

On the Stability of the Atlantic Meridional Overturning Circulation in our Warming Climate

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Nearly every week there is another story about imminent AMOC collapse and tipping point climate disasters. Latest suggests damming the Bering Strait!

Such papers are a sure-fire way to get published in Nature or Science and get lots of media attention for the AMOC collapse derangement community. But they invariably get the water cycle grossly wrong and have incorrect model physics. We claim that AMOC collapse is impossible in our rapidly warming world.

The effects of a constructed closure of the Bering Strait on AMOC tipping behavior

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↓ 3,869



Abstract

The Atlantic Meridional Overturning Circulation (AMOC) is a major tipping element in the present-day climate and could potentially collapse under sufficient freshwater or CO₂ forcing. While the effect of the Bering Strait on AMOC stability has been well studied, it is unknown whether a constructed closure of this Strait can prevent an AMOC collapse under climate change. Here, we show in an Earth system Model of Intermediate Complexity that an artificial closure of the Strait can extend the safe carbon budget of the AMOC, provided that the AMOC is strong enough at the closure time. Specifically, an equilibrium AMOC under a sufficiently low additional freshwater flux has an increased safe carbon budget given a timely closure of the Strait, while for higher freshwater fluxes (and corresponding weaker AMOC), a closure reduces this budget. This indicates that constructing this closure could be a feasible climate intervention strategy to prevent an AMOC collapse.

AMOC Collapse: Could it happen in our warming world?

I've always been a skeptic, since the subpolar gyre density fluxes are completely dominated by heat loss, not freshwater gain (Schmitt et al, 1989). And the melt rate of the Greenland Ice Sheet is too small to have a significant effect (Schmitt, 2008). But I kept quiet because the topic provides a useful motivation for ocean observations and action to curb CO₂ emissions. However, recent papers and associated press attention are so egregiously wrong that I feel compelled to speak out.

1. Vanwesten, Kliphuis & Dijkstra (2024) Physics-based early warning signal shows that AMOC is on tipping course. Science Advances, 10 (6).

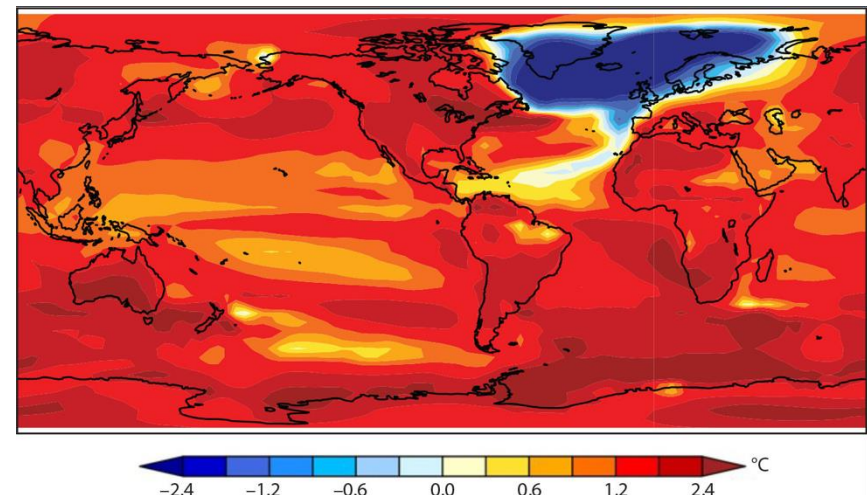
→ Completely wrong water cycle! Physically Impossible Greenland Melt Rate!

2. Gayen and Klocker (2024). Deep Convection Drives Oceanic Overturning. Physics Today, 77 (6).

→ Wrong physics! Surface Deep Convection is not Sinking!

3. Rahmstorf (2024). Is the Atlantic Overturning Circulation Approaching a Tipping Point? Oceanography, 37 (3), 16-29.

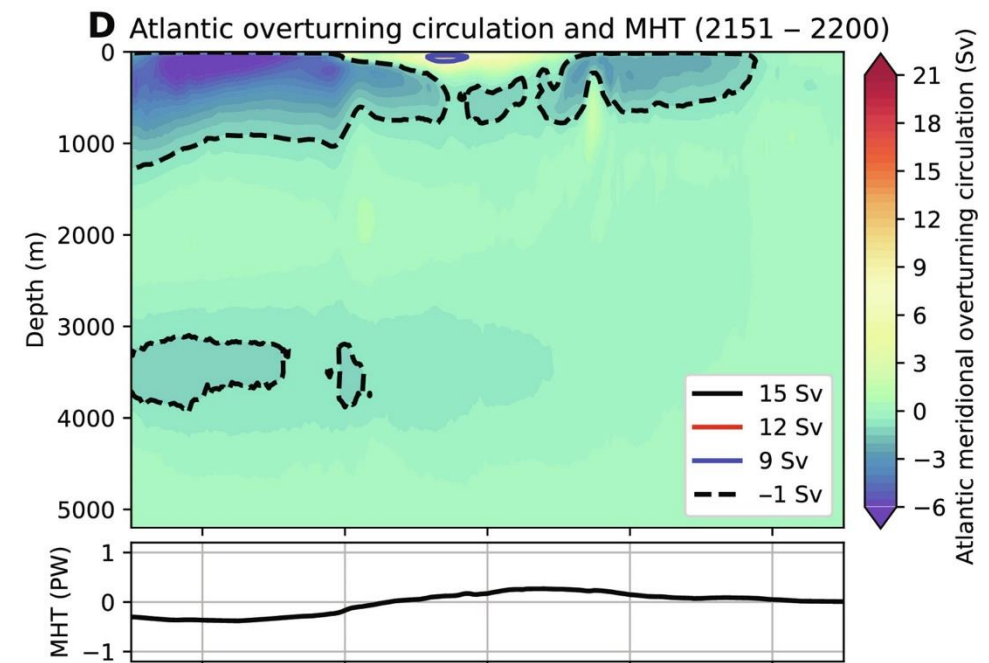
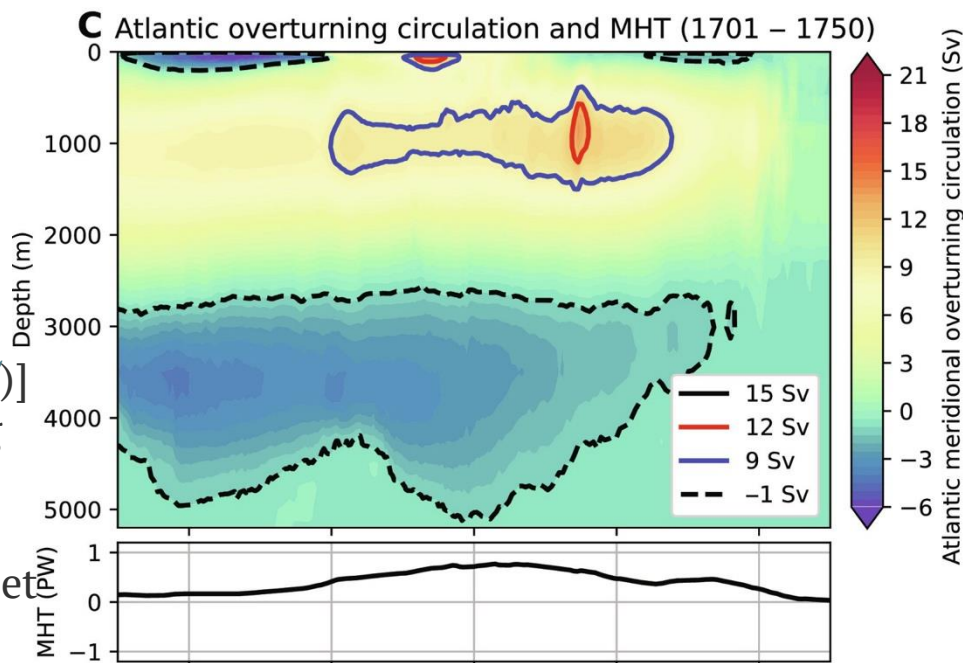
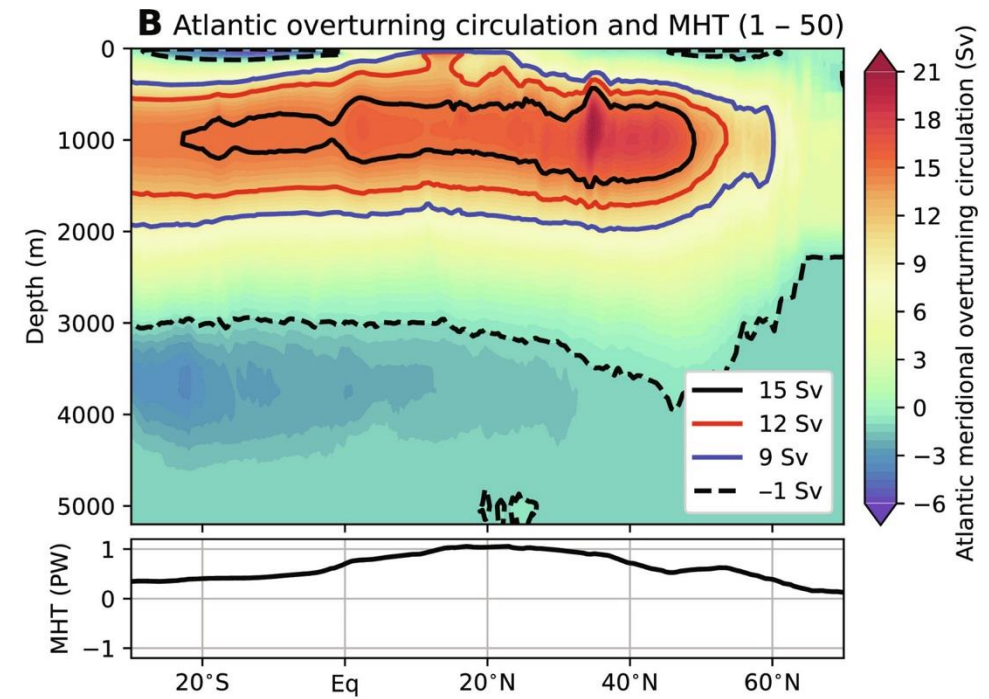
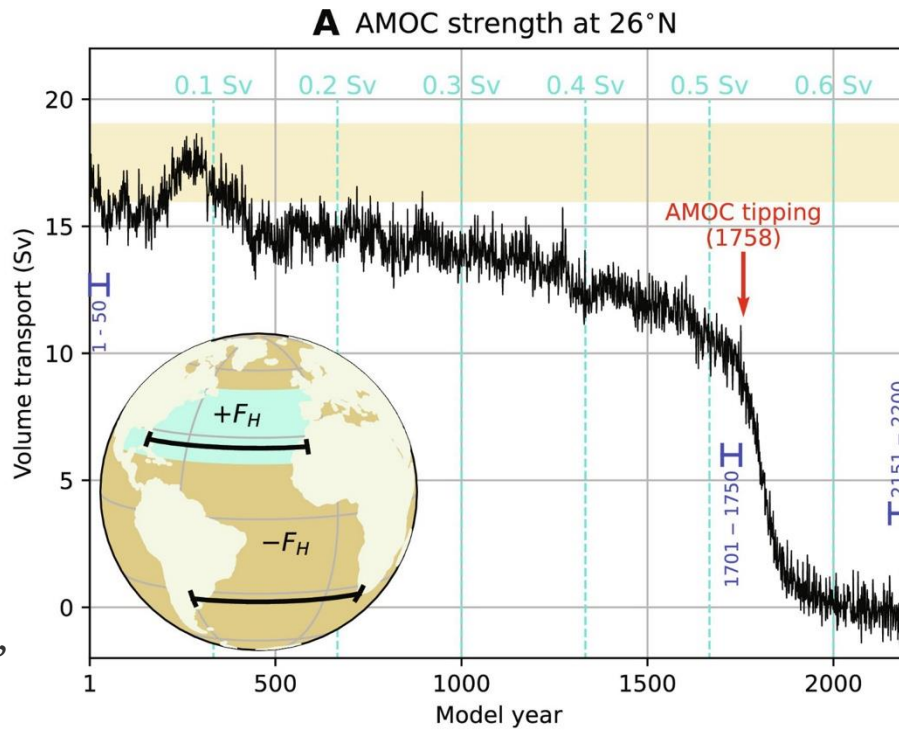
4. Open Letter to the Nordic Council of Ministers (2024).



From recent paper in Science Advances:
Physics-based early warning signal shows that AMOC is on tipping course
[VANWESTEN](#), [KLIPHUIS](#), & [DIJKSTRA](#)

“We linearly increased the freshwater flux forcing with a rate of 3×10^{-4} Sv year⁻¹ until model year 2200, where a maximum of $F_H = 0.66$ Sv is reached.”

“we needed to integrate the CESM to rather large values of the freshwater forcing [~ 0.6 Sv, **about a factor 80 times larger than the present-day melt rate of the Greenland Ice Sheet (55)**] to find the AMOC tipping event.”
 Took 2,200 years and melted Greenland Ice sheet 8 times!



From Schmitt (2008) Greenland Ice melt is SMALL compared to Atlantic Evaporation and Precipitation!

Latest estimate is 221
Km³/yr Green et al 2024
Nature 625, 523–528.

[https://doi.org/10.1038/
s41586-023-06863-2](https://doi.org/10.1038/s41586-023-06863-2)

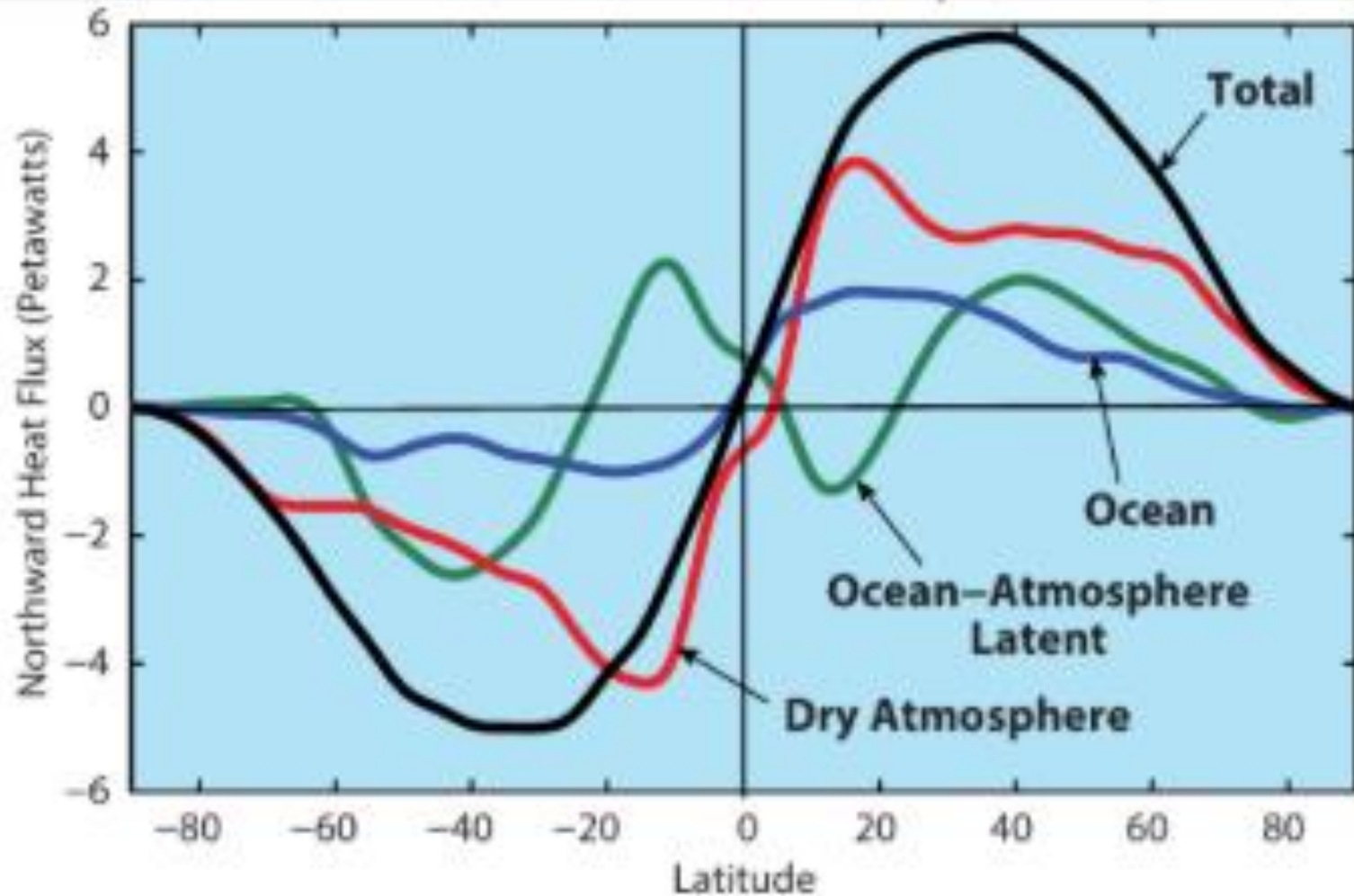
It would take 334
Petawatts to melt ice at
a one Sverdrup rate!!!

Table 1. Some components of the global water cycle
in km³/yr and Sv (= 10⁶ m³/s)

	km ³ /yr	Sv
Pacific Evaporation	212,655	6.74
Pacific Precipitation	228,529	7.24
Atlantic Evaporation	111,085	3.52
Atlantic Precipitation	74,626	2.36
African Precipitation	20,743	0.66
N. American Precipitation	15,561	0.49
European Precipitation	6,587	0.21
Amazon River Discharge	6,000	0.19
Mississippi River Discharge	560	0.017
Greenland Glacial Melt Discharge*	225	0.007

*According to Baumgartner and Reichel (1975) and Rignot and Kanagaratnam (2006)

From Schmitt, 2018
Impossible to find 334 Petawatts!!!



Their “Hosing” rate of 0.66 Sv is impossibly high. The actual melting rate of Greenland Ice is two orders of magnitude too small to have much effect on the AMOC.

The surface density of the sub-polar gyre is thoroughly dominated by heat loss, not freshwater gain (Schmitt, et al, 1989)

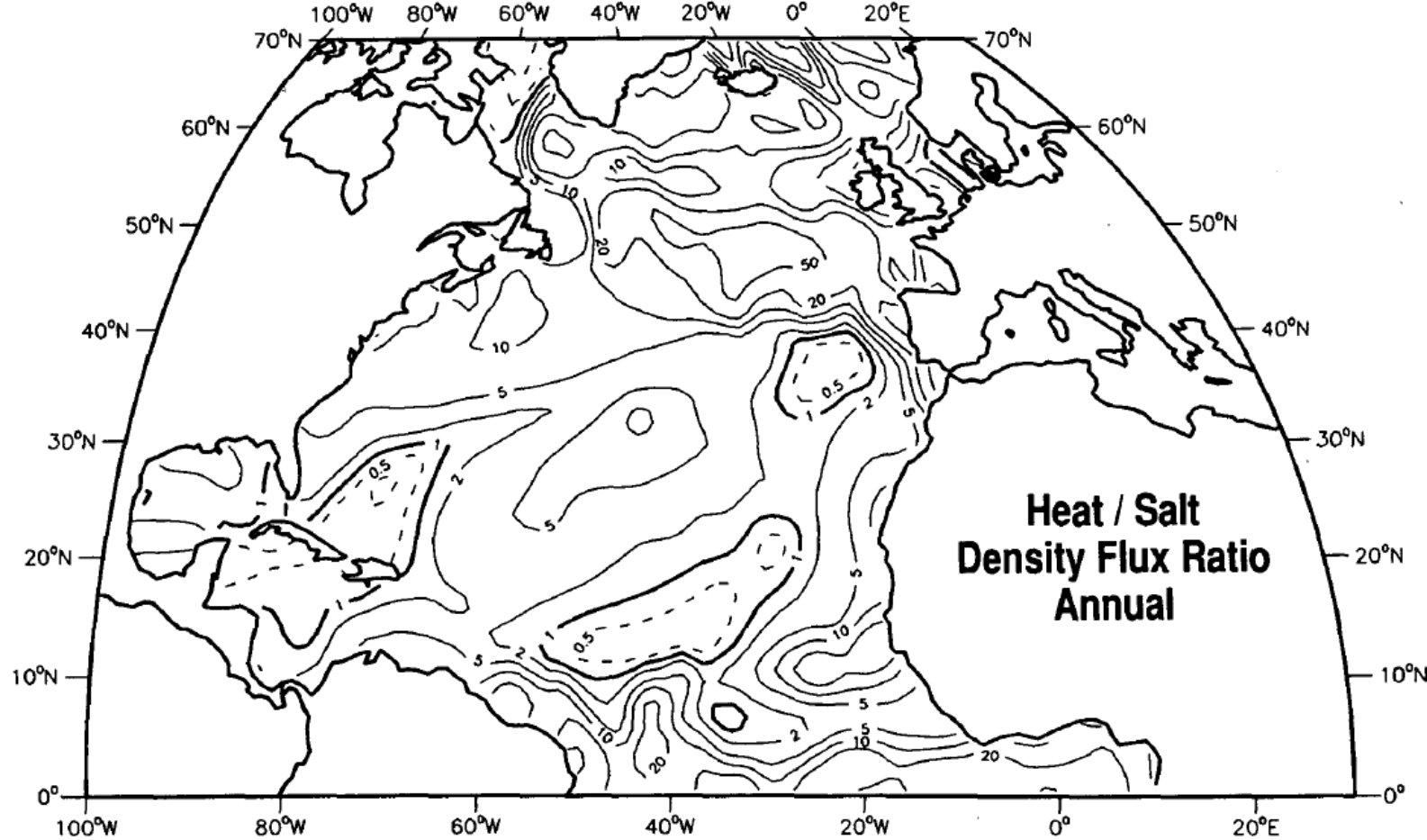
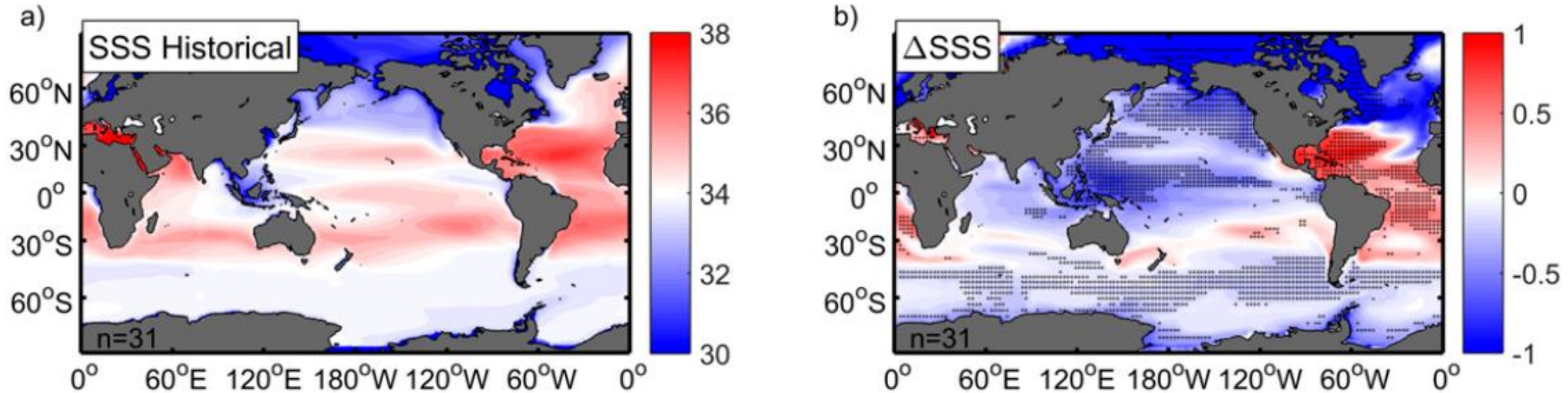


FIG. 5. (Continued) (c) The absolute value of the ratio of the heat and salt density fluxes, $|\alpha F_T / \beta F_S|$.

From **Levang and Schmitt 2015, Journal of Climate**

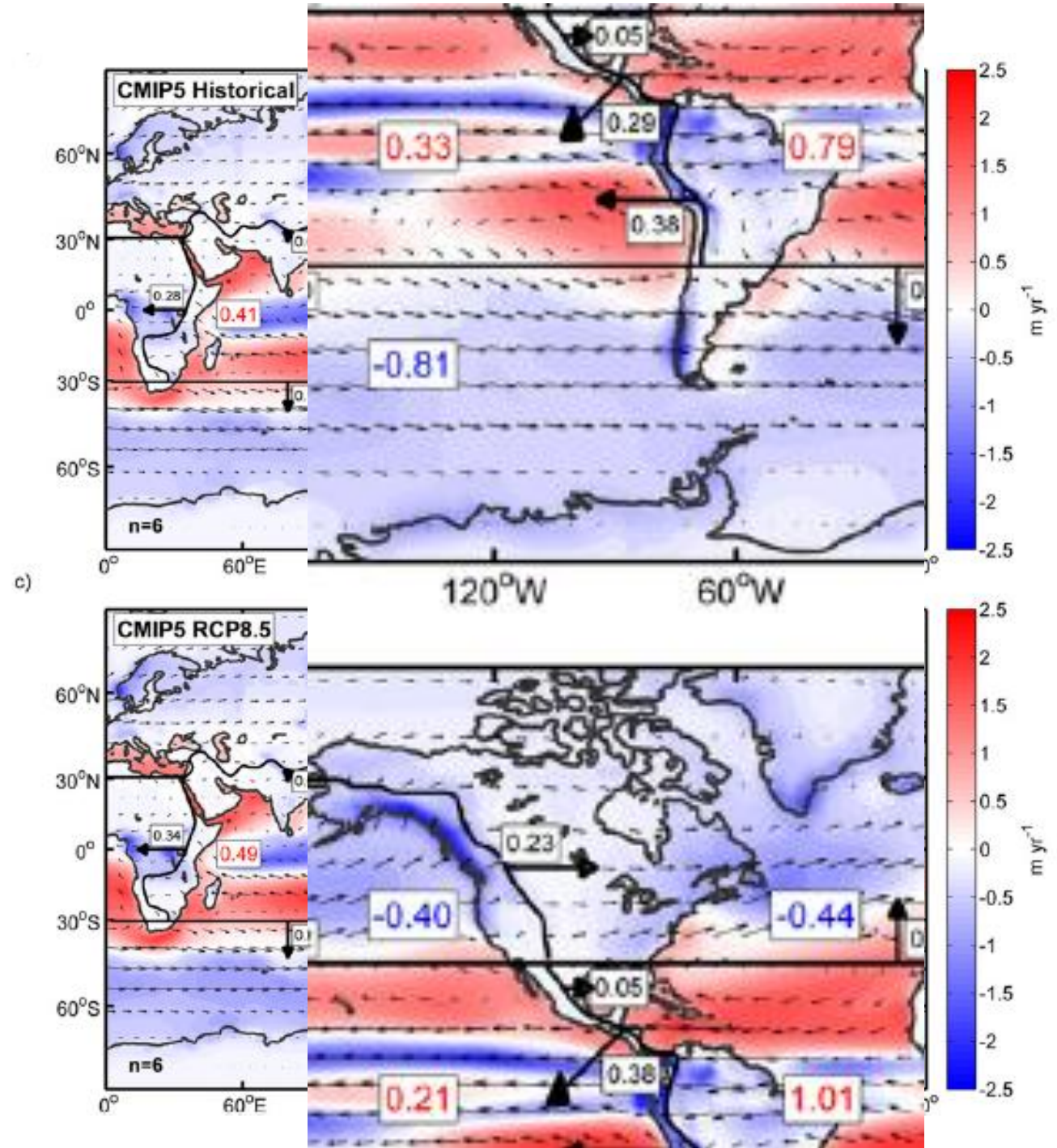
Centennial Changes of the Global Water Cycle in CMIP5 Models



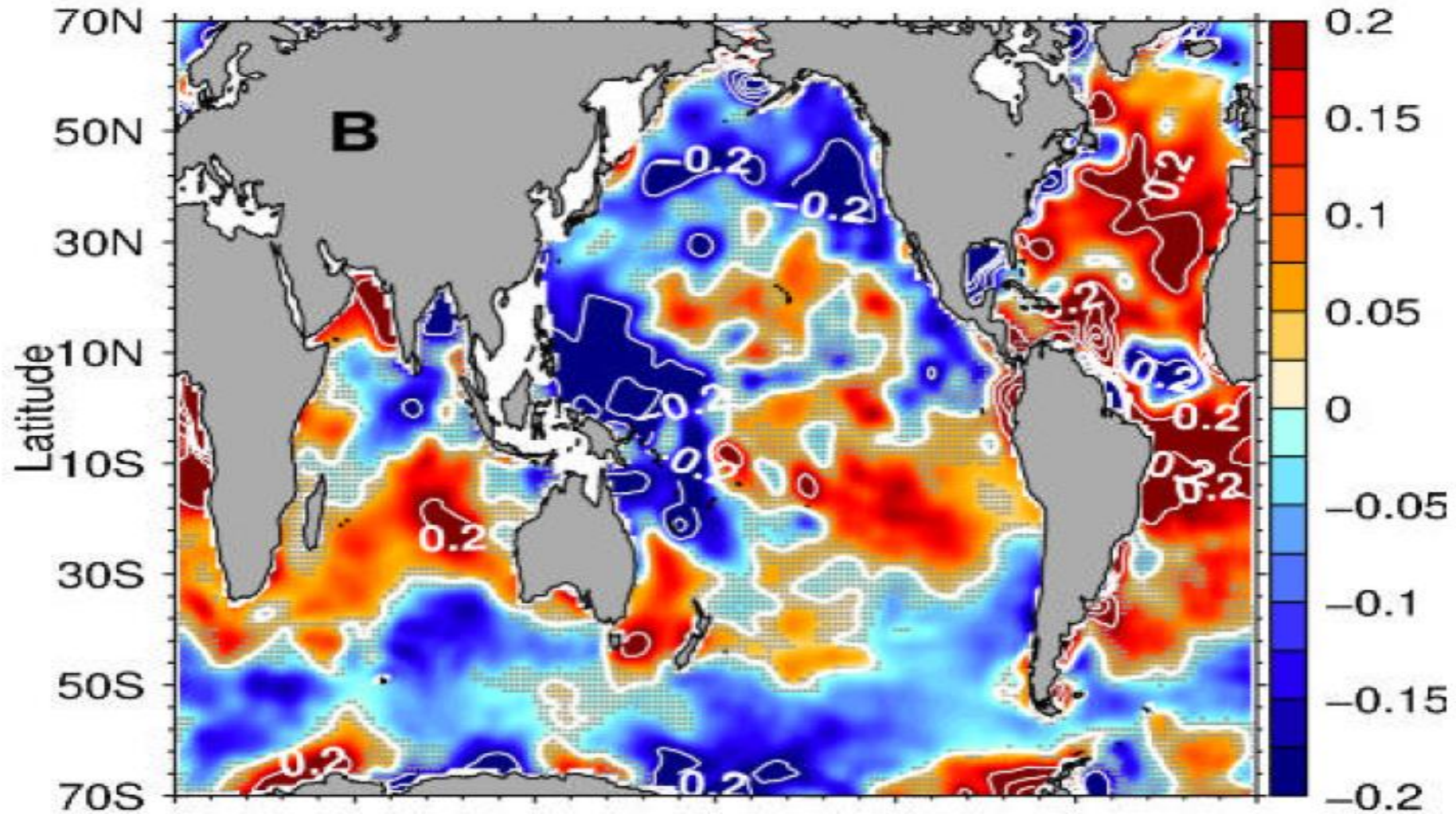
From **Levang and Schmitt 2015, Journal of Climate**

Centennial Changes of the Global Water Cycle in CMIP5 Models

The global water cycle is predicted to intensify under various greenhouse gas emissions scenarios. Here the nature and strength of the expected changes for the ocean in the coming century are assessed by examining the output of several CMIP5 model runs for the periods 1990–2000 and 2090–2100 and comparing them to a dataset built from modern observations. Key elements of the water cycle, such as the atmospheric vapor transport, the evaporation minus precipitation over the ocean, and the surface salinity, show significant changes over the coming century. The intensification of the water cycle leads to increased salinity contrasts in the ocean, both within and between basins. Regional projections for several areas important to large-scale ocean circulation are presented, including the export of atmospheric moisture across the tropical Americas from Atlantic to Pacific Ocean, the freshwater gain of high-latitude deep water formation sites, and the basin averaged evaporation minus precipitation with implications for interbasin mass transports.



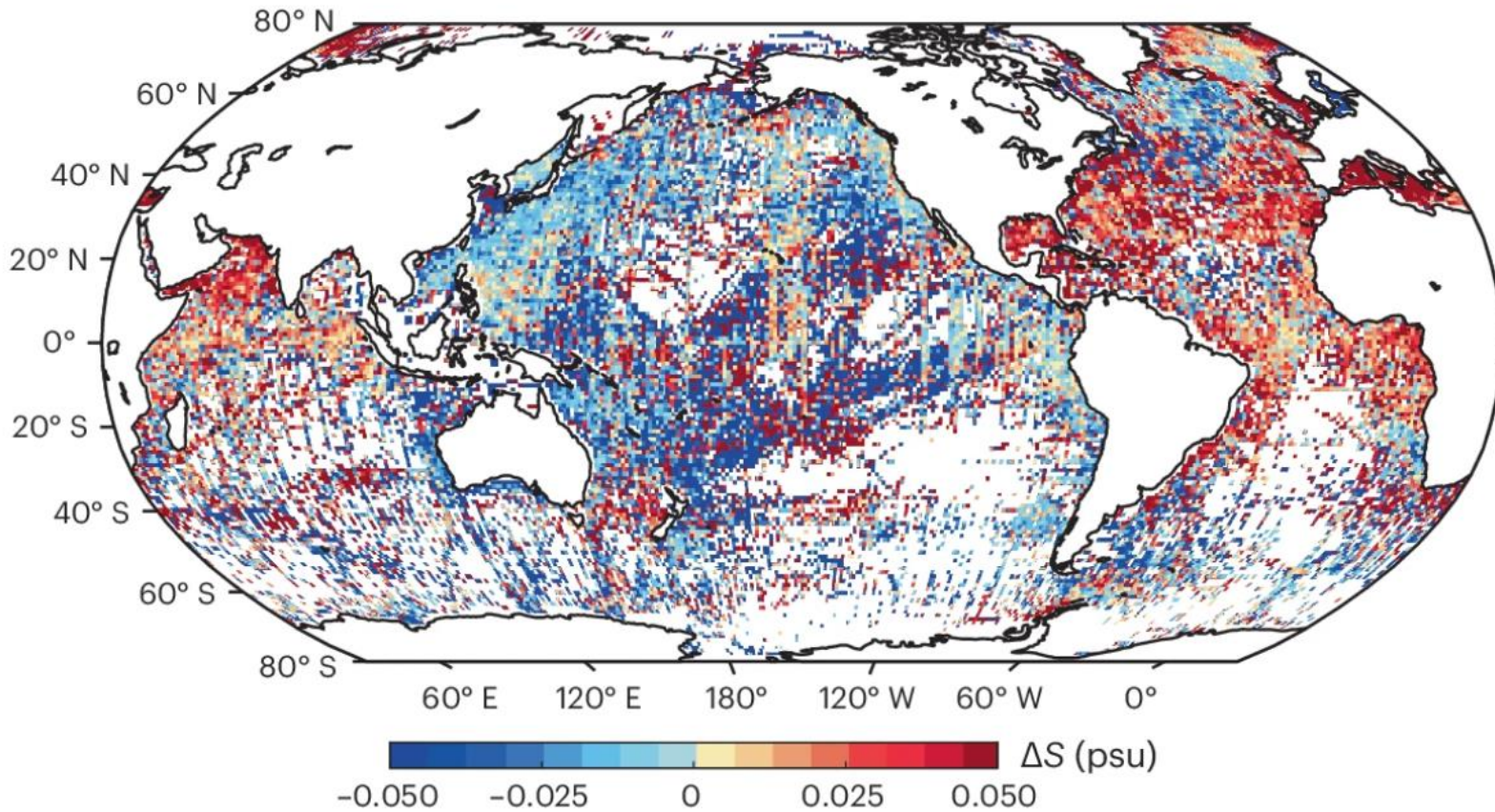
Durack and Wijffels, 2010. Fifty year trend in Sea Surface Salinity



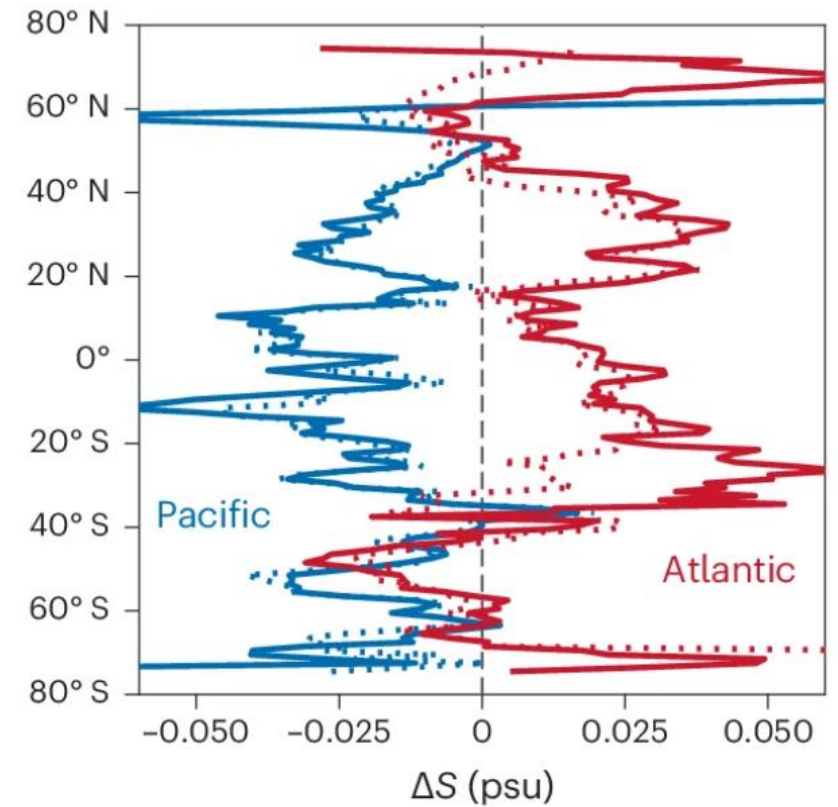
North Atlantic–Pacific salinity contrast enhanced by wind and ocean warming

• [Y. Lu, et al, 2024. *Nature Climate Change* volume 14, pages723–731.](#)

c



d



Changes in the 0–2,000 m average salinity in 1965–2018 (ΔS)

The MOC is driven by diapycnal mixing!

- **Well established theory that MOC $\sim K^{2/3}$**
- **Welander, 1971; Bryan, 1987; Marotzke, 1997; Zhang, Schmitt and Huang, 1999**
- **Deep Convection is a transient water mass formation process, not a driver of the MOC! Interior mixing processes determine how they are incorporated into the MOC. Sinking regions are small (Stommel, 1962) and consequences of the MOC not a driver!**

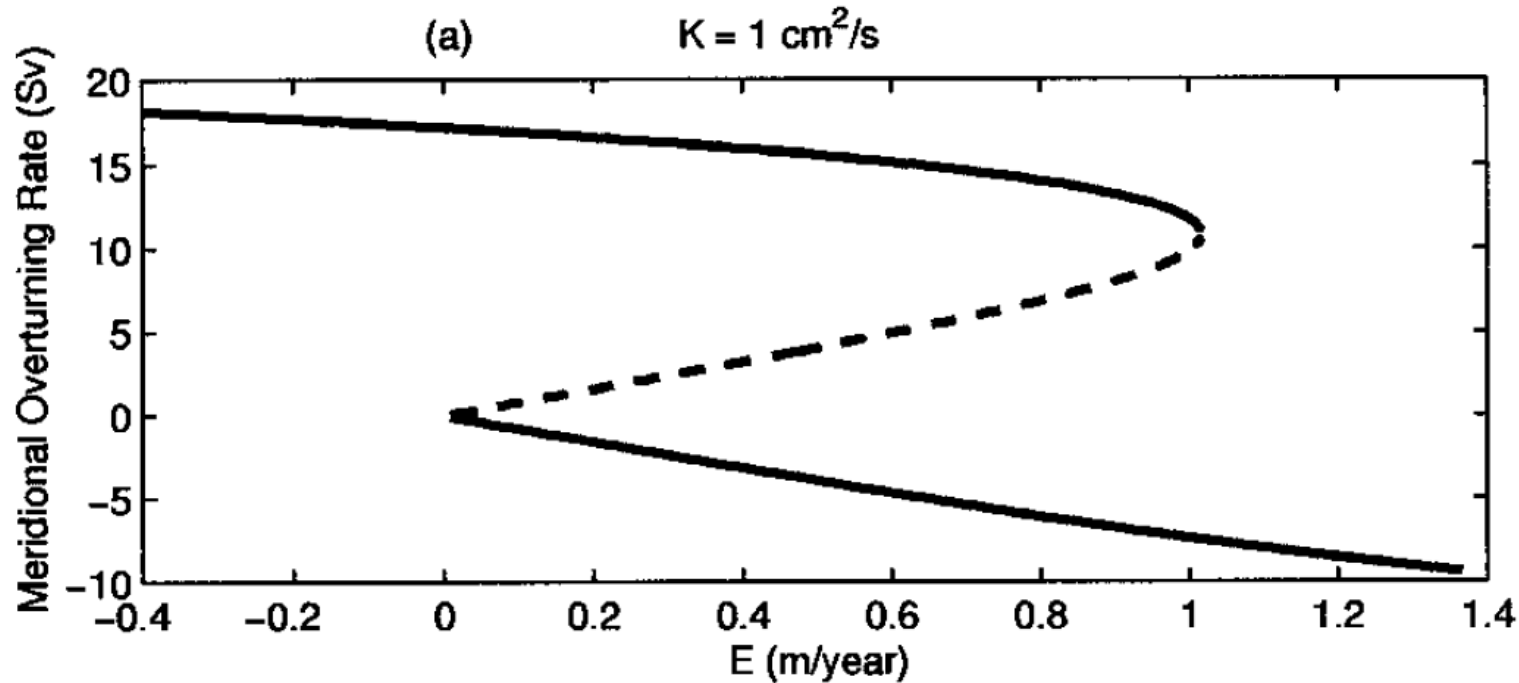
The Relative Influence of Diapycnal Mixing and Hydrologic Forcing on the Stability of the Thermohaline Circulation*

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$$M = \left[\frac{g\alpha\Delta T |R - 1| K^2 L^4}{f} \right]^{1/3} .$$

Our analytic solution implies a critical value for the freshwater forcing to get shut down:

$$E_c(K) = \sqrt[3]{\frac{27g\alpha\Delta T}{256fL^2} \frac{\alpha\Delta T}{\beta S}} K^{2/3} \quad (35)$$

$$= CK^{2/3}. \quad (36)$$

Thus, for a given value of K , there is an upper limit of freshwater forcing $E_c(K)$ beyond which no thermal mode can exist. Below this value two thermal modes, in addition to the haline mode, are possible for all given conditions. Atlantic is in thermal mode, Pacific in haline mode.

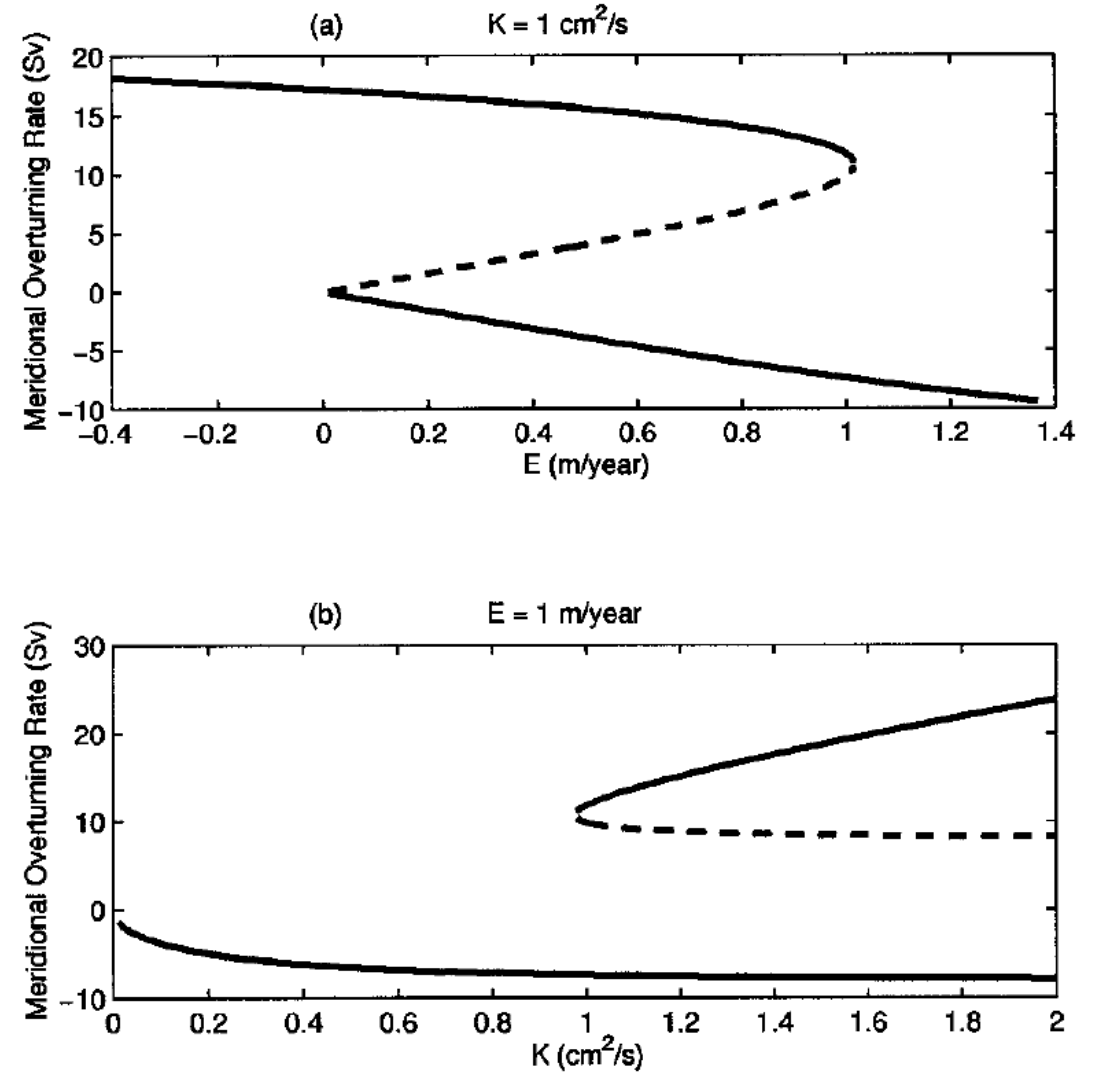


FIG. 2. Solutions of meridional overturning rate under mixed boundary conditions for: (a) fixed $K = 1.0 \text{ cm}^2/\text{s}$ with changing E and (b) fixed $E = 1 \text{ m/yr}$ with changing K .

Deep Mixing is driven by tidal flows over topography.

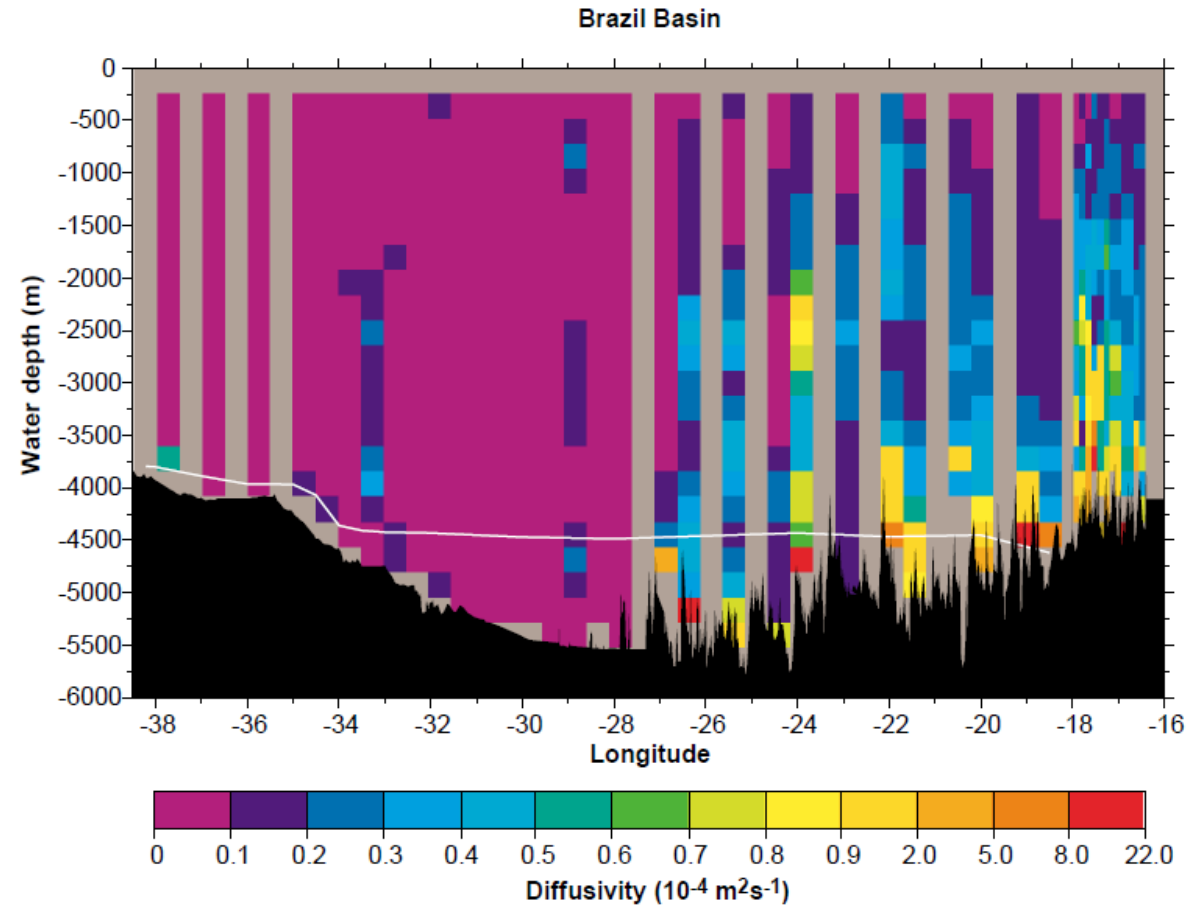
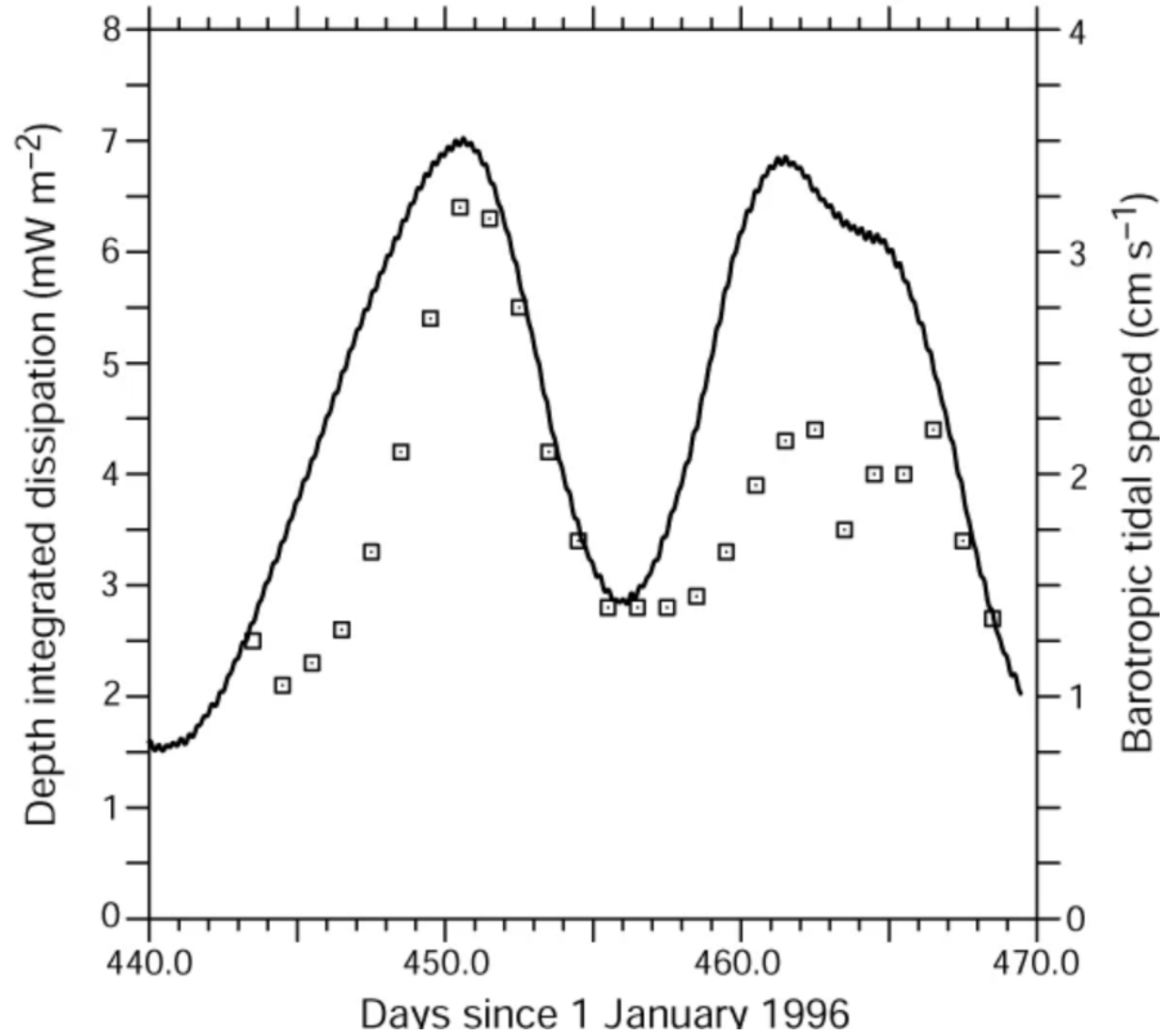


Fig. 2. Depth-longitude section of cross-isopycnal diffusivity in the Brazil Basin inferred from velocity microstructure observations. Note the nonuniform contour scale. Microstructure data from the two quasi-zonal transects have been combined without regard to latitude. The underway bathymetric data to 32°W is from the eastward track, the balance comes from the westward track. The white line marks the observed depth of the 0.8°C surface.

- However, it is now clear that the constant diapycnal diffusivity assumed in models is WRONG. The Brazil Basin Tracer Release Experiment (Ledwell, et al, 2000) showed that ocean mixing is clearly regulated by tides and topography, with greater turbulent dissipation when tides were strong.

- The Tracer and Microstructure experiments also showed that the Osborn (1980) expression for diffusivity is reasonably accurate.

- $K = 0.2 e / N^2$



Standard Model: Assuming incompressibility, thermal wind and vertical advective-diffusive balance (Welander, 1971, Bryan, 1987), Zhang, Schmitt and Huang, 1998) with fixed K :

From the above equations, we obtain the scaling relations:

$$\begin{aligned} UD &= WL, \\ \frac{\Delta\rho}{\rho_0} &= \frac{fUL}{gD}, \\ D &= \frac{K}{W}, \end{aligned} \quad (7)$$

where $U(L)$ and $W(D)$ are horizontal and vertical velocity (length) scales, respectively, and $\Delta\rho$ is the north-south density difference at the ocean surface.

From these we can derive the vertical length scale in terms of $\Delta\rho/\rho_0$:

$$D = \left[\frac{fKL^2}{g\Delta\rho/\rho_0} \right]^{1/3}, \quad (8)$$

which is actually the scale thickness of the thermocline (Samelson and Vallis 1997).

Thus, the strength of the meridional overturning is

$$M = UDL = WL^2 = \left[\frac{g\Delta\rho K^2 L^4}{\rho_0 f} \right]^{1/3}. \quad (9)$$

New model: using Osborn (1980) relation for the diffusivity, where epsilon is the fixed dissipation rate:

$$K_\rho = \Gamma \frac{\epsilon}{N^2}$$

where

$$N^2 = -\frac{g}{\rho_0} \frac{\partial\rho}{\partial z}$$

The scaling law for above equation is,

$$K_\rho = \frac{\Gamma\epsilon}{\frac{g}{\rho_0} \frac{\Delta\rho}{D}} = D \frac{\Gamma\epsilon}{g \frac{\Delta\rho}{\rho_0}}$$

Therefore, plugging into [6](#) we have:

$$W = \frac{K_\rho}{D} = \frac{\Gamma\epsilon}{g \frac{\Delta\rho}{\rho_0}}$$

the vertical speed is in reverse relationship with $\frac{\Delta\rho}{\rho_0}$ MOC can then be updated as,

$$M = WL^2 = \frac{\Gamma\epsilon}{g \frac{\Delta\rho}{\rho_0}} L^2$$

Zhang, Schmitt
and Huang, (1999)

The Meridional
Overturning rate
varies with the 2/3
power of the
diffusivity in
numerical models.

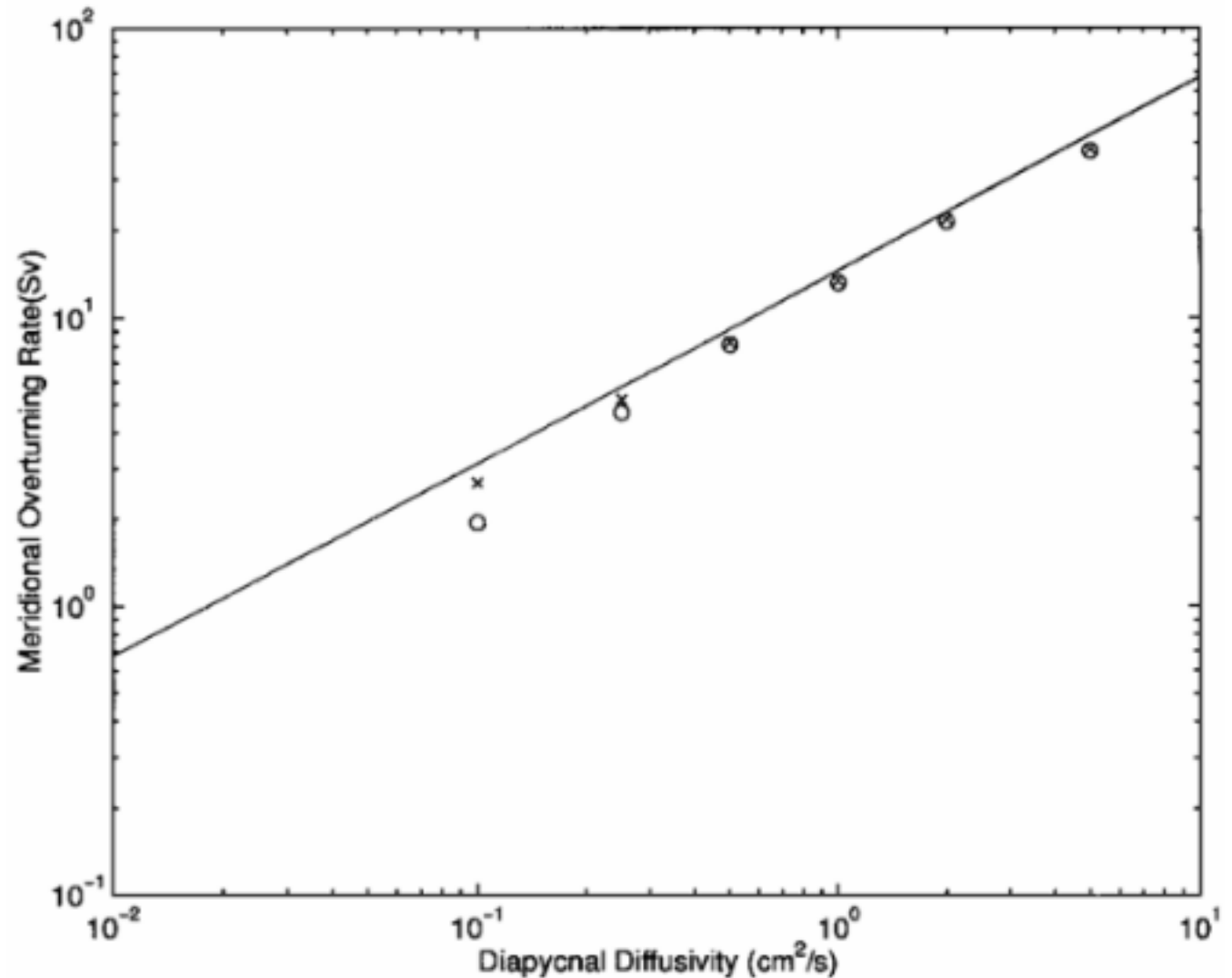


FIG. 4. Meridional overturning rate from scaling analysis and numerical experiments under relaxation boundary conditions. The "x" and "o" represent the numerical results without and with wind stress,

With Fixed Diffusivity:

$$M \sim \Delta\rho^{1/3} K^{2/3}$$

With Fixed Mixing Energy ϵ :

$$M \sim \epsilon/\Delta\rho$$

It's easier to mix when the density contrast is weaker!

Not a new idea, others have looked at an energetically constrained MOC and find that warming or freshening will accelerate the MOC:

- Huang, R.X., 1999. Mixing and energetics of the oceanic thermohaline circulation. *Journal of Physical Oceanography*, 29(4), pp.727-746.
- Nilsson, J. and Walin, G., 2001. Freshwater forcing as a booster of thermohaline circulation. *Tellus A*, 53(5), pp.629-641.
- Wunsch, C. and Ferrari, R., 2004. Vertical mixing, energy, and the general circulation of the oceans. *Annu. Rev. Fluid Mech.*, 36(1), pp.281-314.

Summary:

- There is no Lake Agassiz to supply $\sim 1\text{SV}$ of hosing to the N. Atlantic.
- It is energetically impossible to melt Greenland Ice fast enough to counteract the strong subtropical salinification underway and no ice dams to break.
- Paleo data shows that the AMOC was running strong during the last glacial maximum (Wharton et al, 2025) and Heinrich events (Repschläger et al, 2021)
- There is no evidence for a decline in AMOC transport in the modern era: Volkov et al, (2024); Johns et al, (2023)
- Diapycnal mixing drives the AMOC, not deep convection! Deep sinking is a consequence of the internal mixing, not a driver.

There is no Tipping Point for the AMOC!

- Vertical mixing is a driver of the MOC and is improperly represented by a constant eddy diffusivity.
- In constant mixing energy models it is easier to mix a smaller density contrast arising from warming or freshening, thus accelerating the AMOC.
- The North Atlantic will always be saltier than the North Pacific because of water vapor transport across Central America.
- Wide-spread Sea Ice formation in the barrier-layer from the Freshwater from Lake Agassiz likely caused the European Cooling event of the Younger Dryas. Europe will continue to heat up with Global warming!