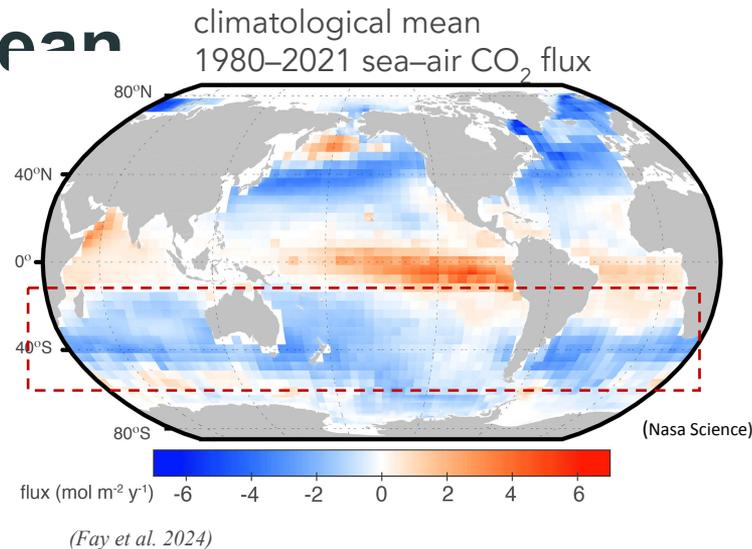


Can Precipitation Alone Reshape the Southern Ocean Carbon Sink?

Evidence from PlioMIP2 Climate Simulations

I. Wainer, Q. Zhang, K. Power, F.O. Matos



Southern Ocean: Earth's Major Carbon Sink

Bourgeois et al., 2022; Sallée et al., 2013; Li et al., 2020; Cheng et al., 2025

THE NUMBERS

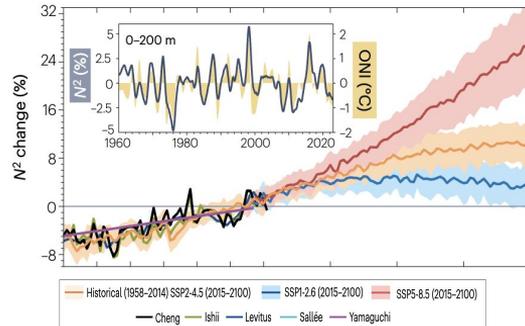
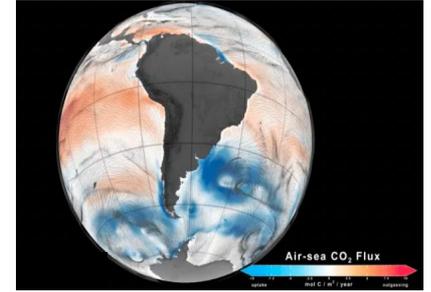
The SO accounts for **40-44% of global oceanic anthropogenic CO₂ uptake** through formation and subduction of Antarctic Intermediate Water (AAIW) and Subantarctic Mode Water (SAMW).

THE CONTROL MECHANISM

Upper ocean stratification regulates carbon sequestration efficiency by acting as a physical barrier to vertical transport, controlling the depth and volume of ventilated waters that carry CO₂ to the deep ocean.

WHAT WE OBSERVE

Stratification has increased 7.9% in the SO since 1960—the strongest regional rate globally with future projections suggesting 0.7-2.9% per decade by 2100.



The Attribution Challenge

At high latitudes, stratification changes results mostly from 2 drivers: (Held & Soden, 2006)

- 1) **the hydrological cycle (PPT)**;
- 2) cryospheric processes such as ice-sheet **meltwater** (*more uncertain*).

THE PROBLEM

ESMs vary widely in their treatment of ice sheet-ocean interactions making it difficult to attribute observed changes to specific mechanisms.

Bourgeois et al., 2022

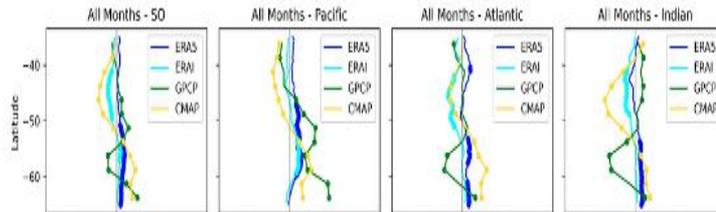
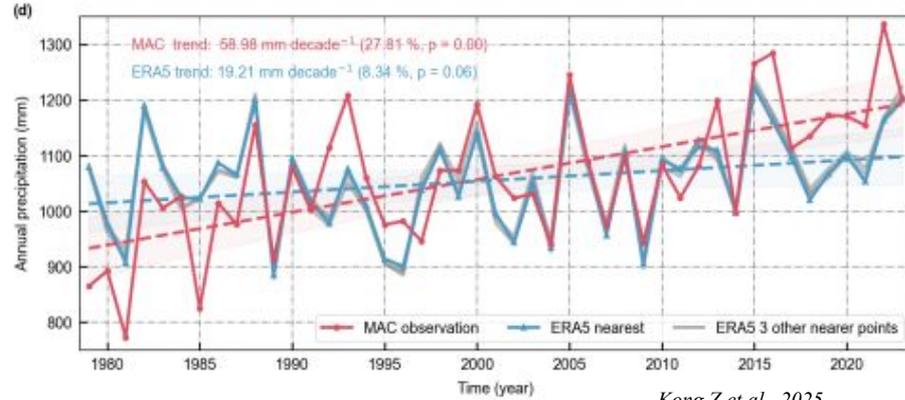
THE RESEARCH QUESTION

Can PPT alone drive stratification changes strong enough to impact CO₂ sink?

If PPT alone produces substantial stratification, current projections may capture the dominant mechanism despite missing cryospheric processes (like meltwater).

PPT is increasing over SO

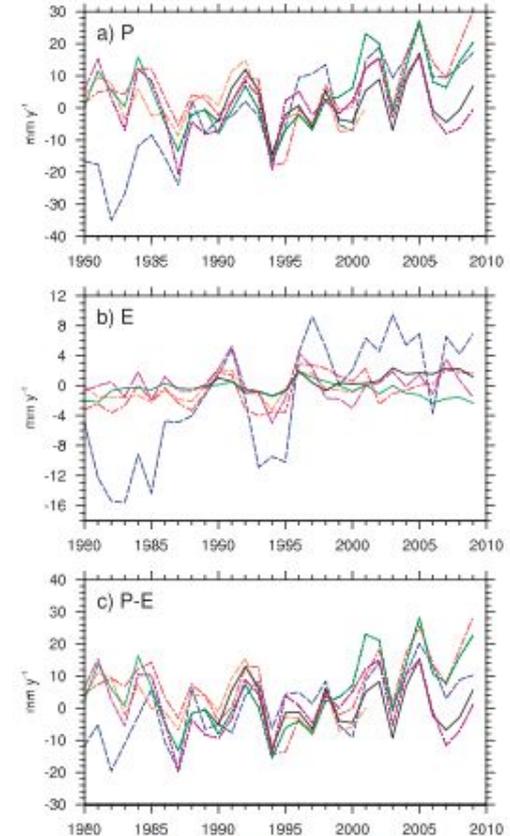
Annual PPT



Trends in precipitation ($\text{mm day}^{-1} \text{ decade}^{-1}$)

Manton et al., 2020

Annual PPT



Bromwich et al., 2011

PlioMIP2 Experiments

WHY THE PLIOCENE?

The mid-Pliocene period simulations (3.3 Ma BP) :

- analog climate with similar CO₂ levels to today (~400 ppm),
- reduced ice sheets, and a warmer equilibrium state.

no prescribed meltwater fluxes. This isolates atmospheric forcing from cryospheric processes.

DATA

6 simulations combining **2 climate states** (Pliocene and PI) with **3 CO₂ levels**

(280, 400, 560 ppm). EC-Earth3-LR

This allows us to **separate CO₂ forcing effects** within a climate state from **climate state effects at fixed CO₂**, while examining the hydrological cycle's role

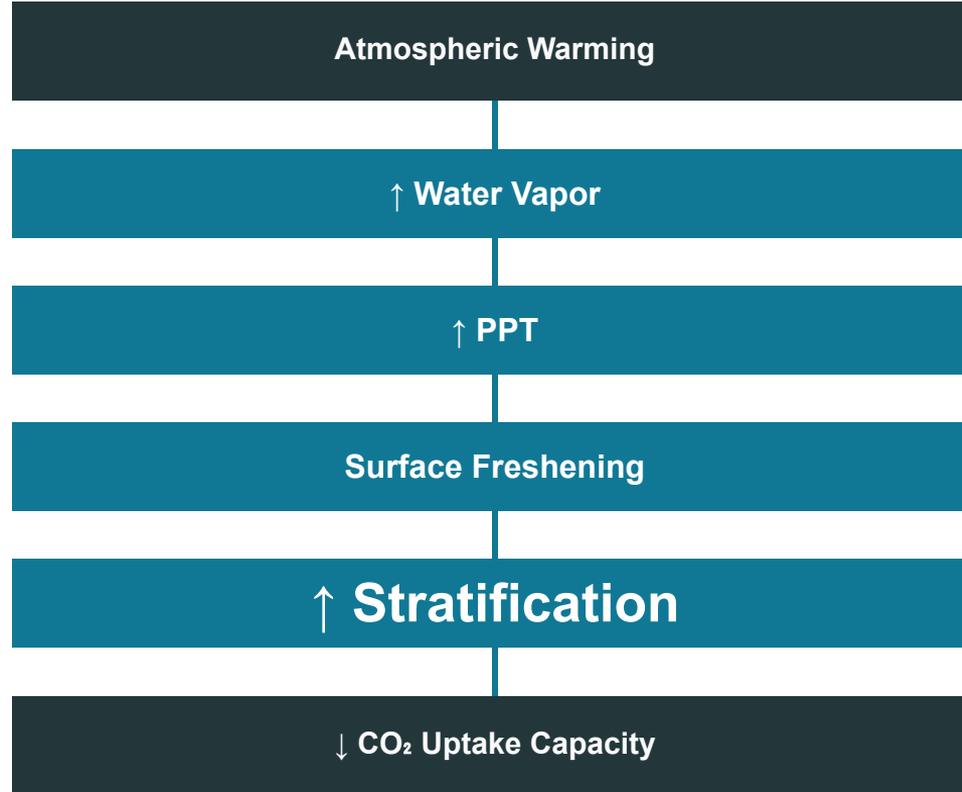
PI: use modern topography, ice sheets, and orbital parameters.

Pliocene: reduced Antarctic ice sheet, modified veg, closed Bering Strait, and orbital parameters.

No prescribed meltwater fluxes are applied in any simulation.

Different levels of CO₂

Rationale



Quantify Stratification

We quantify stratification using the Brunt-Väisälä frequency (N^2), which measures the **ocean's resistance to vertical mixing**:

$$N^2 = - (g/\rho_0) (\partial\rho/\partial z)$$

Physical Meaning

N^2 reflects vertical density gradients created by temperature and salinity. In the SO, surface freshening from PPT increases N^2 by reducing surface density.

Higher N^2 values

Stronger stratification with greater resistance to vertical mixing, which suppresses the transport of nutrients, heat, and carbon between surface and deep waters.

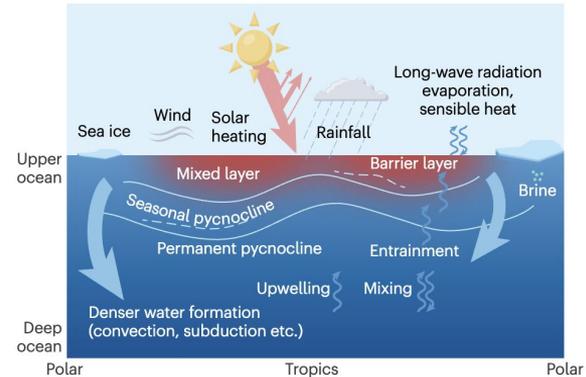


Fig. 1 | Explaining ocean stratification. A schematic representation of the processes and features of ocean stratification. Ocean stratification arises from many dynamic and thermodynamic processes, creating stable ocean conditions that limit vertical mixing. Cheng et al., 2025

Upper Ocean Spatial Patterns for different CO₂ levels (columns) and climate states (rows)

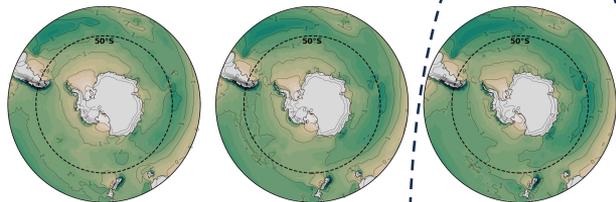
Top row: PI
Bottom row: PLIO

PPT

280

400

560

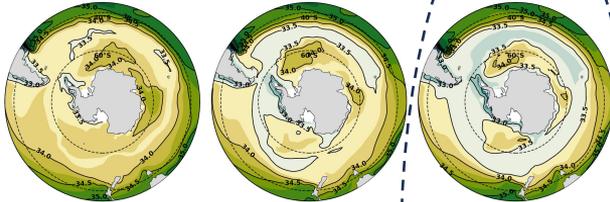


Salinity

280

400

560

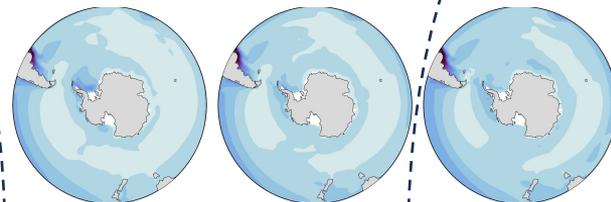


N² (200m mean)

280

400

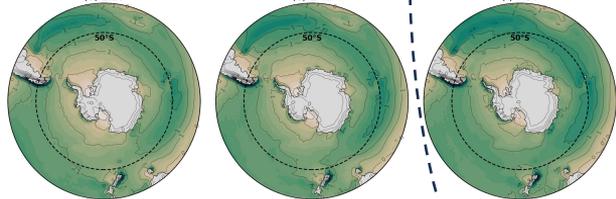
560



(d) Ei28

(e) Ei41

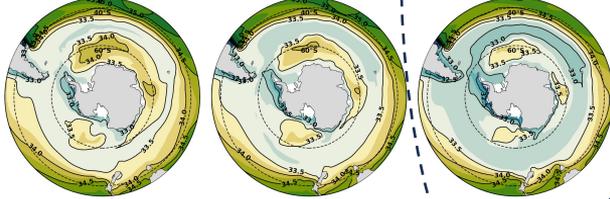
(f) Pi56



(d) Ei28

(e) Ei41

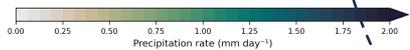
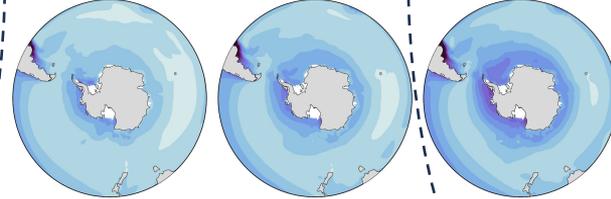
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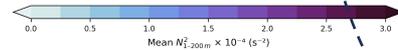
(f) Pi56



Precipitation rate (mm day⁻¹)



Surface Salinity (psu)



Mean $N_{2,200m} \times 10^{-4}$ (s⁻²)

increase with CO₂

decrease with CO₂

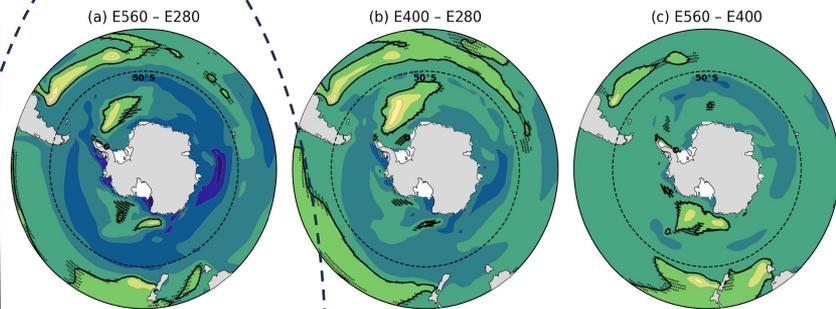
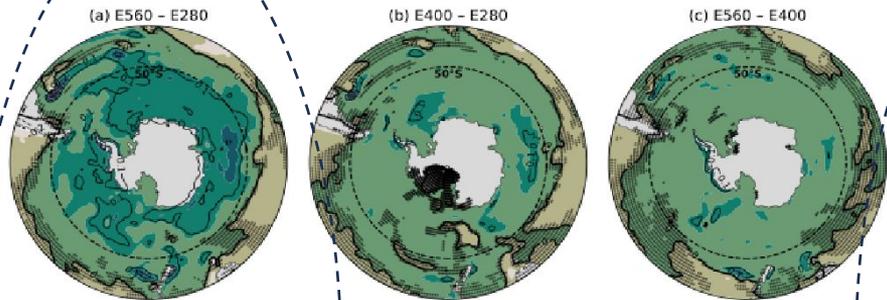
increase with CO₂

Top row: PI
Bottom row: PLIO

differences (CO₂ levels)

PPT

SAL
T



(PI)

(PLIO)



Stippling: $p \geq 0.05$ (not significant)

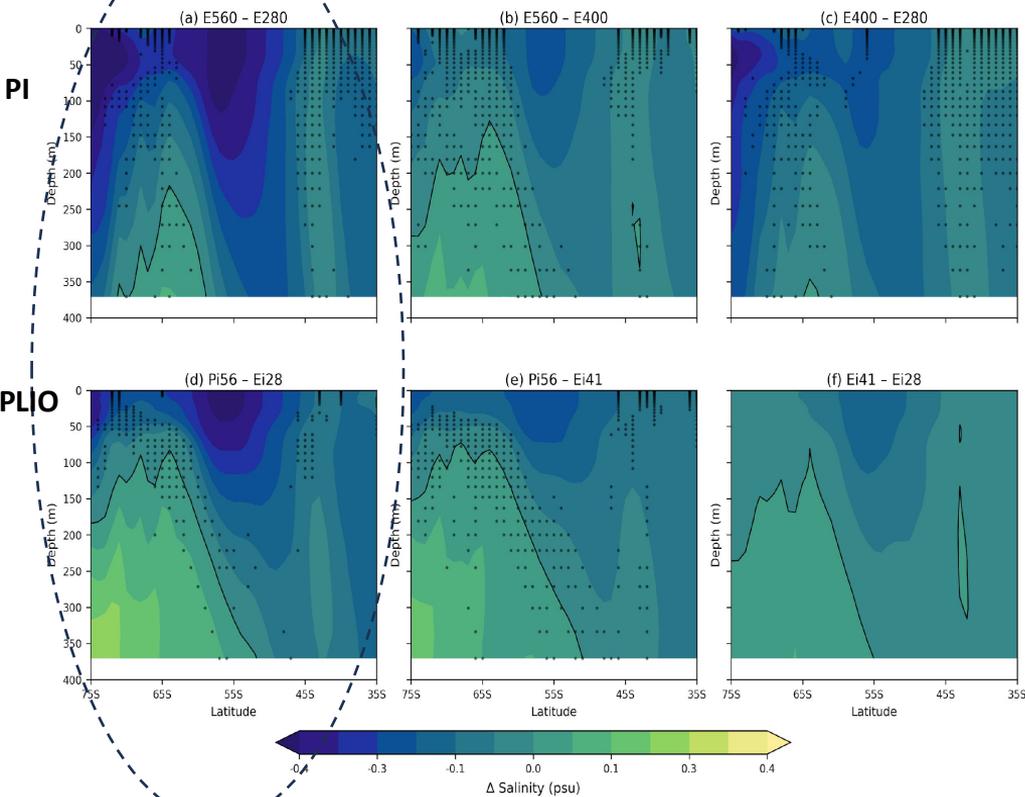
CO₂ doubling

CO₂ doubling

Vertical Profiles: zonal mean SALINITY differences

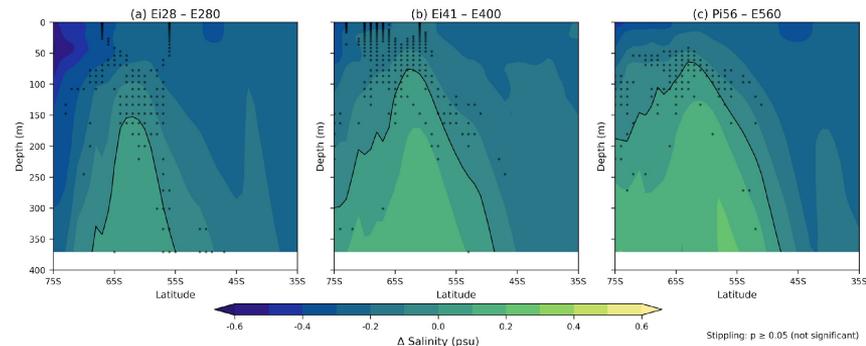
Top row: PI
Bottom row: PLIO

CO2 diffs



- Enhanced freshening
- Strongest at ~55°S

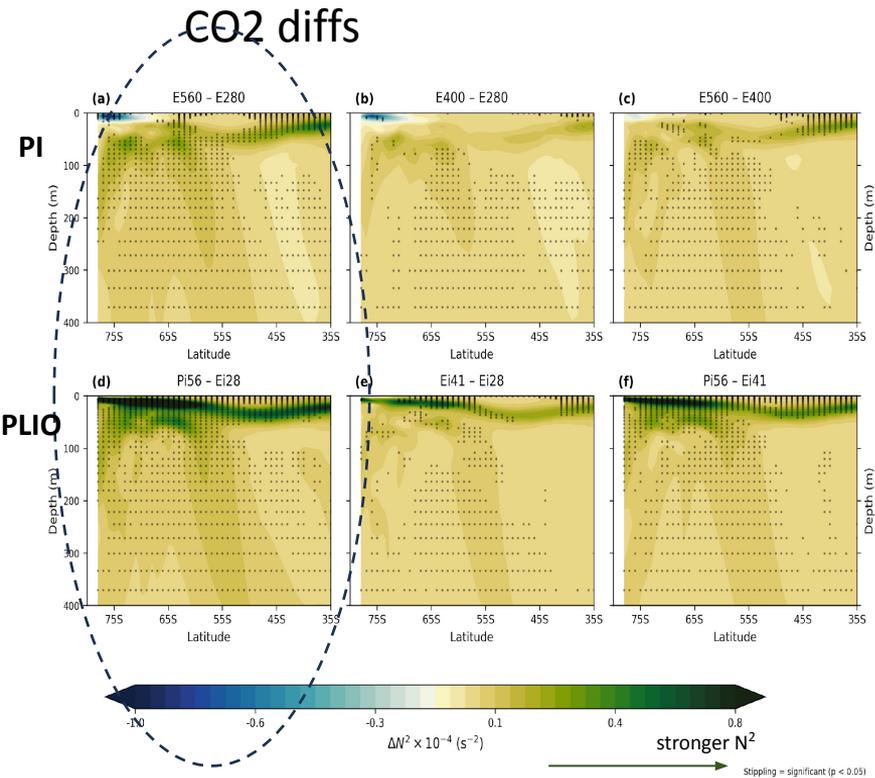
Climate State diffs (Plio – PI)



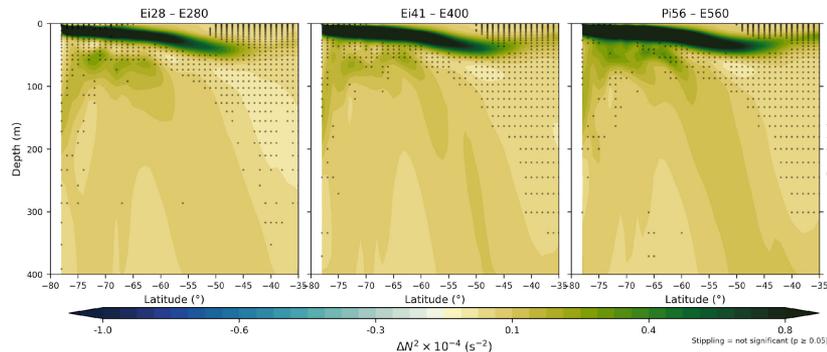
- Plio fresher
- Same general spatial pattern – broader spatial / depth differences with increase CO2

Stippling: $p \geq 0.05$ (not significant)

Vertical Profiles of zonal mean N^2 differences



Climate State diffs (Plio - PI)



Stronger stratification: greater resistance to vertical mixing

- Max in upper 200m
- Surface N^2 increases 20-40% for CO₂ doubling
- Enhanced stratification ~ Drake Passage

Can PPT Alone Reshape the Carbon Sink?

YES

PPT dominates the surface freshwater budget In the 50–65°S storm track region , making it a reliable indicator of hydrological changes and net freshwater forcing

[This dominance is well-supported by both reanalysis and observational studies.]

Akhoudas, C. et al 2023; Siems, S. et al., 2022; Papritz, L. et al, 2014

These results exclude meltwater contributions, providing a conservative lower bound.

Conclusions

1. Hydrological cycle is a very important driver

A 10-20% PPT increase produces surface freshening in the 50-65°.

2. Stratification strengthens

The upper ocean is affected with max response at 50-100m depth. CO₂ doubling produces a 20-40% increase in N²

3. Different forcing pathways emerge

CO₂ forcing vs. Climate State transitions (fixed CO₂). The implication for the Plio/PI difference is the lack of continental ice-sheet (impacts radiation?)

4. Ventilation and CO₂ uptake decline

Isopycnals shoaling suppressing SAMW and AAIW subduction and weakening the ocean's carbon sequestration capacity.

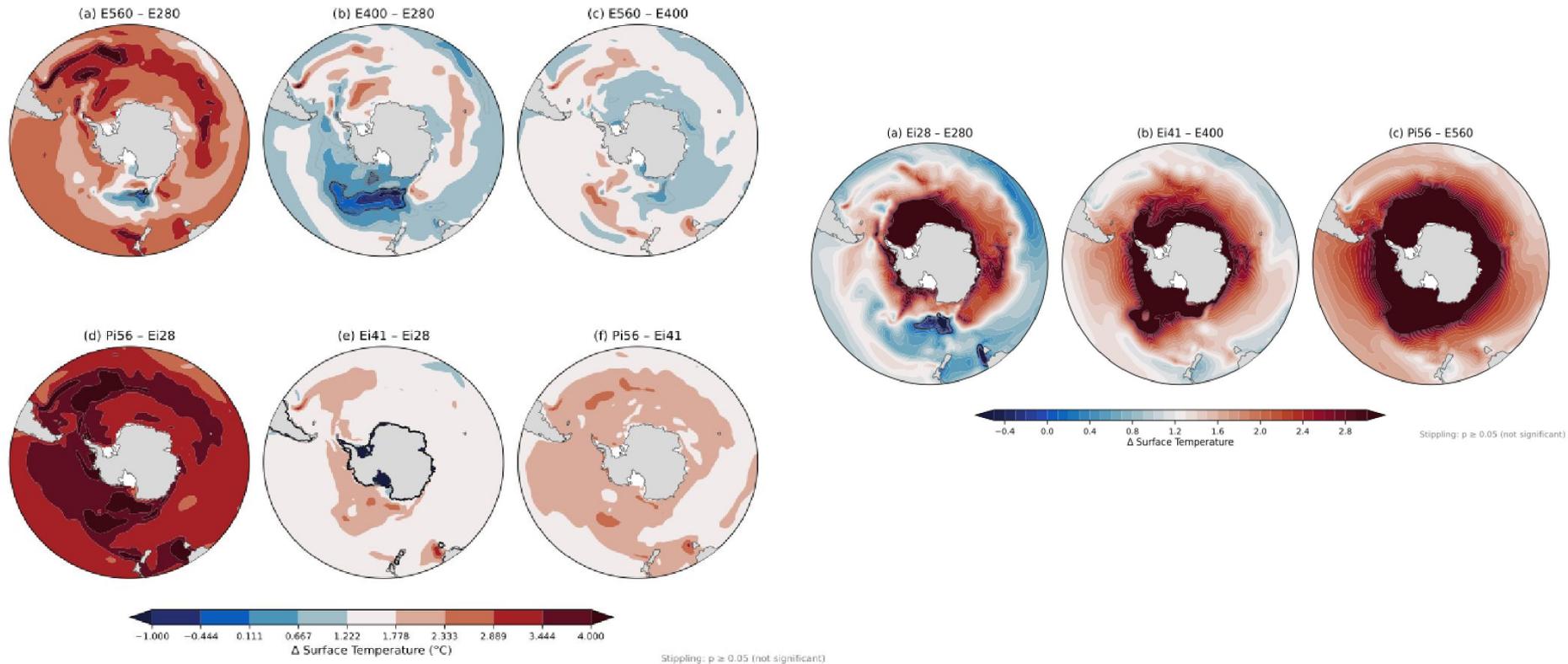
As stratification strengthens, the ocean's capacity to absorb atmospheric CO₂ weakens, potentially accelerating atmospheric accumulation.

Thank You

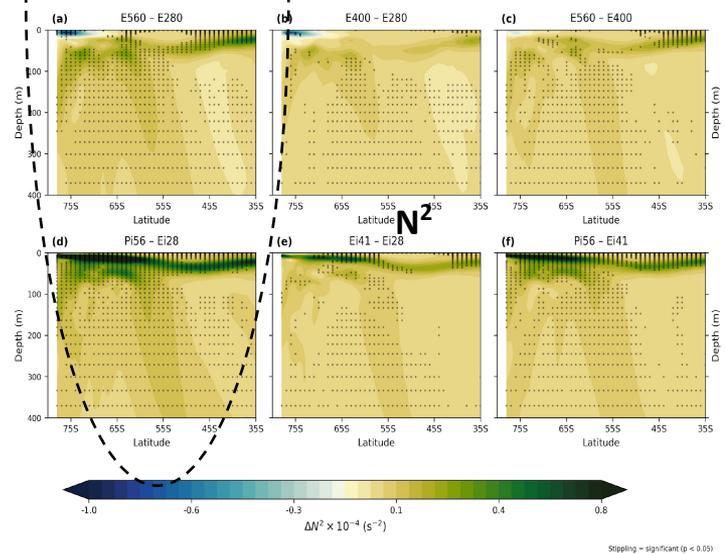
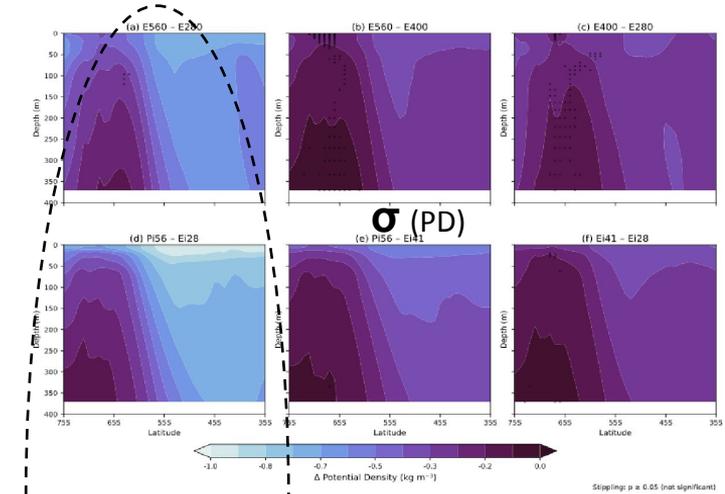
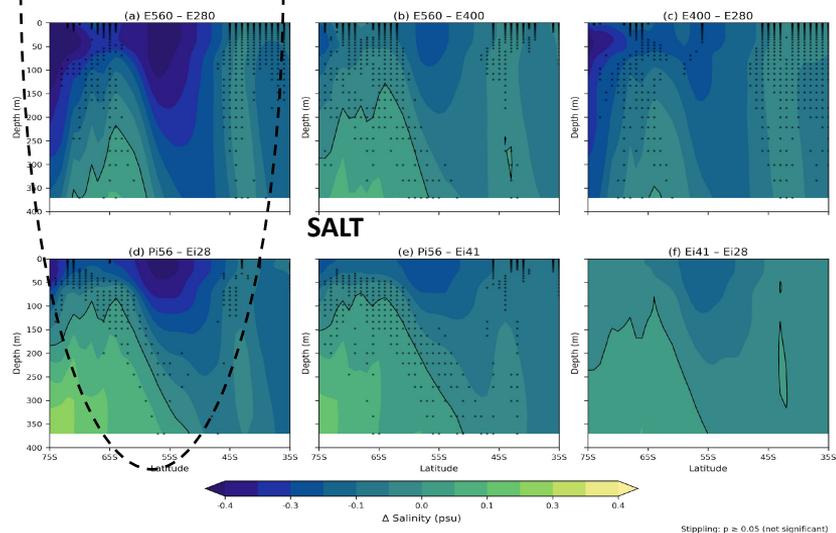
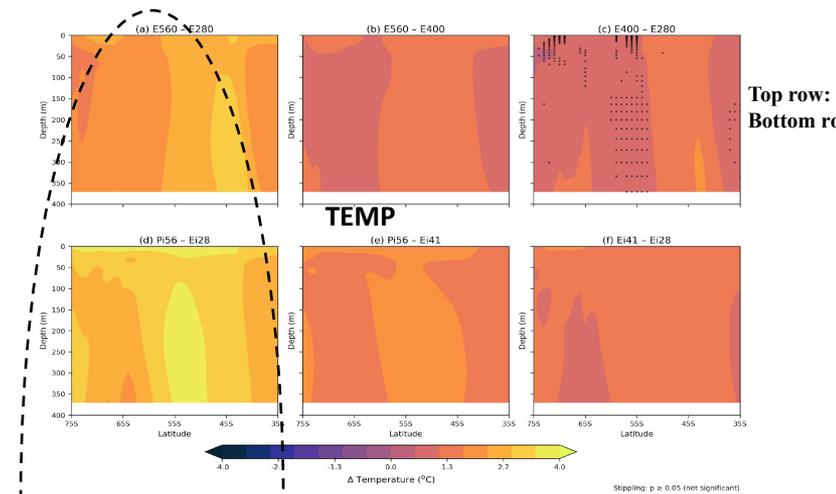


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Surface Temperature differences

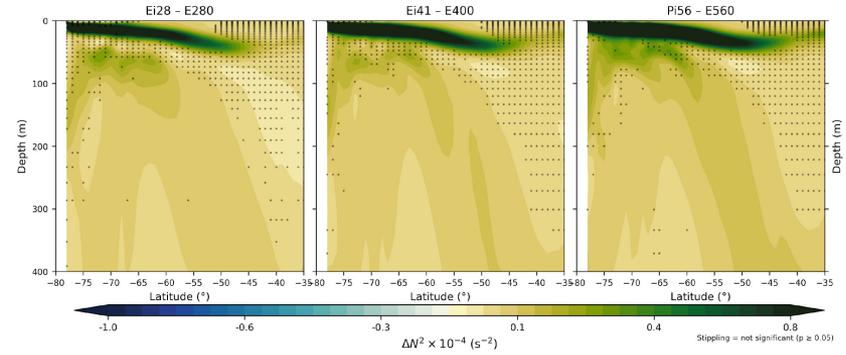
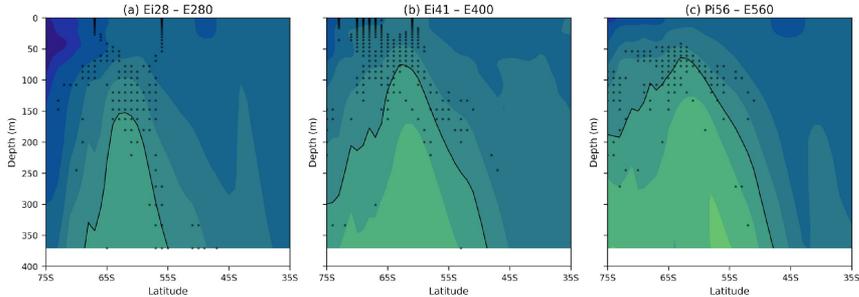
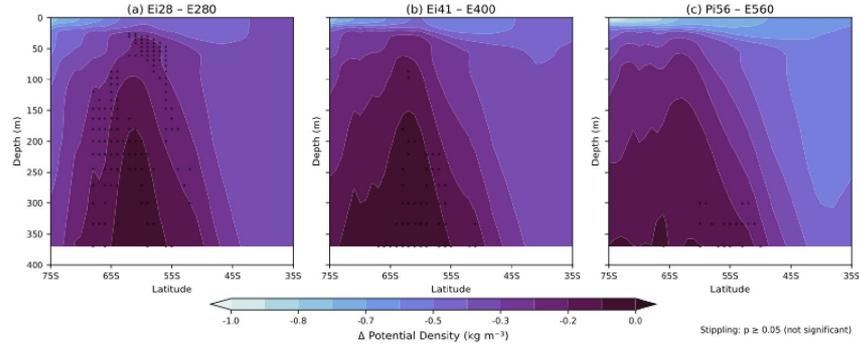
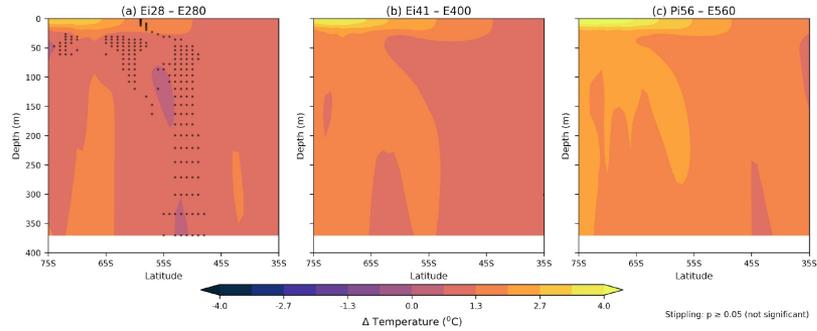


Top row: PI
Bottom row: PLIO



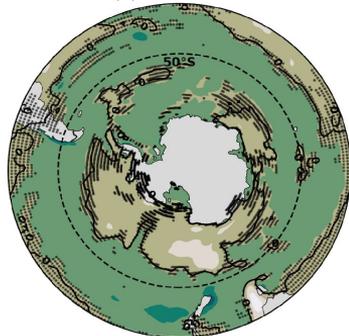
Vertical Profiles

Climate State diffs (Plio – PI)

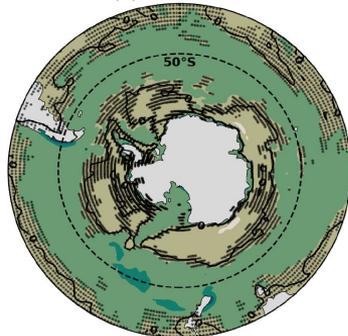


PPT

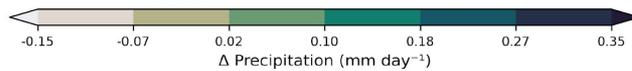
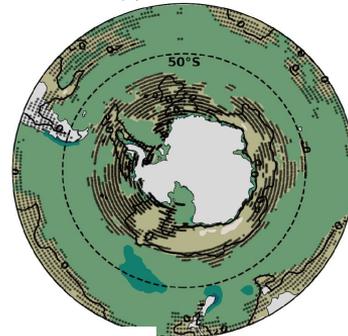
(a) Ei28 - E280



(b) Ei41 - E400



(c) Pi56 - E560

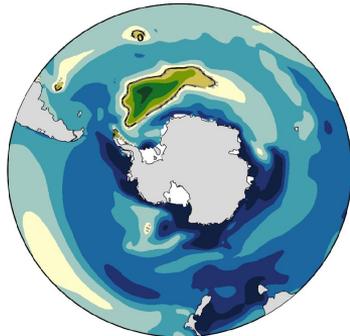


Stippling: $p \geq 0.05$ (not significant)

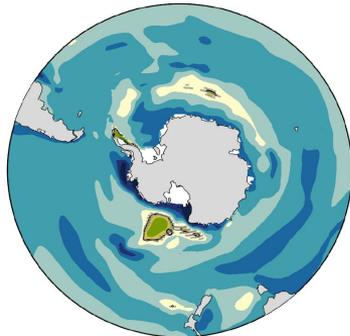
CLIMATE state diffs
PLIO-PI
(fixed CO₂)

SALT

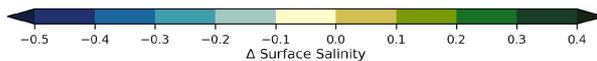
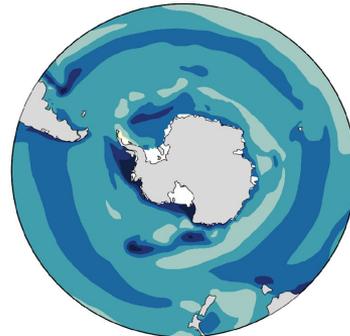
(a) Ei28 - E280



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