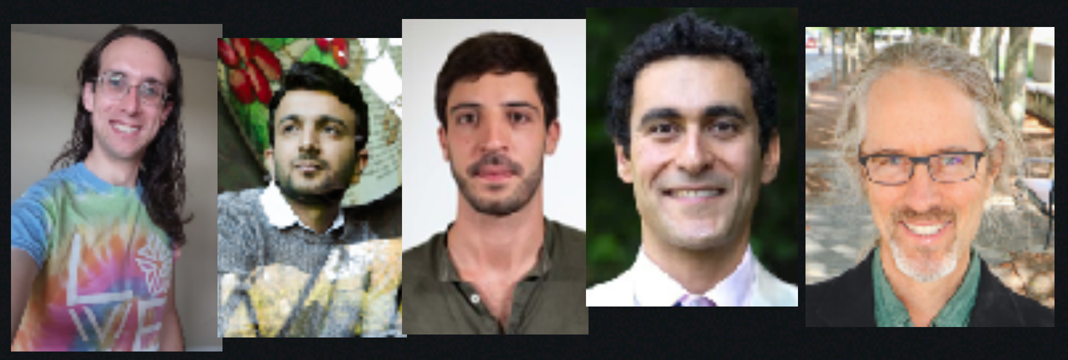
Studies on the General Development of Motion in a Two-Dimensional, Ideal Fluid

Journal of Marine Research 1955

By PIERRE WELANDER, Institute of Meteorology, University of Stockholm

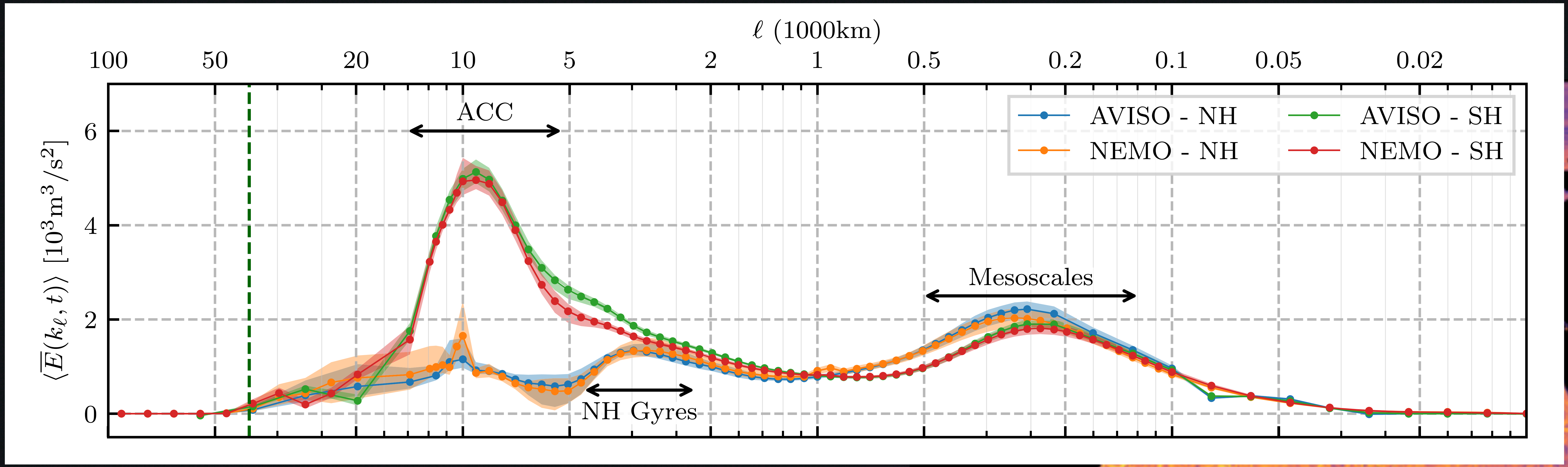
- Stirring is reversible and it increases the magnitude of tracer gradients. Advection in a perfect fluid is a reversible transport process.
- Mixing is irreversible and it decreases tracer gradients. Mixing happens when gradients are strong enough for molecular diffusion to be relevant.
- Ocean stirring is dominated by mesoscale eddies.
- Ocean mixing is dominated by breaking gravity waves.
- Eddy-induced advection or skew diffusion are the canonical methods in ocean models to parameterize stirring by unresolved motions.
- Downgradient diffusion is the canonical method in ocean models to parameterize mixing by unresolved motions.



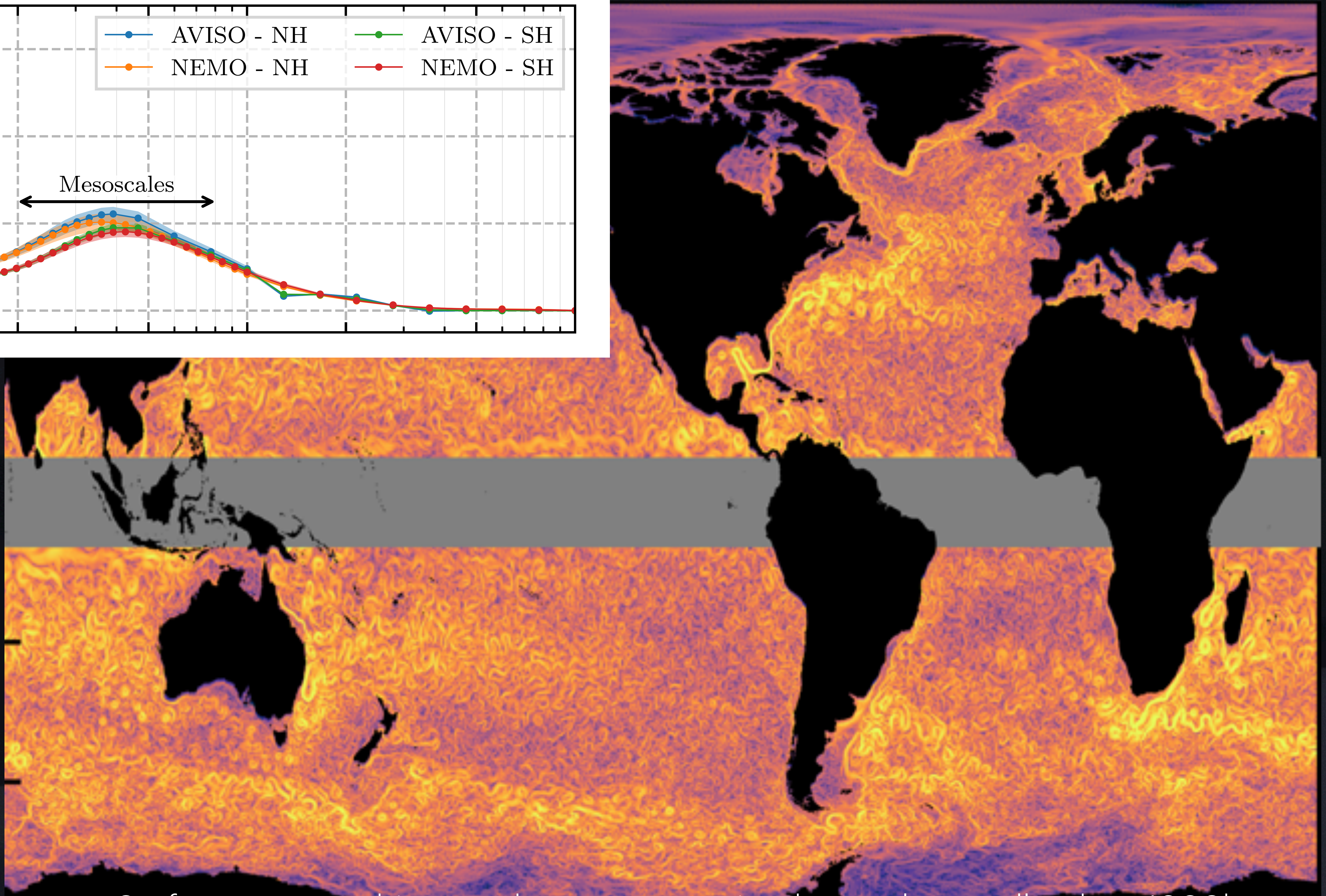


Stirring is dominated by mesoscales:

Global power spectrum from an O(10km) NEMO global model



Storer et al 2022 Nature Comm

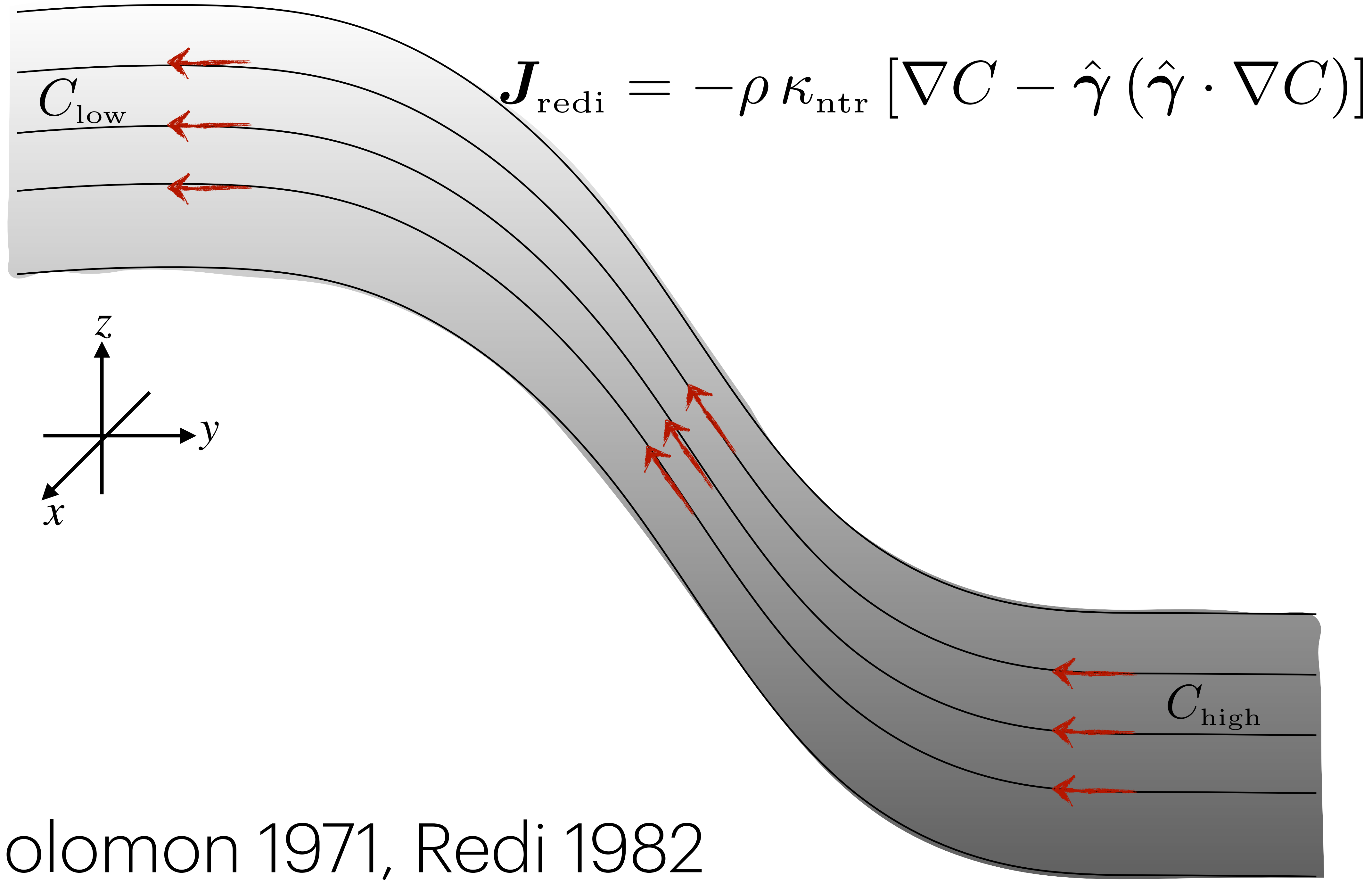


Surface geostrophic speed as coarse-grained to scales smaller than 1000km

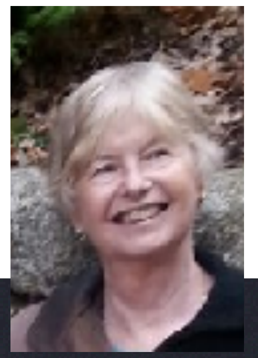
- Transient turbulent mesoscale motions give rise to the bump in the band from 10s of km to 100s of km.
- The ACC has the largest power density at scales upwards of 10,000km.
- ACC and gyres are large-scale currents that might meander, but are largely not transient turbulence.
- Yet there are many turbulent mesoscale motions associated with large scale currents.
- Analysis here focuses on geostrophic motions, thus allowing for comparisons to satellite sea level products.

Cartoons of mesoscale stirring+mixing

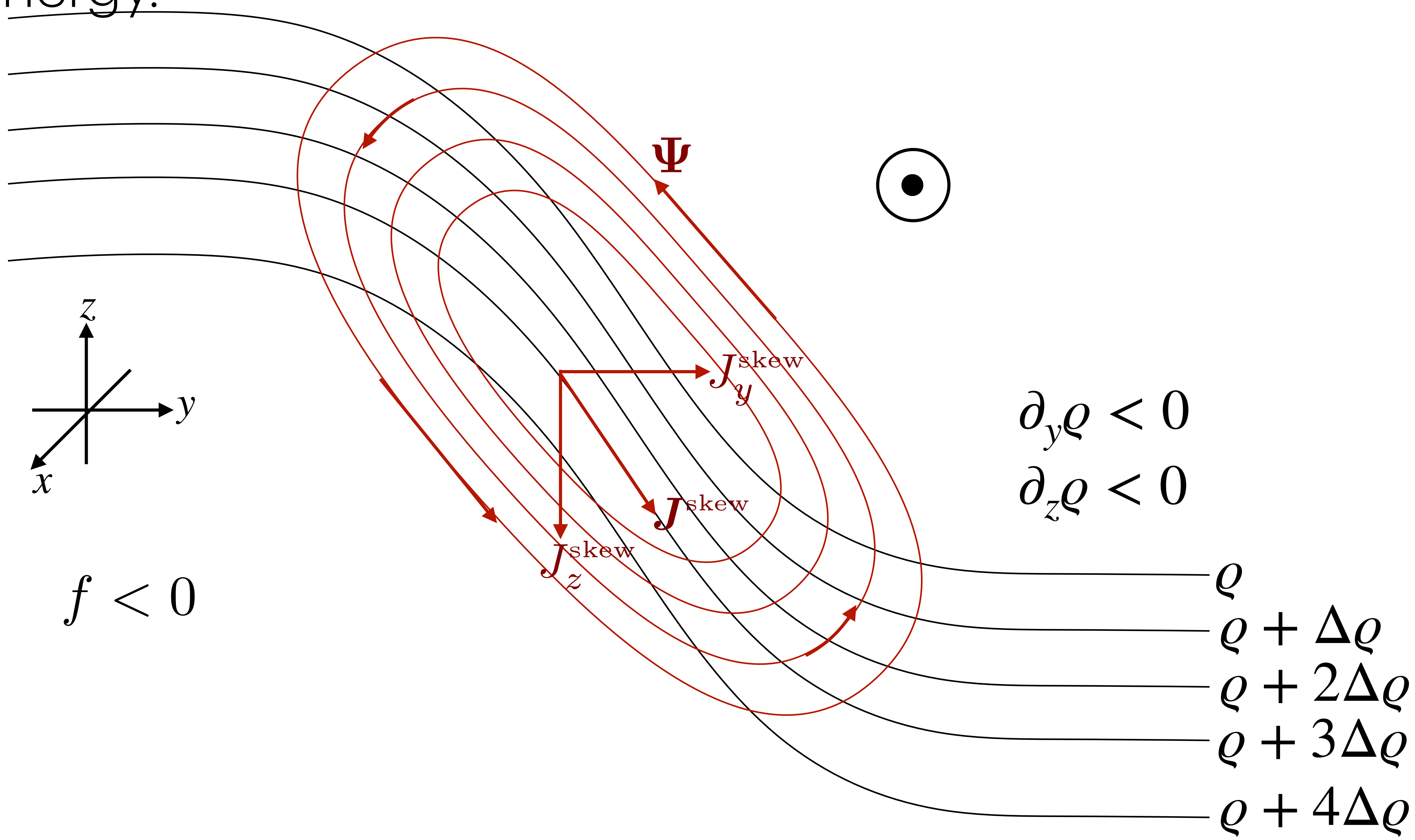
Eddy-induced **neutral diffusion** refers to the downgradient diffusion mediated by mesoscale eddy stirring that is aligned with neutral directions.



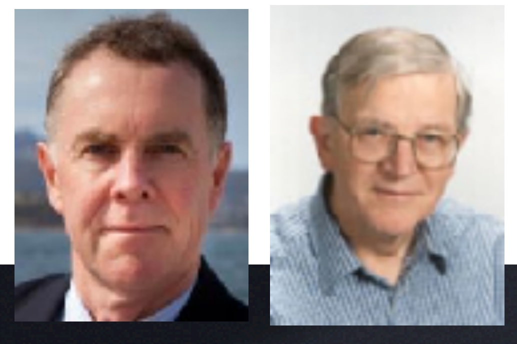
Solomon 1971, Redi 1982



Mesoscale eddy-induced advection (or skew diffusion) aka the **Gent-McWilliams effect** refers to a secondary circulation induced by transient mesoscale eddies that slumps isopycnals to affect a reduction of potential energy.



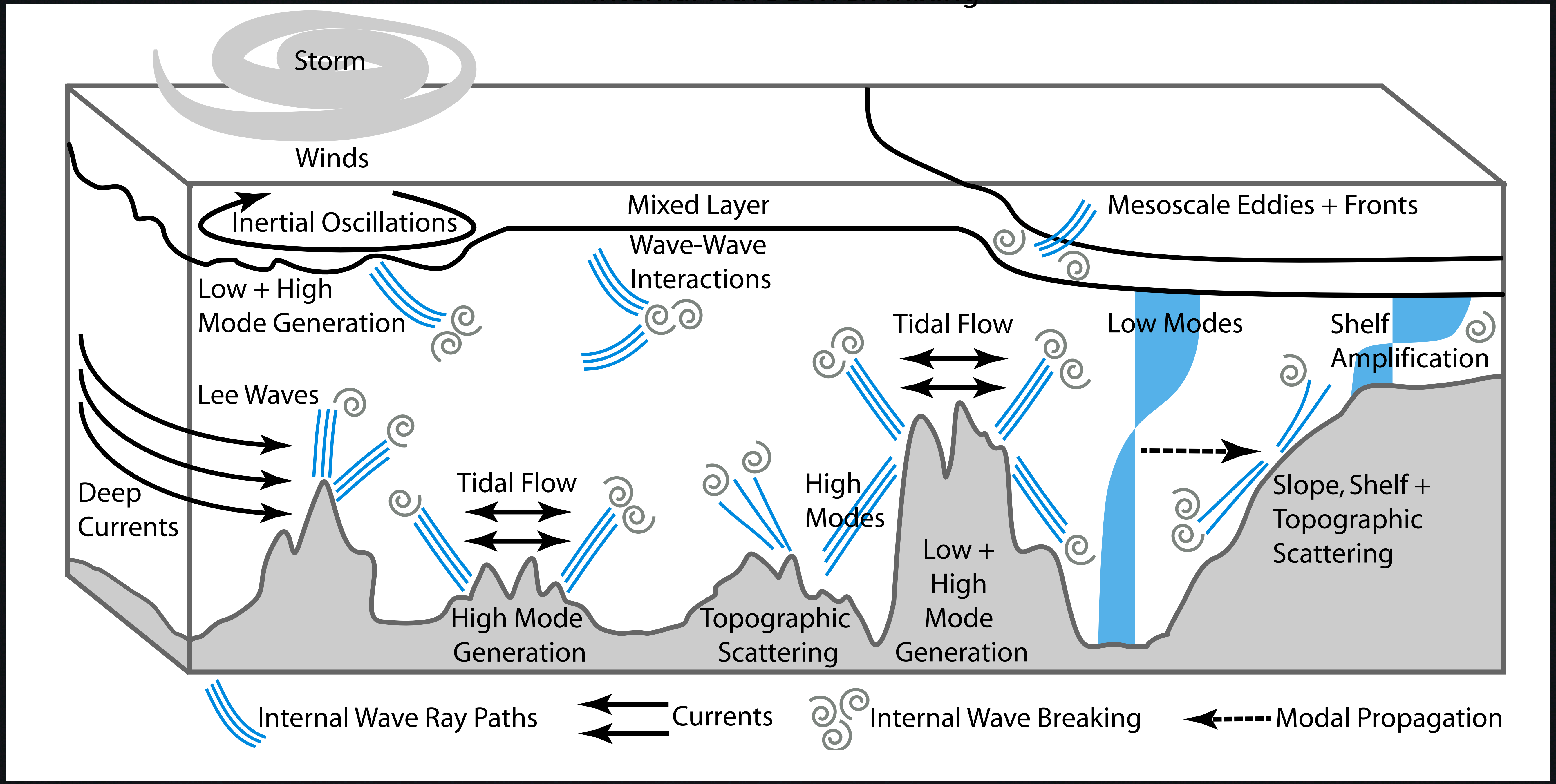
Gent+McWilliams 1990, Gent et al 1995, Griffies 1998



Mixing in the natural and numerical ocean

Internal Wave Driven Mixing

MacKinnon et al 2017

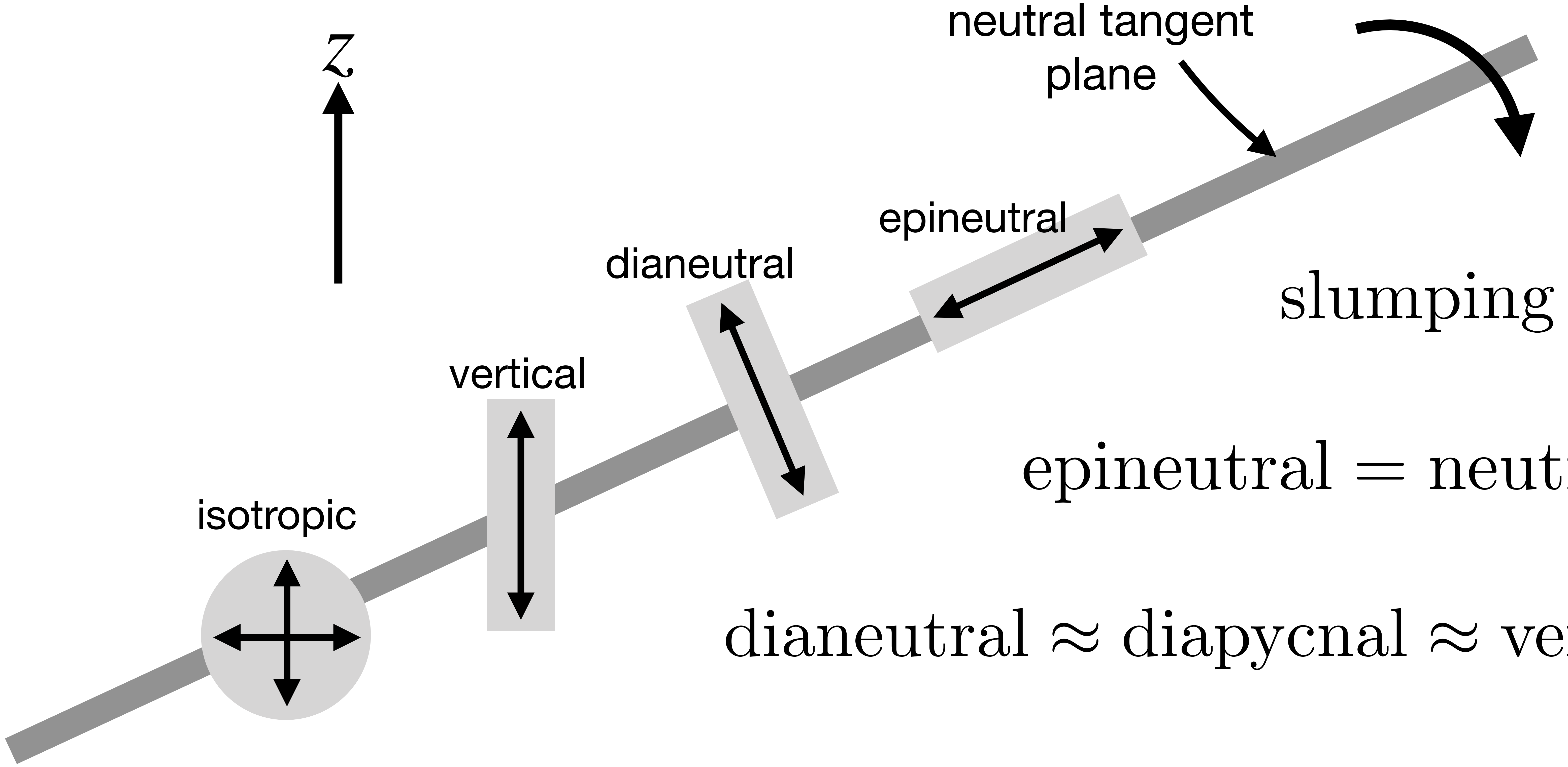


There are many sources of interior ocean mixing, most associated with breaking gravity waves.

How do ocean models mix?

1. Parameterizations have greatly improved through efforts such as the 2010-2015 Climate Process Team led by Jen MacKinnon.
2. Spurious numerical mixing from poor representation of advection is a recurring issue that underlies many efforts to improve numerical parameterizations. Indeed, in some models spurious mixing swamps physically parameterized mixing.
3. **This point underlies much of the research into ocean models at GFDL since 1990s.**

Cartoon summary of stirring/mixing processes



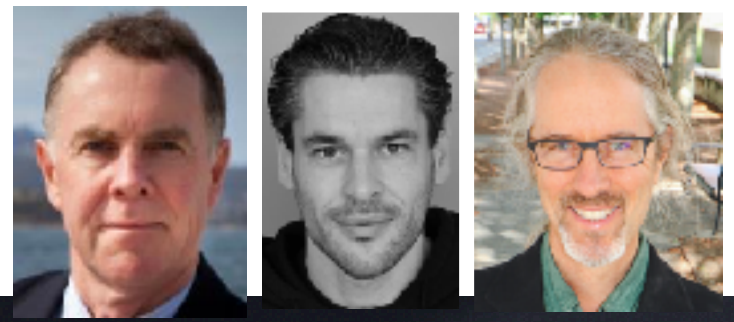
$$\text{slumping} = \text{Gent-McWilliams effect}$$

$$\text{epineutral} = \text{neutral diffusion}$$

$$\text{dianeutral} \approx \text{diapycnal} \approx \text{vertical} = \text{gravity wave mixing}$$

$$\text{isotropic} \approx \text{molecular diffusion}$$

Based on McDougall, Groeskamp, Griffies 2014



The spurious mixing problem

The numerical representation of advection $= \nabla \cdot (\rho\, C\, \boldsymbol{v})$ generally introduces spurious mixing and unmixing due to truncation errors

$$\nabla \cdot (\rho\, C\, \boldsymbol{v})_{\text{model}} = \nabla \cdot (\rho\, C\, \boldsymbol{v})_{\text{exact}} + \nabla \cdot (\rho\, C\, \boldsymbol{v})_{\text{error}} \tag{1}$$

- ⋆ Errors in numerical advection can be interpreted as an extra SGS term

$$\frac{\partial(\rho\, C)}{\partial t} + \nabla \cdot (\rho\, C\, \boldsymbol{v})_{\text{exact}} = -\nabla \cdot \left[\boldsymbol{J} + (\rho\, C\, \boldsymbol{v})_{\text{error}}\right]. \tag{2}$$

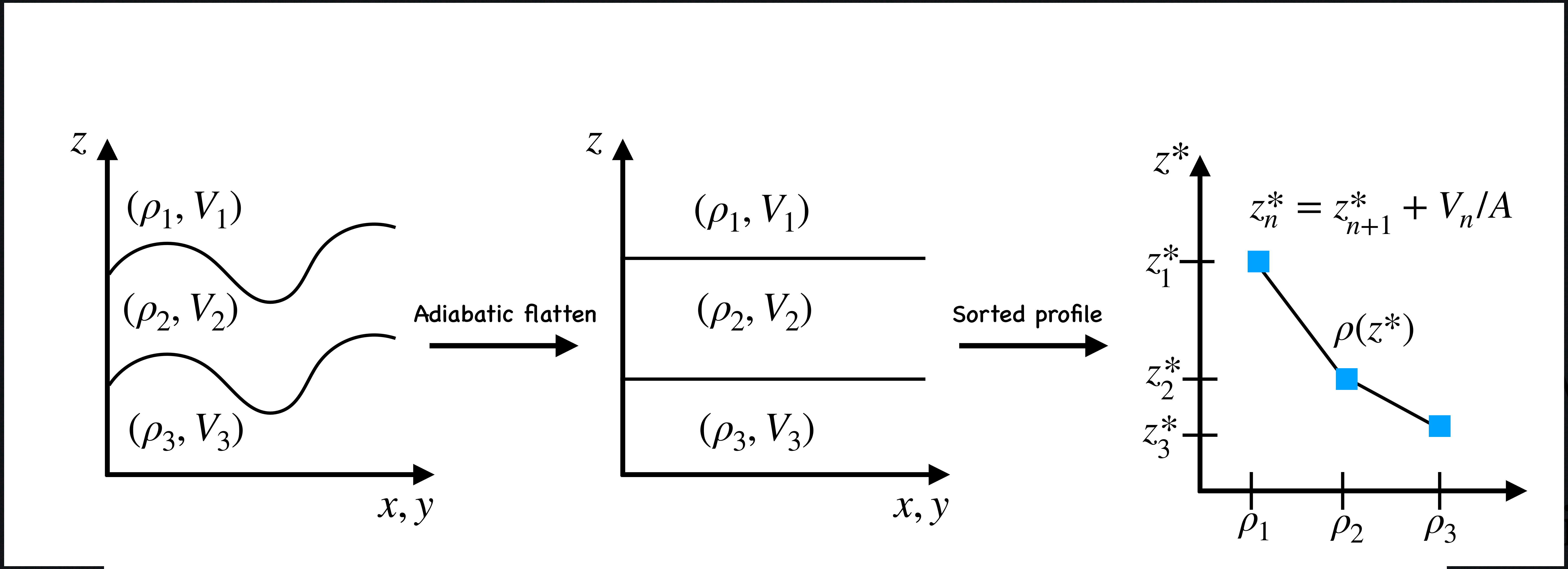
- ⋆ Error term is not physical nor is it under our direct control. If large it can corrupt physical integrity of the simulation.
- ⋆ Error term can become larger when refine grid spacing to partially resolve mesoscale eddies, which pump tracer variance to the grid scale.
- ⋆ Spurious mixing from the error term is reduced (but not eliminated) when use higher order accurate advection.
- ⋆ Key concern for climate is spurious diapycnal mixing.
- ⋆ Spurious diapycnal mixing is reduced when use quasi-isopycnal vertical coordinate; errors stopped at layer interface.

effect

mixing

s 2014

Sorting method to diagnose spurious mixing



- ⋆ A method based on density sorting to produce a stable background profile, ρ_{back}, following Winters and D'Asaro (1995).
- ⋆ In an adiabatic simulation, evolution of the background state only arises from spurious numerical sources, which we interpret as an effective diffusivity, κ_{eff}

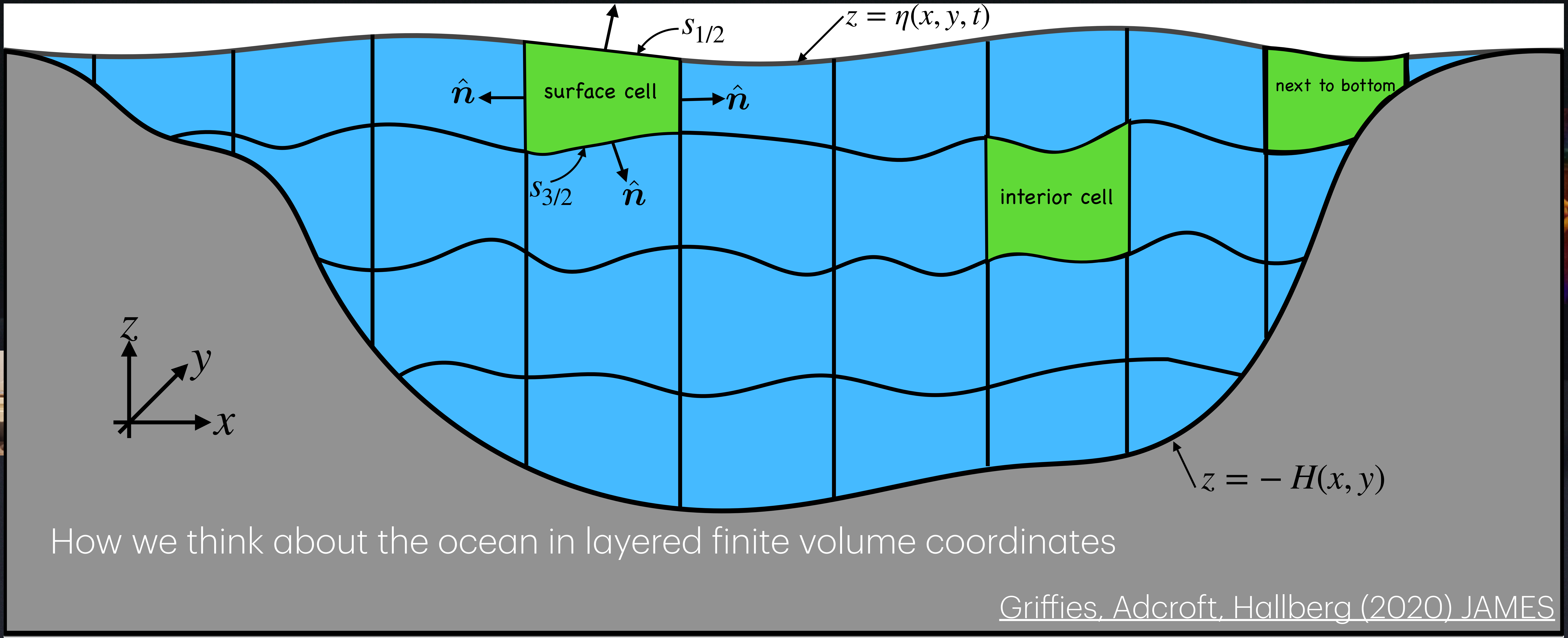
$$\frac{\partial \rho_{\mathrm{back}}}{\partial t} = \frac{\partial}{\partial z^*}\left[\kappa_{eff}\frac{\partial \rho_{\mathrm{back}}}{\partial z^*}\right]$$

Griffies, Pacanowski, Hallberg 2000

, Griffies 2014

Layered vertical coordinates to respect the stirring/mixing paradigm

- Modelers realize there are limitations to the tools we build, so the quest for the next "big thing" is relentless.
- Some ideas are old (e.g., use layers not levels), but can take decades to realize in a manner sufficient for realistic climate models.
- MOM6 has its roots in Hallberg's PhD thesis (from 1995), Bleck's HYCOM (2002), as wells MOM5 (Griffies) and MITgcm (Adcroft).



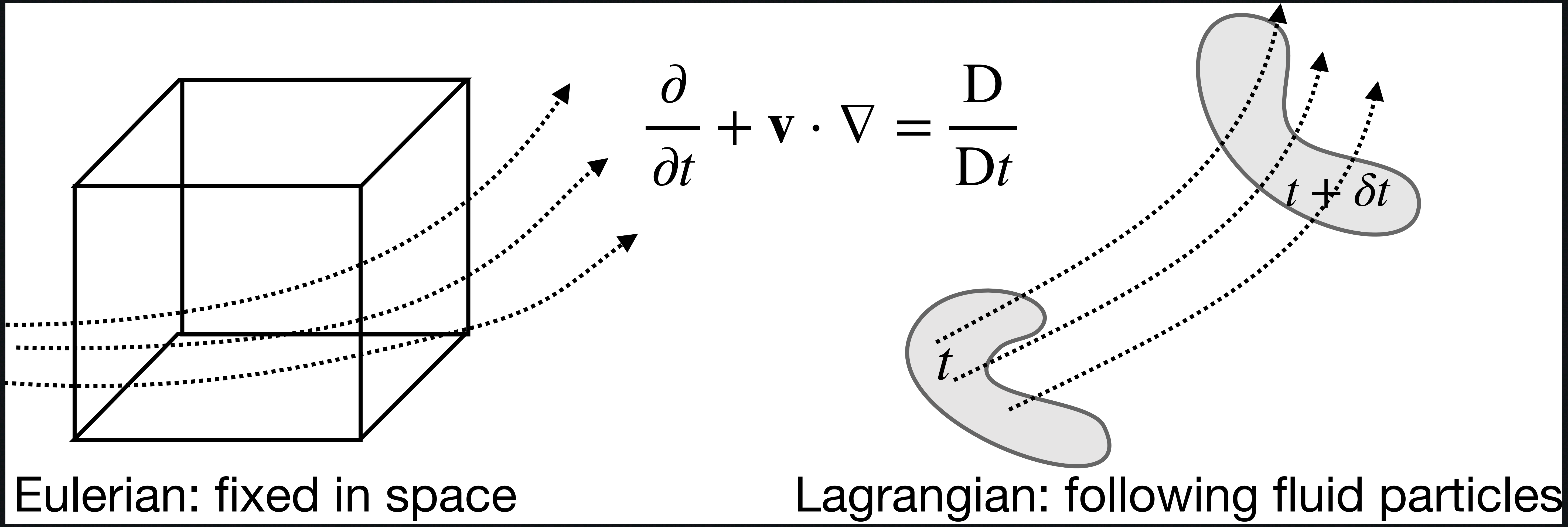
How we think about the ocean in layered finite volume coordinates

Griffies, Adcroft, Hallberg (2020) JAMES

"The ocean has no sides, though some numerical models do."

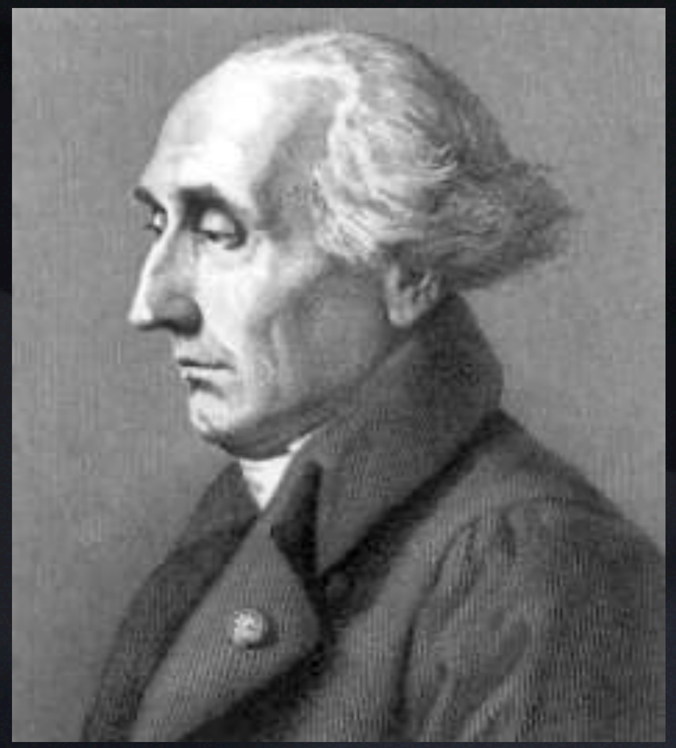
Lagrangian methods in the continuum

- Follow a fluid region and base the evolution equations relative to the moving region.
- Eulerian: static reference frame, so all flow transport is advection
- Full Lagrangian: zero advection since co-moving reference frame with the flow
- Historical aside: It was Euler, not Lagrange, who originated "Lagrangian fluid kinematics." See chapter II in "The kinematics of vorticity" by Truesdell (1954) for a long footnote on this interesting story about miss-attribution.



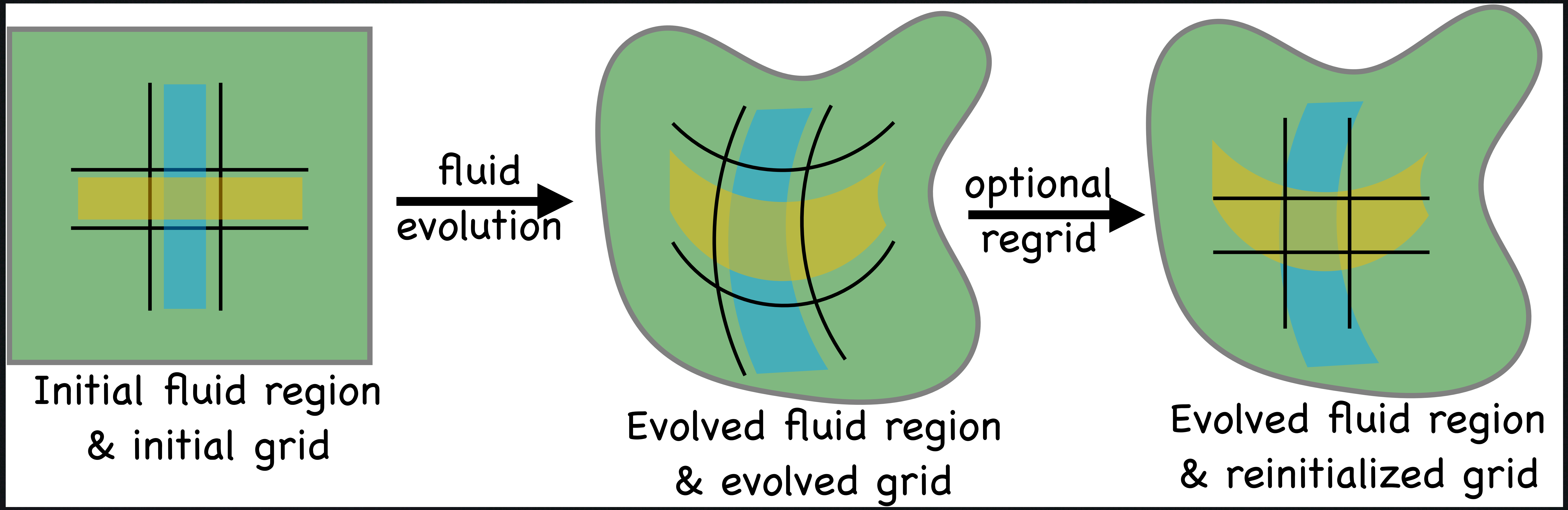
Griffies, 2024: *Geophysical Fluid Mechanics*

https://stephengriffies.github.io/assets/pdfs/GFM_lectures.pdf



Lagrangian methods for numerical models

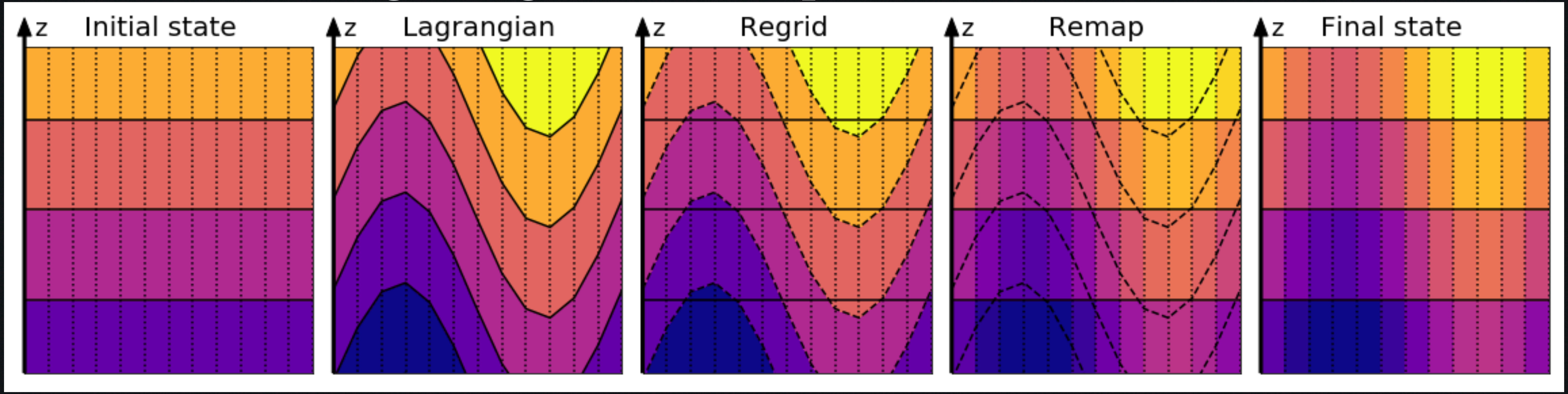
- Arbitrary Lagrangian-Eulerian (ALE) refers to any method that allows for moving grid cell boundaries.
- "Advection" refers to the transport of fluid relative to the grid cells.
  - Step 1: Lagrangian step: grid moves with flow (no advection)
  - Step 2: Regrid/remap step to reorganize the grid back to a target (acts like advection)
- Ideally, step 2 has no impact on the fluid state, but in practice there are truncation errors that impact the representation (i.e., spurious mixing).



Griffies, Adcroft, Hallberg (2020) JAMES

Many of the early ideas about Lagrangian methods started at Los Alamos in the 1970s as reviewed in Hirt, Amsden, Cook (1974)

Vertical Lagrangian remap method for ocean models



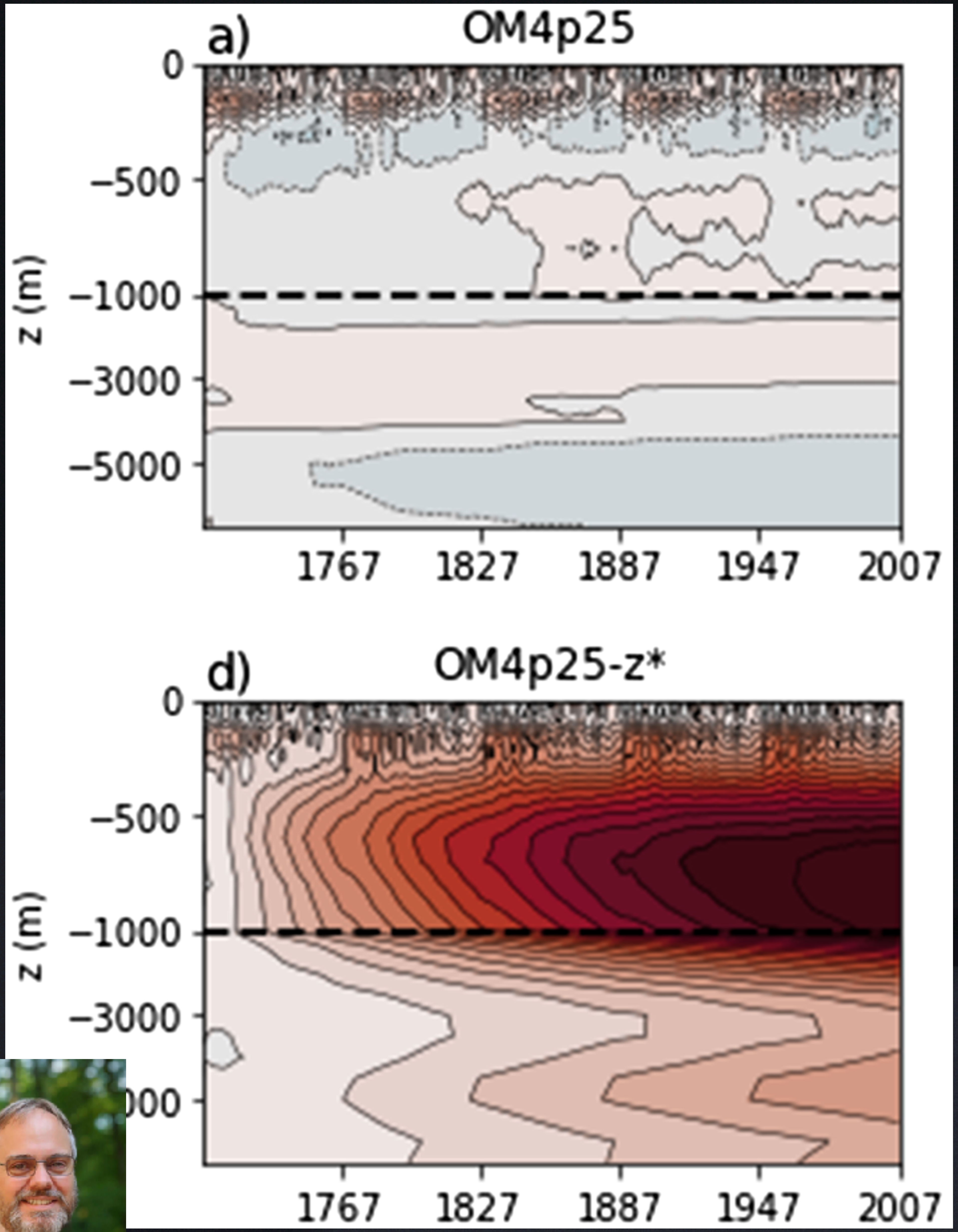
Griffies, Adcroft, Hallberg (2020) JAMES

- Vertical Lagrangian: zero vertical advection but nonzero horizontal advection.
- Vertical transport is realized by remapping. It is mathematically identical to vertical advection, but numerically it is very distinct.
- There is no CFL associated with vertical transport, so can have infinitesimally thin cells.
- Geophysical fluid models only do vertical Lagrangian; not 3d.
- Method was pioneered for ocean modeling by Rainer Black (2002) in HyCOM.
- HyCOM development has today been merged with MOM6.

Rainer Bleck

Practical motivation for the MOM6 dycore

- Depending on vertical coordinate choice, it can greatly reduce spurious mixing. This is a key point for this talk!
- Adiabatic shallow water limit, just like isopycnal models.
- Vanishing layers to allow for conservative modeling of estuaries and ice-shelf grounding lines.
    - No vertical CFL, so can have infinitesimally thin grid cells.
- Arbitrary vertical coordinates, including hybrid (we use z-rho hybrid).
- Online remapping needed for prognostic fields (i.e., to evolve the model state) can also be used for diagnostic fields, and diagnostic grids can be distinct from prognostic.
- Caveat: the method is far far more complex than Eulerian approaches, so there is overhead in both understanding the model fundamentals and in writing analysis code.



Adcroft et al 2019, JAMES

Details for the interested “math-physics” person

JAMES | Journal of Advances in Modeling Earth Systems

RESEARCH ARTICLE
10.1029/2019MS001954

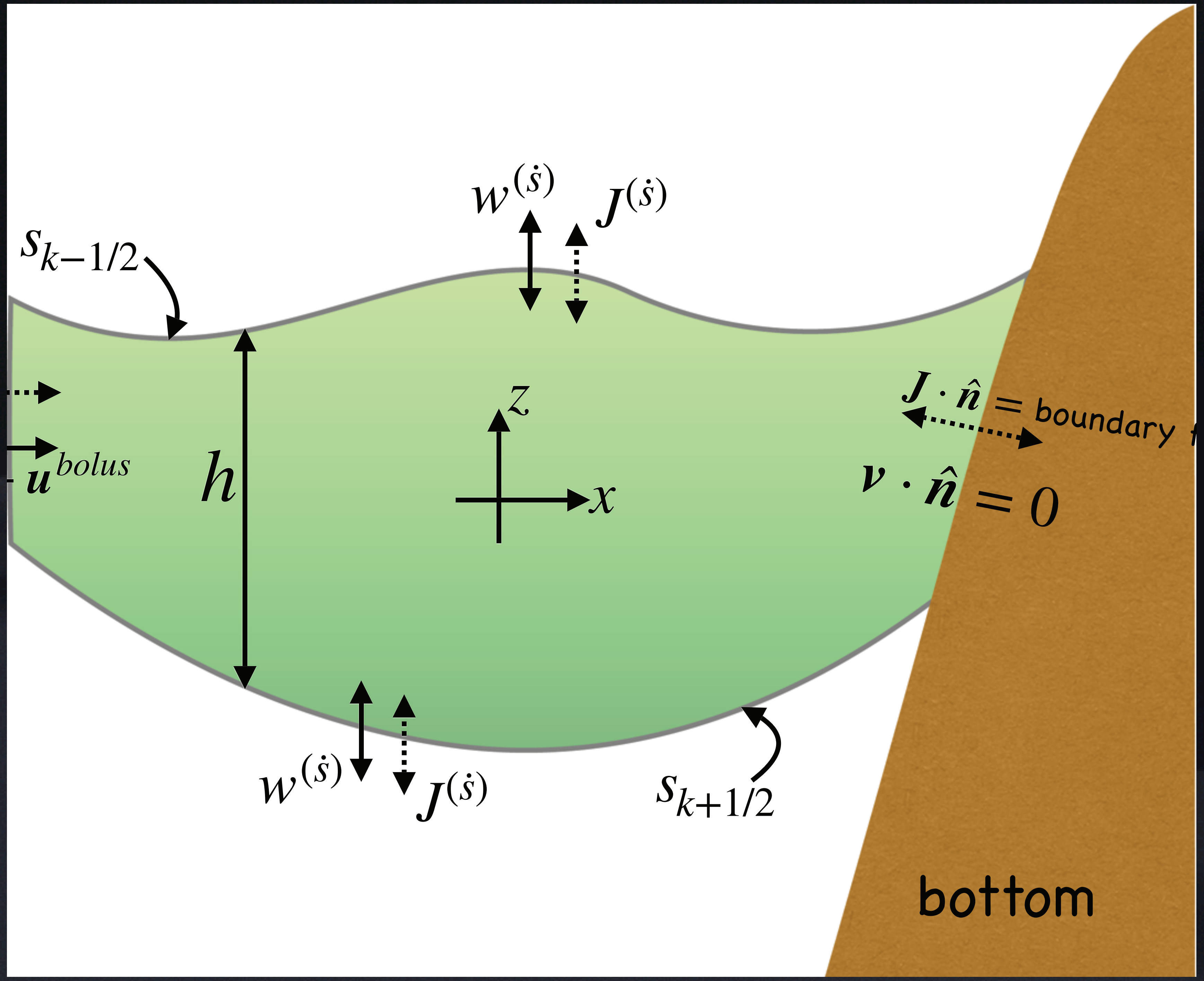
Special Section:
Dynamical Cores of Oceanic Models Across all Scales and their Evaluation

Key Points:

A Primer on the Vertical Lagrangian-Remap Method in Ocean Models Based on Finite Volume Generalized Vertical Coordinates

Stephen M. Griffies[1,2], Alistair Adcroft[1,2], and Robert W. Hallberg[1,2]

[1]NOAA/GFDL, Princeton, NJ, USA, [2]Program in Atmospheric and Oceanic Sciences, Princeton University, Princeton, NJ, USA



C3. Tracer Conservation

Setting $\varphi = \rho S$ in the Leibniz-Reynolds transport theorem (C3) yields the time change for the salt content in the finite volume

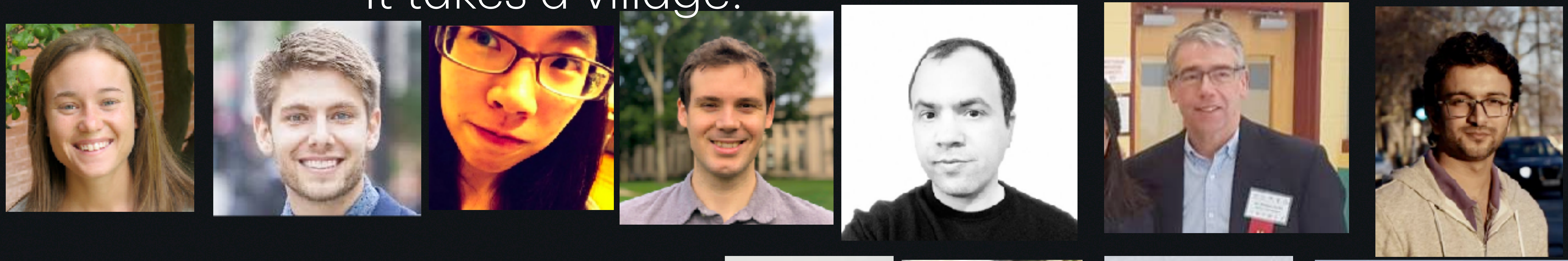
$$\frac{\mathrm{d}}{\mathrm{d}t}\left[\int_{\mathcal{R}} \rho S \,\mathrm{d}V\right] = \int_{\mathcal{R}} \left[\frac{\partial(\rho S)}{\partial t} + \nabla\cdot(\rho S \boldsymbol{v}^{(b)})\right] \mathrm{d}V. \tag{C10}$$

A region that moves with the velocity, $\boldsymbol{v}^{\mathrm{S}}$, of the salt within a seawater fluid element maintains a constant salt mass

$$0 = \frac{\mathrm{d}}{\mathrm{d}t}\left[\int_{\mathcal{R}(\boldsymbol{v}^{\mathrm{S}})} \rho S \,\mathrm{d}V\right] = \int_{\mathcal{R}(\boldsymbol{v}^{\mathrm{S}})} \left[\frac{\partial(\rho S)}{\partial t} + \nabla\cdot(\rho S \boldsymbol{v}) + \nabla\cdot\boldsymbol{J}(S)\right] \mathrm{d}V, \tag{C11}$$

The CM4X hierarchy of climate models

It takes a village!



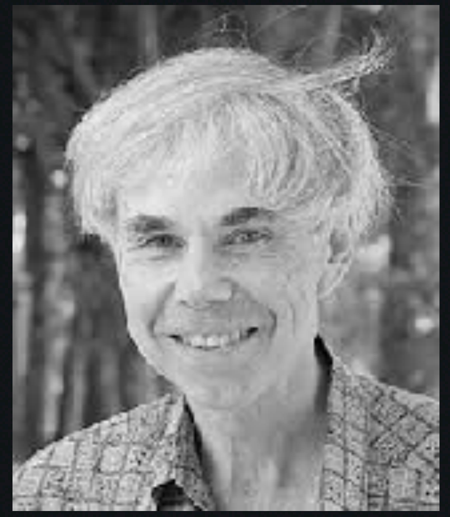
The GFDL-CM4X climate model hierarchy, Part I: overview and thermal properties, 2024

The GFDL-CM4X climate model hierarchy, Part II: Case studies, 2024

In prep for JAMES

Two principles of model development

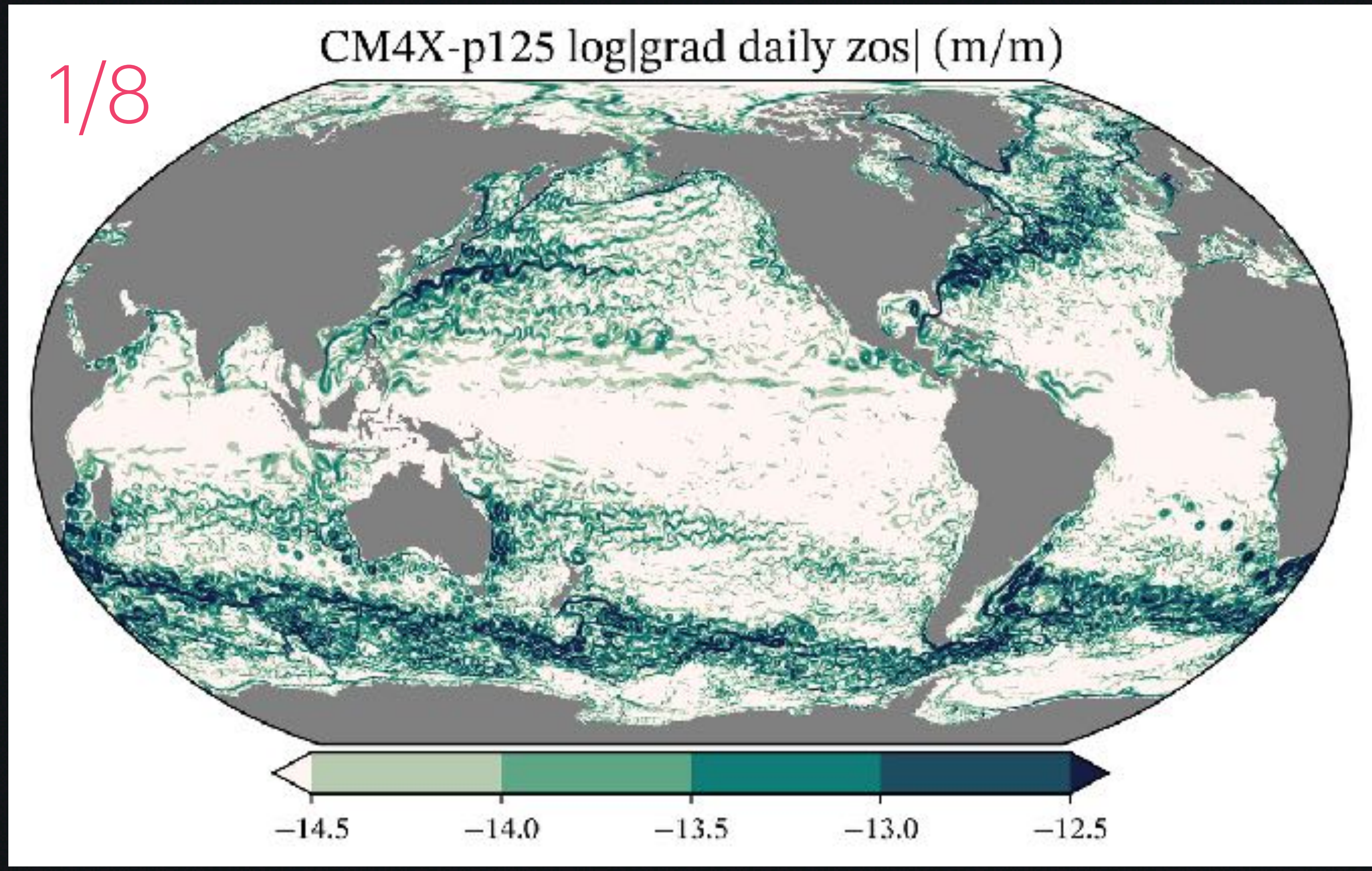
- **Hofstadter’s Law**: *Every project takes longer than you expect, even when accounting for Hofstadter’s Law.*

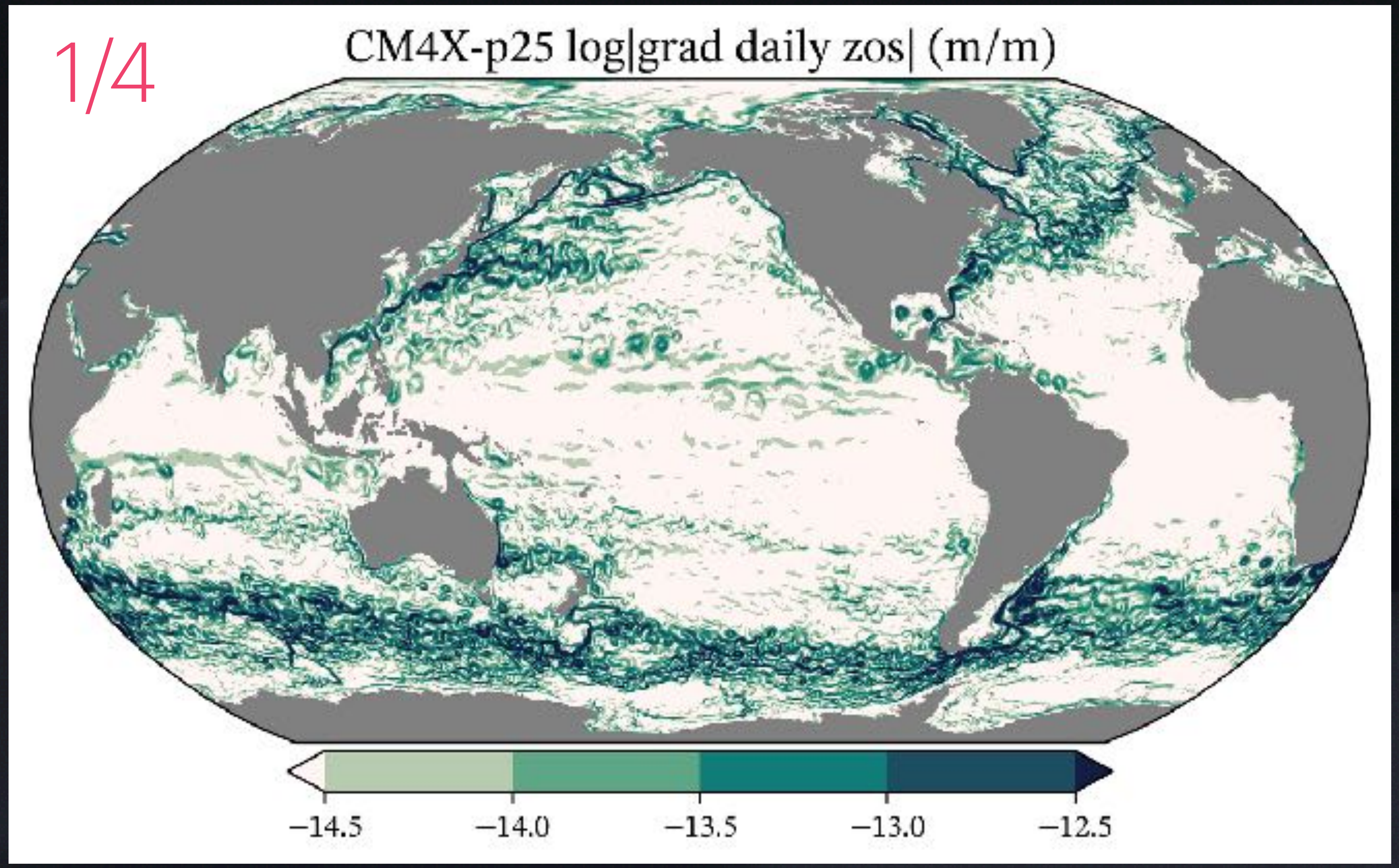


- **Hallberg’s Principle for Model Development**: *Climate models are Murphy's Law Machines: anything that can go wrong will go wrong and at the least convenient time.*

Specs for the two configurations of CM4X

- MOM6 at 1/4 and 1/8 degree grids coupled to 50km atmosphere.
- 75 hybrid z-rho vertical layers.
- No mesoscale eddy closure in tracer or continuity equations.
- Submesoscale closure for mixed layer processes.
- Focused on studying role of horizontal grid spacing and corresponding representation of dynamics. Everything else is identical.
- Shares much with CMIP6 model CM4.0, but with finer grid in both atmosphere and ocean, and updates to physics schemes.





Griffies et al 2024, in prep

Simulations conducted

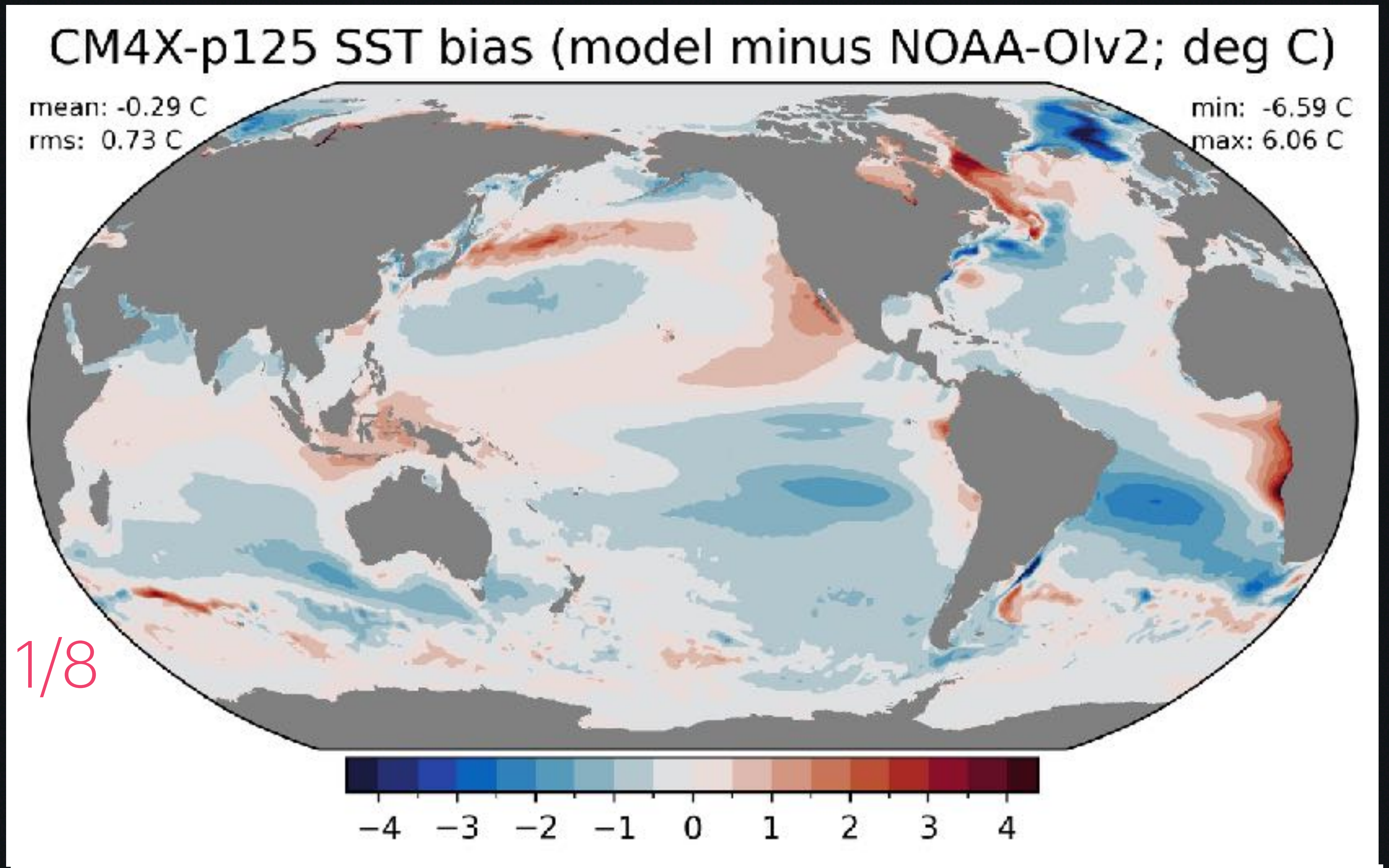
- CM4X-p25: 1000 year piControl + 1850-2014 historical + 2015-2100 SSP-5.85.
- CM4X-p125: 400 years piControl (and still running) + 1850-2014 historical + 2015-2100 SSP-5.85.

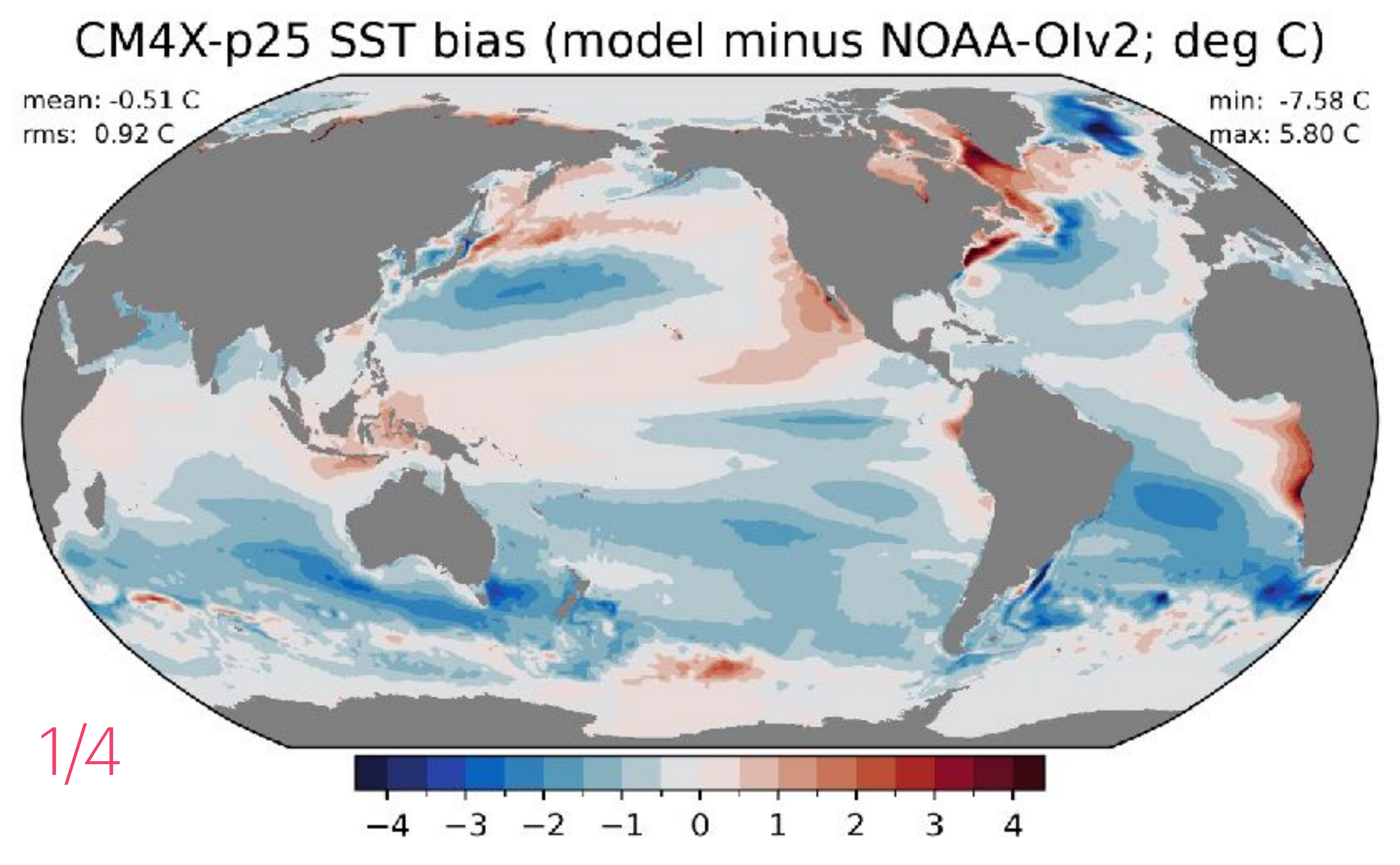
CM4X SST biases in historical

- CM4X-p125 has the lowest SST biases we have ever found in GFDL models.
- 20% bias reduction going from 1/4 to 1/8 degree.

- Hypothesis: enhanced eddy activity reduces the typical cold over warm bias drift found in climate models.
- We found a similar bias reduction in CM2.5/CM2.6 hierarchy with MOM5 in Griffies et al (2015).

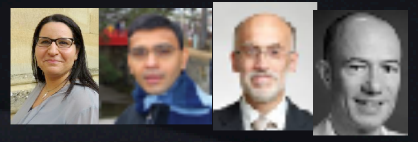
Griffies et al 2024, in prep

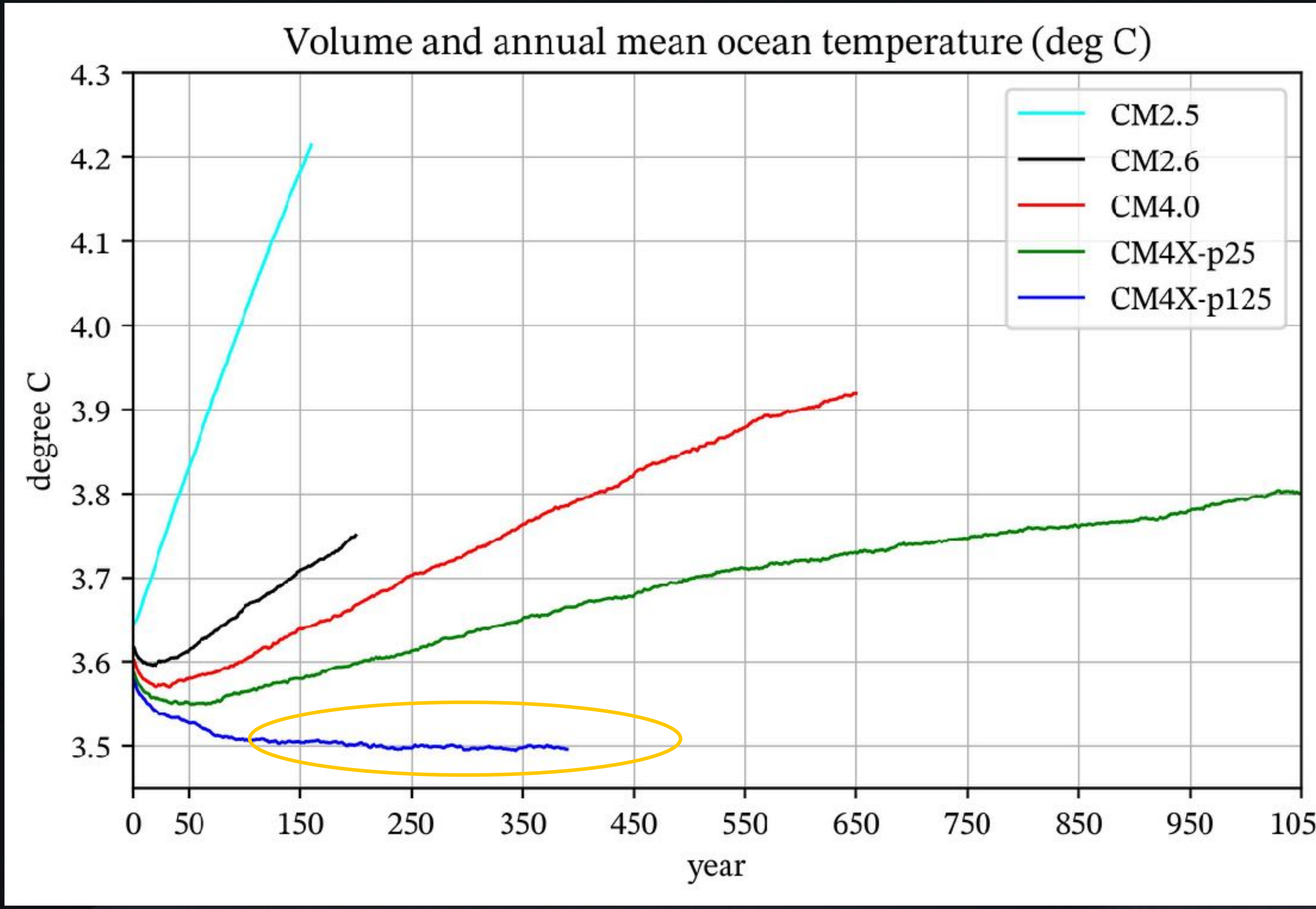




piControl thermal equilibration

Griffies et al 2024, in prep

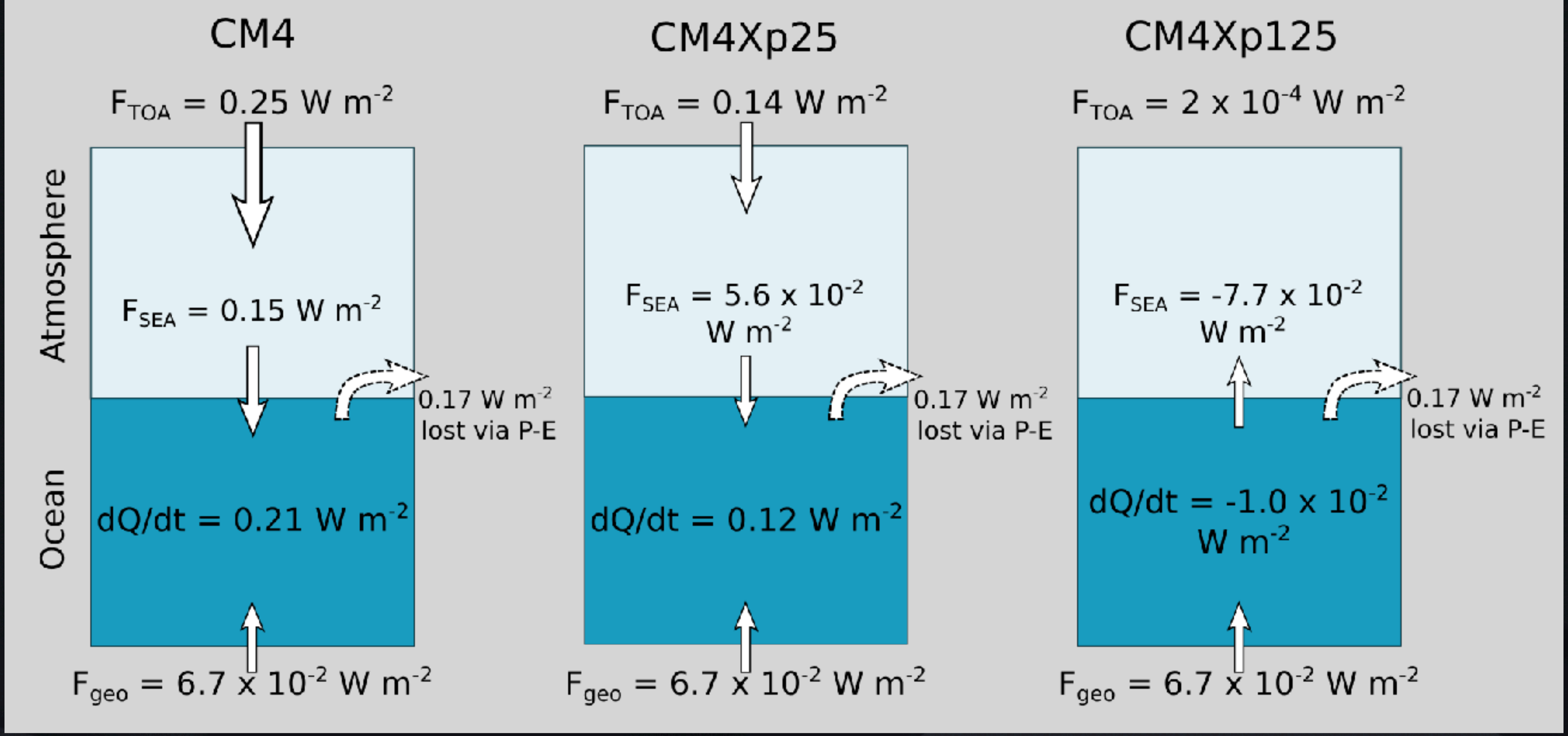
- CM4X-p125 spins up within ~100 years to a steady state with -0.02W/m2 global imbalance
- CM4X-p25 takes ~1000 years, whereas CM2.5 and CM2.6 appear to need even longer (though they are far from equilibrated).
- In the process of equilibrating, CM4X-p125 releases about 400ZJ of heat, which is comparable to the Zanna et al (2019) estimate of anthropogenic heat uptake since 1870. 
- All models that have a piControl temp greater than initial conditions are inconsistent with ocean measurements. So CM4X-p125 is the only consistent model among this batch.



piControl: an instantaneous cooling experiment

- piControl experiment needs to extract roughly 150 years of climate warming (since late 1800s).
- Most of this anthropogenic heat is in the upper 1500m of ocean (some is in the deep ocean but that is relatively small).
- There is no fundamental reason the models should take 1000s of years to reach thermal equilibrium.
- Models take 1000s of years if deep diabatic processes are engaged, either via poor params or spurious mixing, during the spin-up.

Global climate enthalpy (heat) budget



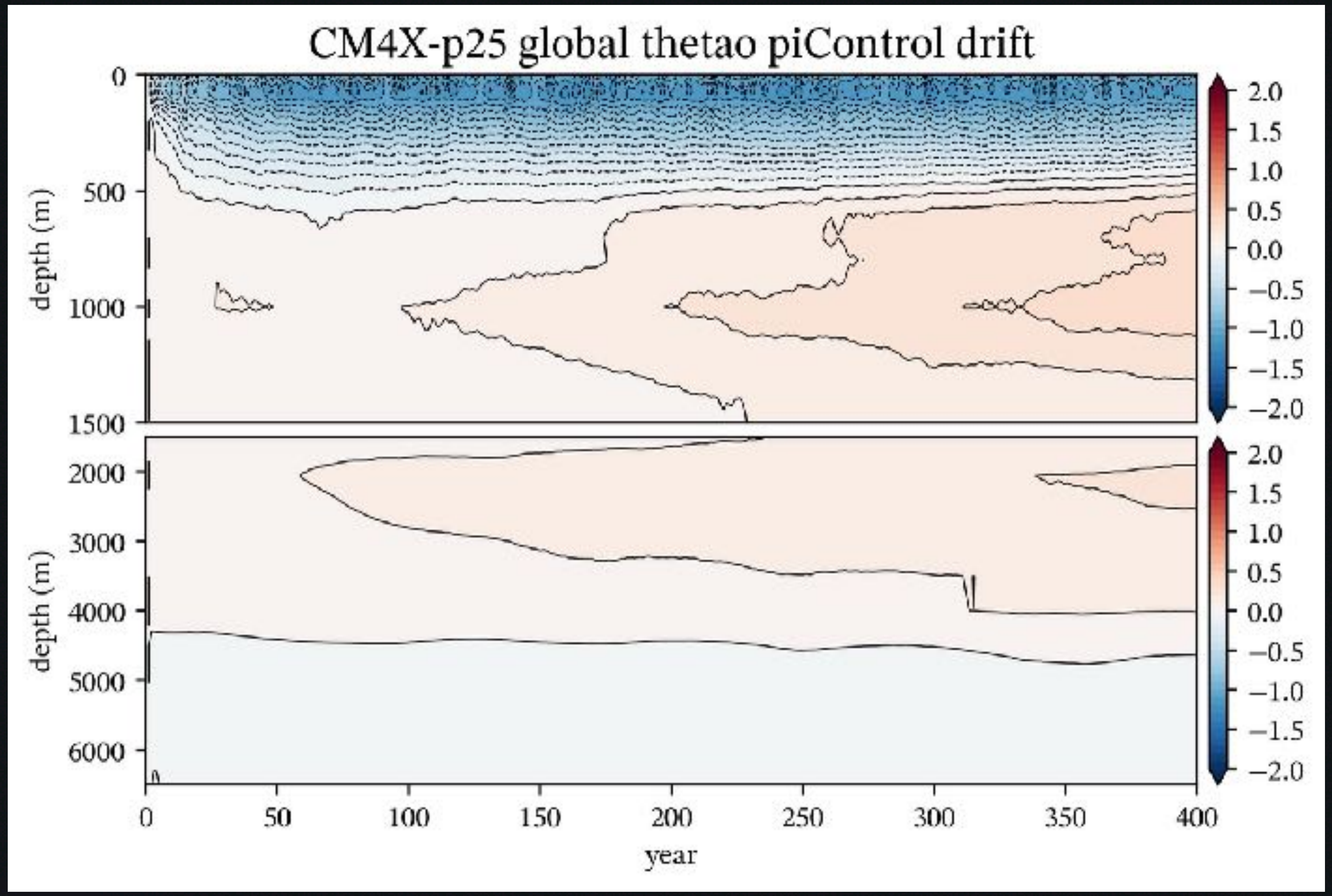
- Ocean thermal equilibration corresponds to global climate equilibration.
- Here are the global heat budgets as time averaged over years 151-350.
- CM4X-p125 is thermally equilibrated whereas CM4.0 and CM4X-p25 are not.

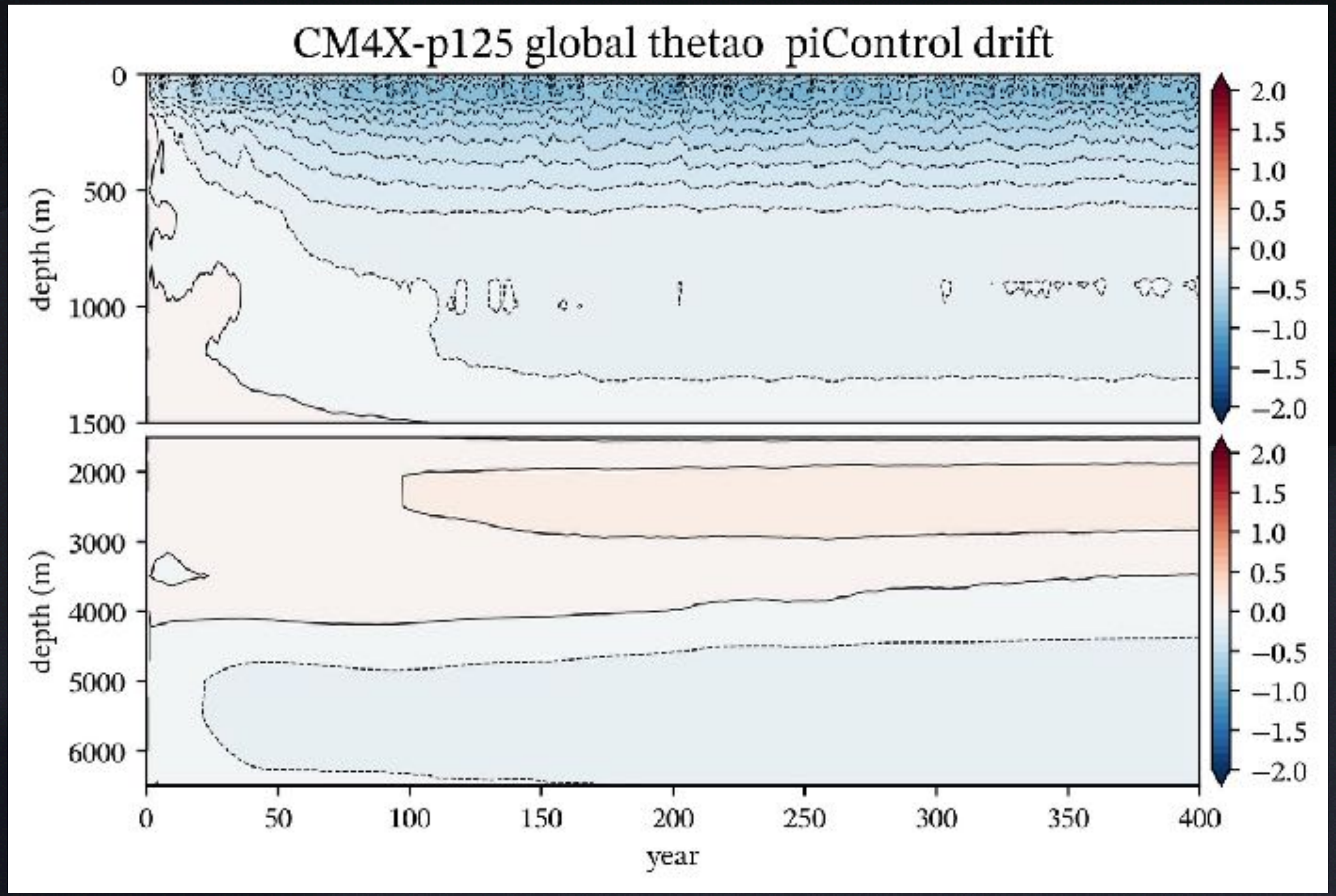
Importance of the piControl

- piControl is the central experiment performed by all CMIP models before running the historical and climate change scenarios.
- 1000s yrs spin up => huge amounts of computational energy and wall clock time.
- 1000s yrs spin up => nontrivial drifts away from realistic ocean.
  - Solutions that drift warmer than present-day are inconsistent with ocean measurements.
  - Few oceanographers are interested in such simulations, which has led to a relative dearth of analysis of CMIP ocean model components.
  - Questions about nonlinear tipping points (e.g., AMOC) are far more satisfyingly studied with a low-drift model.

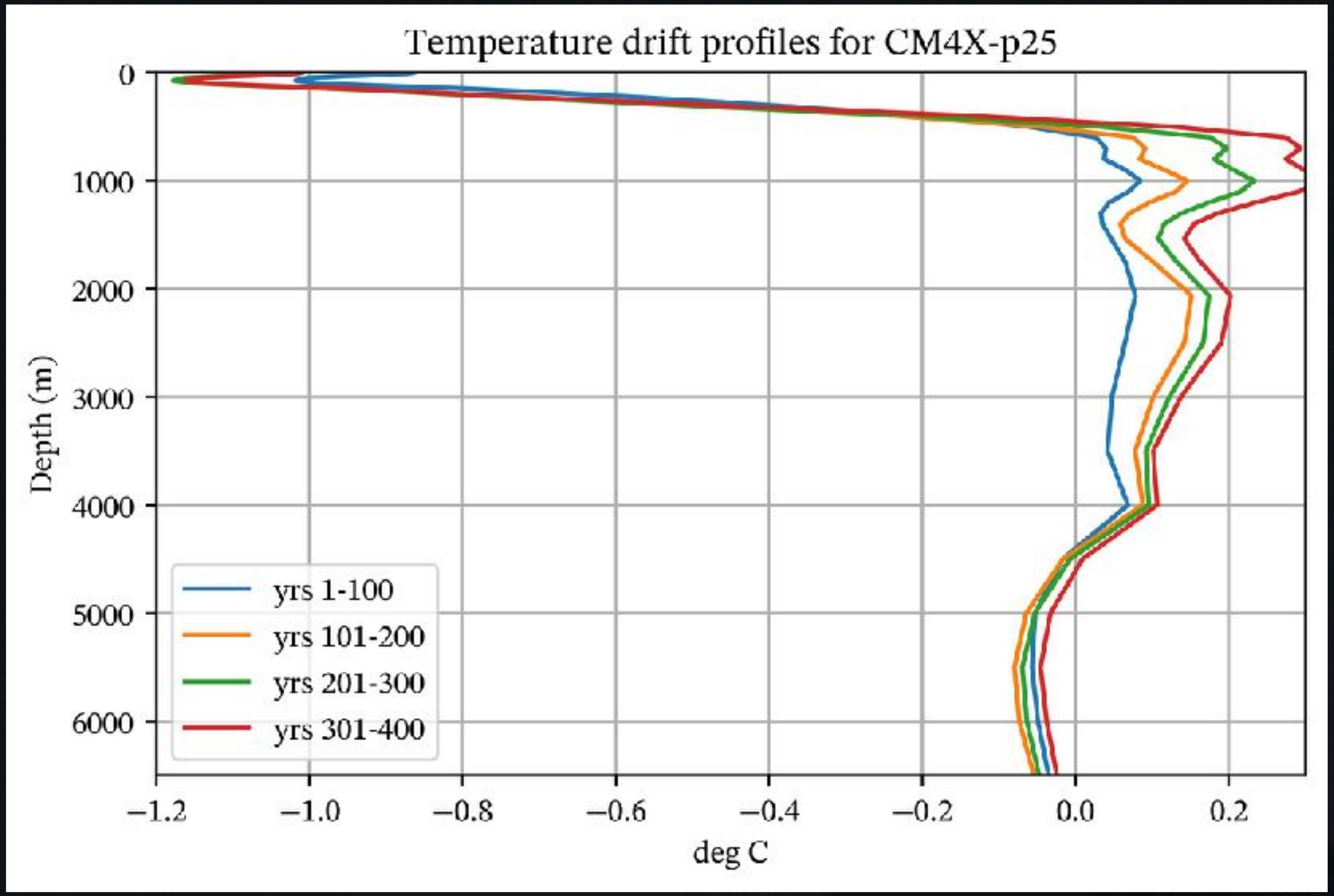
Thermal equilibration: interior drift

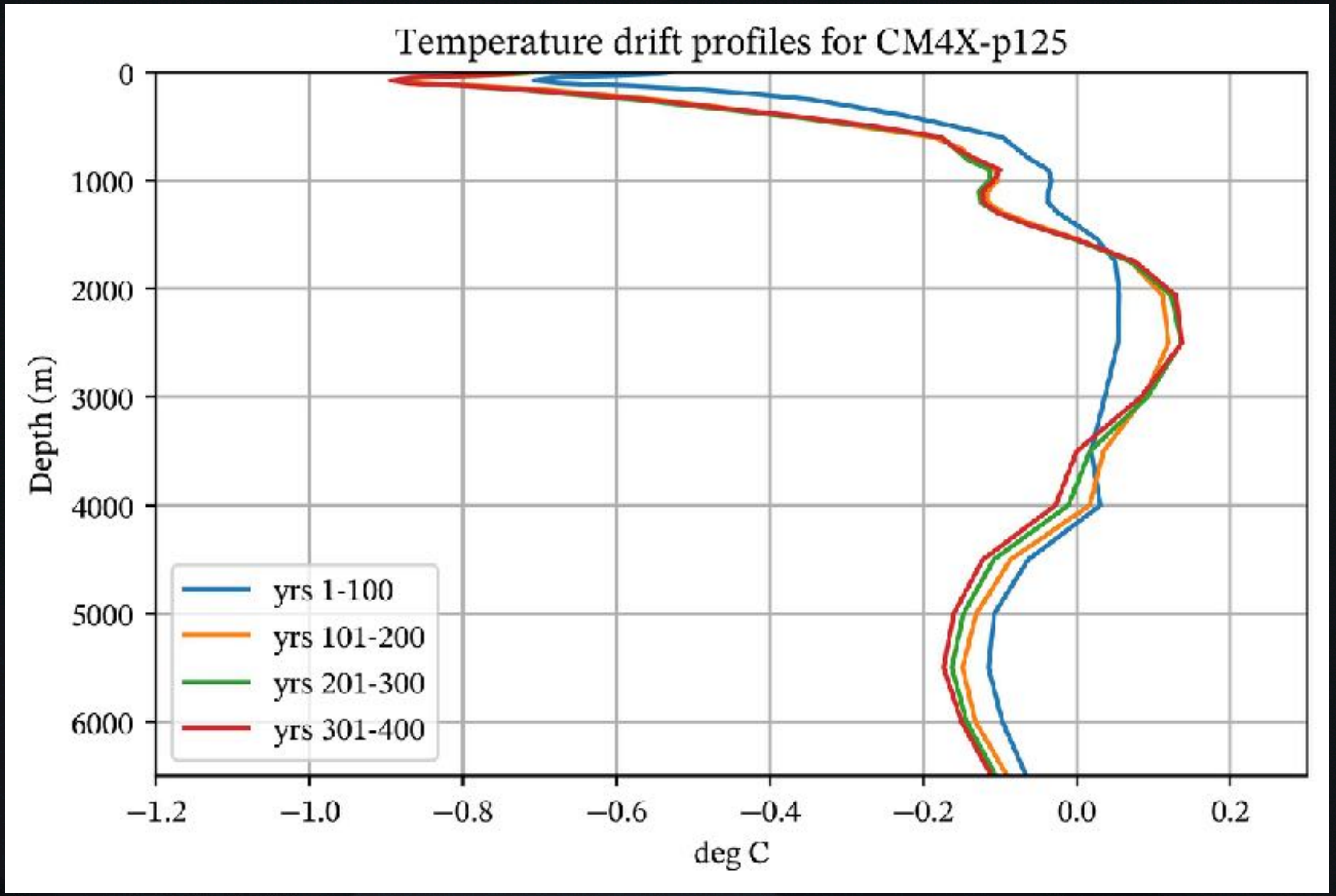
- CM4X-p25 temperature structure continues to drift, with cool over warm.
- In contrast, CM4X-p125 equilibrates after ~150 years and stays generally constant for remaining years.





Thermal equilibration: temp stratification drift



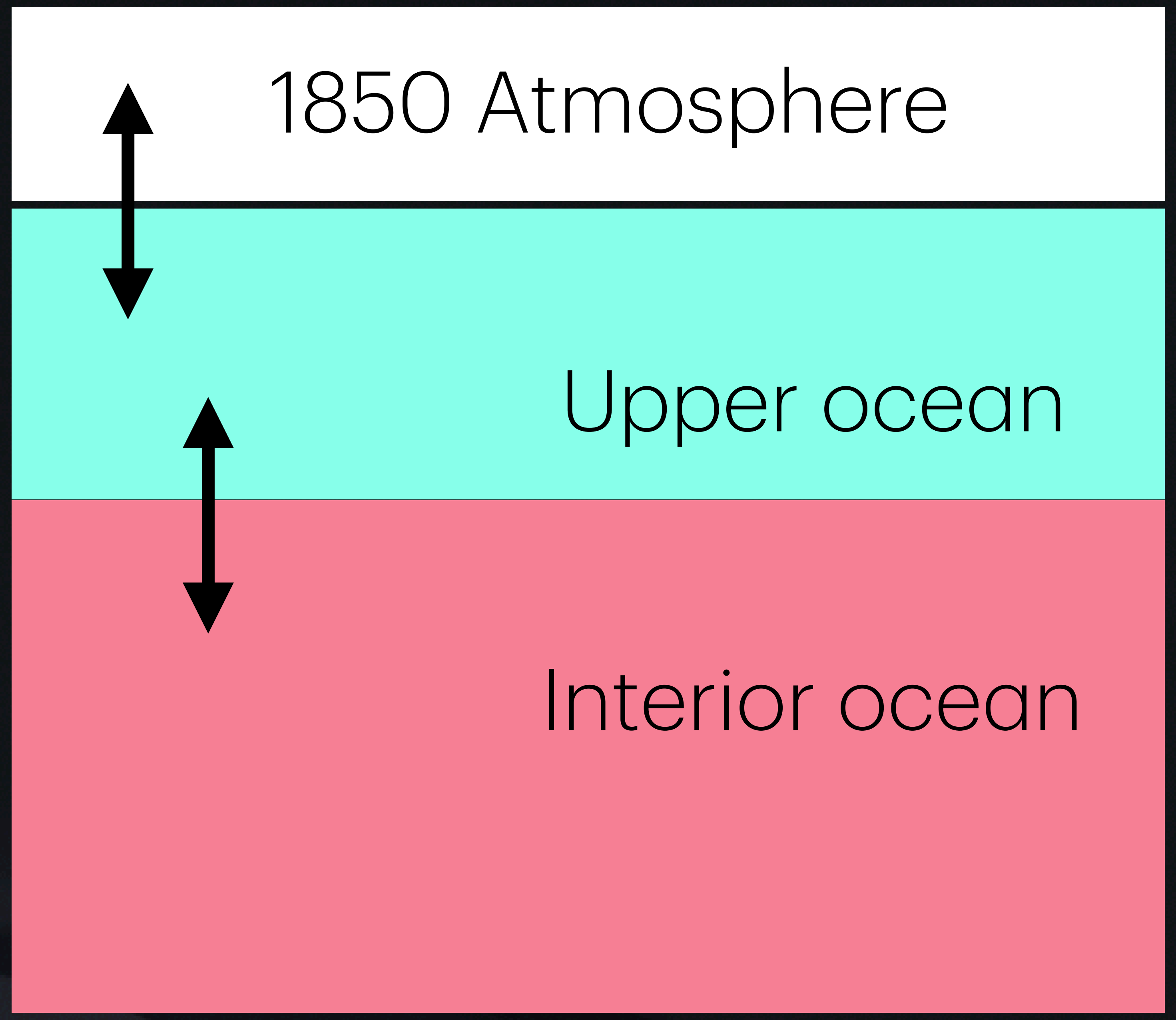


- CM4X-p25 temperature profile continues to drift, with cool over warm so to reduce vertical stratification.
- CM4X-p125 equilibrates after ~150 years and stays generally constant for remaining years.

Griffies et al 2024, in prep

Basics of piControl thermal equilibration

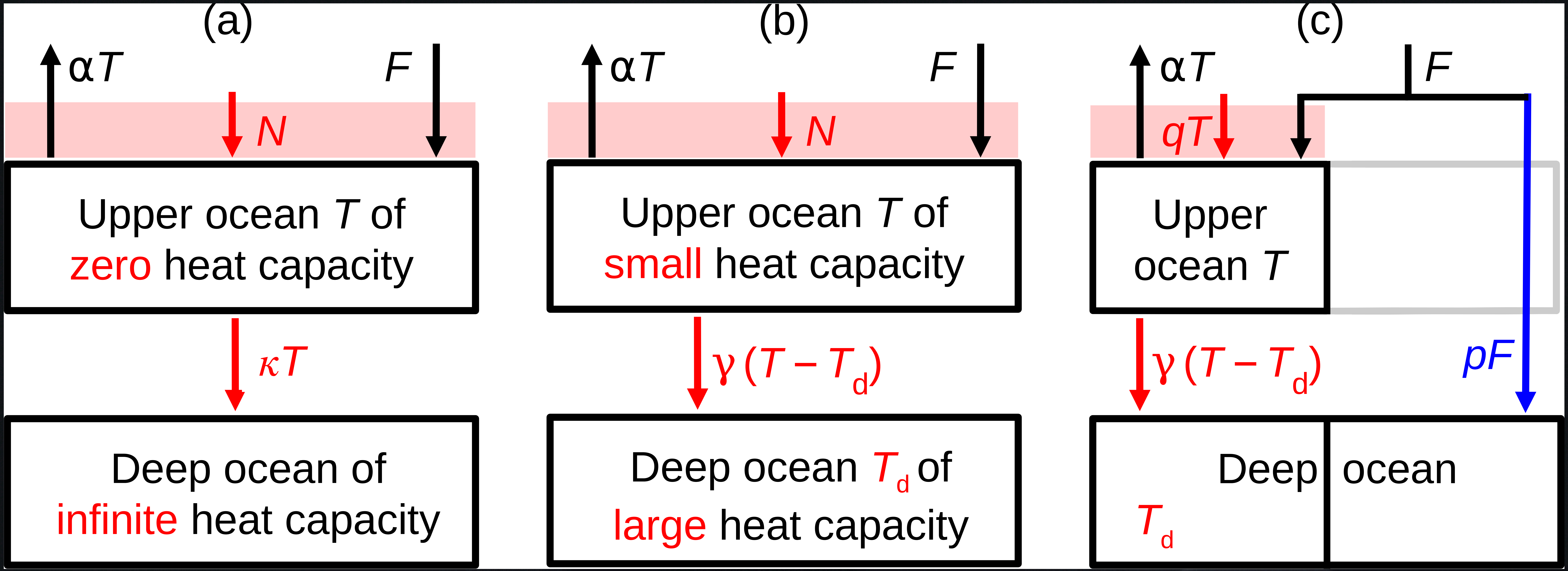
- At start of the experiment, SST cools due to return to 1850 pre-industrial atmosphere.
- This cooling reduces upper ocean vertical stratification and so increases vertical exchange with ocean interior.
- Upper ocean transfer processes mix the relatively warm surface water into the interior*, thus warming the interior. (*Even though surface is cooling due to 1850 forcing, it is still warm relative to interior.)
- Conversely, relatively cool interior waters are mixed to the surface, thus cooling the SSTs.
- An atmosphere, in the presence of relatively cool SSTs, acts to warm the ocean.
- The net effect is an ocean that warms in the global volume mean but in which the upper ocean cools (cooler SSTs) and the interior ocean warms.



Coupled climate models have atmospheres that respond to SSTs.

- Mesoscale eddies strengthen the vertical stratification and so reduce the exchange between upper and interior.
- In effect, active eddies (or an accurate parameterization) throttle the heat exchange to allow for a faster thermal equilibration.

More detailed conceptual models of atm/ocn heat exchange



Gregory et al 2023

- In general, a more engaged deep ocean leads to longer thermal equilibration time and greater net heat uptake.
- Importance of deep ocean is enhanced through large parameterized or spurious diapycnal mixing, and through weak mesoscale eddies.

Mesoscale dominance hypothesis

- Necessary condition for climate models to reach piControl equilibrium in 100s rather than 1000s of years, and for ocean heat released to correspond to the ~400ZJ estimated from Zanna et al 2019:
  - Low levels of spurious numerical mixing (as realized in MOM6 with the Lagrangian remap method)
  - Accurate parameterization of sub grid mixing (i.e., MacKinnon et al picture)
  - High integrity mesoscale transport properties (as realized in CM4X-p125).
- If we can reproduce the 150-year spin up in other models, it will signal a new regime for the routine use of eddying ocean climate models.

CM4X shortcomings and ongoing work

- Poor representation of Gulf Stream: consistent with other models of this class, it seems we need ~5km grid spacing (work by Eric Chassignet), and we are not there yet.
- Poor representation of ENSO: typically a coupled issue, but some suggestions that we modified ocean mixing in a manner that damped tropical variability.
- Poor representation of North Atlantic overflows: the hybrid coordinate in weakly stratified regions is largely z-coordinate, and z-coord has well known problems with spurious mixing in overflow regions.
- Poor representation of the Southern Ocean mode and intermediate waters, likely due to next point.
- Eddy parameterizations remain "in the works" for the "gray zone" of mesoscale eddy admitting models. Ongoing work for CMIP7 via this CPT.
- CM4X has no ice shelves, and that is a primary focus of ongoing GFDL (and community) development.

But CM4X has some very promising features

- The 1/8 degree CM4X-p125 has minimal thermal drift in its piControl, and as such it offers an opportunity to study the ocean climate within the context of a realistic eddying coupled model.
    - An eddying model that is actually better for water masses than a non-eddying model.
    - Perhaps this result is the first of its kind…(NCAR folks?)
- The Southern Ocean simulation is particularly promising given the removal of the pesky super-polynyas found in CM4.0 (and in some other climate models).
- There are improvements in the overall climate state, though, again, there are (as always) limitations that prompt ongoing work.

Summary points

- Stirring and mixing of ocean tracers are key processes that affect how the ocean works as part of the climate system.
- Ocean models need to provide accurate parameterizations and/or representations of the zoo of stirring/mixing processes.
- Models also need to minimize their spurious levels of mixing in order to maintain accurate representations of stratification.
- Methods matter, with the vertical Lagrangian-remap method favored by GFDL/MOM6 along with an isopycnal-geopotential hybrid vertical coordinate (inspired by HYCOM).
- The CM4X-p125 climate model provides one example of an approximately ``mesoscale dominant'' model whose piControl thermally equilibrates within roughly 150 years after releasing about 400ZJ of heat, both of which accord with estimates of the natural world.
- Mesoscale dominant models do not solve all problems (e.g., there are biases in boundary currents, overflows).
- But they can result in a 10x faster thermal equilibration for piControl simulations, thus reducing the energy footprint of climate modeling, which is a huge issue with growing needs of fine resolution climate models.
- In particular, when incorporating equilibration time, CM4X-p25 is **more** expensive than CM4X-p125.

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Thanks for your attention!

Views from the Scotia Sea during April/May 2017 from the RRS JC Ross