How the Ocean Redistributes Heat

Massachusetts Institute of Technology

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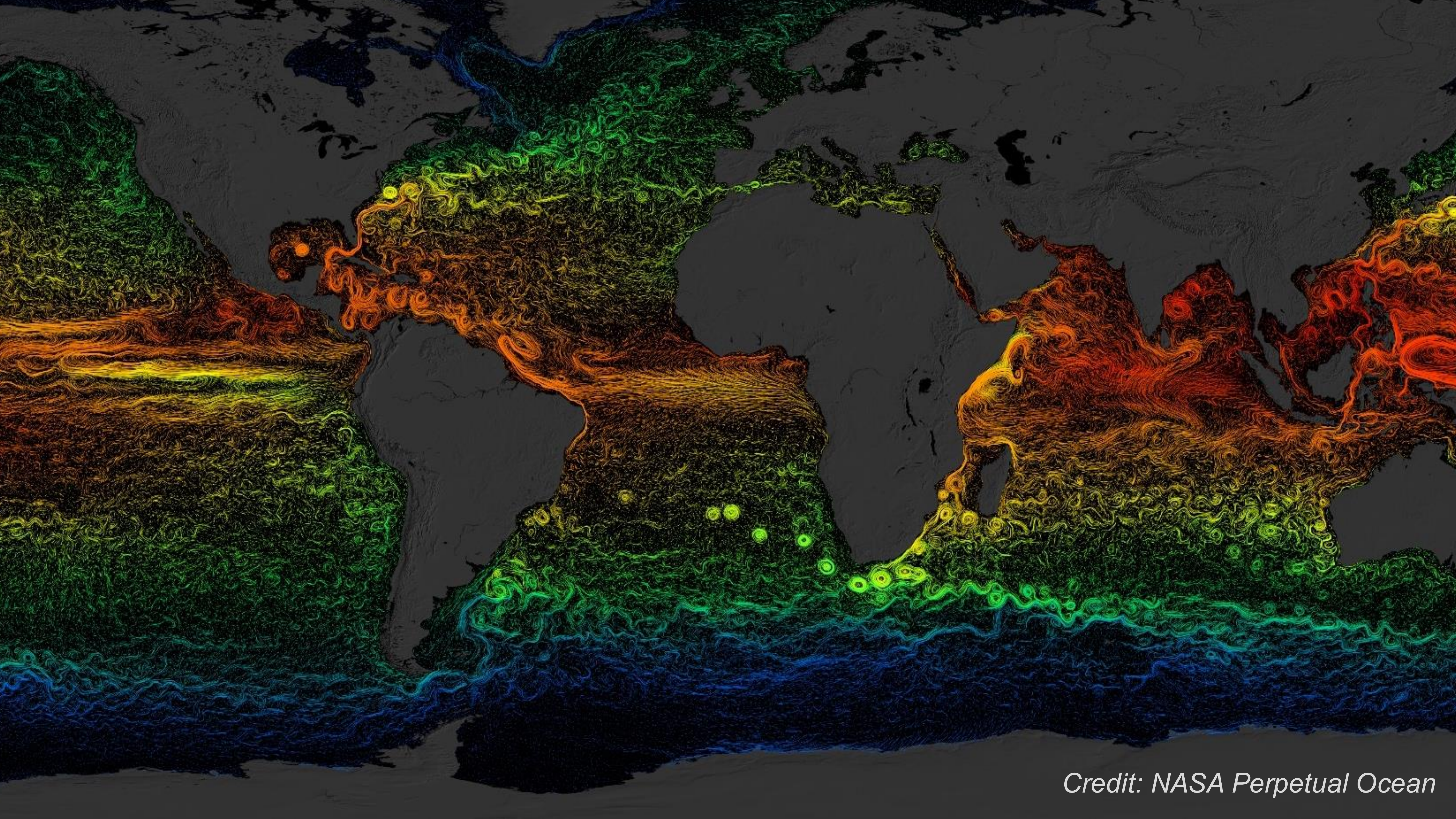
MIT-WHOI Joint Program

AOML/PhOD Seminar

May 19 2026

Credit: NASA Perpetual Ocean


Credit: NASA Perpetual Ocean

Introduction and outline

My Ph.D. thesis focuses on global ocean circulation variability and how it shapes abyssal tracer distributions.

My tools:

- High-res coupled climate models
- Ocean & atmospheric reanalyses
- Satellite & in-situ observations
- Idealized & statistical modeling

1) Background

2) Deep Pacific cooling inferred from 19th century observations

3) Explaining cooling found in the ECCO state estimate

4) Summary & takeaways

The ocean stores and redistributes heat

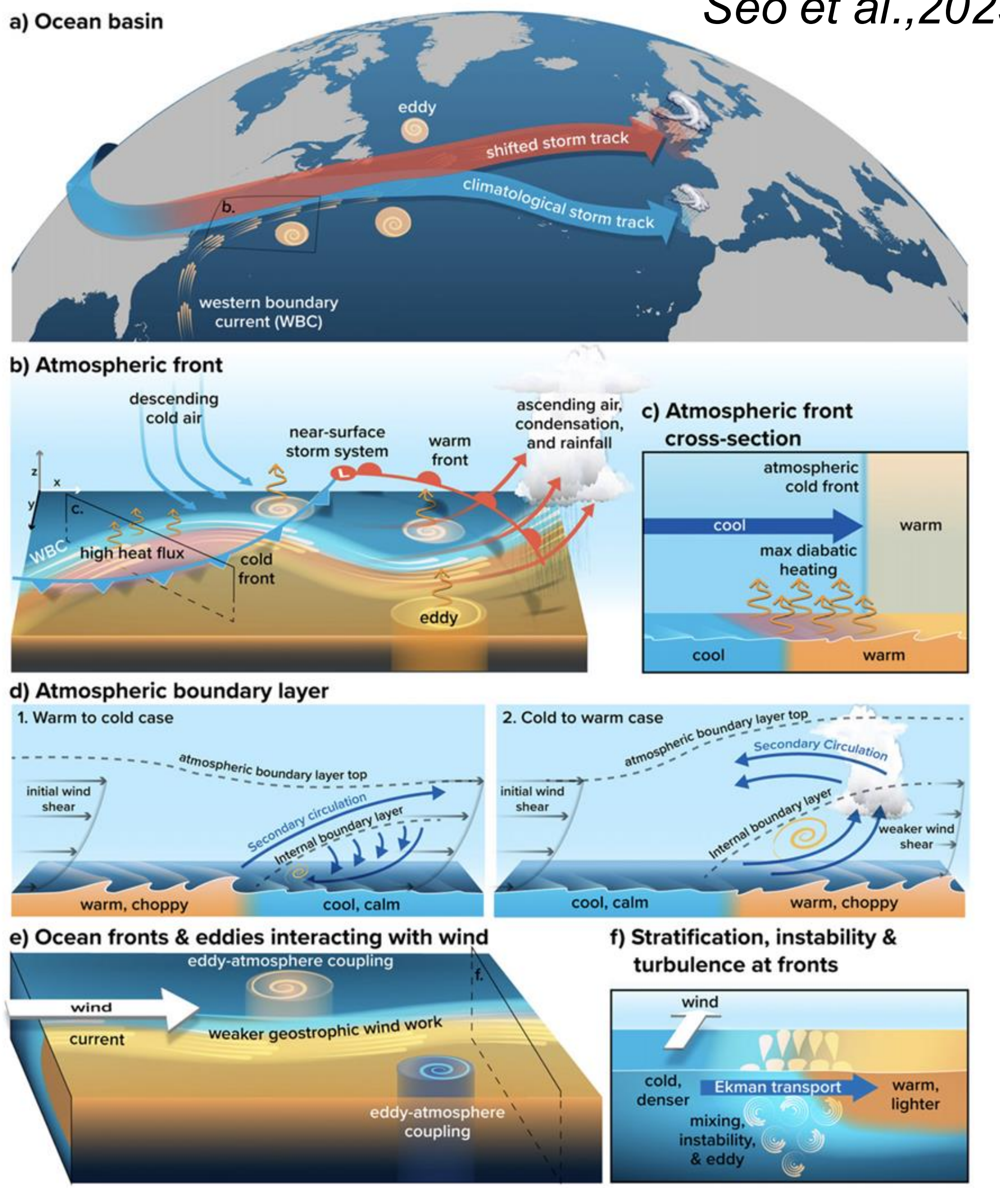
Seo et al.,2023

Heat enters and leaves at the surface

Large-scale currents redistribute heat in the interior

Eddies and turbulence mix heat across gradients

Ocean pathways influence heat re-emergence



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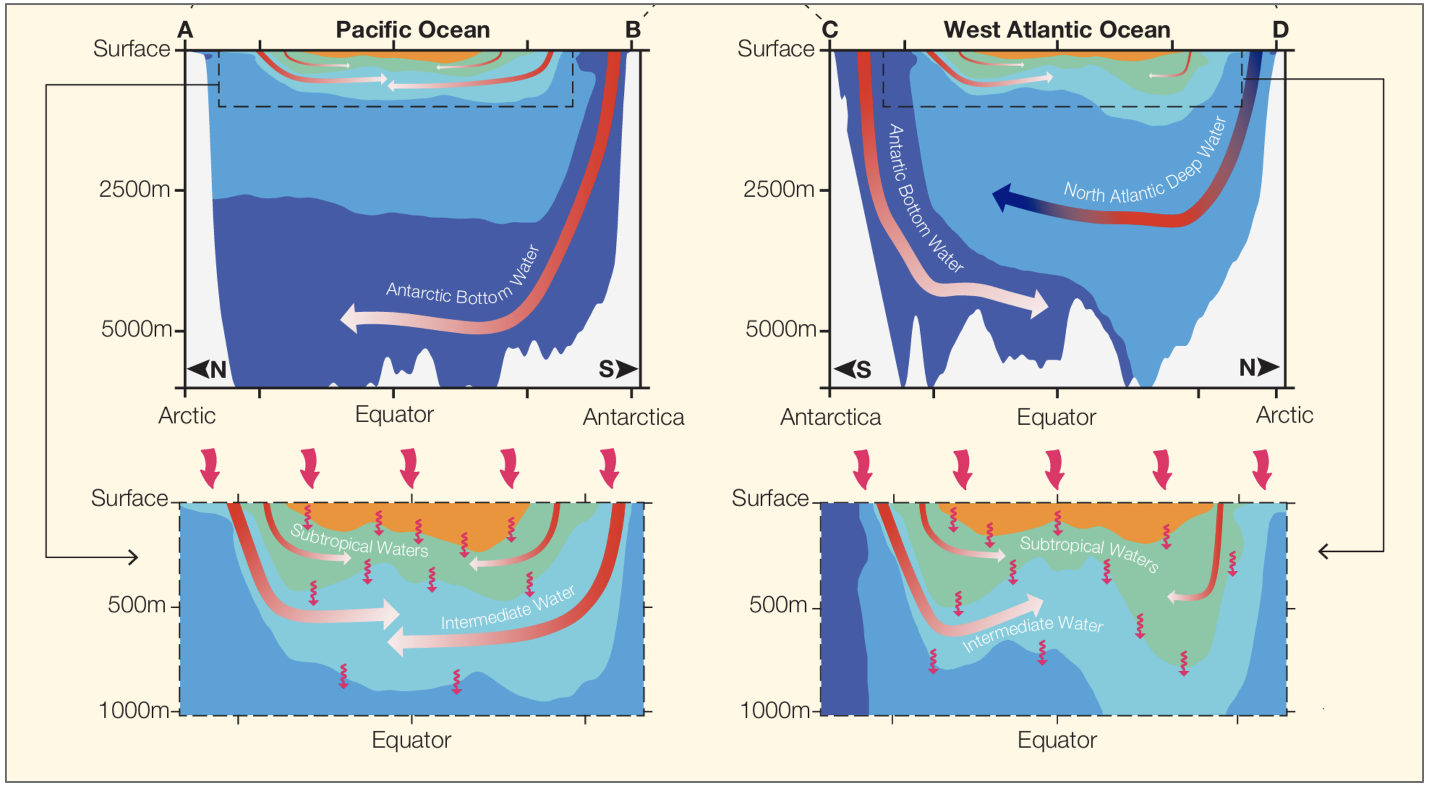

IPCC AR5 FAQ 3.1, Figure 1

The ocean stores and redistributes heat

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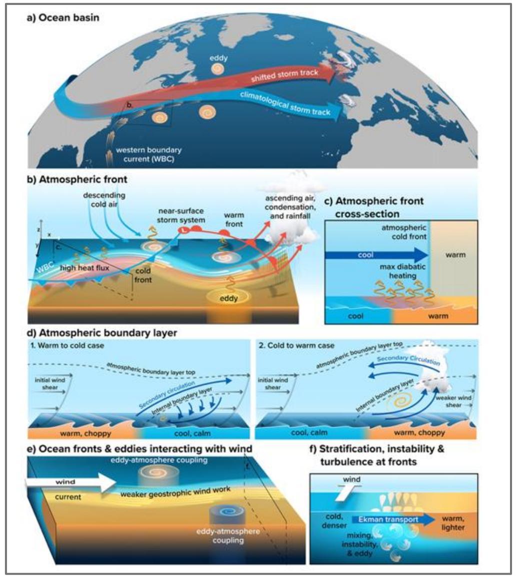
Eddies and turbulence mix heat across gradients

Ocean dynamics influence heat storage and re-emergence



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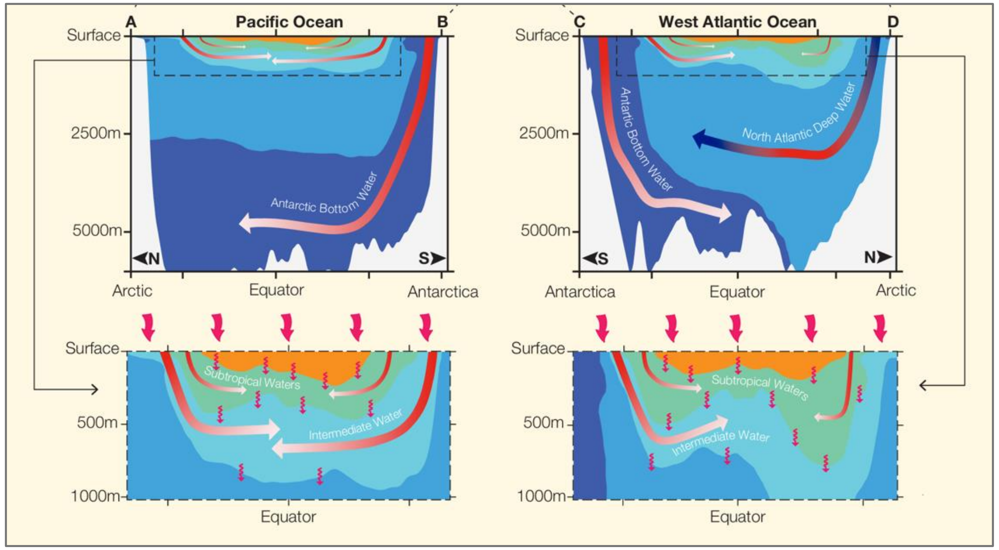

The ocean stores and redistributes heat

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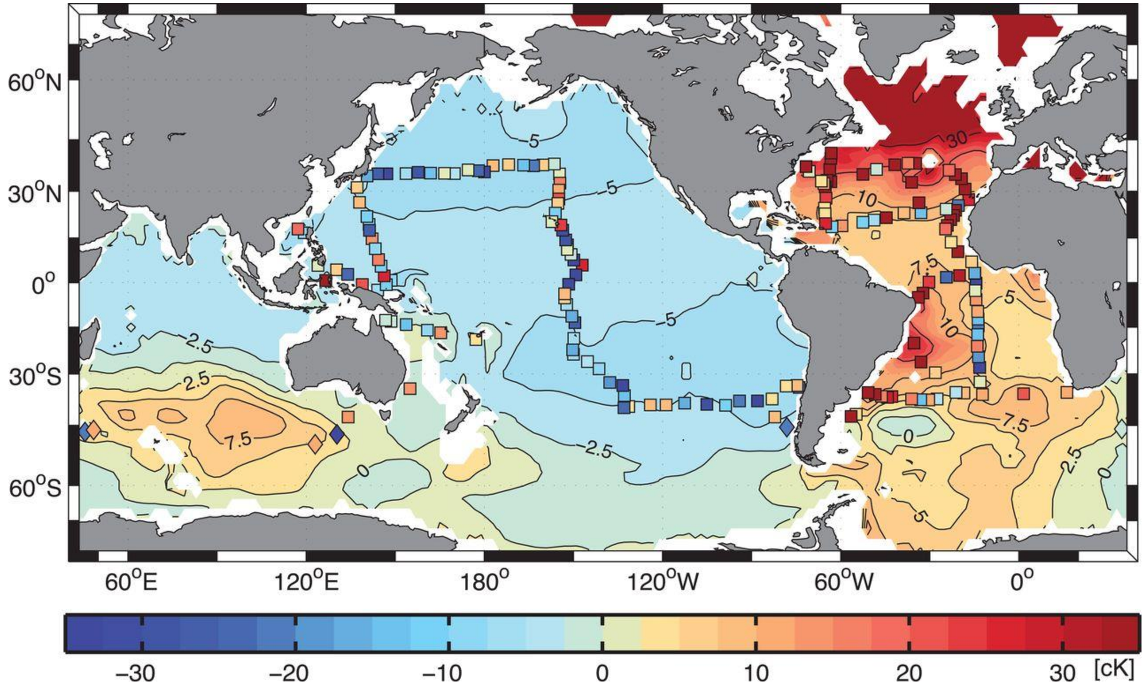
This work

A century of deep ocean temperature trends

Deep temperature differences (1870–1990)

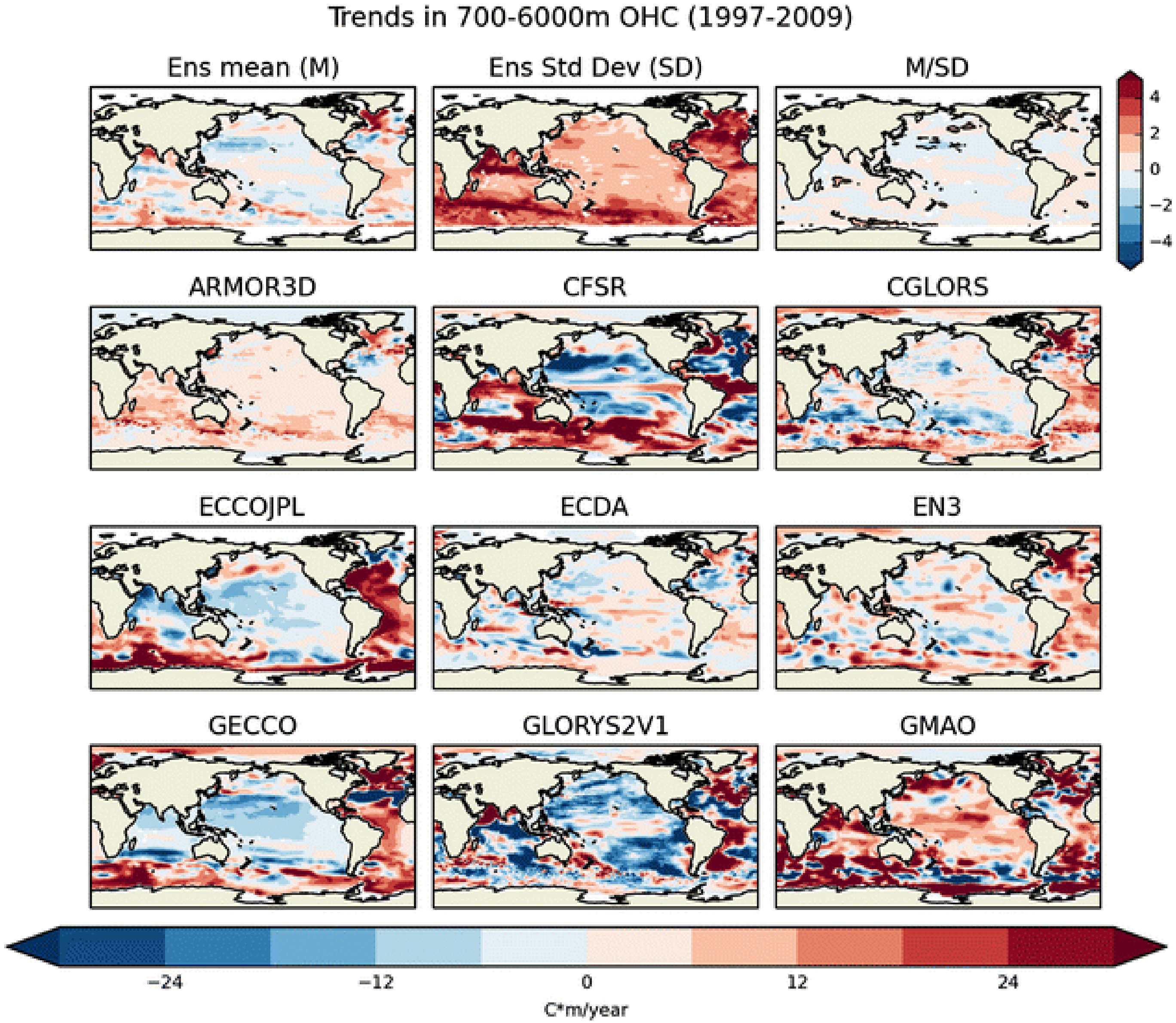


1 cK = 0.01 deg C

Gebbie & Huybers 2019

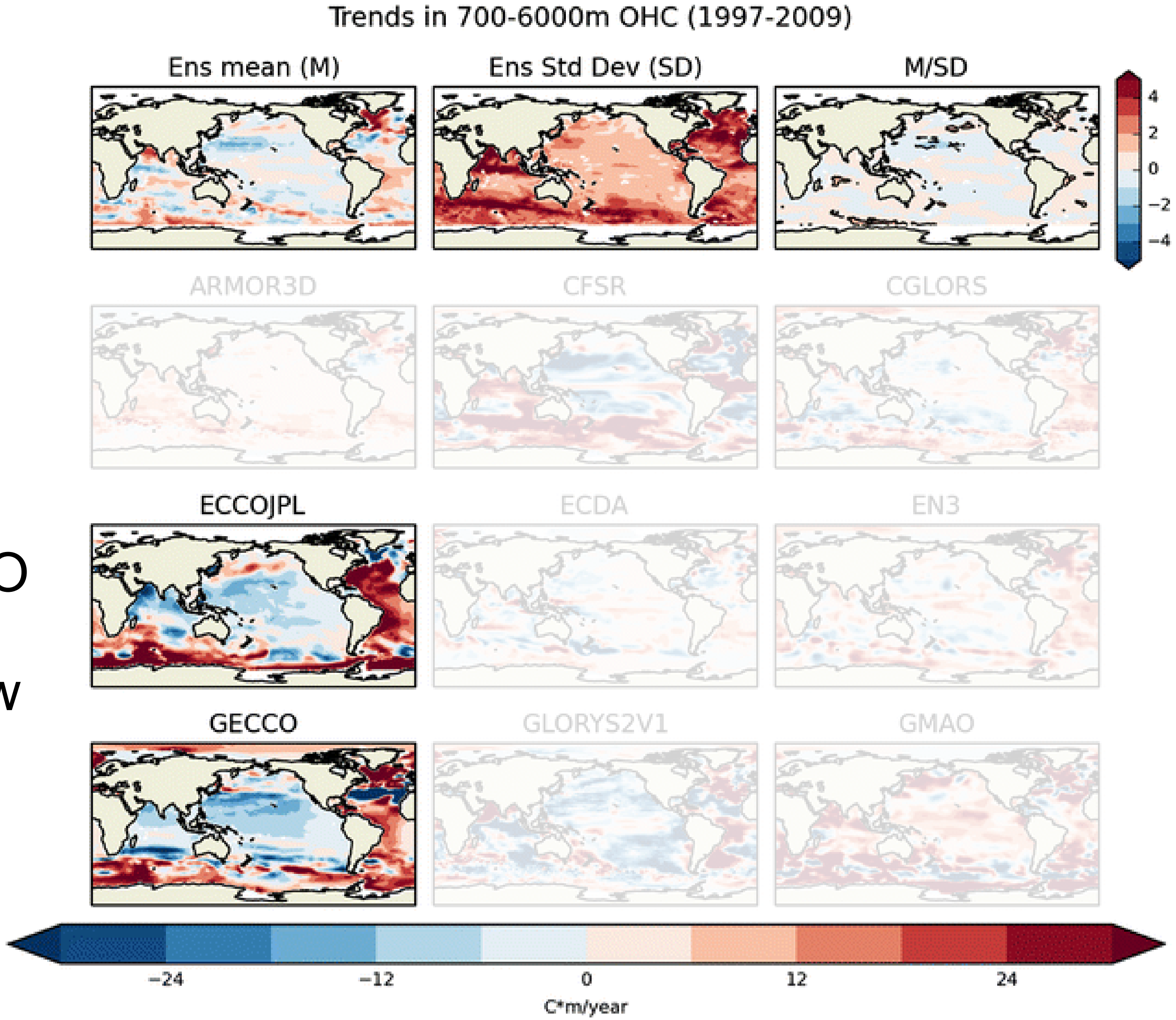
- 5 ± 3 cK/century cooling trend in deep Pacific inferred from HMS *Challenger* data
- A fixed-circulation inverse model explained the trend as a response to Little Ice Age surface temperature anomalies
- The inversion also suggested that the signal could <u>still</u> be in the modern ocean

Trend uncertainty among ocean reanalyses



Adapted from Palmer et al., 2017

Trend uncertainty among ocean reanalyses



- Previous ECCO ocean state estimates show cooling in the deep Pacific

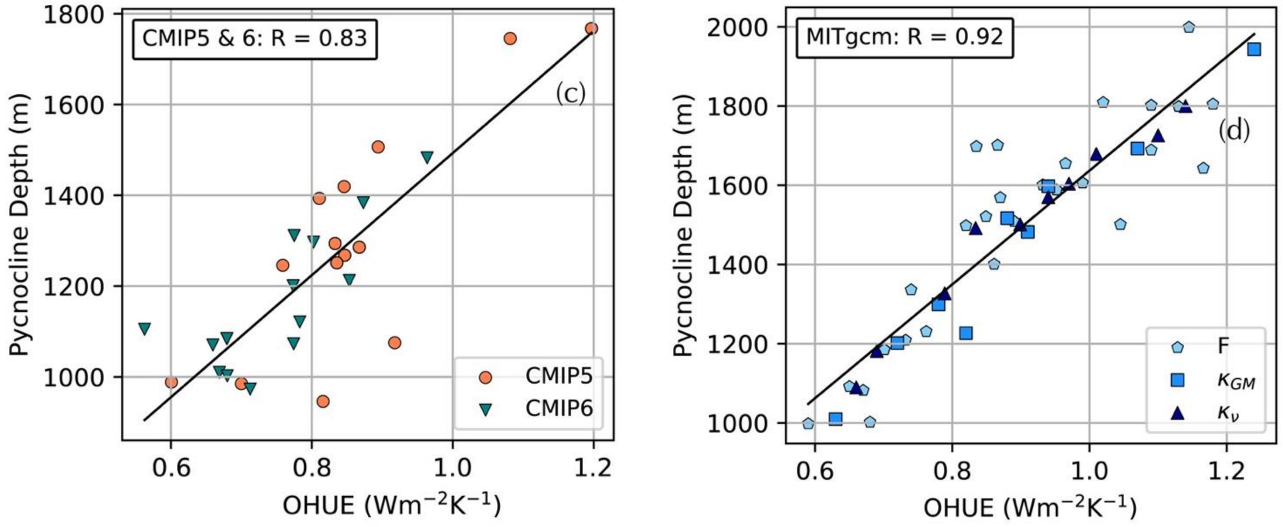
Adapted from Palmer et al., 2017

Initialization matters for climate simulations

- There is growing evidence that background temperature and salinity fields constrain ocean heat uptake

Multi-model comparison between pycnocline depth and ocean heat uptake

Newsom et al.,2023



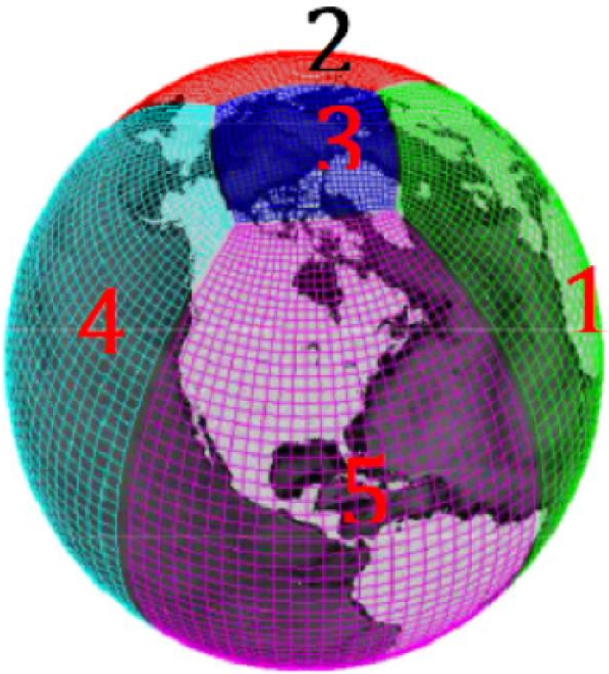
Initialization matters for climate simulations

- There is … that bac… and sali… ocean h…

Research questions:

- Does ECCO still have deep Pacific cooling?
- Does this signal emerge from constraining the model to observations?
- What physical mechanisms explain the cooling?

ECCO Version 4 release 4



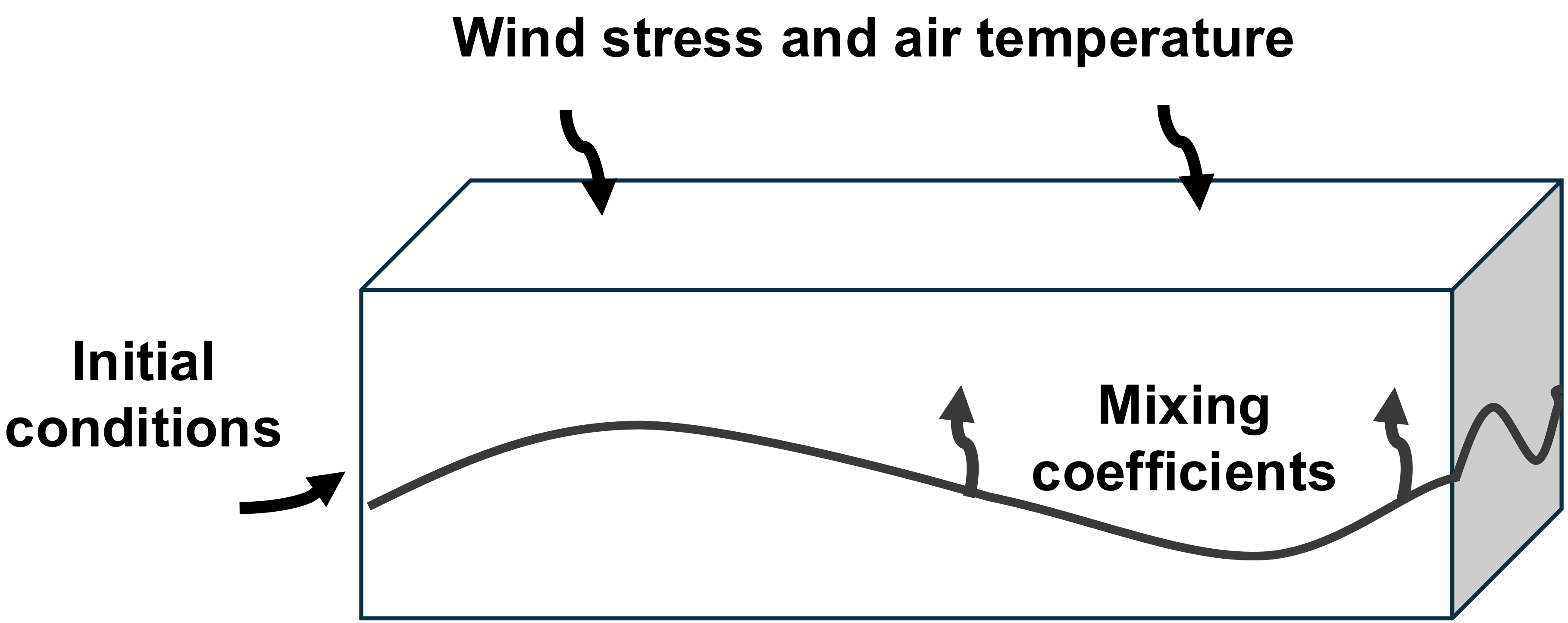
ECCO Version 4 release 4 (V4r4)

- Ocean state estimate spanning 1992–2017
- Nominal 1° resolution with 50 vertical levels
- Constrained by millions of observations

First-guess model configuration:

- Atmospheric forcing from reanalysis winds and air temperature
- Initial condition from the WOCE 2009 climatology
- Uniform mixing parameters

How ECCO V4r4 works



ECCO changes a few sets of parameters to fit to millions of ocean observations

Experimental design

- Initial set of perturbation experiments

- These quantify the effect of the adjustments used in Iteration 129 on temperature variability

Experiment Name	Control Adjustments Applied			
	Initial Condition	Wind Stress	Buoyancy Forcing	Mixing Parameters
Iteration 129 (*ECCO V4r4*)	✓	✓	✓	✓
Adjusted Initial Conditions	✓	×	×	×
Adjusted Wind Stress	×	✓	×	×
Adjusted Buoyancy Forcing	×	×	✓	×
Adjusted Mixing Parameters	×	×	×	✓
Iteration 0 (*ECCO V4r4 First Guess Solution*)	×	×	×	×

Experimental design

$$\begin{matrix}\text{Mixing}\\\text{adjustment}\\\text{effect}\end{matrix} \approx \begin{matrix}\text{Adjusted}\\\text{mixing}\\\text{parameters}\end{matrix} - \text{Iteration 0}$$

Experimental design

$$\text{Iteration 129} \approx \text{Iteration 0} + \sum \text{Effects}_\text{i}$$

Experimental design

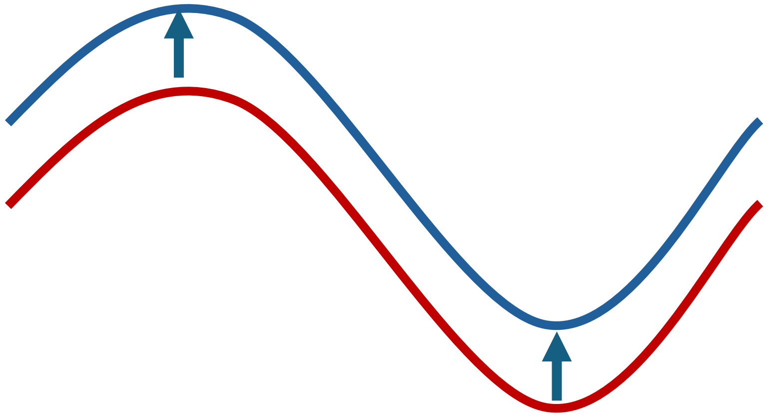
Experiment Name	Wind Stress Fields			
	First-Guess Seasonal Cycle	First-Guess Extraseasonal	Adjusted Seasonal Cycle	Adjusted Extraseasonal
Seasonal Adjusted Wind Stress	×	×	✓	×
Seasonal First-Guess Wind Stress	✓	×	×	×

- These quantify the effects of Iteration 129 mean seasonal cycle adjustments on temperature variability

Experimental design

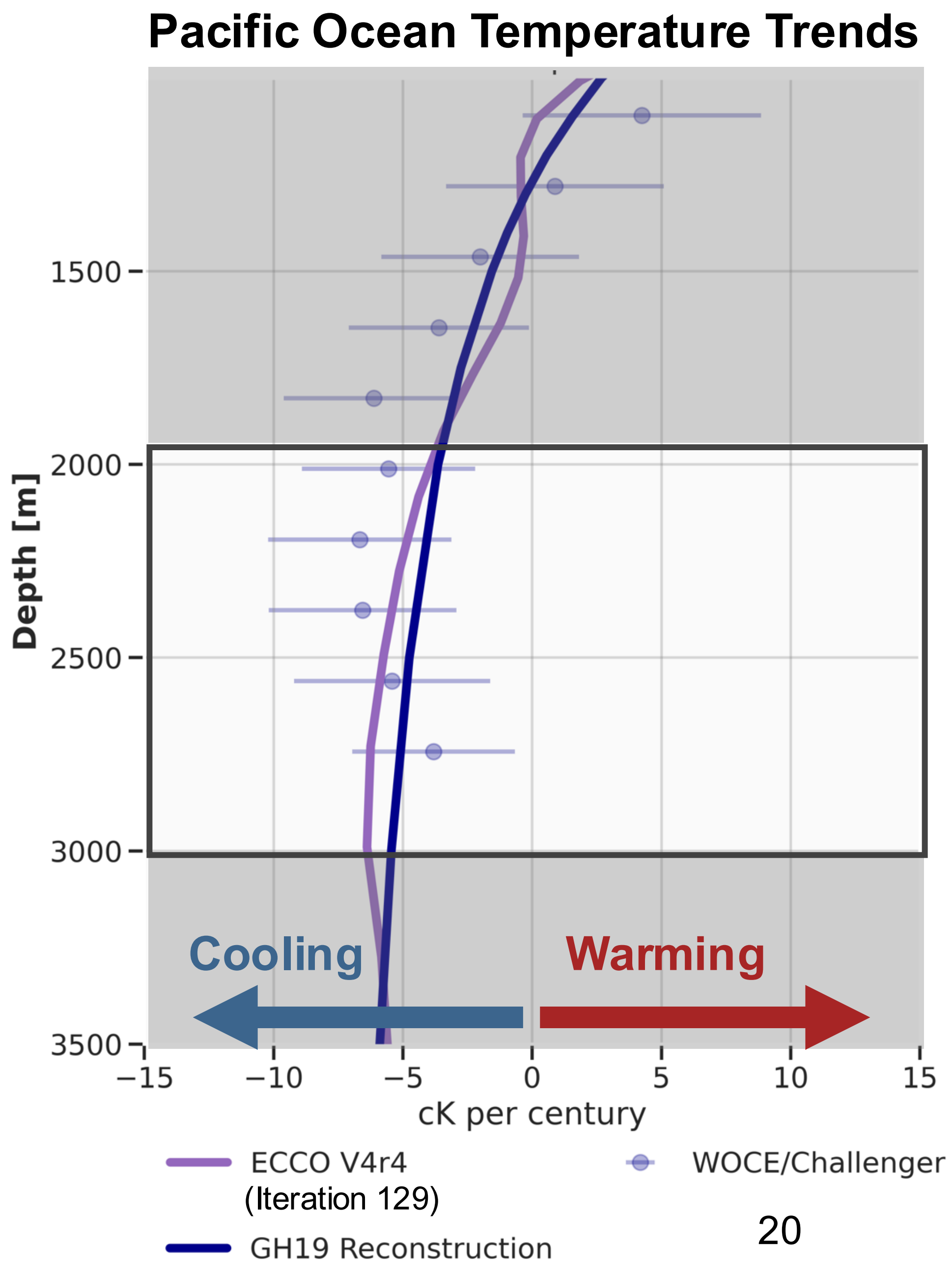
Mean seasonal cycle adjustment effect ≈ Seasonal adjusted wind stress – Seasonal first-guess wind stress

Example adjustments



Pacific cooling in ECCO V4r4

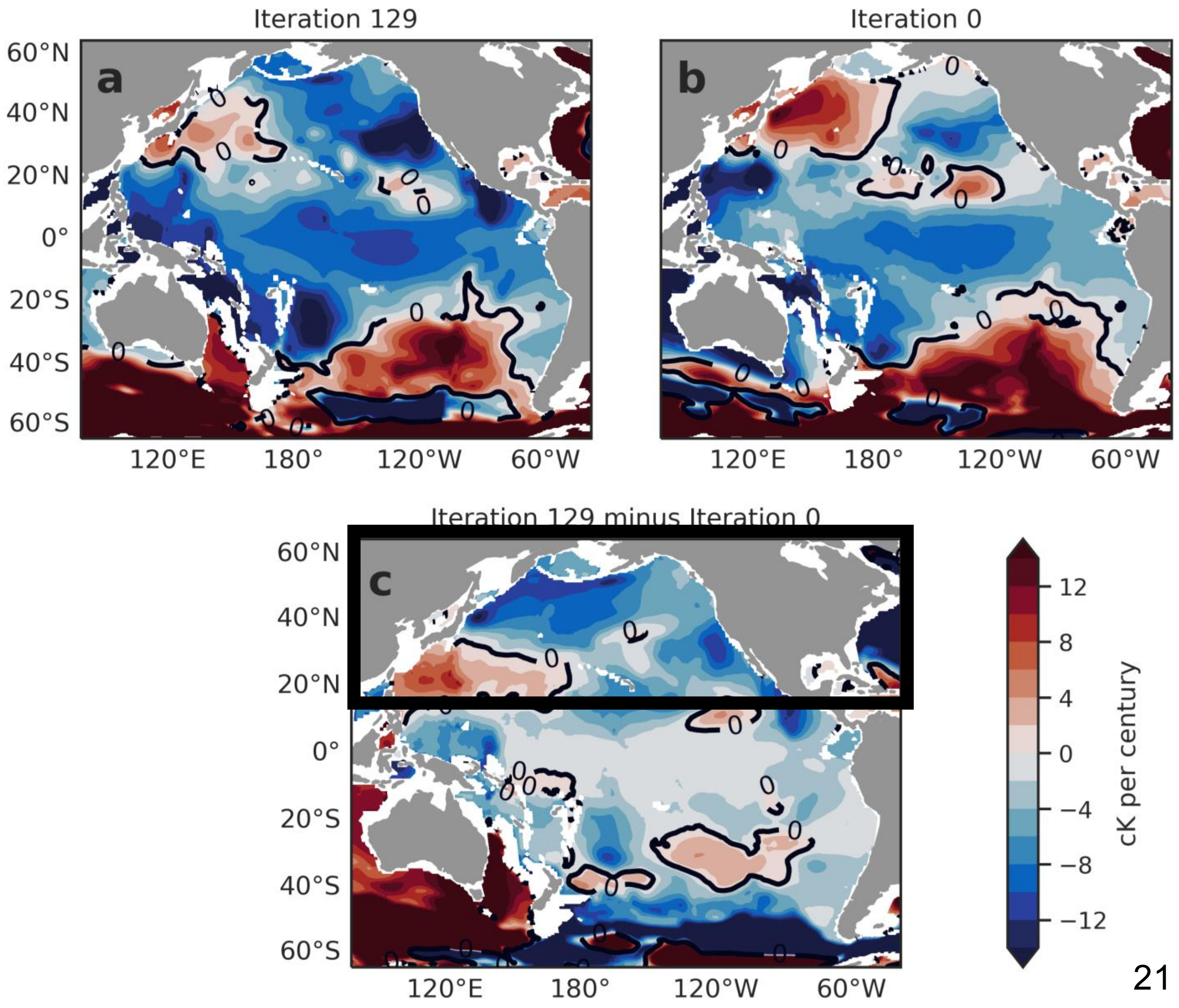
- Below 1000 meter, ECCO cooling trends are comparable to the HMS *Challenger*/WOCE temperature differences



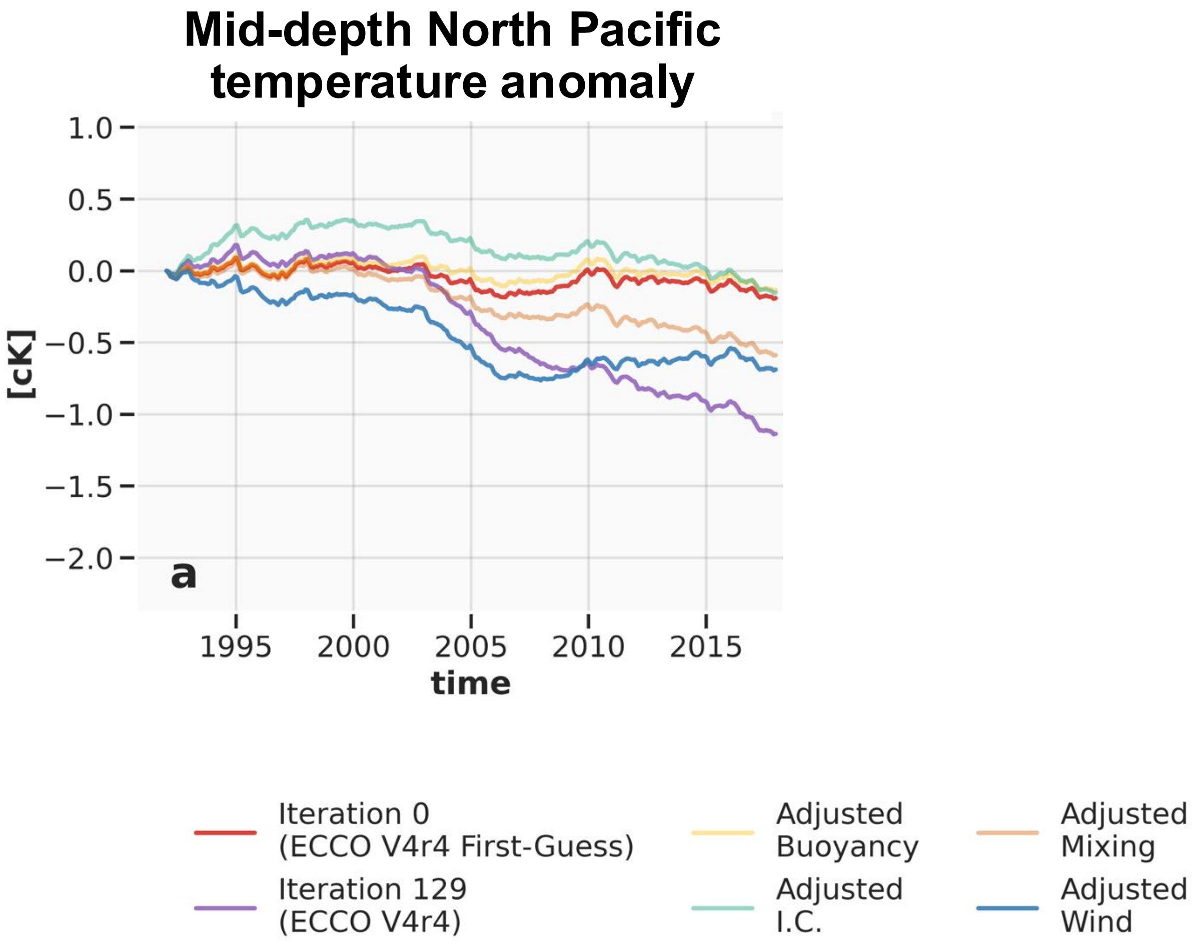
Mid-depth (2-3km) Pacific temperature trends

- Deep Pacific cooling intensifies after fitting ECCO V4r4 to data

- Enhanced North Pacific cooling is especially apparent

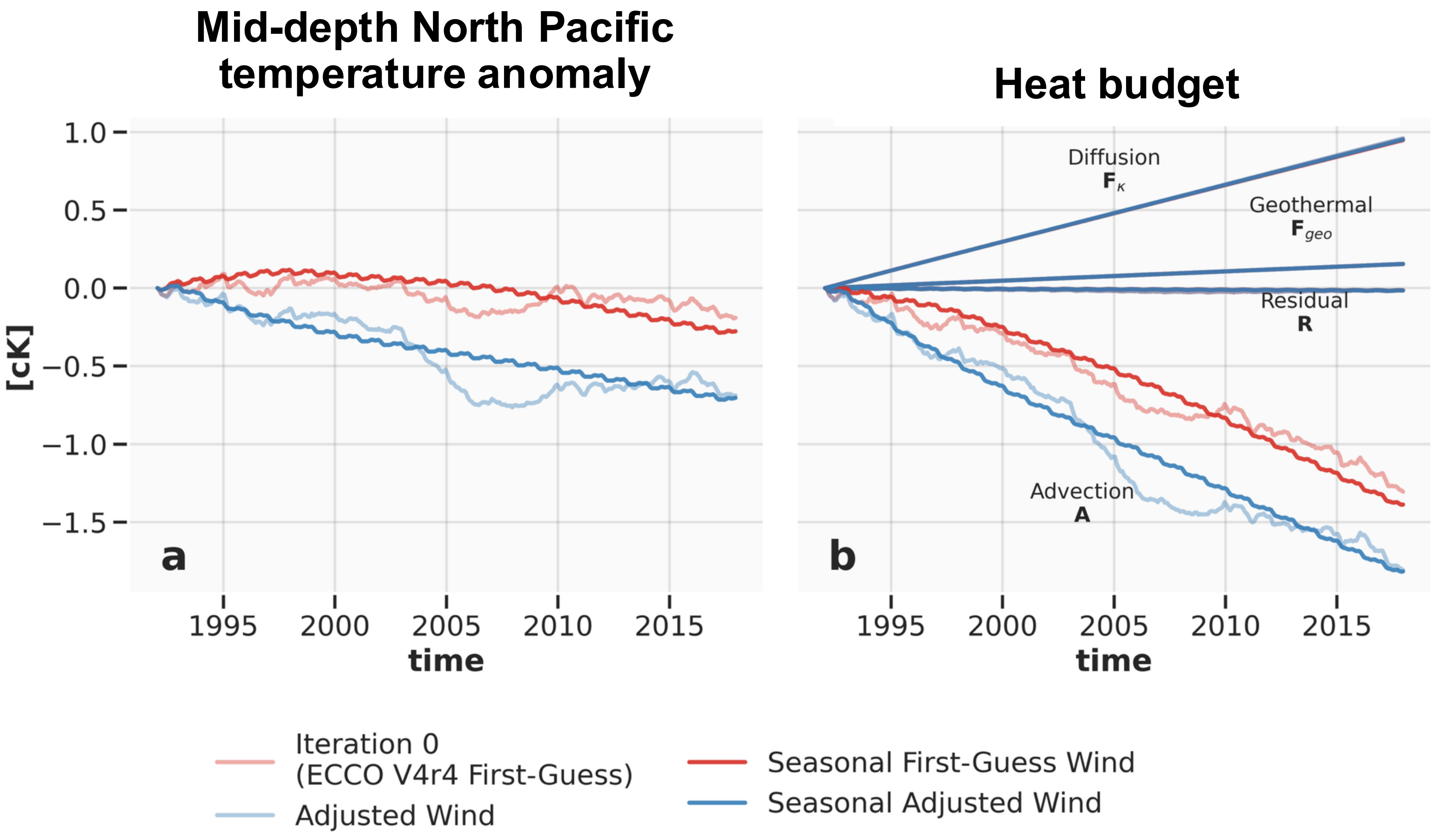


Mid-depth North Pacific heat budgets



- Data-driven wind adjustments cause most of the cooling

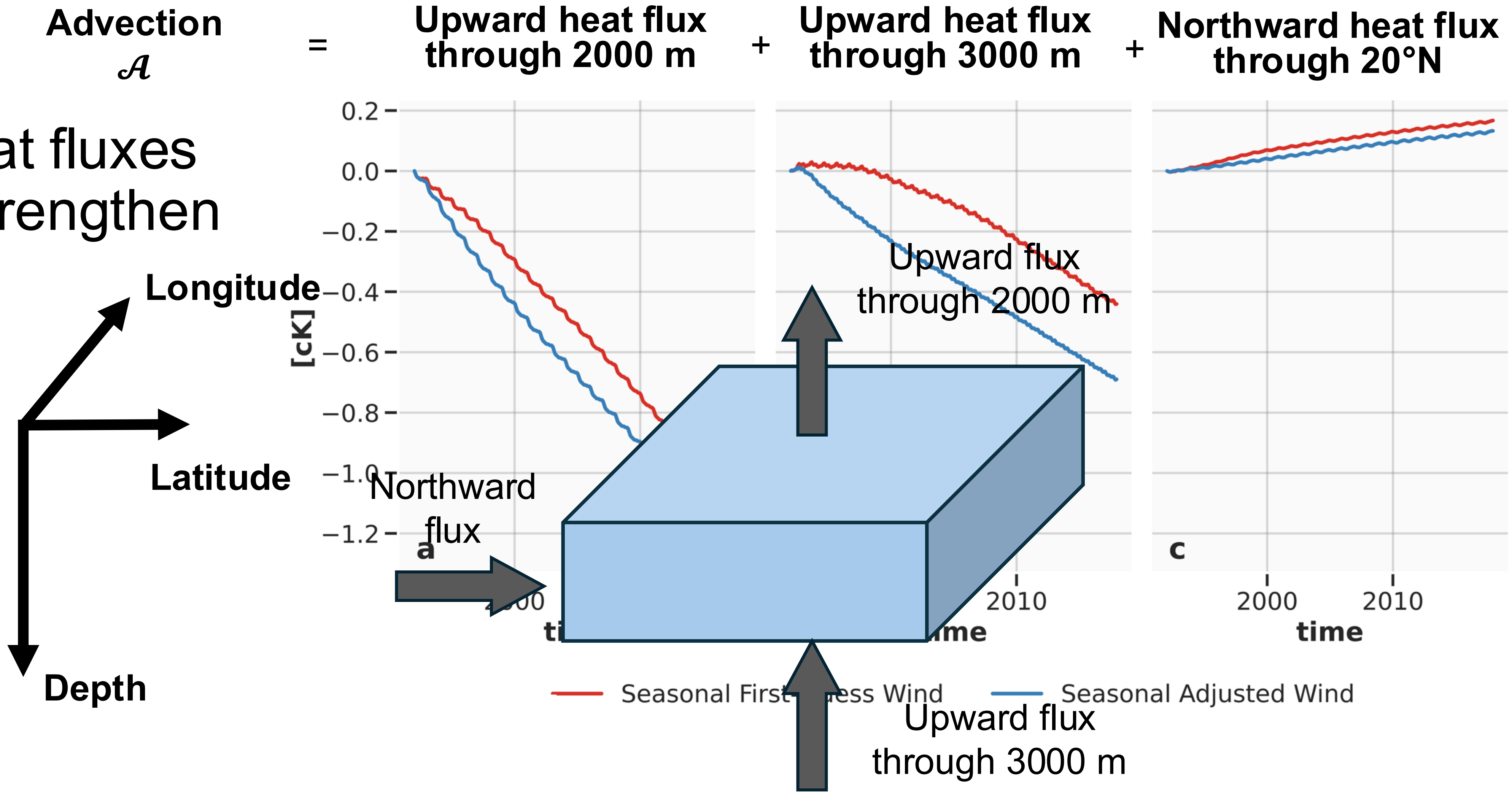
Mid-depth North Pacific heat budgets



- Adjustments to wind stress seasonal cycle explain majority of wind-driven cooling
- Cooling driven by anomalous advection

Directional decomposition of advection

- Vertical heat fluxes primarily strengthen cooling

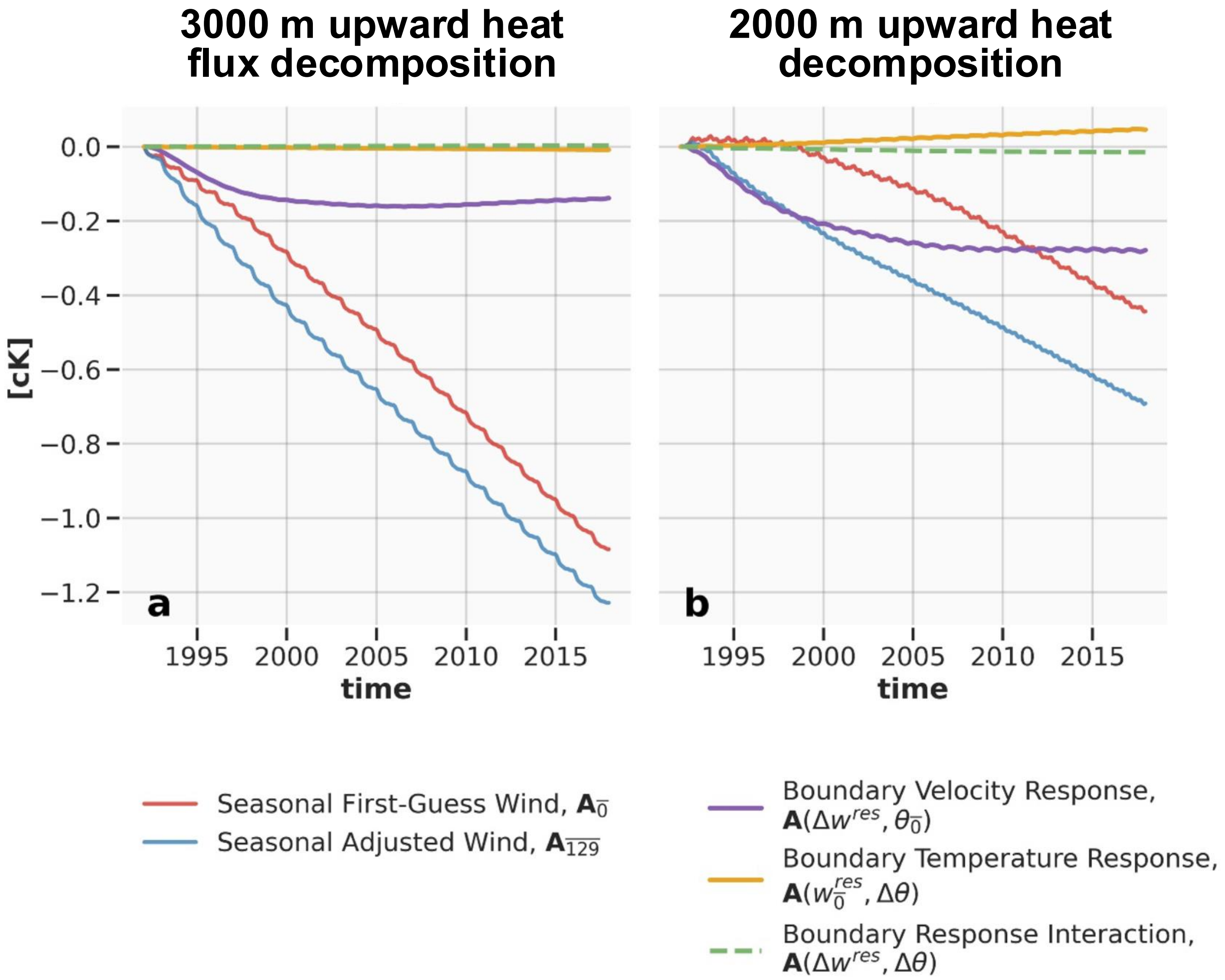


Vertical advection Reynolds decomposition

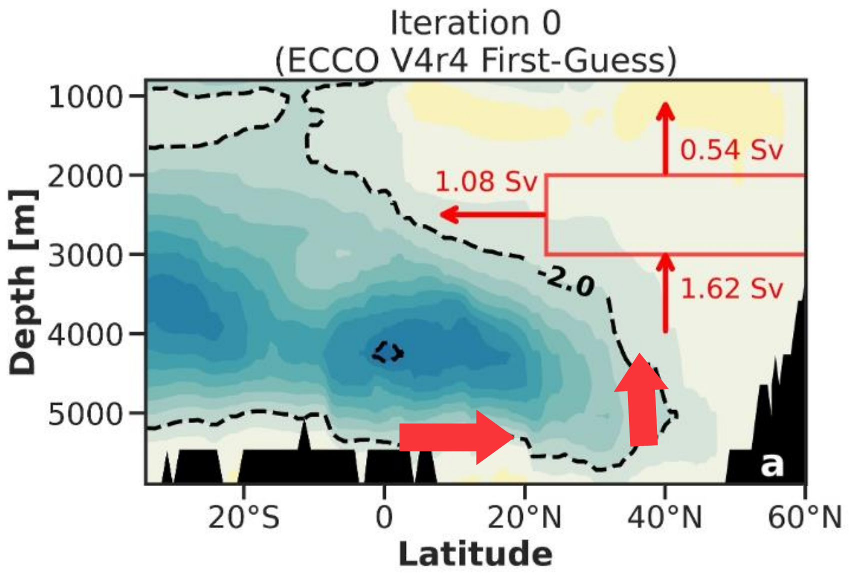
$$\mathbf{\Delta A} = \mathbf{A}(\Delta w, \theta_0) + \mathbf{A}(w_0, \Delta\theta) + \mathbf{A}(\Delta w, \Delta\theta)$$

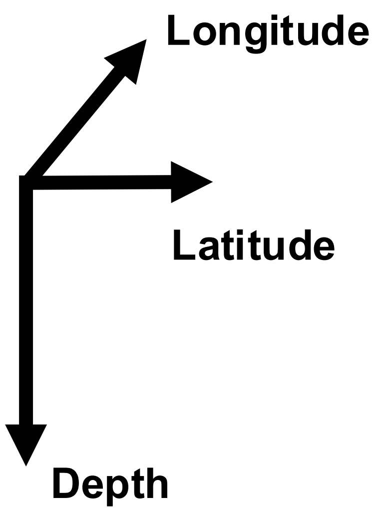
Vertical advection Reynolds decomposition

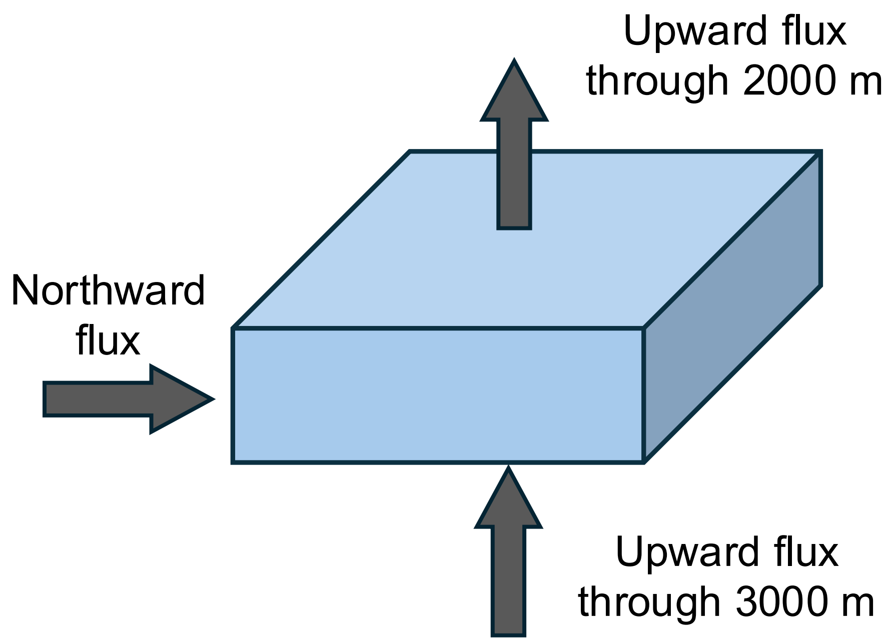
- Anomalous advection is driven by anomalous volume transport



Deep vertical transport response to winds







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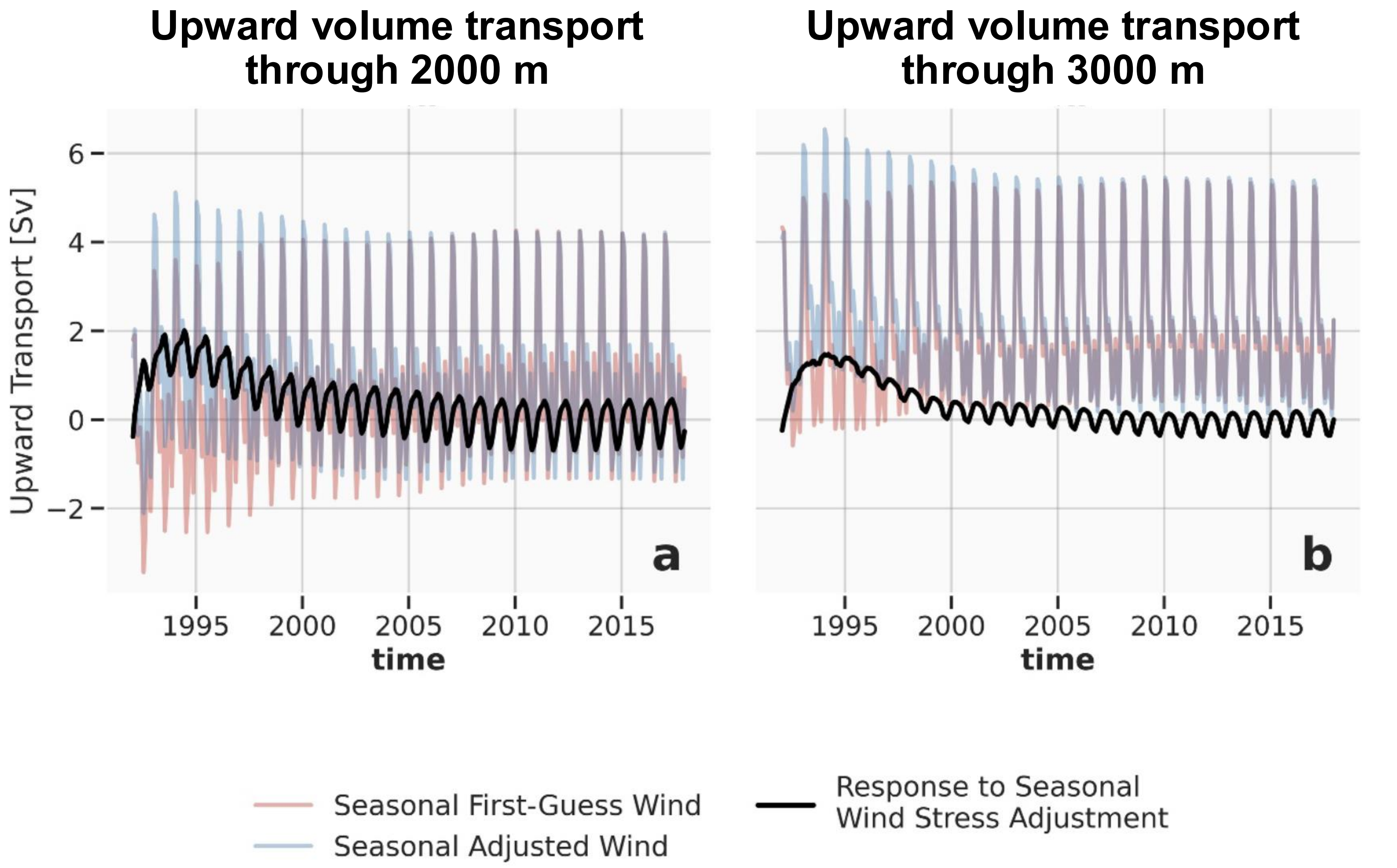
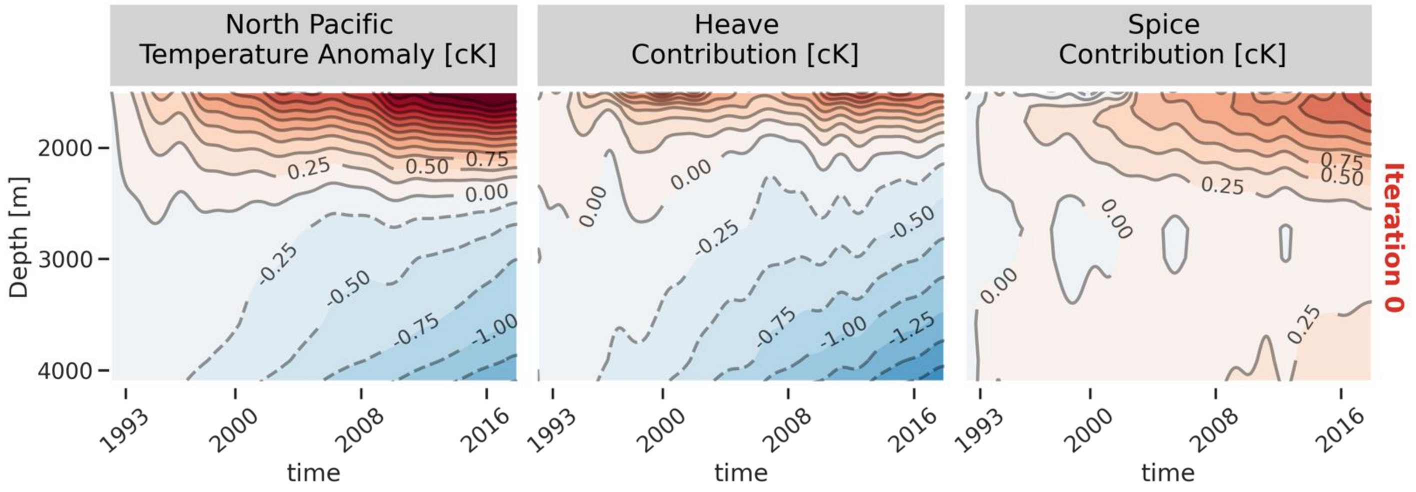


- Vertical transport anomalies are strongest during first 8 years of run
- Damped behavior consistent with Rossby wave superposition

Effects of isopycnal heave and spice



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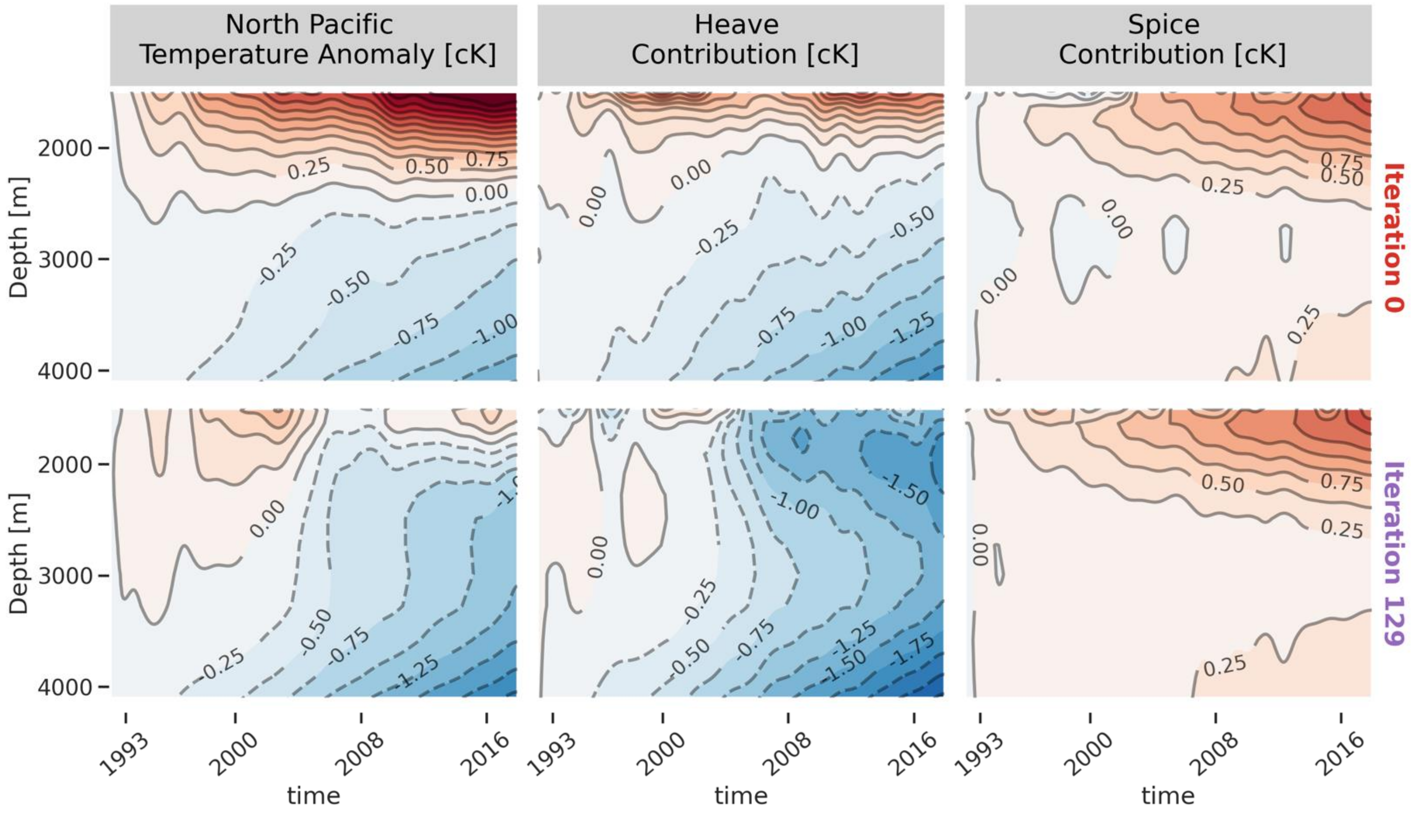


Effects of isopycnal heave and spice

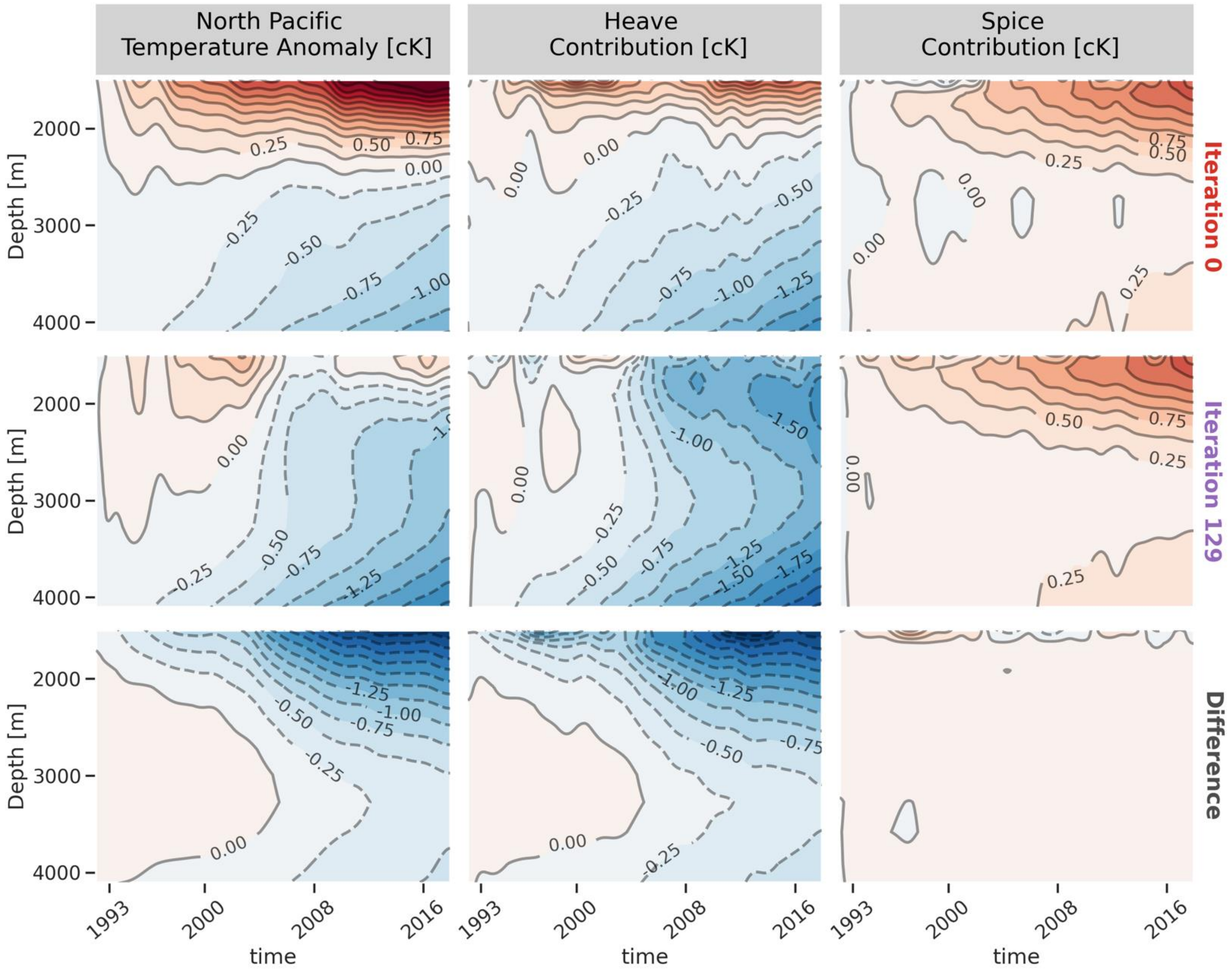
Wind-induced
vertical transport anomalies

⬇

Isopycnal upwelling

⬇

Mid-depth cooling



Summary

- ECCO V4r4 has a 5 cK/century mid-depth Pacific cooling trend resembling trends inferred from HMS *Challenger* observations

- Cooling only emerges after ECCO V4r4 is constrained to observations

- The data-constrained wind fields cause adiabatic isopycnal heave that upwells cool waters

Takeaways

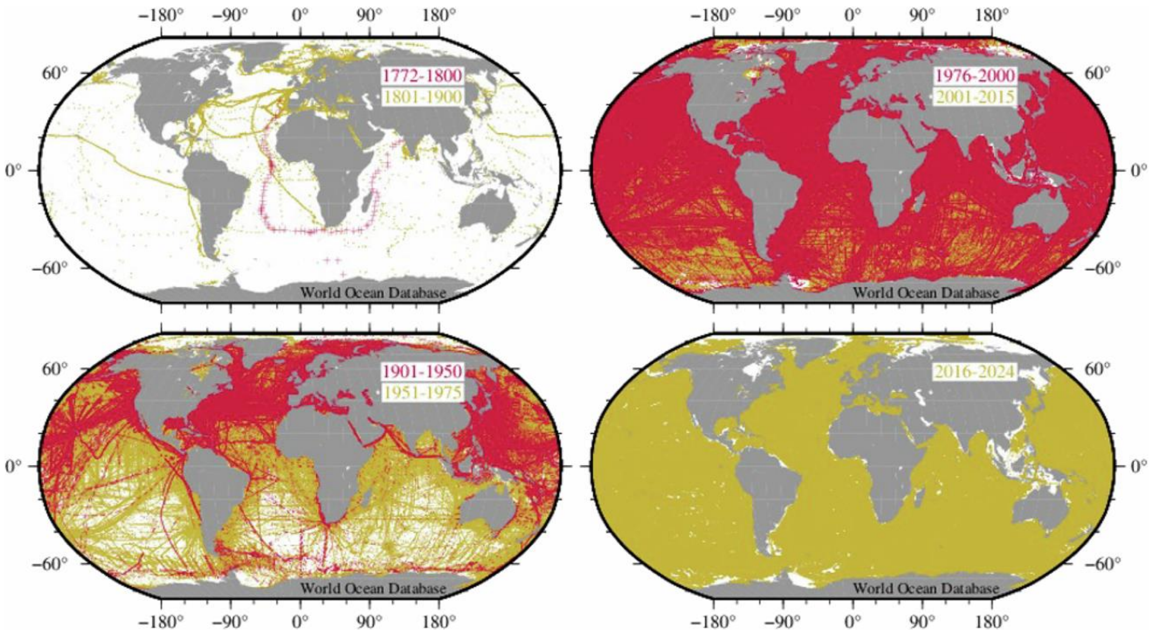
- Wind can affect deep ocean temperature trends through planetary wave adjustment
- **Adiabatic heave should be considered when interpreting deep ocean temperature records**

Where do we go from here?

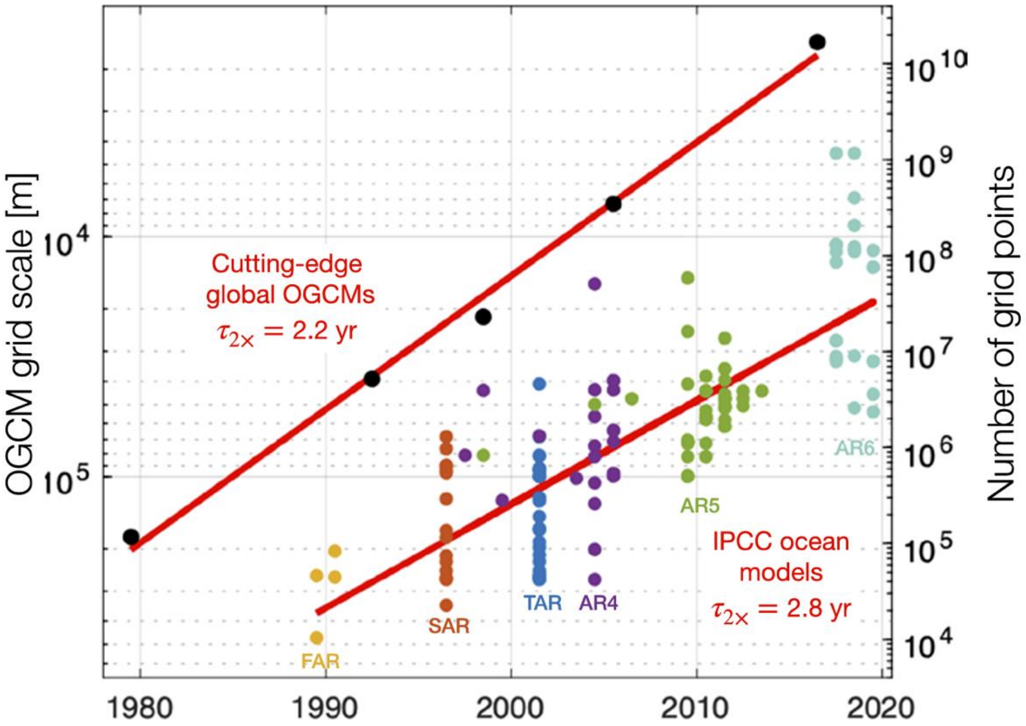
Is Computational Oceanography Coming of Age?

Thomas W. N. Haine, Renske Gelderloos, Miguel A. Jimenez-Urias, Ali H. Siddiqui, Gerard Lemson, Dimitri Medvedev, Alex Szalay, Ryan P. Abernathey, Mattia Almansi, and Christopher N. Hill

Unprecedented ocean observing *Garcia et al.,2026*



Exponential growth of OGCM resolution *Haine et al.,2021*



Thank you! ☺

The River Thames (in London) during the Little Ice Age

The River Thames today