# Large-scale ocean circulation and climate: Deep convection and overturning

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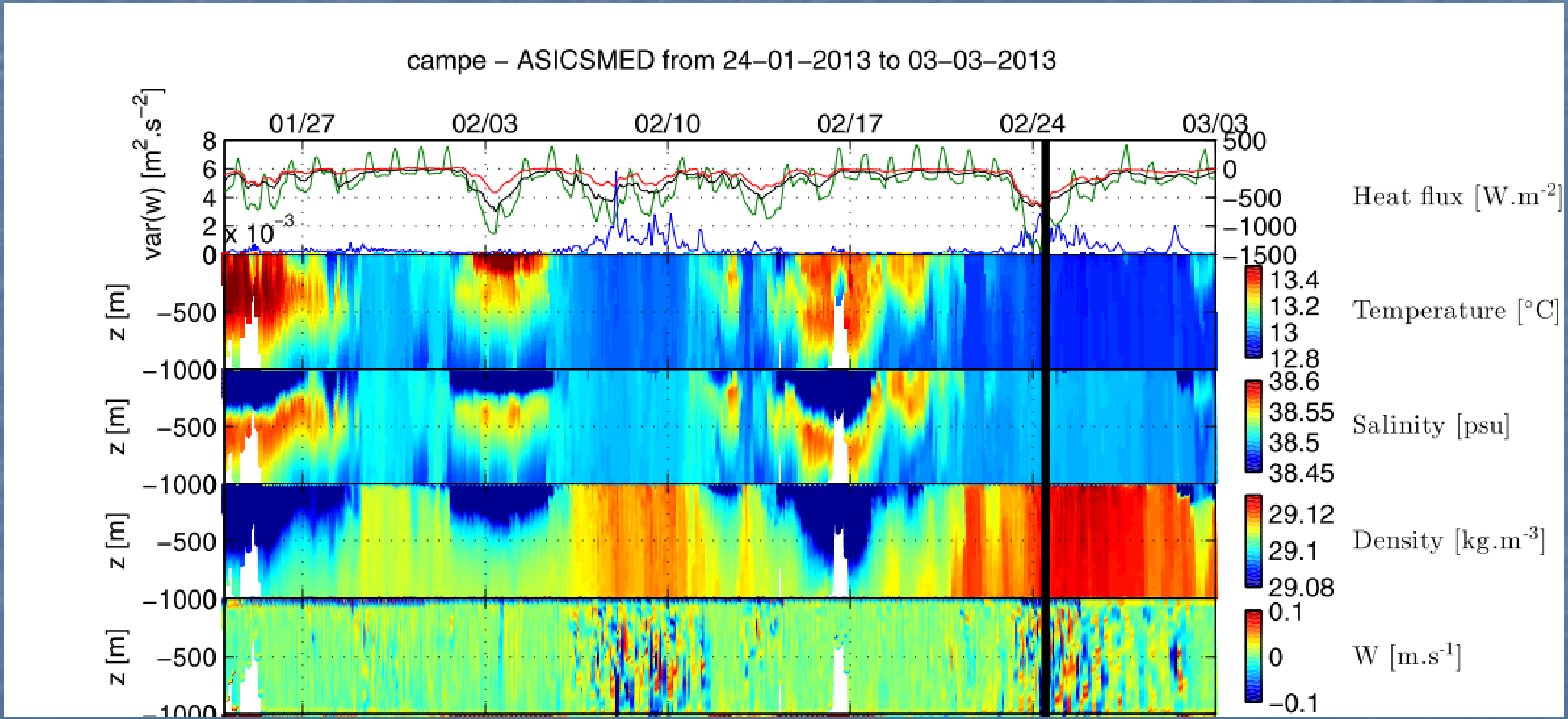
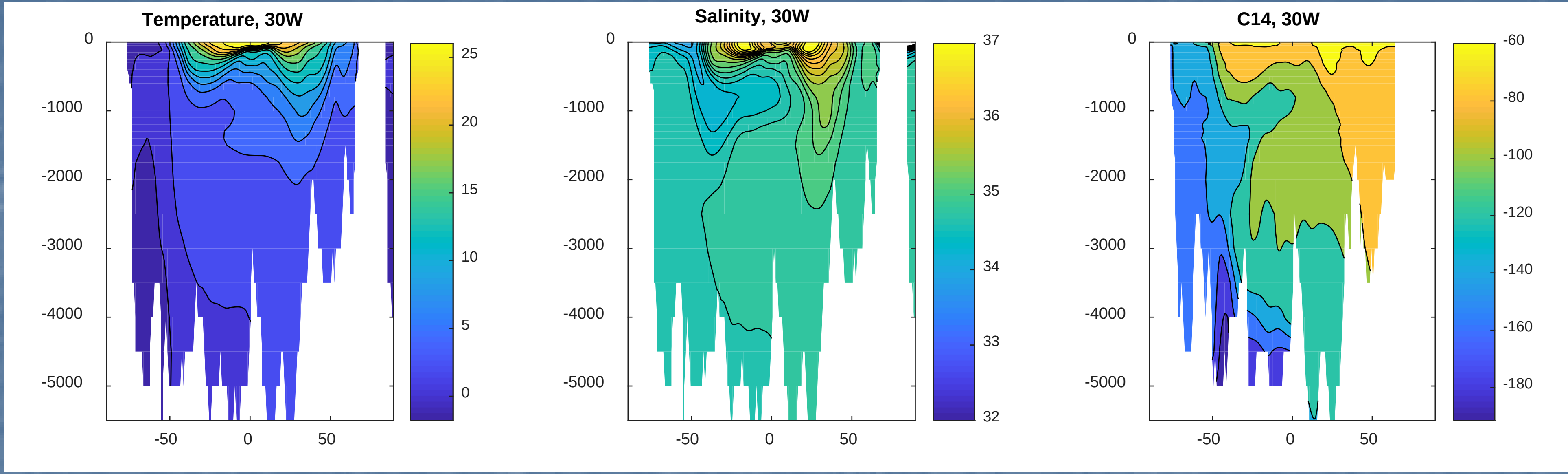
2023 ICTS Summer School on
Mathematical modeling of Climate Ocean
and Atmospheric Processes

# Measurements in Gulf of Lyons




Marginier et al., GRL, 2017

# Atlantic Temperature, salinity and radiocarbon

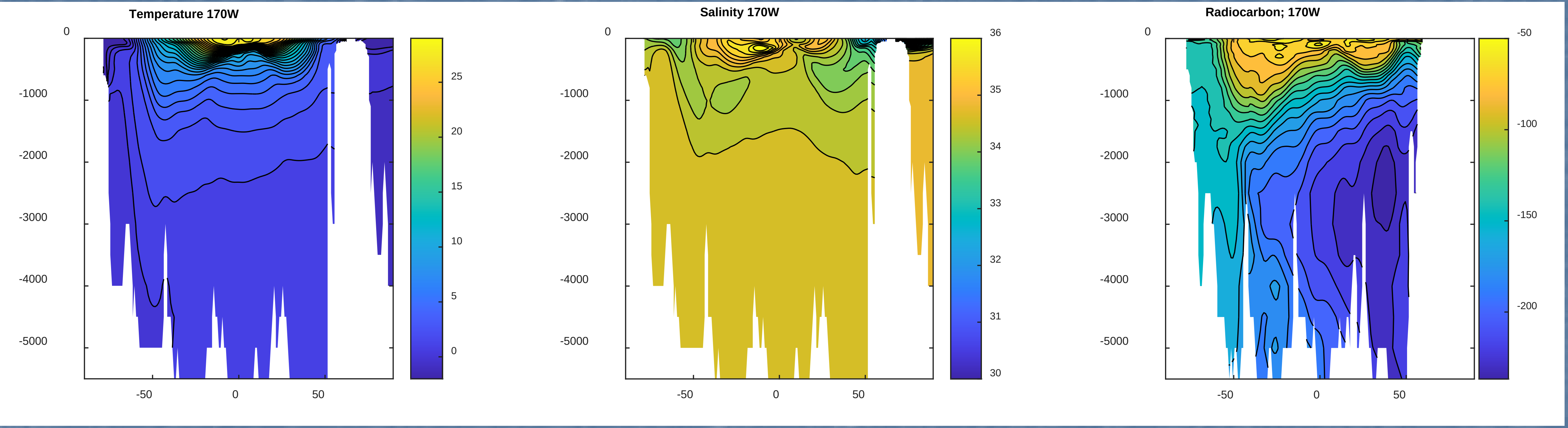



Deep water is cold- water has to reach tropics from high latitudes.

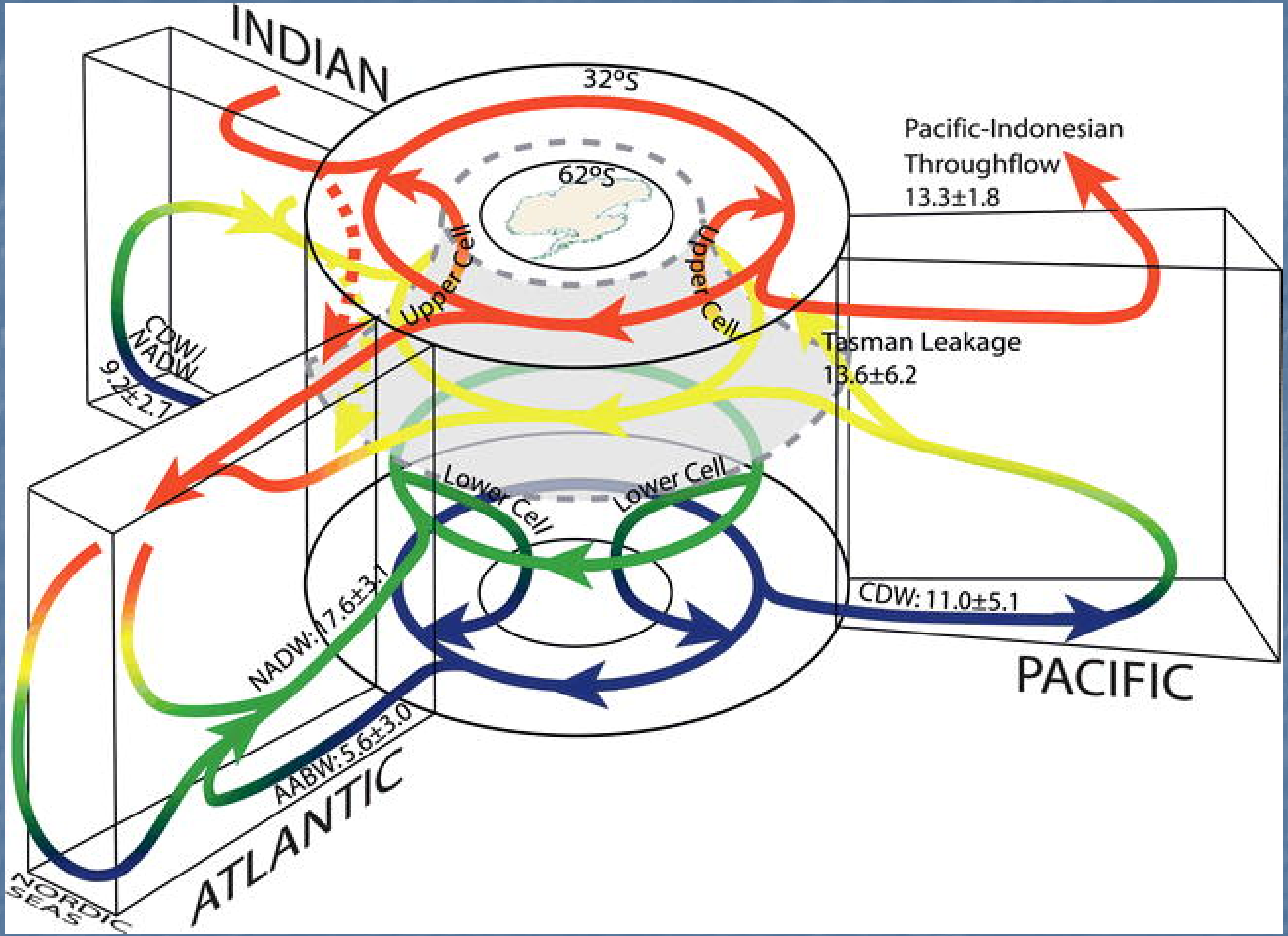
Northern Hemisphere is salty, slightly warm, southern hemisphere fresh

Northern hemisphere has more radiocarbon (more equilibrated with atmosphere)

# Pacific looks very different!

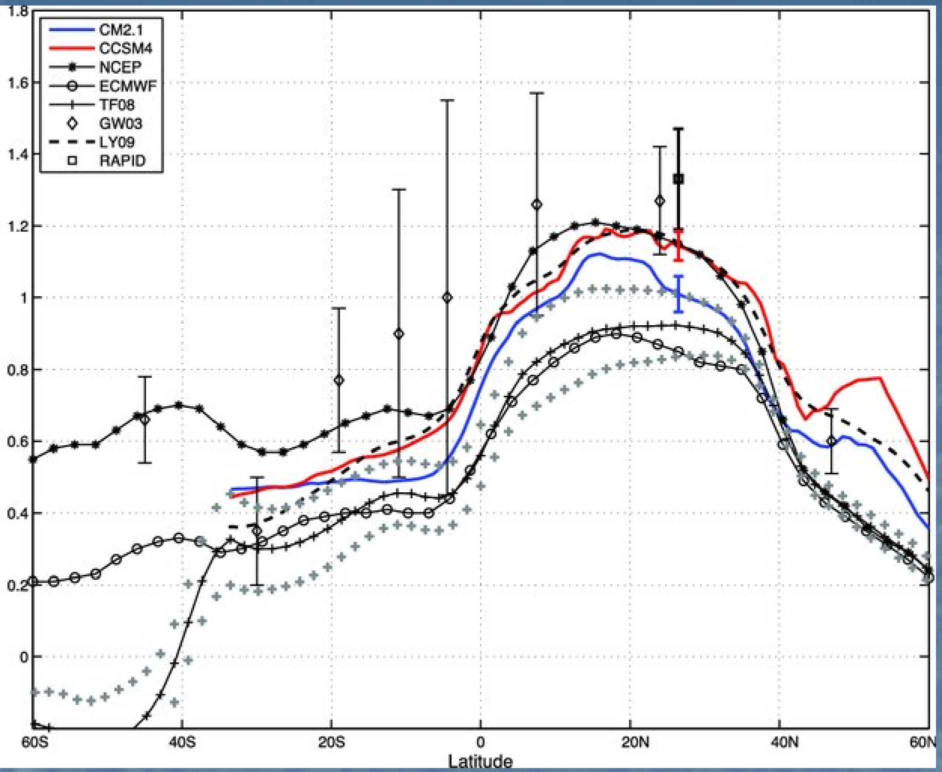


# Global overturning




Lumpkin and Speer, Journal of Physical Oceanography, 2007

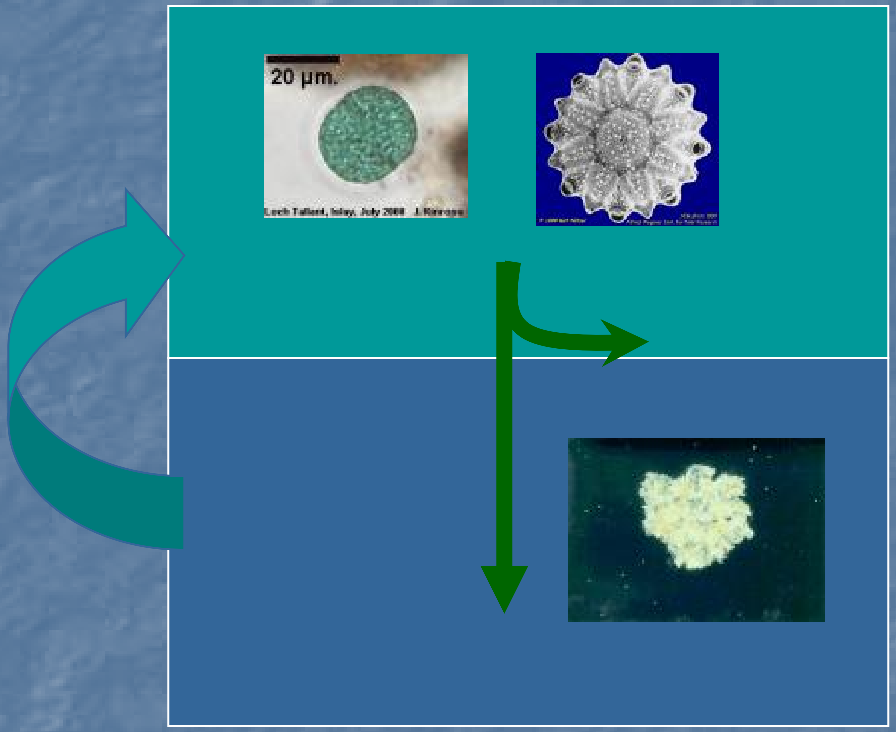
# Why do we care?




Heat transport in Atlantic is from south to north.

Biological activity takes up these nutrients

Mixing and upwelling bring nutrients to the surface.




Shallow sunlit euphotic zone

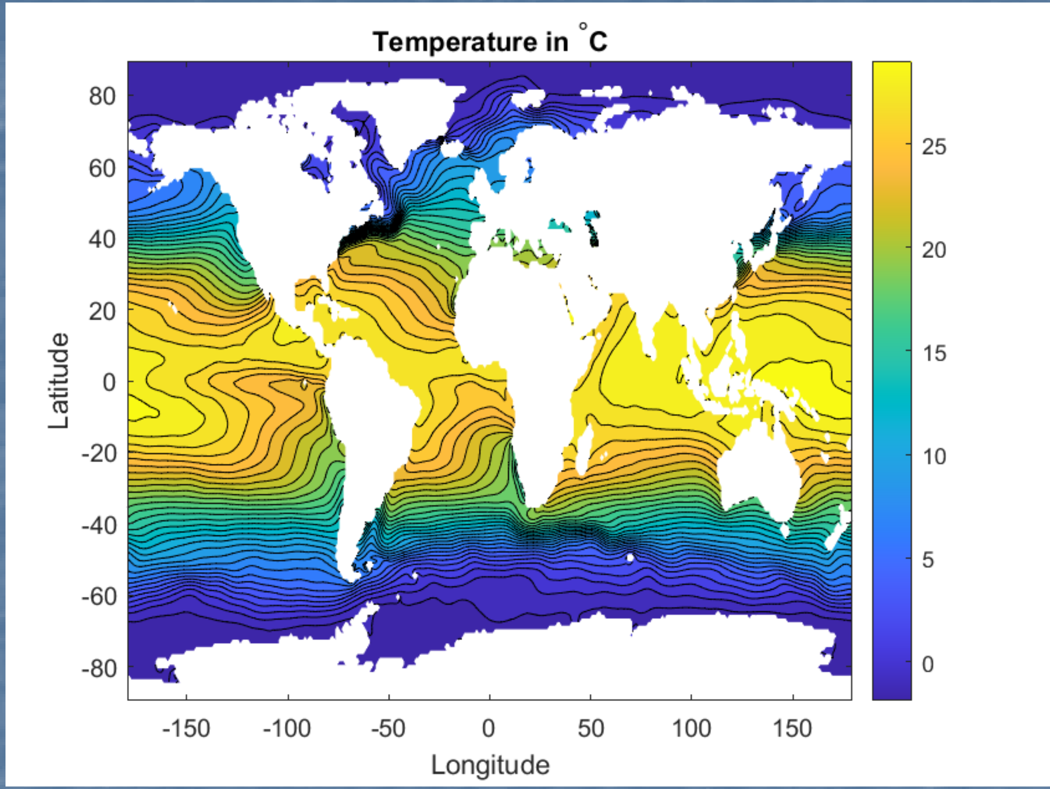
High nutrient ocean interior

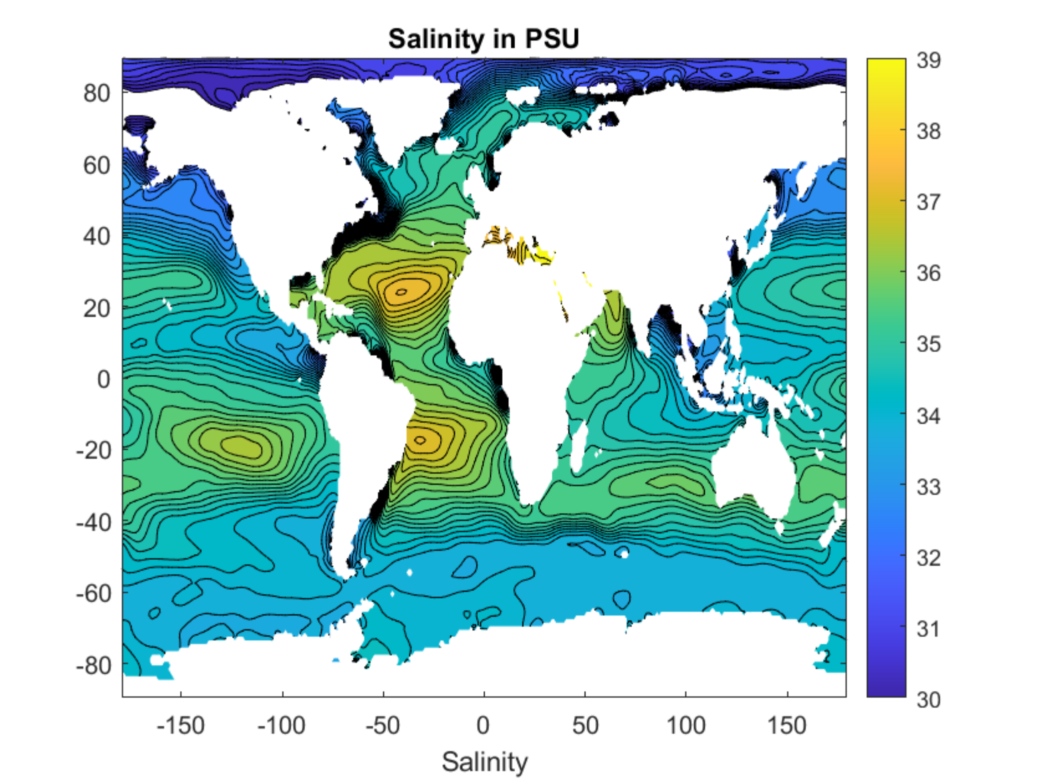
Sinking fluxes export nutrients back to depth

# Goals for this lecture

- What processes control the magnitude of overturning?
  - Understanding the role of salt vs. temperature
  - Understanding the role of Southern Ocean winds and turbulence.
- Why isn't there overturning in the Pacific?
  - Role of the geometry of the hydrological cycle.
  - Role of mixing.

# Key idea 1: Ocean density depends on both T and S

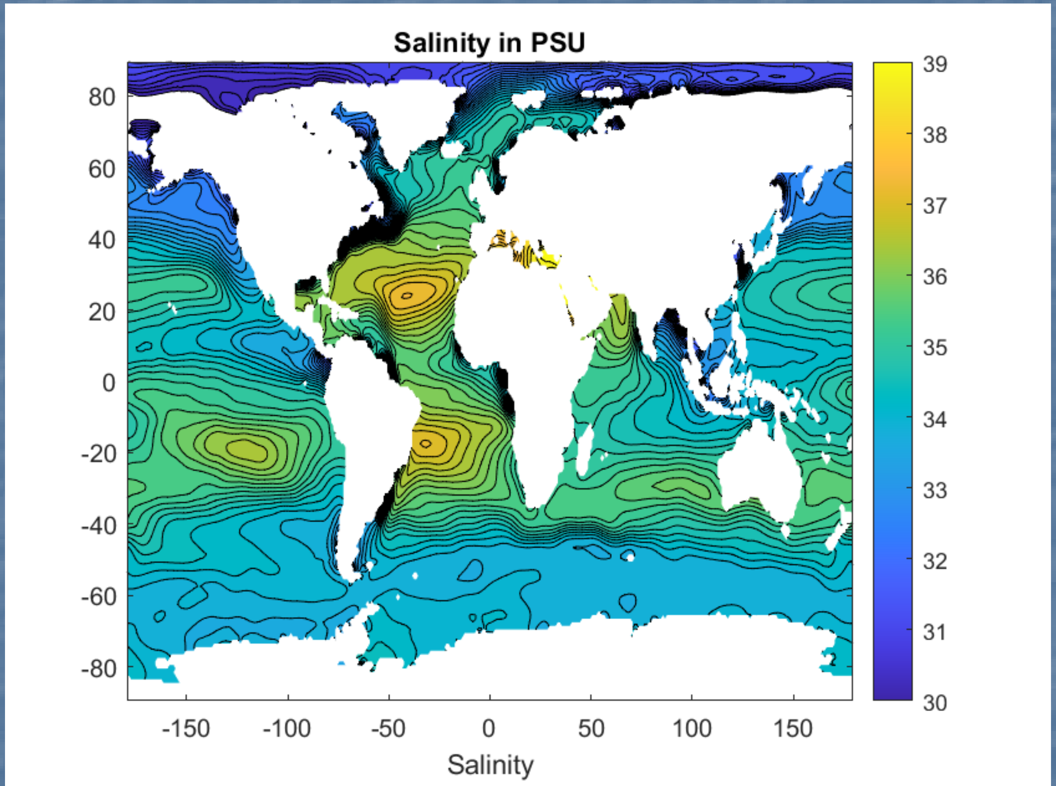


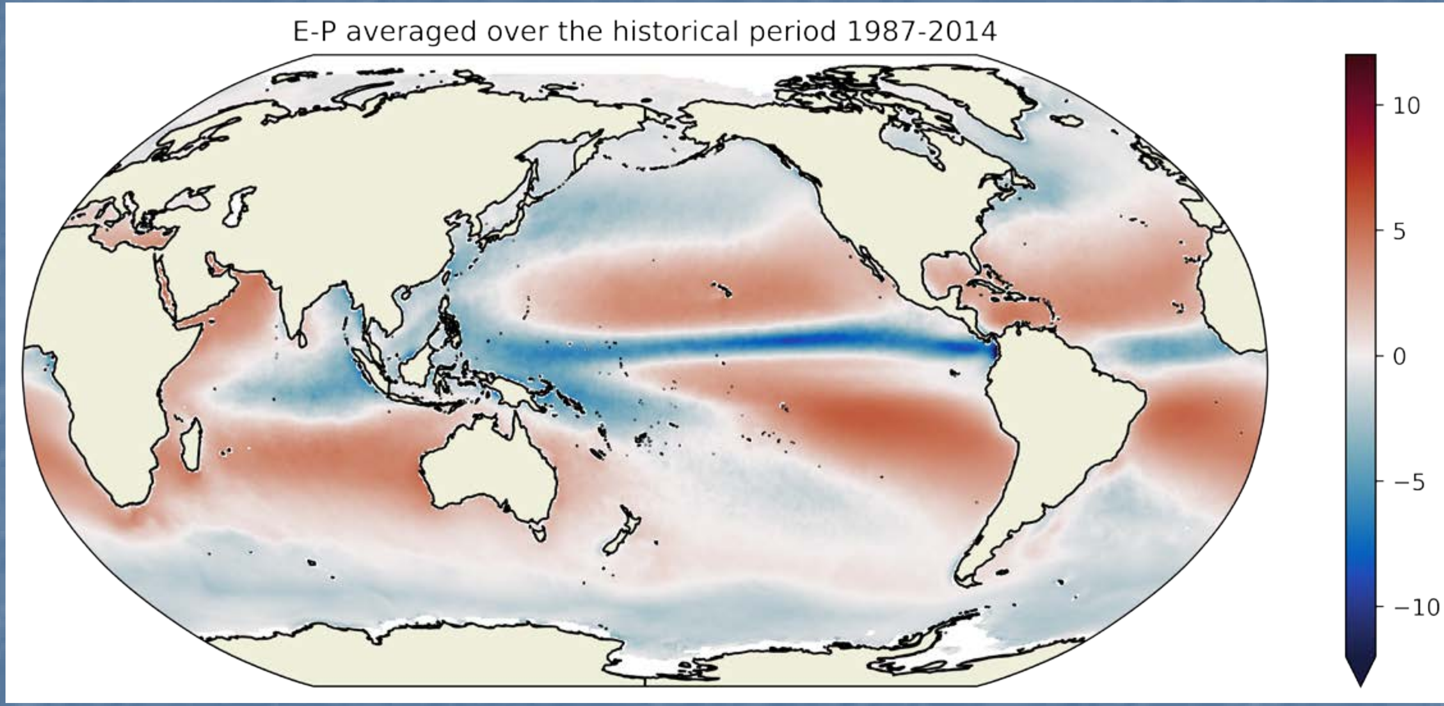




Salt water gets denser as it gets colder (maximum density just before freezing)- so temperature makes poles dense.

Water gets lighter as it gets fresher... salinity makes high latitudes lighter.

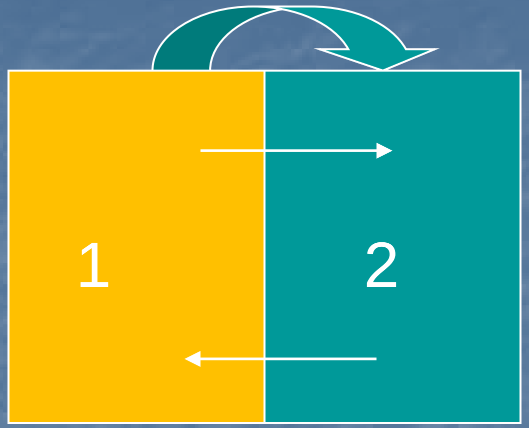
# Clear linkage to hydrological cycle… but not exact



# Freshwater flux

Suppose we take two boxes and drive a freshwater flux between the two.

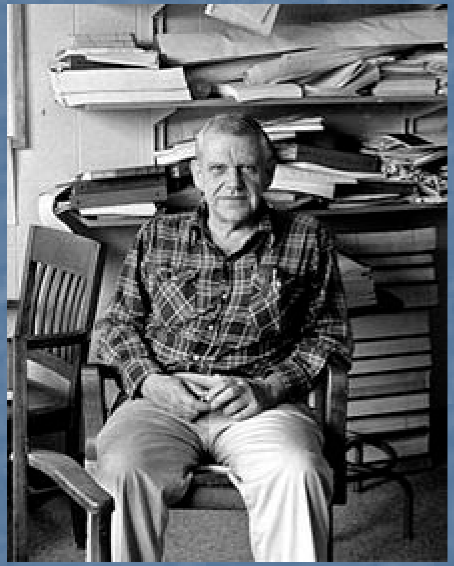



Salt balance requires a flow between the two boxes. Let the mass flux from the box losing the freshwater be M and the freshwater flux be Fw. Set up this balance and solve for the salinity difference.

$$M\ S_1 = (M+F_w)\ S_2$$

$$(S_1-S_2) = F_w S_2/M$$

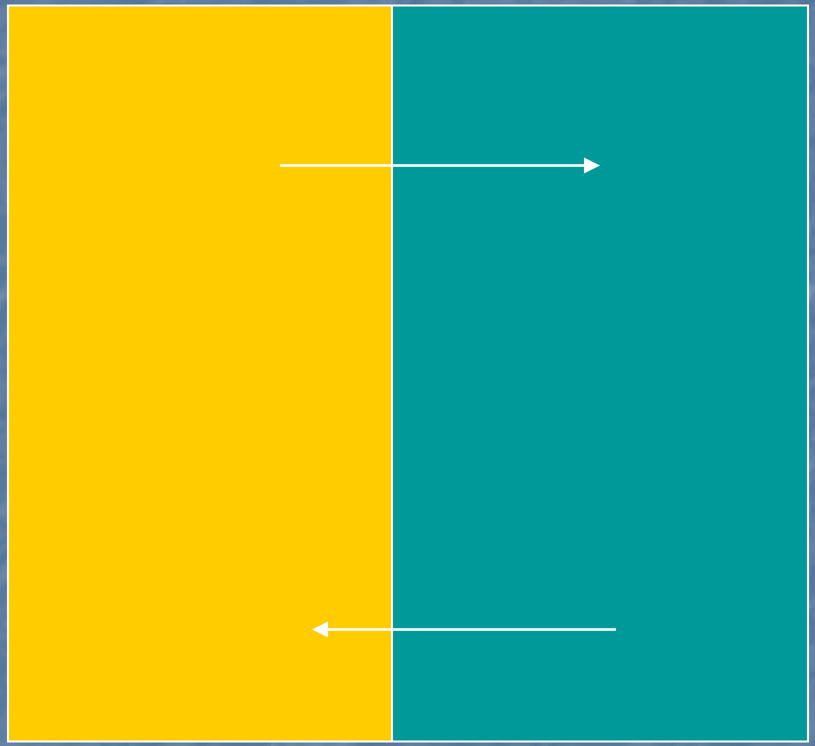
Salinity difference is proportional to the freshwater flux, inversely proportional to the mass flux



Henry Stommel
1920-1992

So we need to relate the overturning to the salinity.

Stommel's Model (Tellus, 1961)



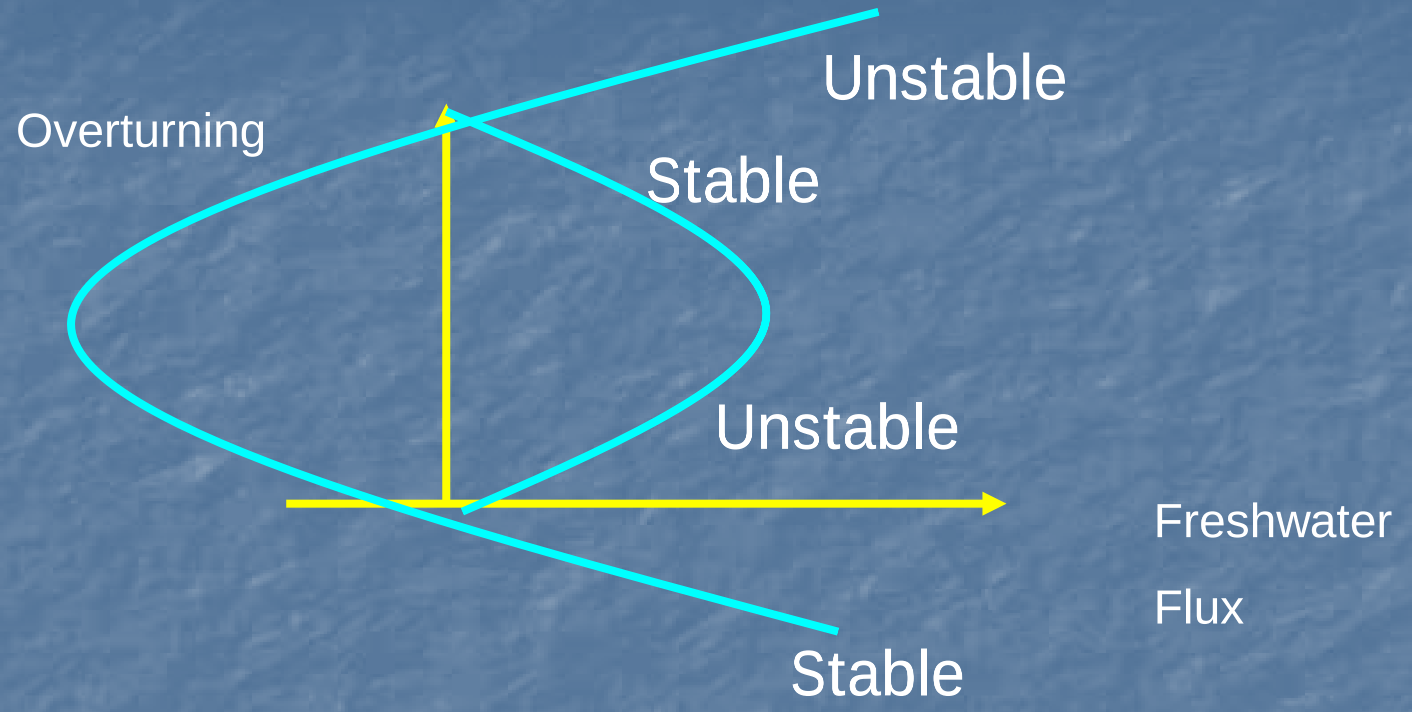
Take two boxes. Assume both are well mixed, and that the flow between them is simply proportional to the density difference.

$$M = M_0 |\Delta\rho|/\rho$$

We already know that the density difference can be described as

$$\frac{\Delta\rho}{\rho} = \alpha\Delta T + \beta_S * \frac{F_w}{|M|} * S_0$$

$$\pm M^2 - \alpha \Delta T * M = \beta S_0 M_0$$

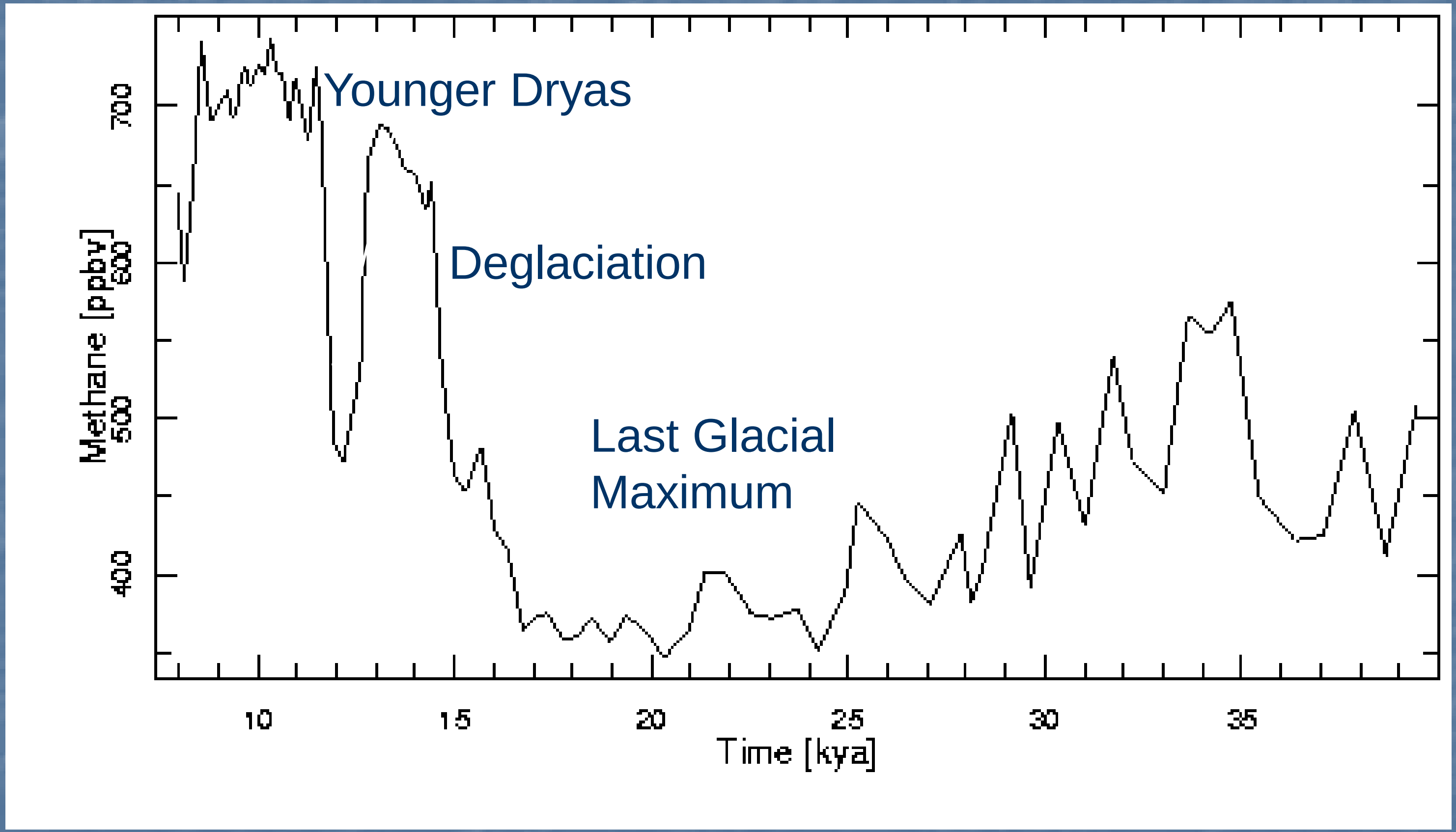



Key ideas- multiple solutions for each value of freshwater flux…

But central value is unstable.

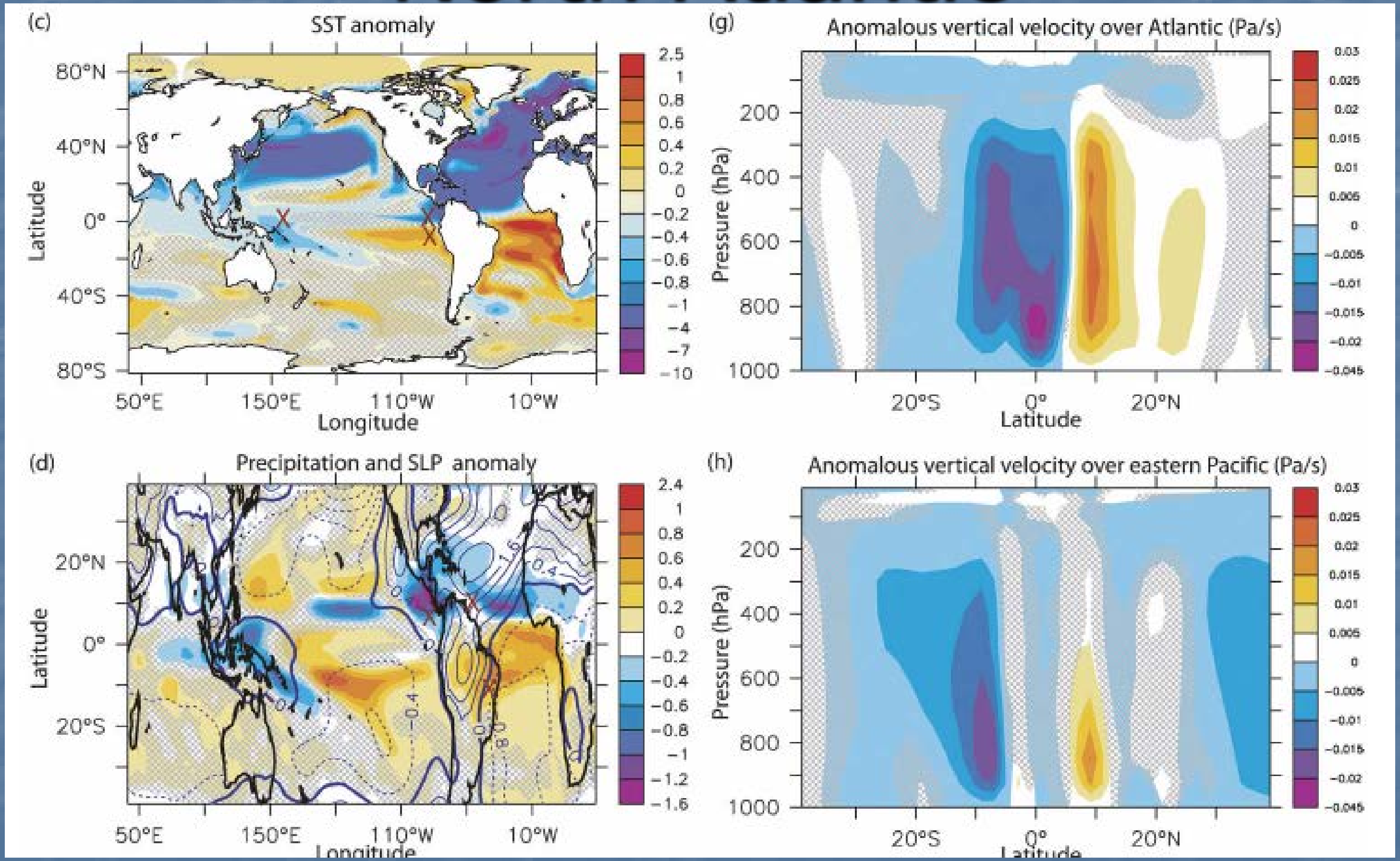
Key insight is that a “big enough” freshwater flux can turn off the overturning.

Evidence of these dynamics in the past, as the earth emerged from the last glaciation there was a brief return to glacial conditions.



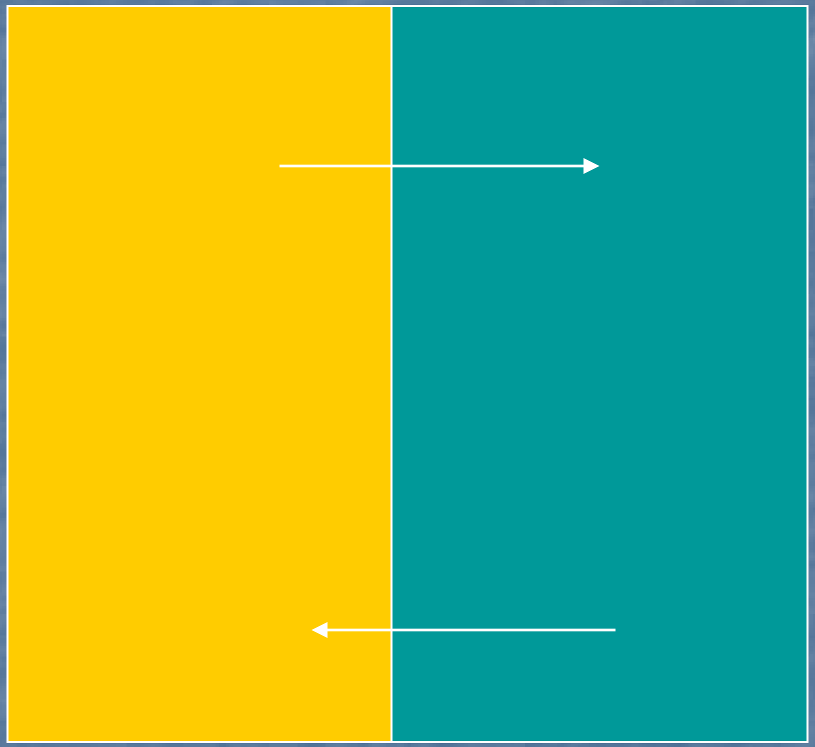

A number of models have proposed that this “Younger Dryas” period is caused by glacial meltwater flooding the North Atlantic.

# Global impacts of freshwater addition to the North Atlantic



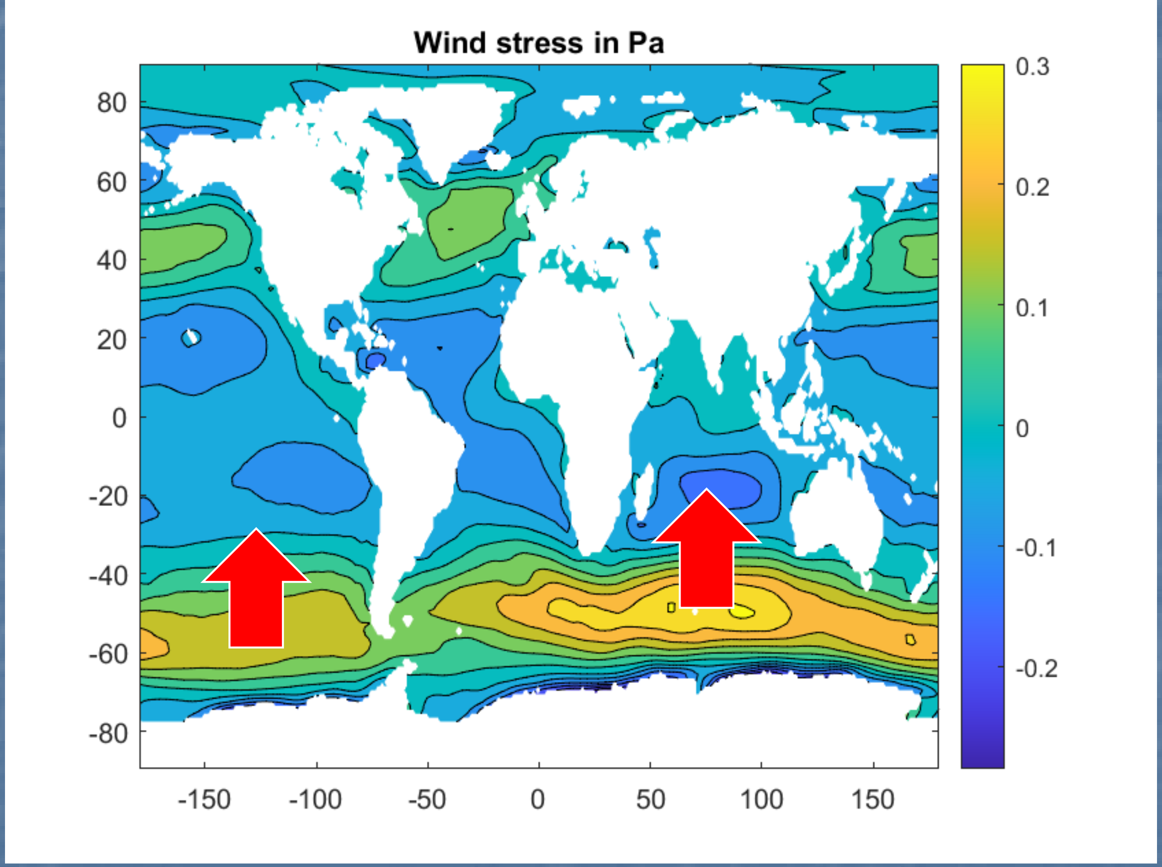

Zhang and Delworth, J. Climate, 18, 1853-1860, 2005.

# Problems with the Stommel model

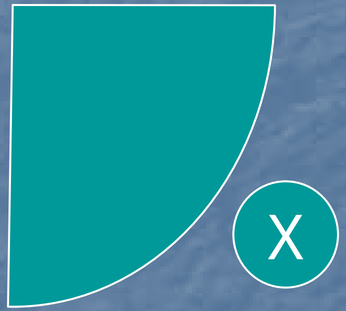


- Easy to see how dense water sinks...
- But how does dense water get transformed back into light water?

# Closing the loop




Winds in the Southern Ocean (Toggweiler and Samuels, 1995, 1998; Gnanadesikan, 1999)




Pushing water in the same direction that the earth is spinning...

Leads to a flow outwards from the axis of rotation

In open latitudes, must be supplied from below.

# Key caveat- role of eddies

Credit: Ryan Abernathey

- Ocean is full of turbulent eddies.
- What do they do?

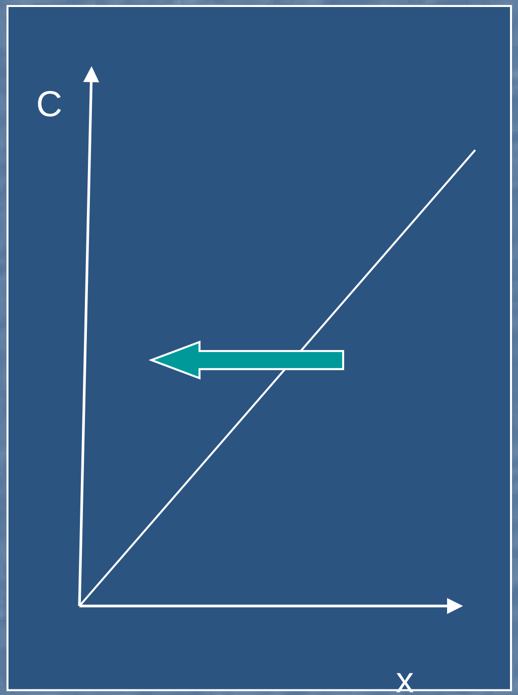
# Characterizing tracer transport

Flux of some tracer C depends on local gradient of concentration

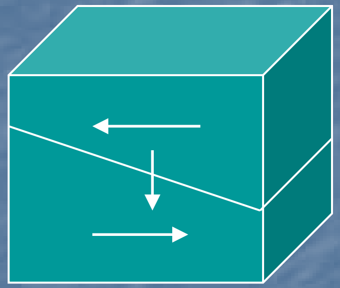
$$F_C = -K_h \frac{\partial C}{\partial s}$$

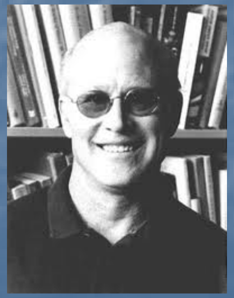
$K_h$ is a diffusion coefficient with units

$$K_h \sim \delta L^2 / \delta t$$



# Complication: "Thickness" diffusion

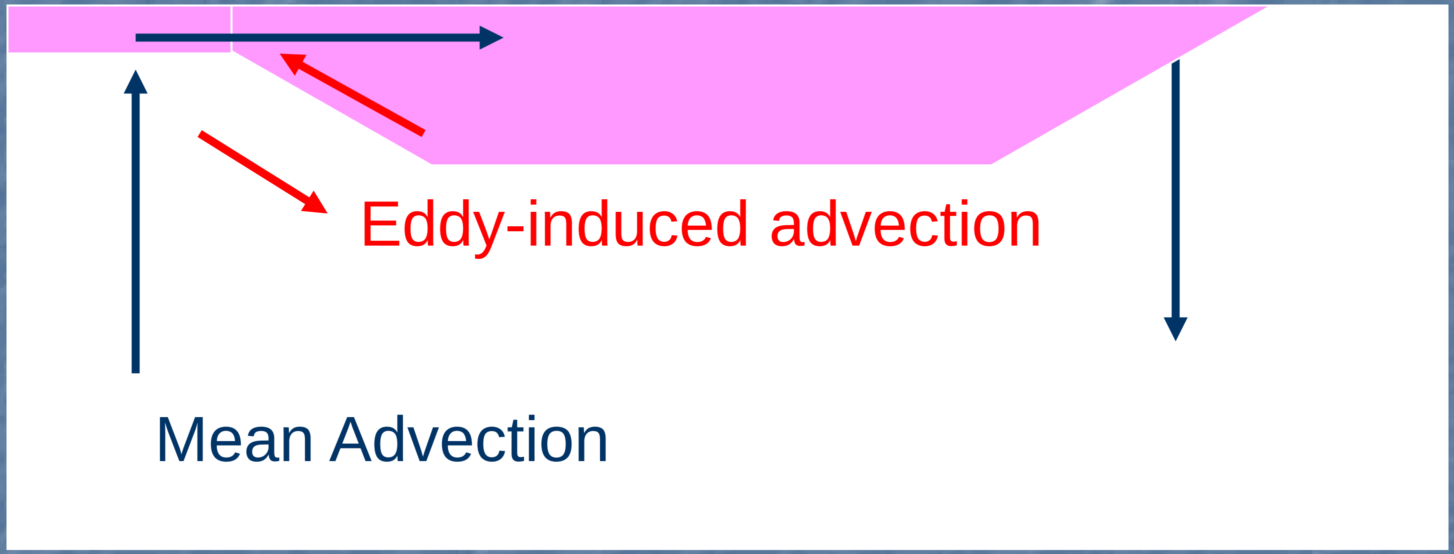




- Basic idea is that eddies flatten layer interfaces.
- Corresponds to an advective effect...
- Or a vertical momentum transfer.
- Gent and McWilliams (1990)

# An alternative picture: Advective-eddy balance

Gnanadesikan, 1999



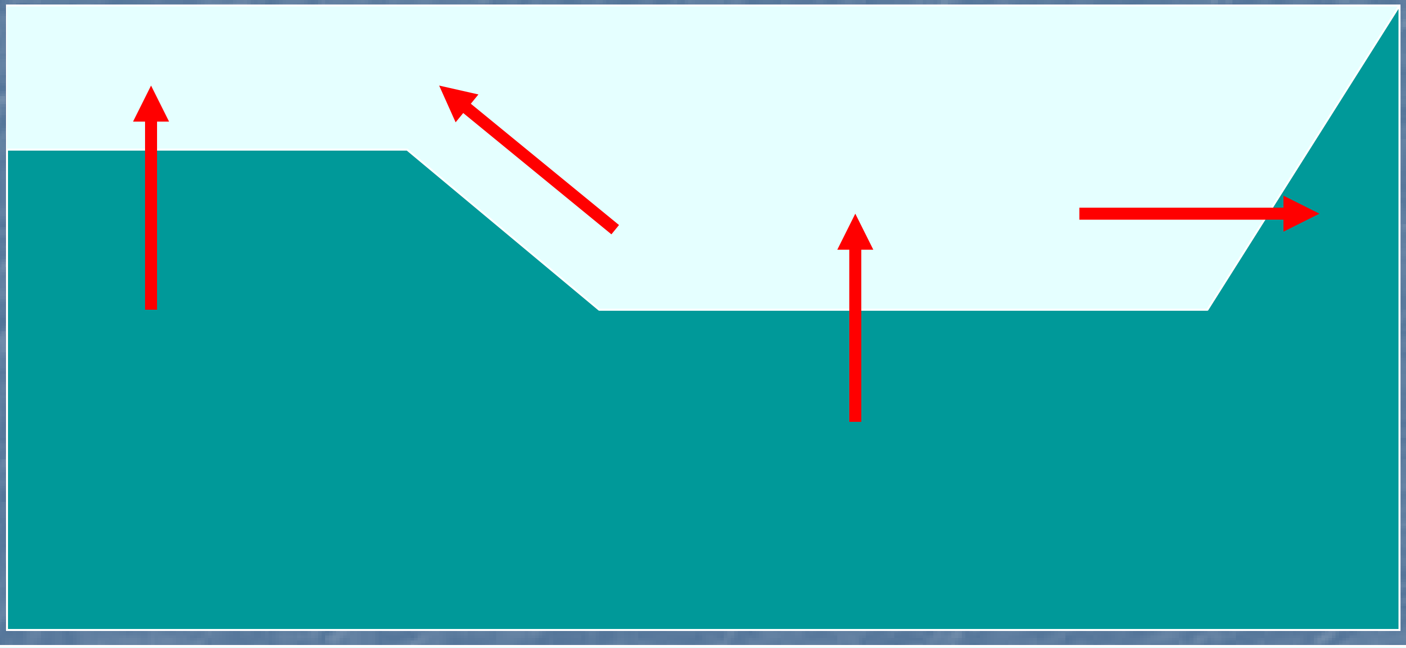

South

North

Ekman upwelling tilts isopycnals over…

Eddies allow them to slump back.

# Diagnostic balance

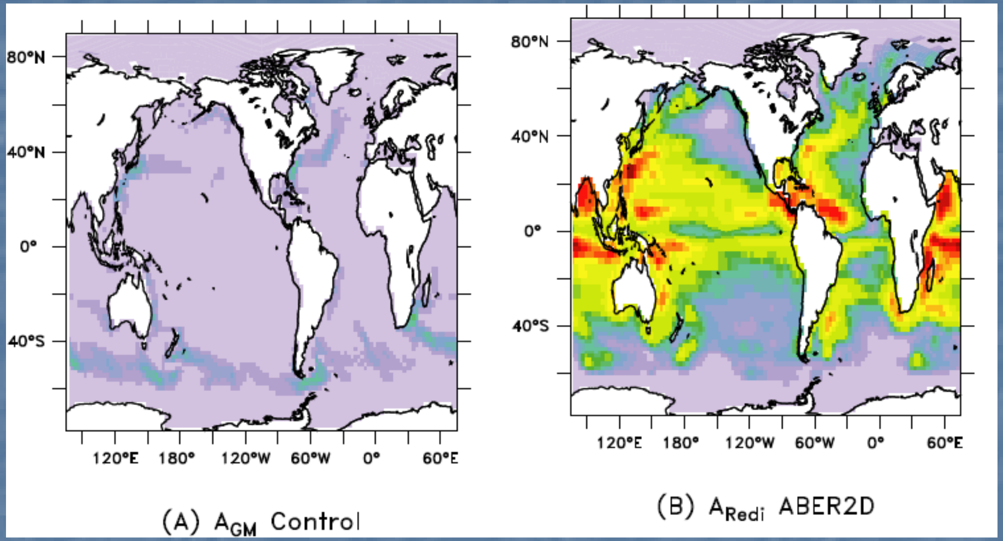


$$\frac{\tau_x L_x^s}{\rho f} - \frac{A_I D L_x^s}{L_y} + \frac{K_v A}{D} - \frac{g' D^2}{\varepsilon} = 0$$

Gnanadesikan, Science, 1999

# Problems:

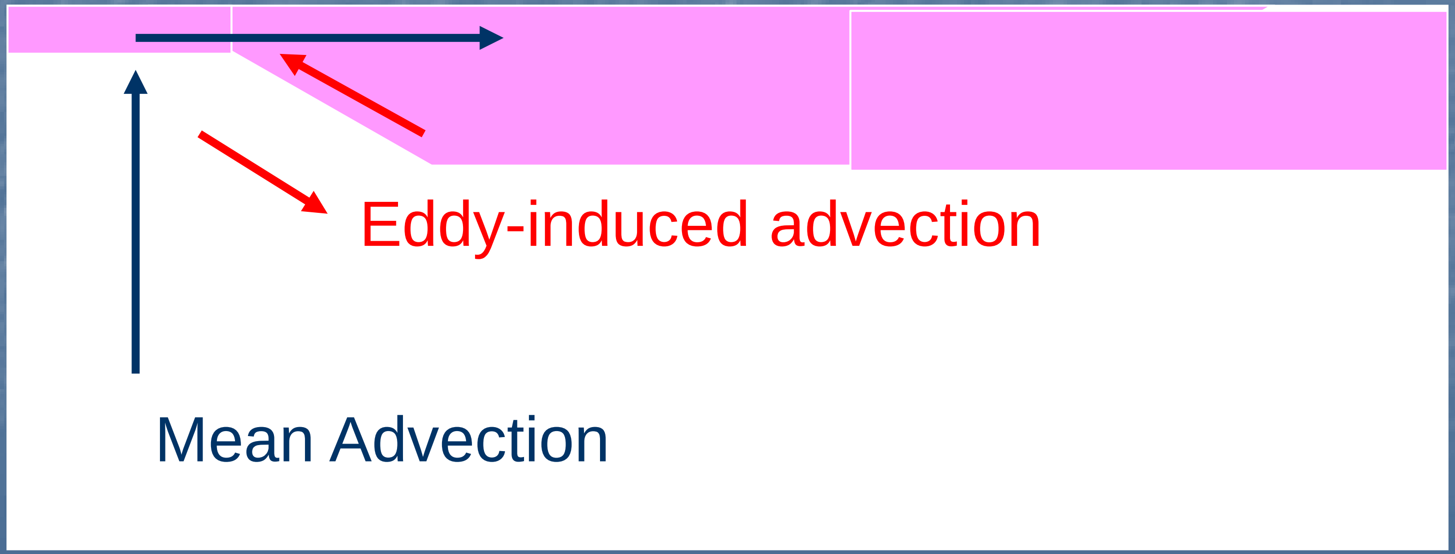
- Size of eddy coefficients isn't well understood/constrained- varies significantly between models
- Interaction with topography plays a major role- eddies mound up water over topography (not a strict drain on PE), not well represented in current climate models.
- Physics of Antarctic Circumpolar Current neglects processes known to be important for atmospheric jets (gravity wave drag).



# More complications...

- Insofar as this picture depends on the Southern Ocean being a key location where dense waters are transformed into light waters...
- ... you actually need to have the waters get "light enough"
- What if they don't?

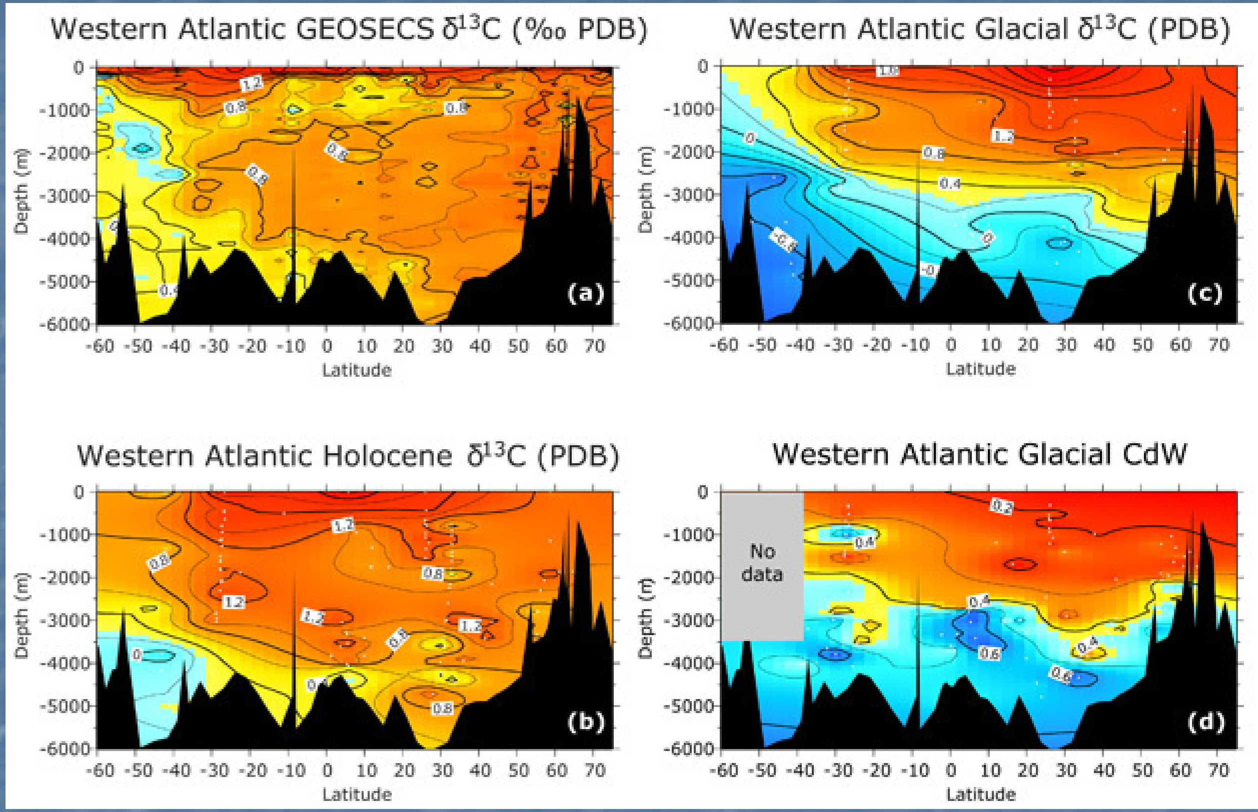
Johnson and Marshall, 2008




South

North

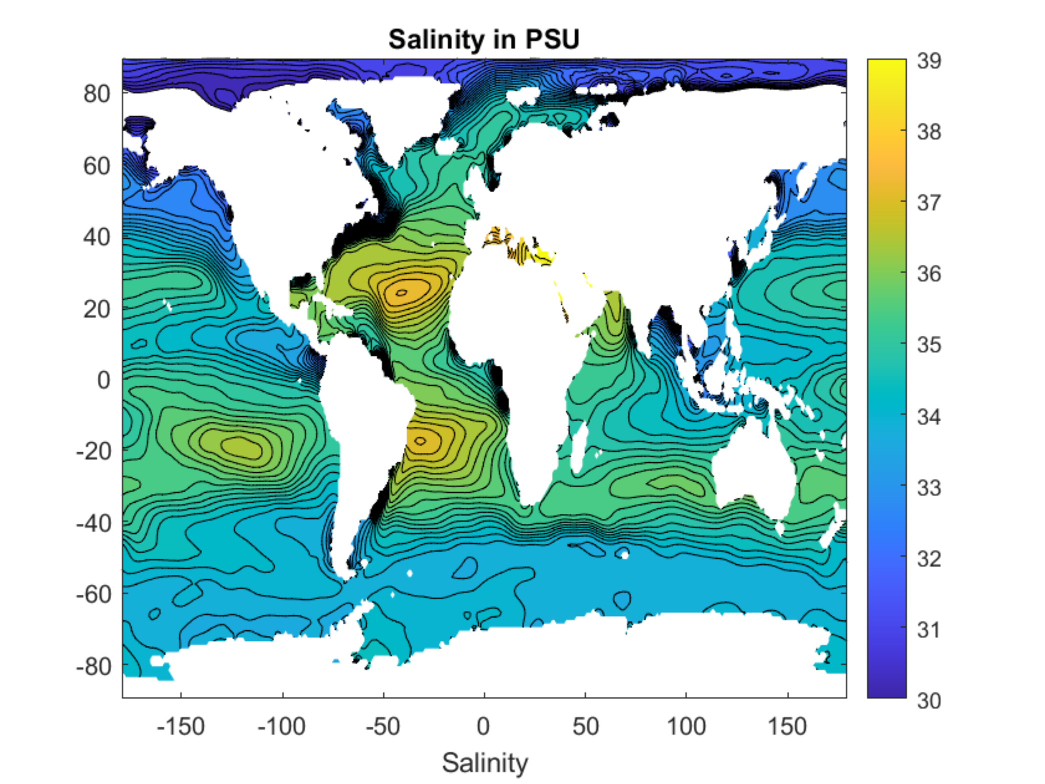
# Has this happened in the past?

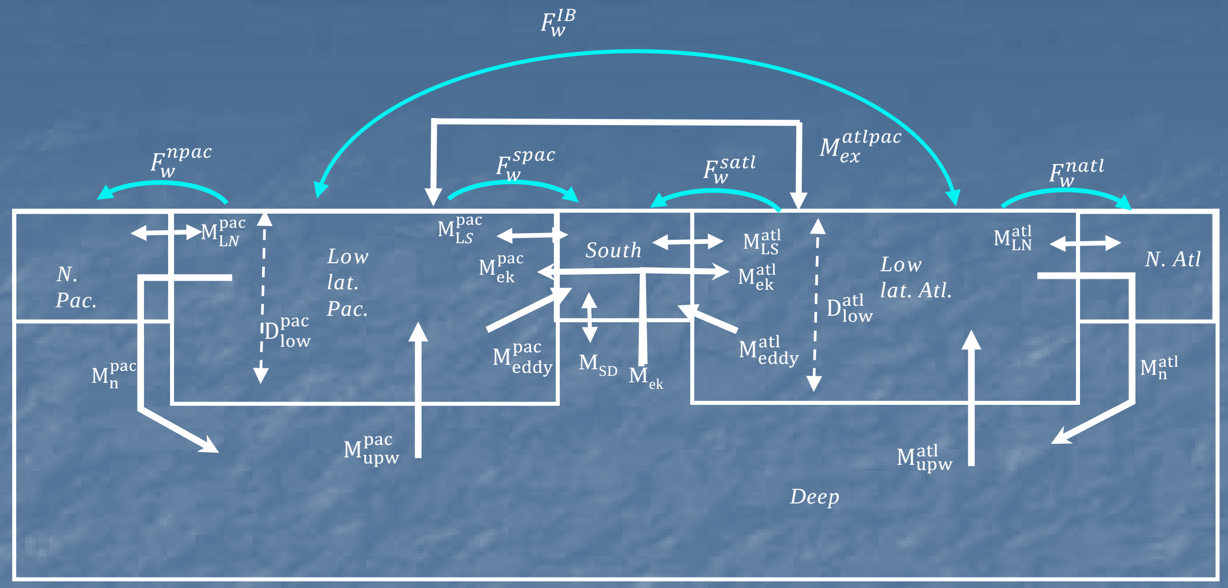



- https://www.nature.com/scitable/knowledge/library/deep-atlantic-circulation-during-the-last-glacial-25858002/

# What about the Pacific?

- Atlantic is saltier than Pacific... suggests atmospheric transport of freshwater to Pacific.
- North Pacific very fresh...
  - Higher freshwater transport?
  - Or lower oceanic transport?






$M_n^{\{atl,pac\}} = \frac{g'_{Atl,Pac} {D_{low}^{atl,pac}}^2}{\epsilon_{atl,pac}}$ i.e ~depth-integrated pressure difference (Bryan, Hughes and Weaver, Park, Levermann....)

$$M_{eddy}^{atl,pac} \sim A_I * D_{low}^{atl,pac} * L_x^{atl,pac} / L_y \qquad M_{upw}^{atl.pac} = K_V * \frac{A_{atl,pac}}{D_{low}^{atl,pac}}$$

$$M_{ex}^{atlpac} = \frac{\left(g'_{atl} * D_{low}^{atl} - g'_{pac} D_{low}^{pac}\right) * \min\left(D_{low}^{atl}, D_{low}^{pac}\right)}{\epsilon_{IB}}$$

# Calibrating the model...

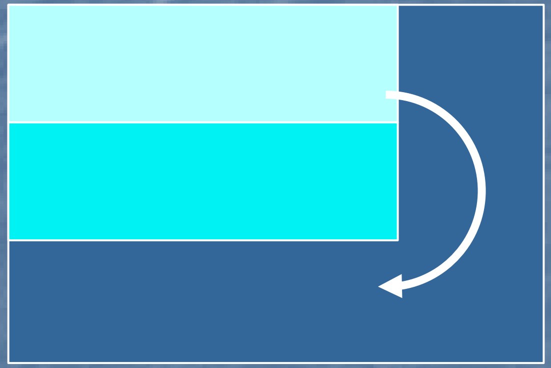
| | Atlantic | Pacific |
|---|---|---|
| Pycnocline depth | 420 | 380 |
| Low-Latitude T,S | 16.2/35.8 | 17.2/35 |
| High latitude T,S | 4/35 | 5.2/33.8 |
| Density difference | 1.46 | 1.23 |
| Driving APE $g'D^2$ | 2500 $m^3/s^2$ | 1700 $m^3/s^2$ |
| Estimated overturning/mixing | 18 Sv/2Sv | 6 Sv/4 Sv |
| Freshwater flux | 0.45 Sv | 0.34 Sv |
| Resistance factor $\epsilon$ | 1.4 x $10^{-4}$ | 2.8 x $10^{-4}$ |

Two definite surprises...
Pacific gets less freshwater than Atlantic (Arctic matters!)
Pacific much less efficient at converting APE to overturning.

# What’s going on here?

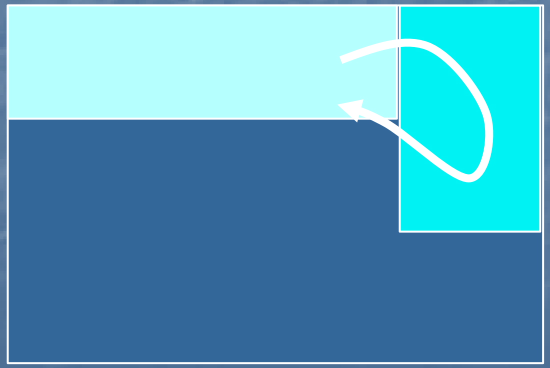
- Atlantic is denser than Southern Ocean.

  Sinking gets kick from
  both intermediate and shallow
  water. (low resistance)



- Pacific is *lighter* than Southern Ocean

  Sinking is opposed by AAIW…
  (higher resistance)



# Encoding this in the model

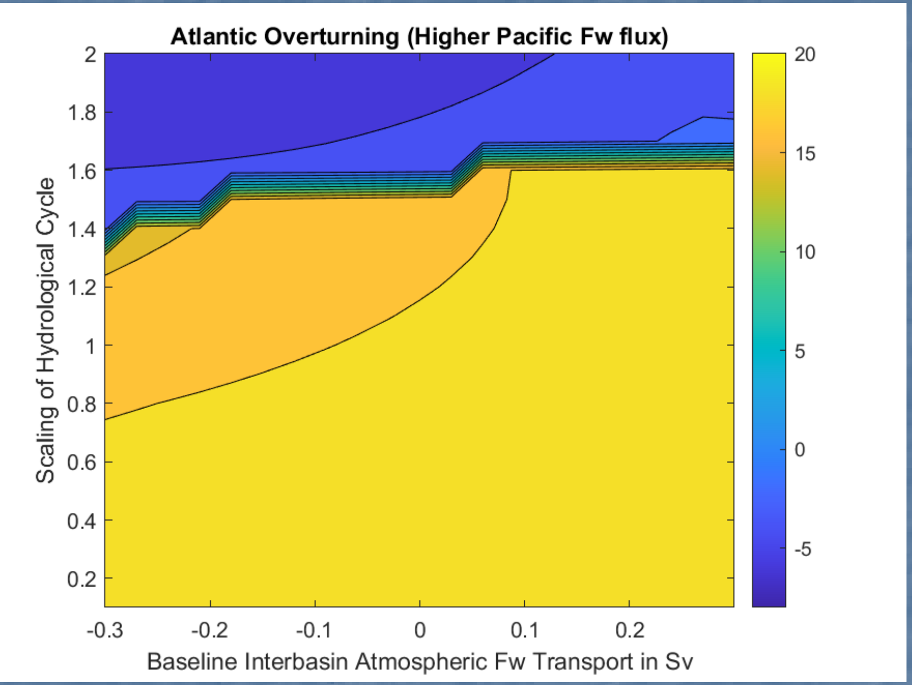
- Let resistance be low when northern basin is denser than Southern Basin.
- Let resistance be high (double) when northern basin is lighter than Southern Basin.
- Hyperbolic tangent transition between the two.

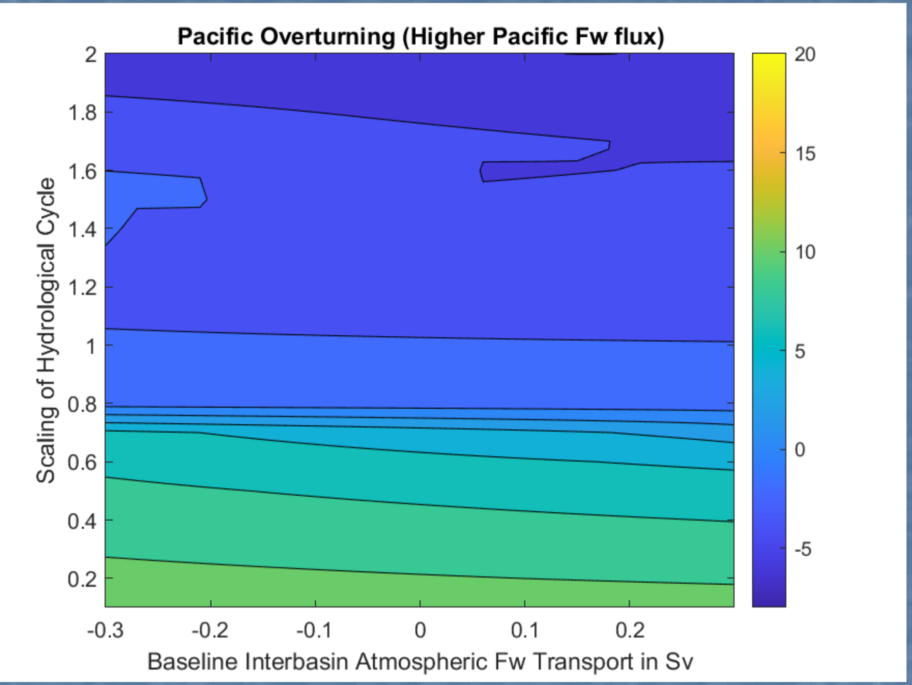
# Counterfactual Simulation

- Freshwater fluxes
  - Atlantic=0.45 Sv (RAPID array gives 0.17-0.57)
  - Pacific=0.34 Sv-> 0.6Sv
  - Southern Ocean = 1.1 Sv
- Result
  - NADW: T=3.94, S=35.11, Flux= 19.1 Sv (RAPID 16-20 Sv)
  - NPIW: T=3.57, S=31.4, Flux =-1.8 Sv
  - AAIW:  T=4.15, S=34.08, Flux=15.1 Sv

Differences largely in North Pacific!!

# What if there were *more* Fw Flux in Pacific

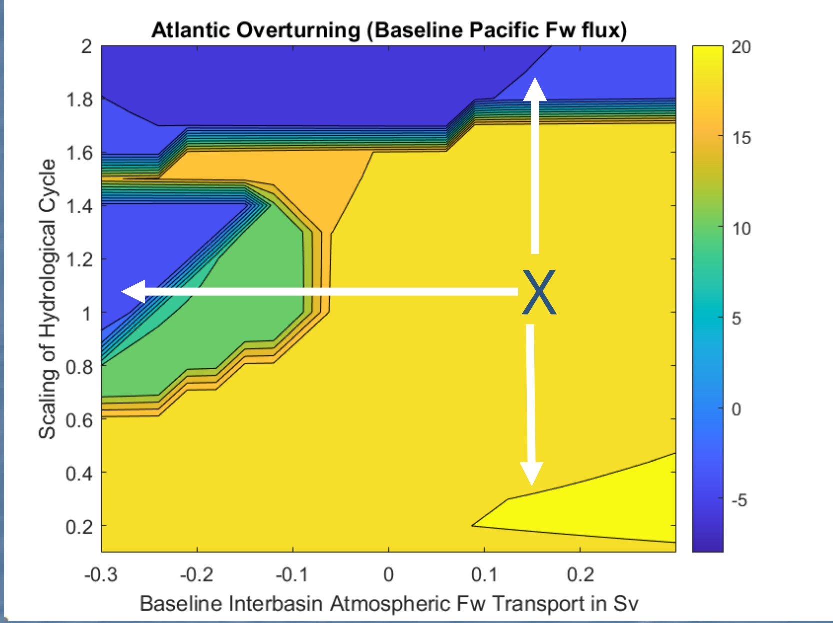


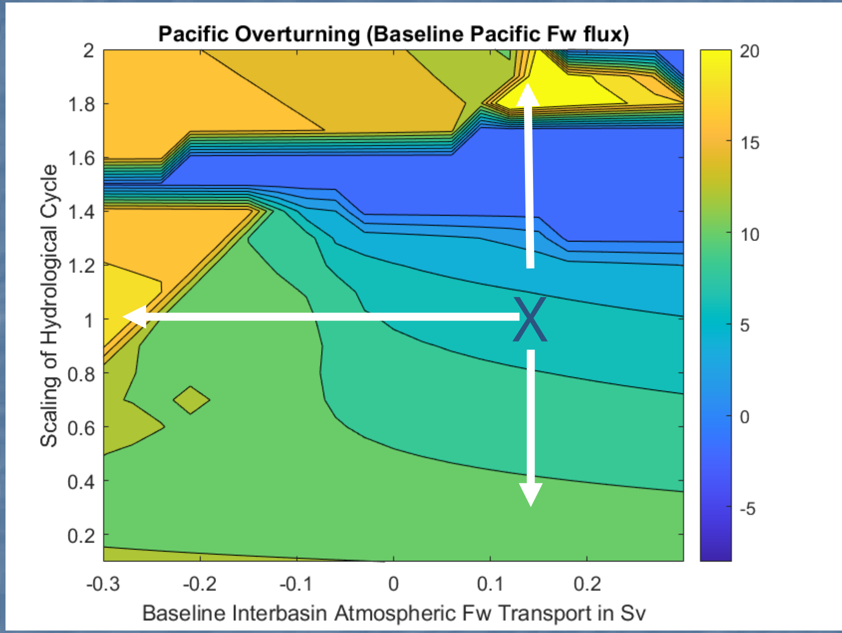




As hydrological cycle increases (move upwards) we collapse the Pacific first and the Atlantic next.

Interbasin transport (move left to right) modulates this slightly.

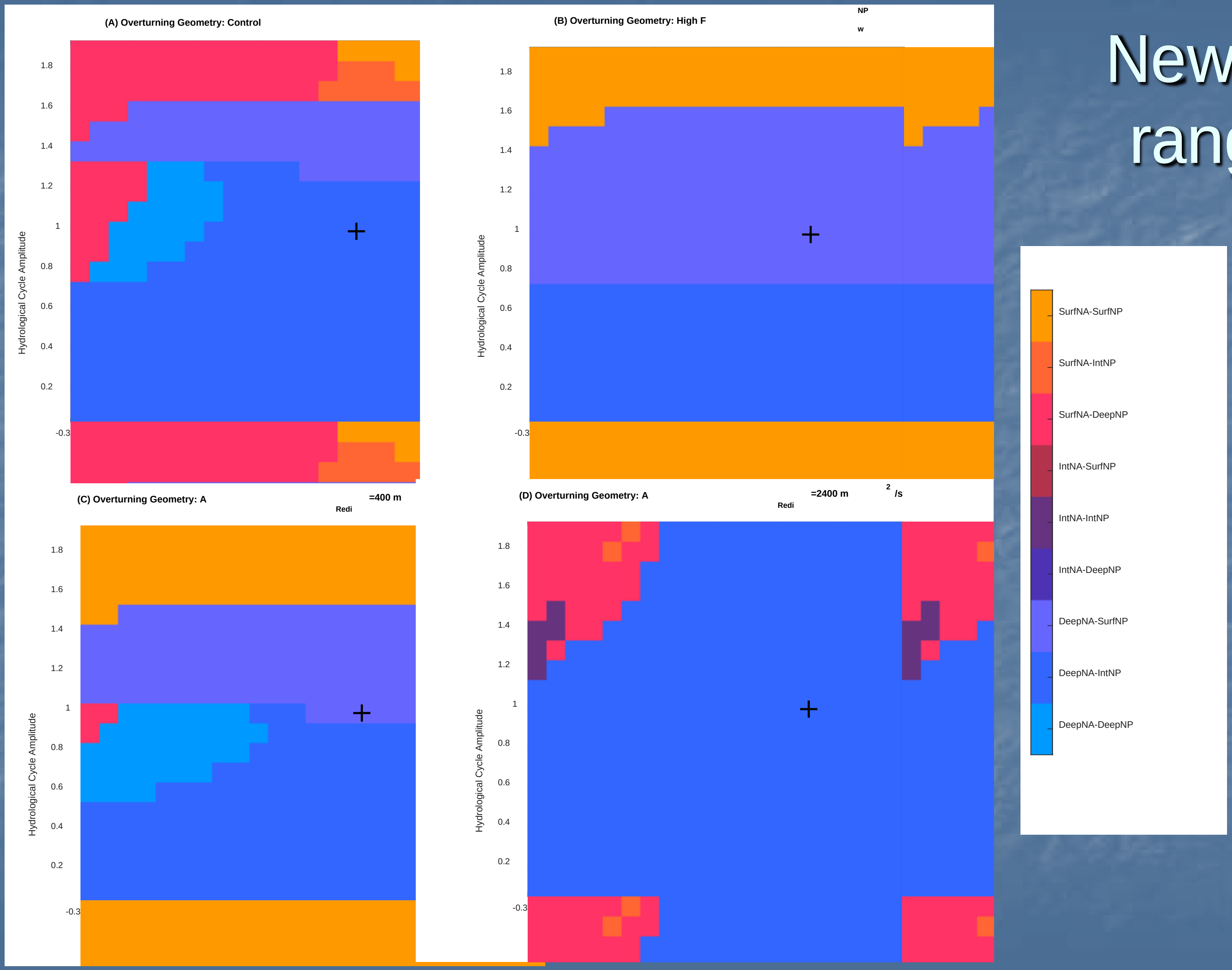
# But for more realistic fluxes..



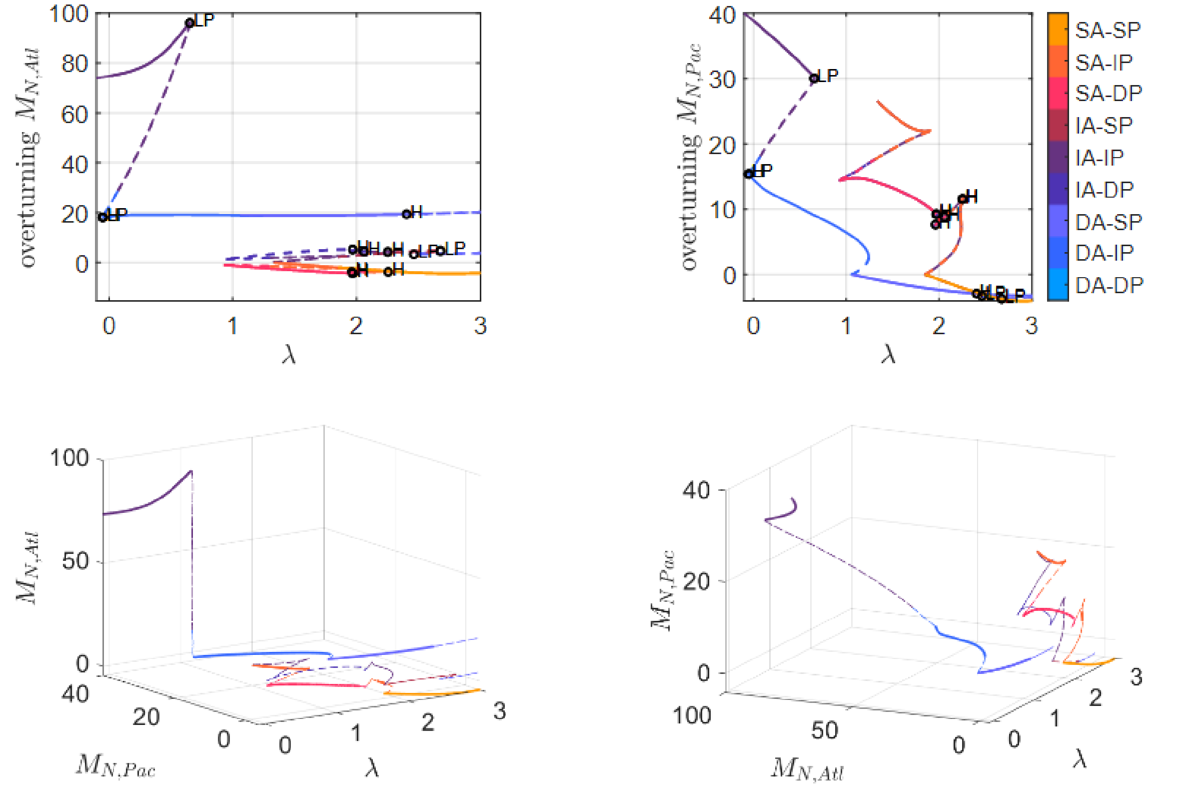




Can increase/turn on Pacific overturning by...
Reversing interbasin atmospheric freshwater flux
Decreasing hydrological cycle
*Increasing* hydrological cycle strongly enough.

# New model predicts a range of geometries



# Bifurcation diagrams show rich behavior




758 FIG. 8. Bifurcation diagrams showing steady states of the overturning computed using the matCont code and
759 the dependence of these steady states on $A_{Redi}$=1. GIANLUCA: Last two panels show the bif.diag. in 3D from
760 two different prospective. (c) MnAtl as Z axis and (d) MnPac as Zaxis.

Gnanadesikan et al., manuscript in prep.

# Conclusions

- Ocean convects too!
- Global overturning circulation has profound impact on transport of heat, salt, nutrients in global ocean.
- In turn it is affected by heat and salt.
- Geometry of this circulation is tightly linked to hydrological cycle.
- Strongly dependent on representation of effects of geophysical turbulence
- Rich dynamical behavior potentially allowing for variability (more on this tomorrow).