Cooperative Institute for Modeling the Earth System

A Princeton University and Geophysical Fluid Dynamics Laboratory Collaboration

Ocean heat uptake in the era of eddying models and AI

Presented by Alistair Adcroft
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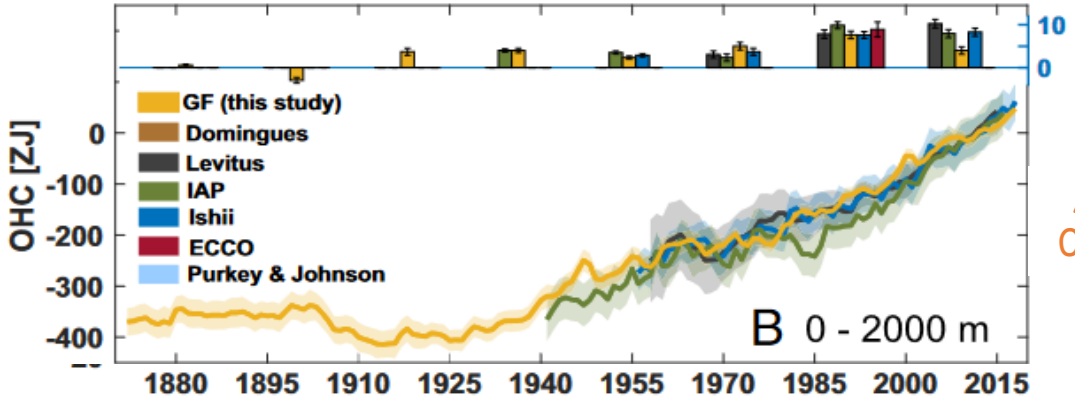
drawing on the works of colleagues and the community

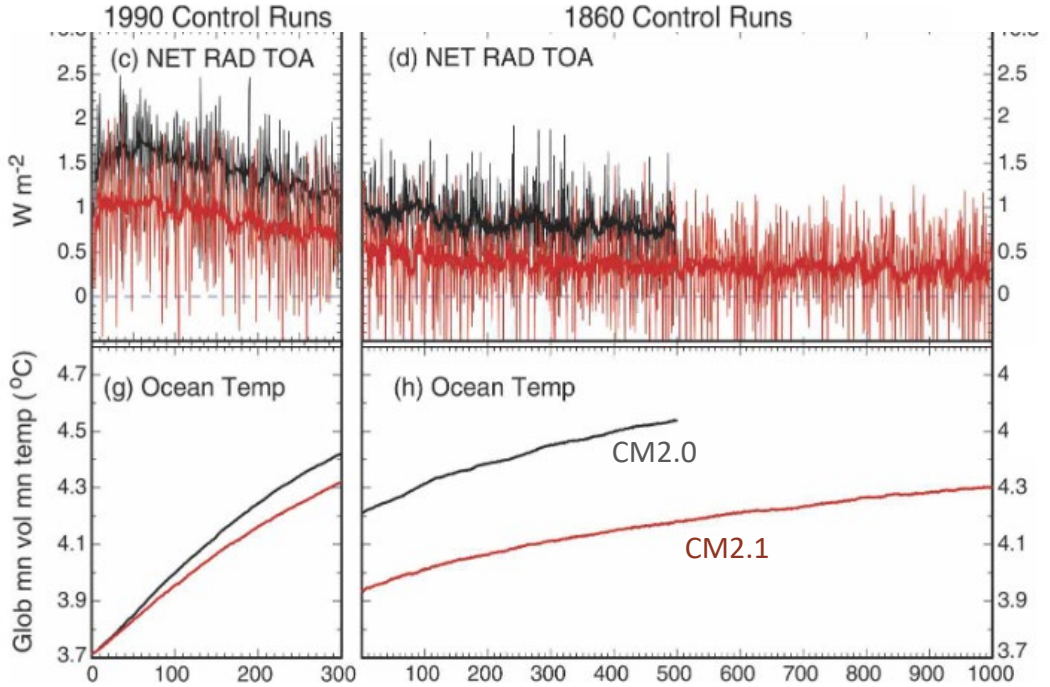
Ocean Heat Uptake in Climate Models

- Most (~90%) of the excess energy stored in the climate system due to anthropogenic greenhouse gas emissions has been taken up by the oceans
- Long term drift is typically due to evolving ocean heat content
- How do can we build a climate model that is in equilibrium for pre-industrial forcings?

  (climate was not in equilibrium but it is a reasonable approximation)

Zanna et al., 2019



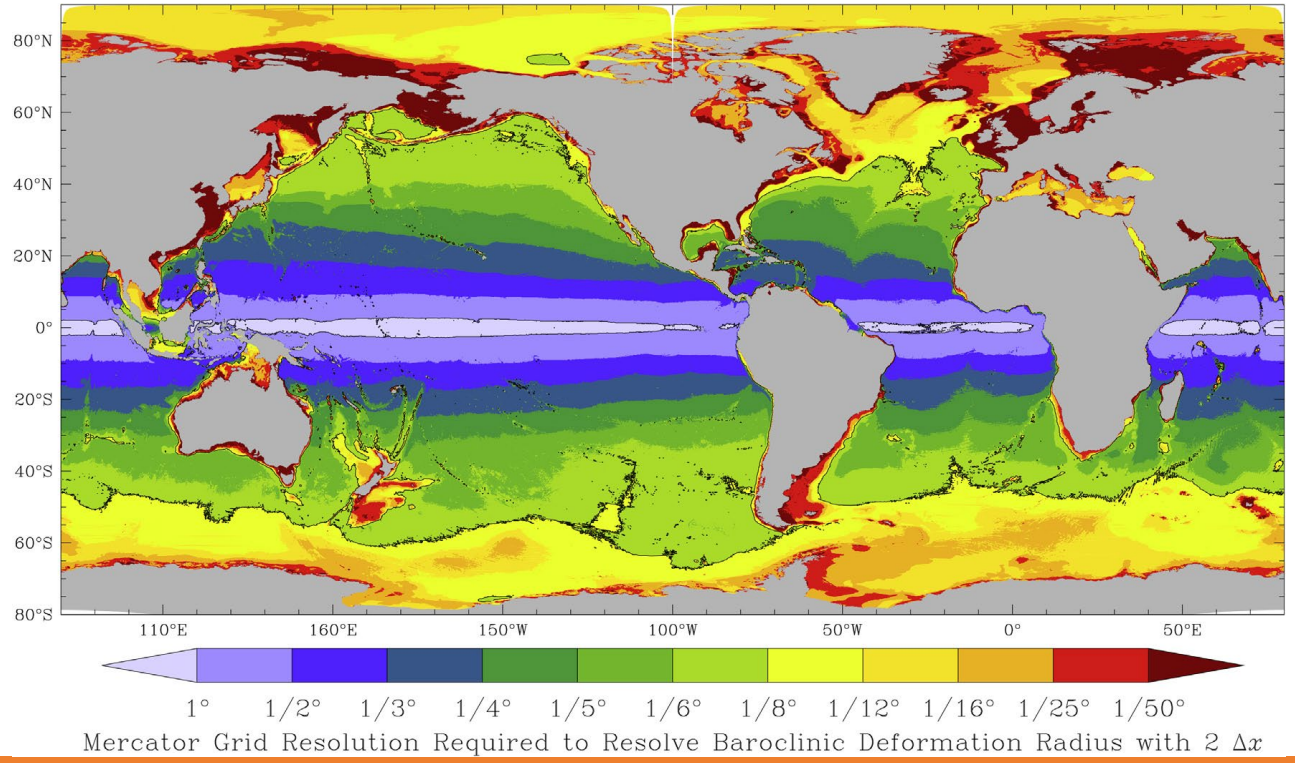


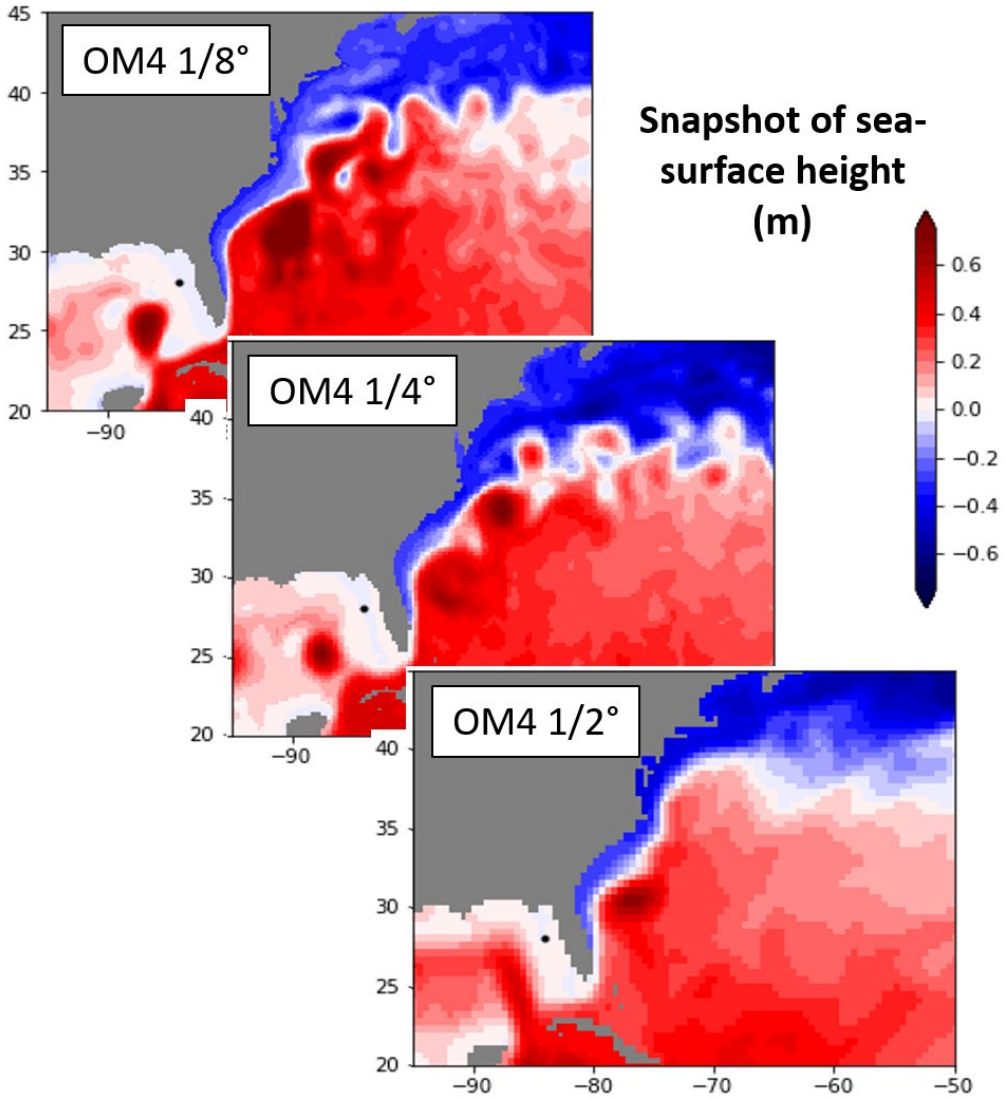
Delworth et al., 2006

“Era of eddying models”

- Ocean models exhibit eddy-like variability at horizontal resolutions finer than around ⅓°
  - “Eddy permitting” – need much finer to resolve eddies well

Hallberg, 2013



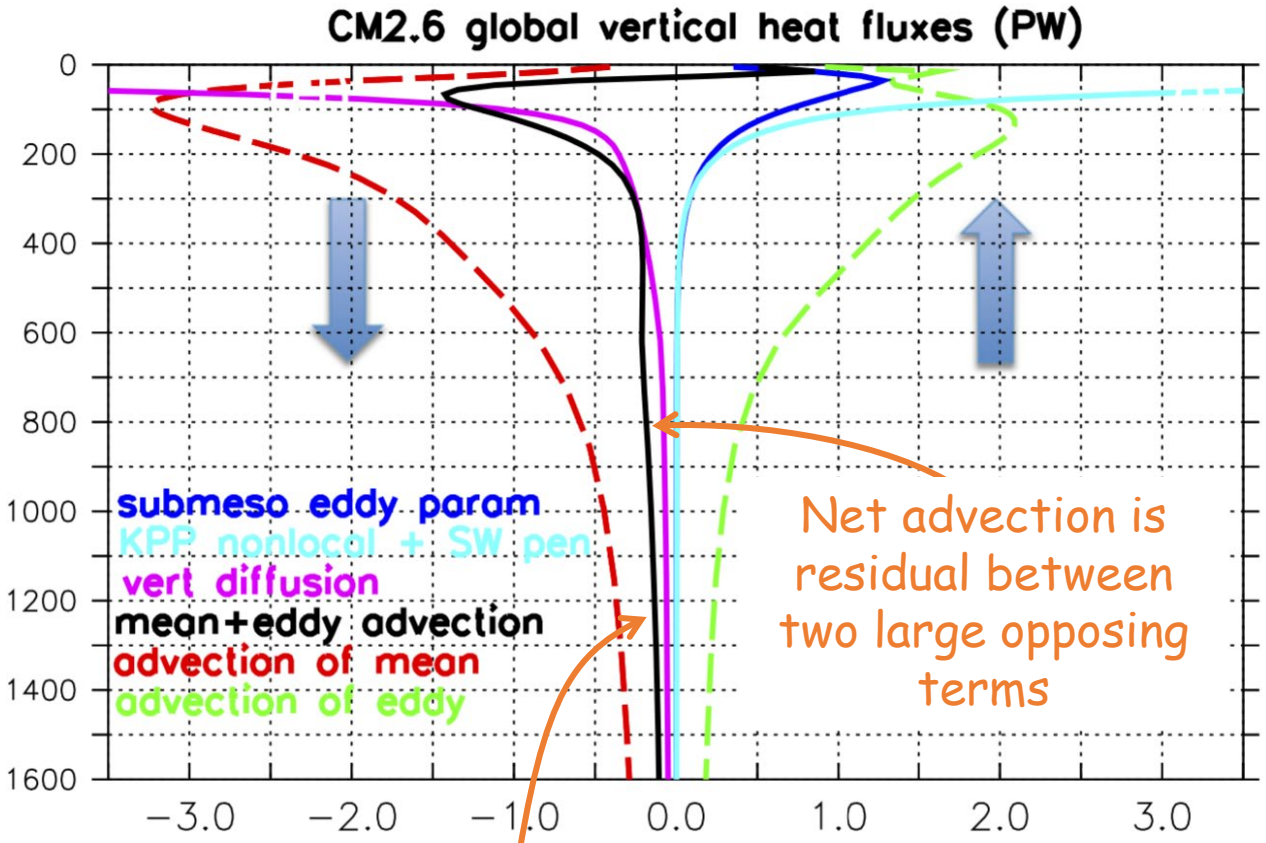


- <¼° OGCMs becoming more routine

How does the ocean take up heat?

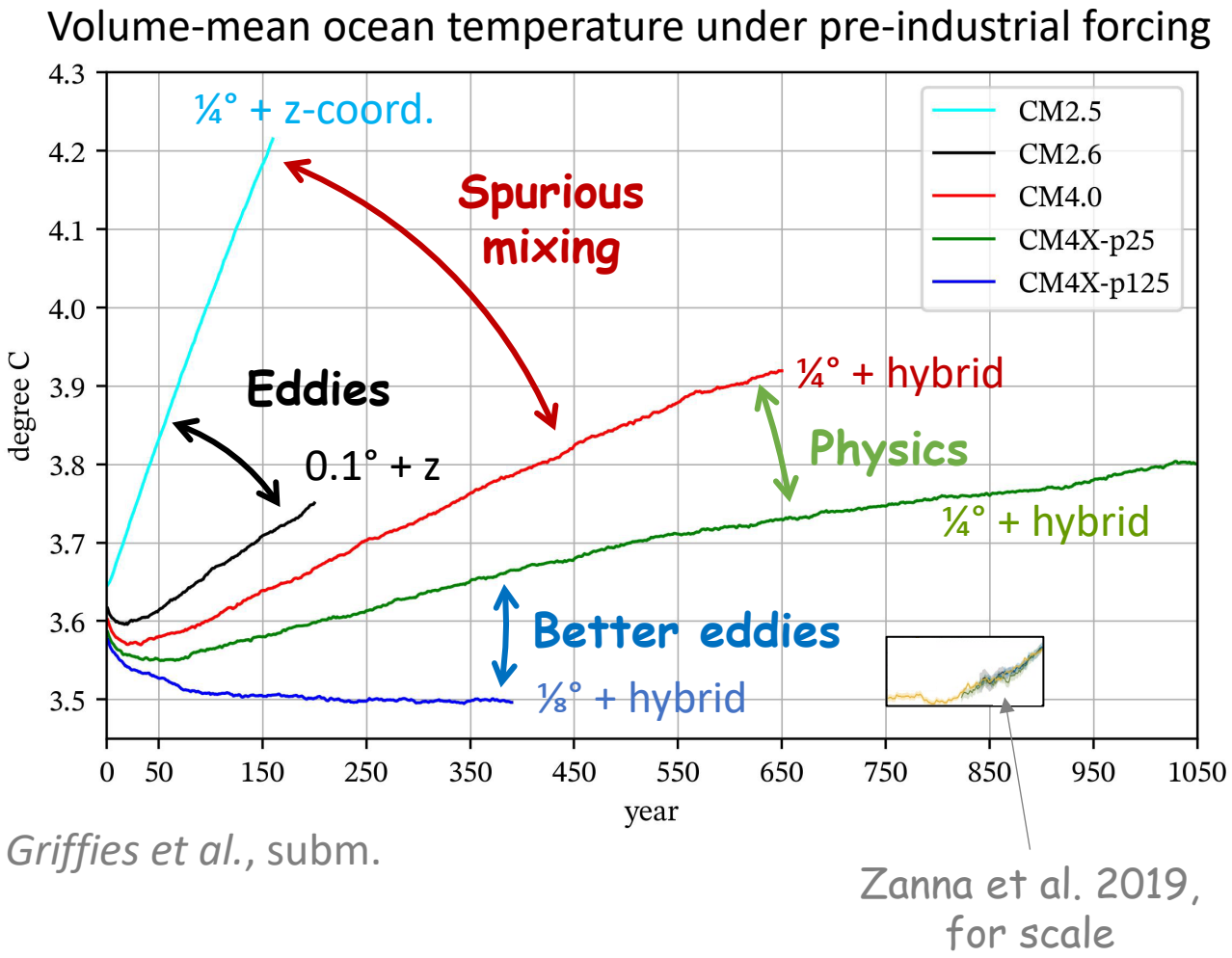
~ 2.8 W m^{-2} over the ocean

- Diagnose vertical fluxes in a $\frac{1}{10}^{\circ}$ global ocean climate model
- Away from surface
  - diabatic mixing (diffusion) leads to downward heat flux
  - heat transport by "mean" circulation is downward
  - heat transport by mesoscale eddies is upward
  - net advection is a small residual and should be upward, but isn't due to numerical errors in advective fluxes



Griffies et al., 2015

Inferring contribution of spurious mixing to OHU



Griffies et al., subm.

Zanna et al. 2019, for scale

- All z-coordinate models: +ve OHU
- Hybrid-coordinate models always reduced OHU relative to z-coord
- Finer resolution reduces OHU
- CM4 (hybrid ¼°) has less OHU than CM2.6 (z, $\frac{1}{10}$°)
- CM4X-⅛° is able to balanced OHU
  - improvements in vertical physics (SBL, BBL)
  - refined resolution (eddies)
  - reduced spurious mixing
  - remarkably: equilibrium time is ~100 years instead of 1000's
  - however, we expect there is still a compensation of errors

Lessons so far …

- The easiest way to get the vertical heat fluxes to balance is to minimize spurious mixing …

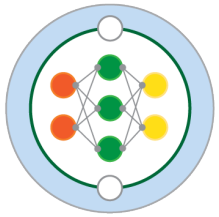
  … which means we should work in isopycnal [isentropic] coordinates as much as possible

- Eddies are important, and resolving them as best we can is beneficial …

  … which means using finer resolution

On ocean emulators

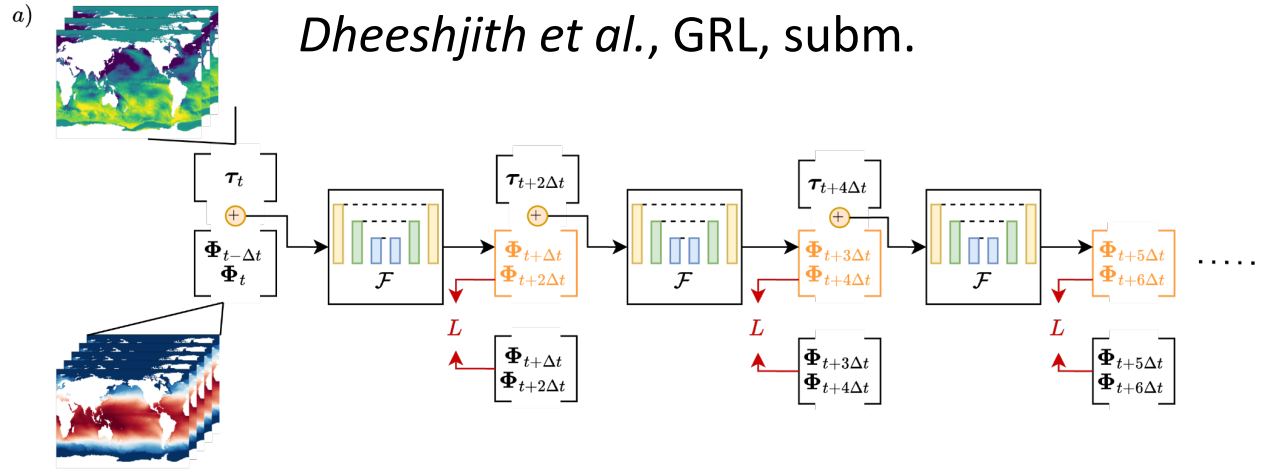
- Emulators offer opportunity for a huge reduction in time-to-solution for ocean state prediction
- Many examples in atmosphere already, with several nascent forecasting efforts for the ocean
  e.g. *Wang et al.*, arXiv 2025
- Samudra:
  - trained on forced ice-ocean (OM4)
  - ¼° data coarsened to 1°
  - 75 hybrid-layers remapped to 19 z-levels (full depth)
  - 60 years of OM4 data, trained on 40 (1975-2014)

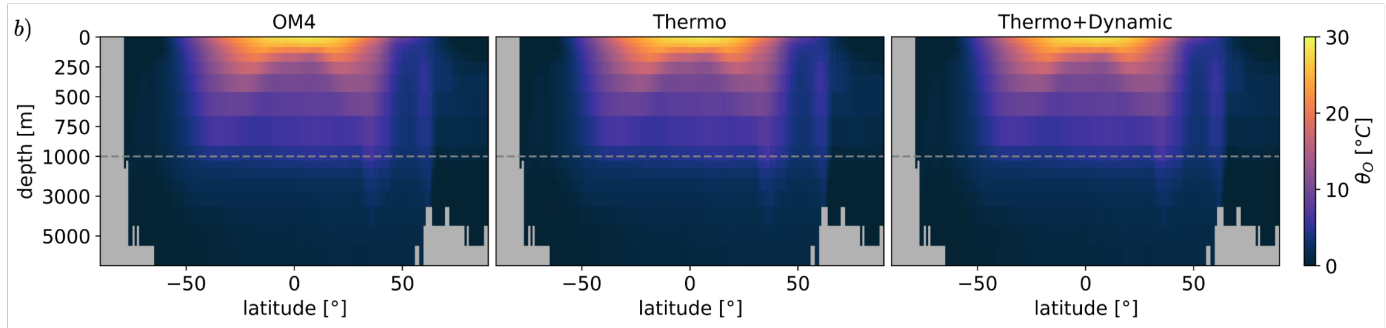


***M²LInES** is led by Laure Zanna and is a VESRI project funded by Schmidt Sciences*

Samudra: An AI Global Ocean Emulator for Climate

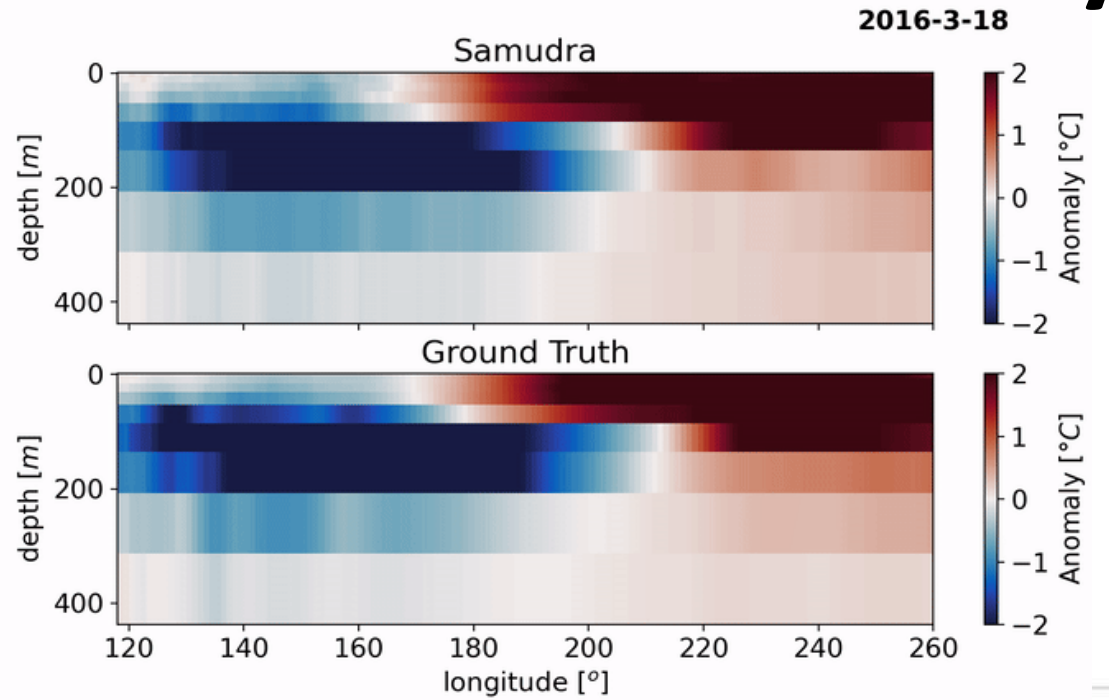
Dheeshjith et al., GRL, subm.

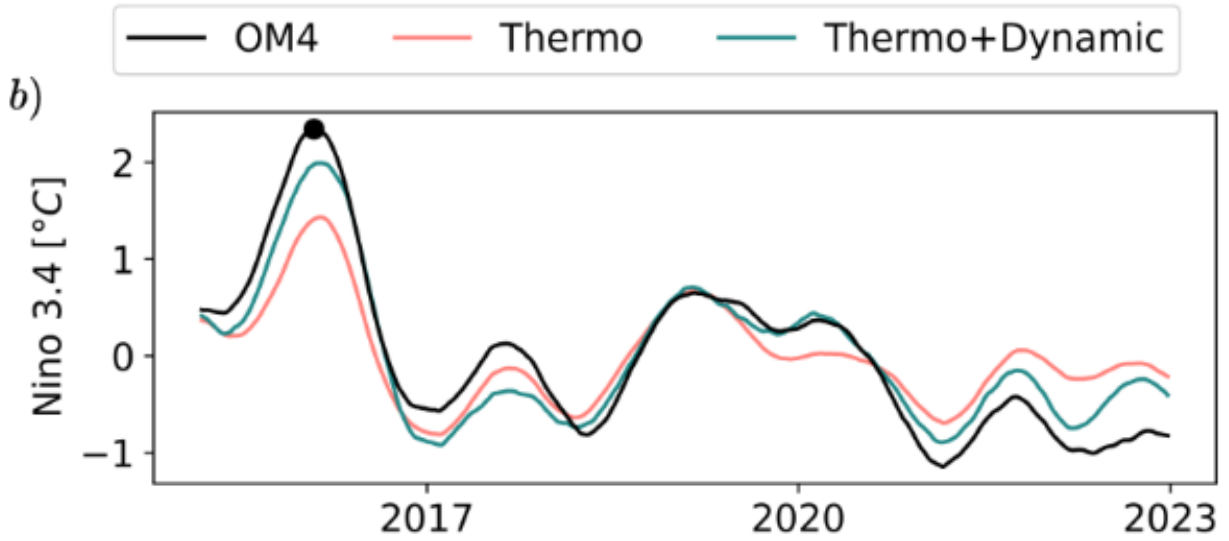


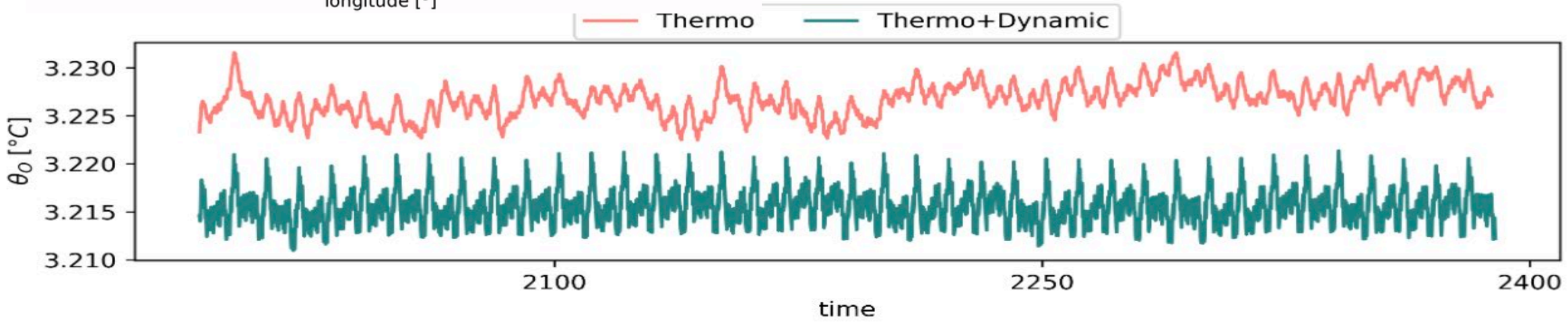


Inference: Variability 2014-2022

Dheeshjith et al., GRL, subm.

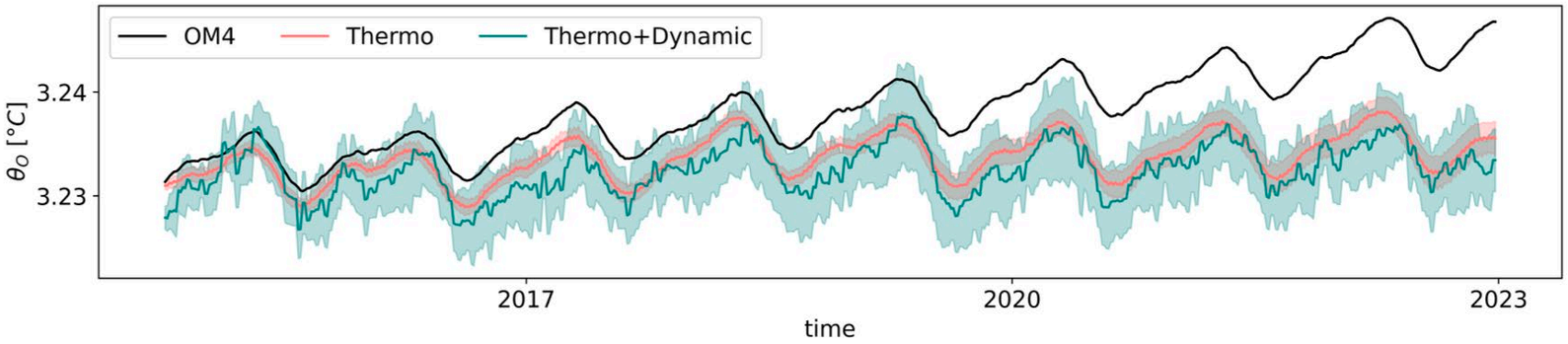






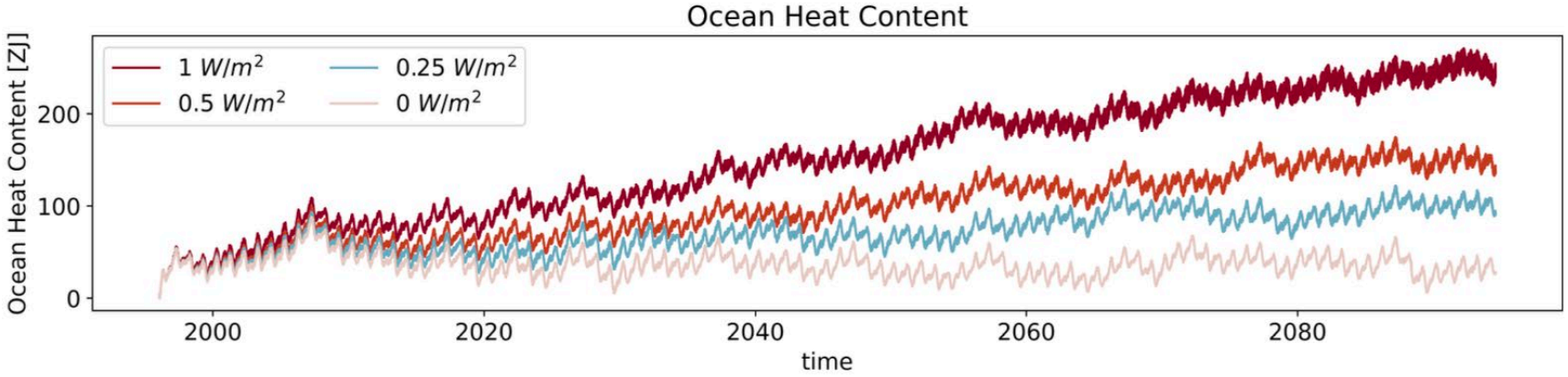
Challenges: Trends & Stability

Dheeshjith et al., GRL, subm.



Test set: very small warming

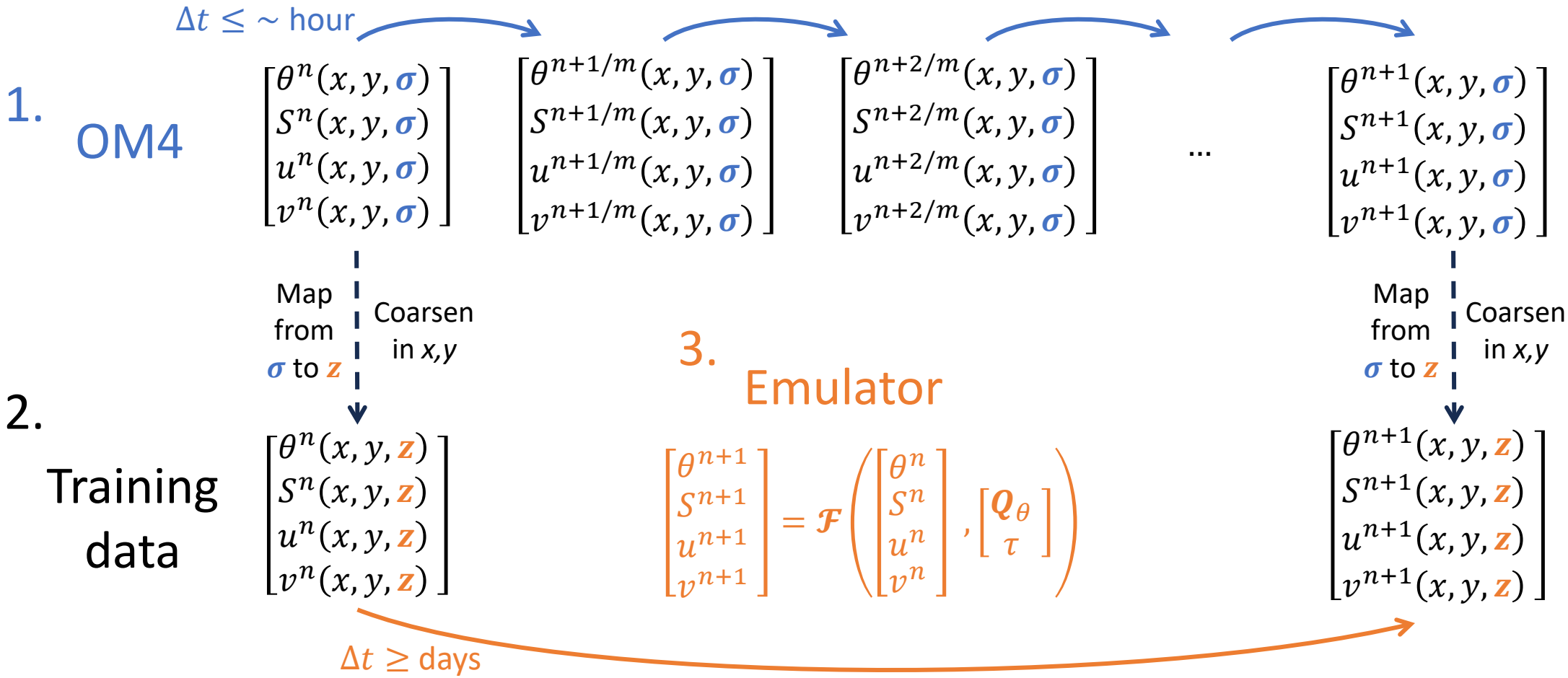
Climate Change (100 year): too weak signal



- we need a training dataset that contains different climates to use for climate change
- Surya Dheeshjith et al. are now collaborating with AI2 to emulate CM4 data

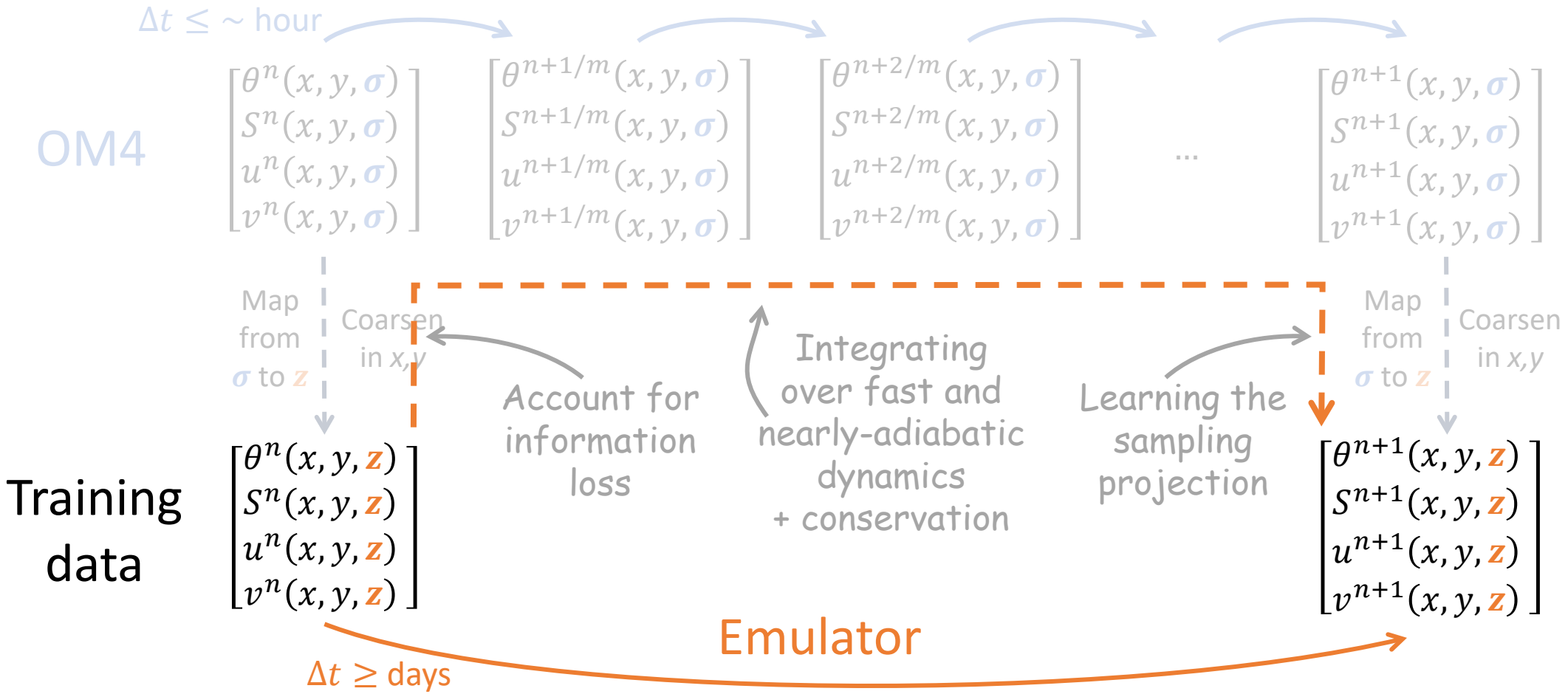
Building an [ocean model] emulator

- Lots effort went into OM4 to make it preserve water masses
- Samudra is not conserving, let alone preserving water masses



Emulators can only learn what is in the data

- Preservation of water masses and conservation should be in the data. How precise should it be, and how much data will it take to learn these properties?



More lessons, and speculation

- Emulators are as good as the data they are trained on
- It seems unlikely they will get ocean heat uptake right for the right reasons without some further attention

- Conservation could be addressed by architecture, adding constraints, …
- Preserving water masses seems hard to achieve without **teaching the emulator to work in isopycnal space**, just as we've learned is needed for OGCMs

Summary

- Resolving eddies appears to help balance newest climate models
  - CM4X-⅛° has a credible, near-zero drift under pre-industrial forcing
  - Crazy short time-scale for reaching equilibration in the physical ocean
- Spurious mixing is still a problem for us, and likely all, models
  - Hybrid coordinates seem necessary for contemporary resolutions
- We should not ignore history when building emulators
  - We typically emulate filtered and vertically re-gridded data
  - This first generation will be useful for many applications (data assimilation, UQ, ensembles), but do not inherently conserve or preserve water masses