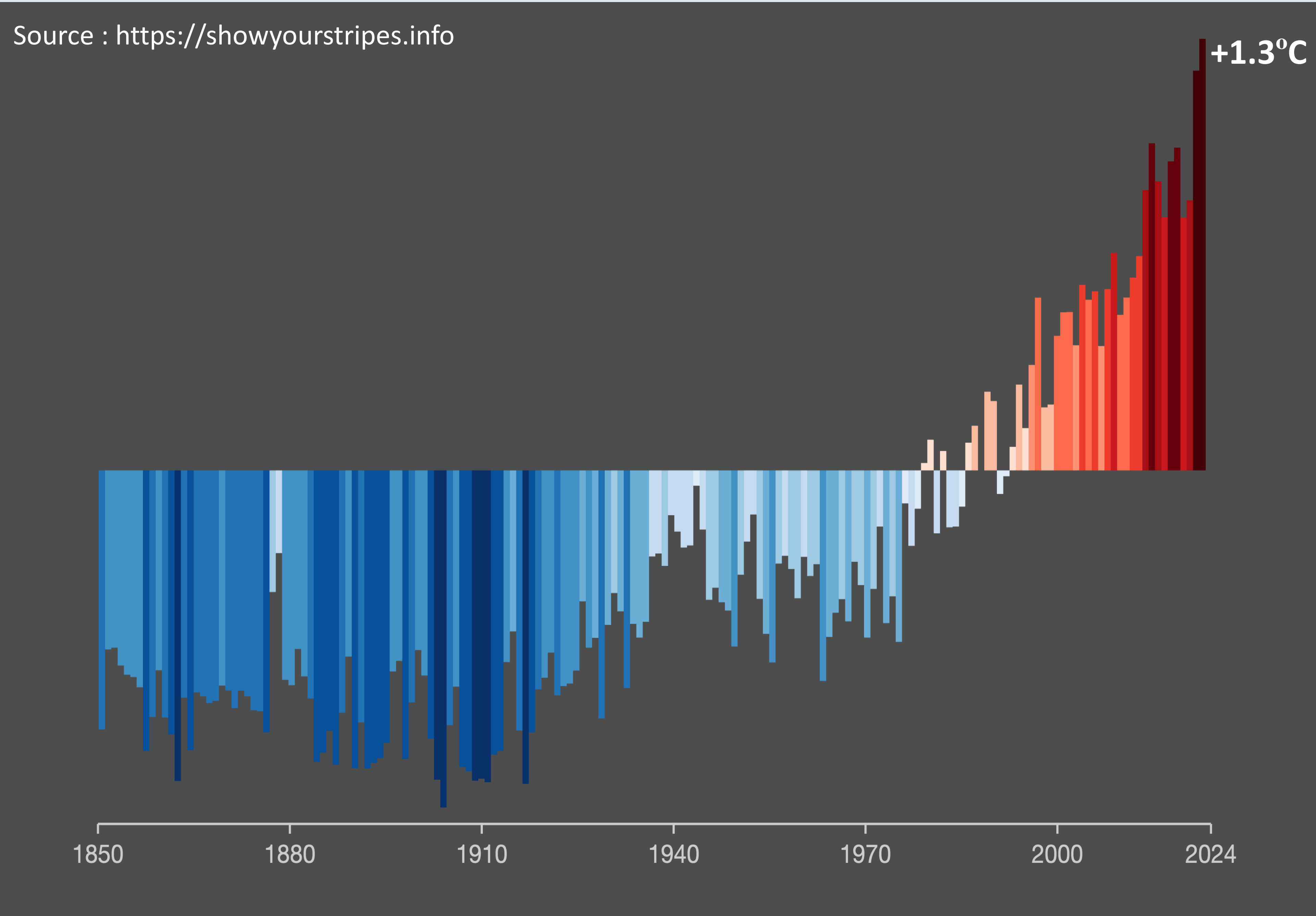
The Atlantic Meridional Overturning Circulation

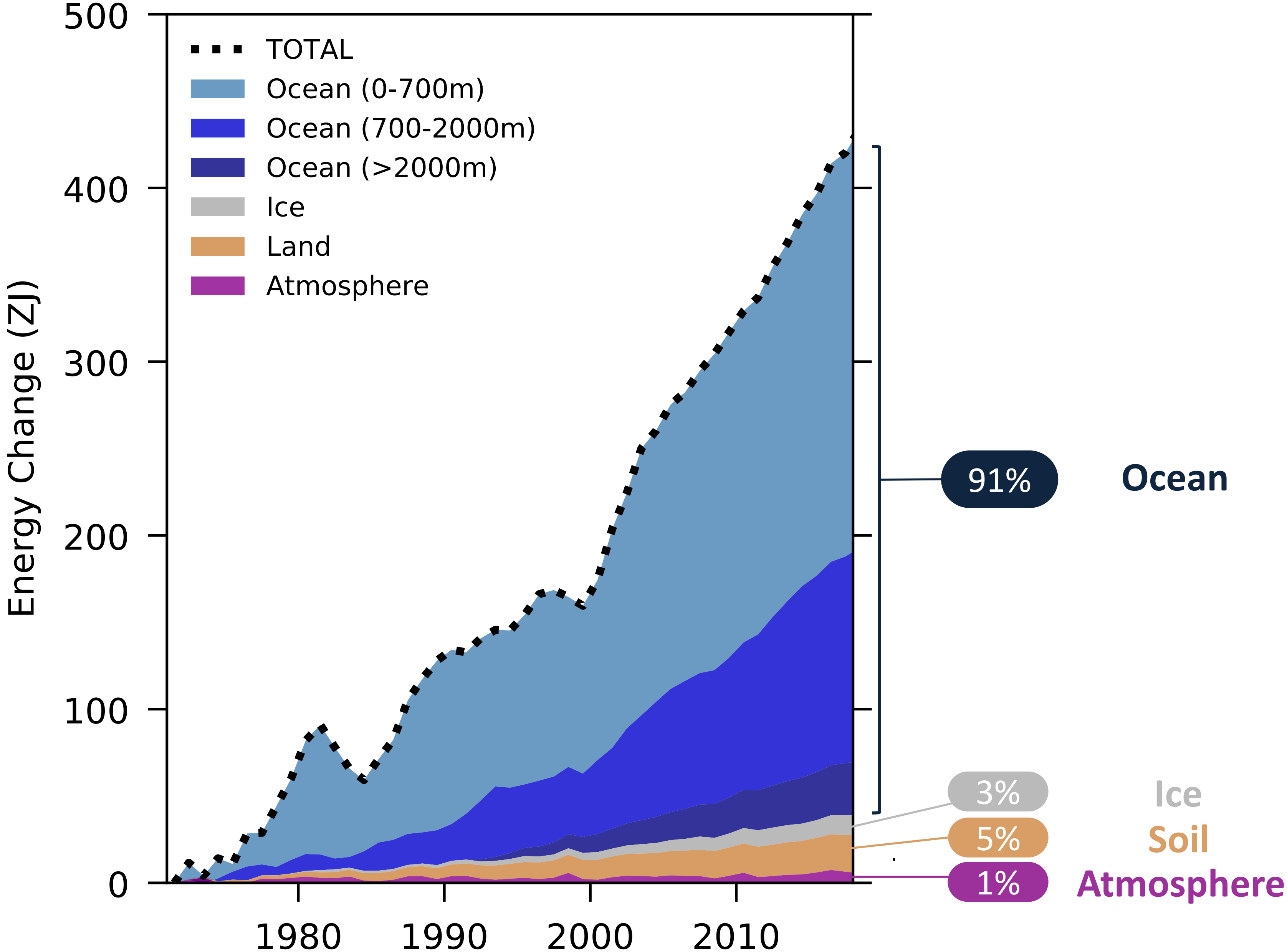
Casimir de Lavergne

Autumn school, Lyon, November 2025

Global mean surface air temperature

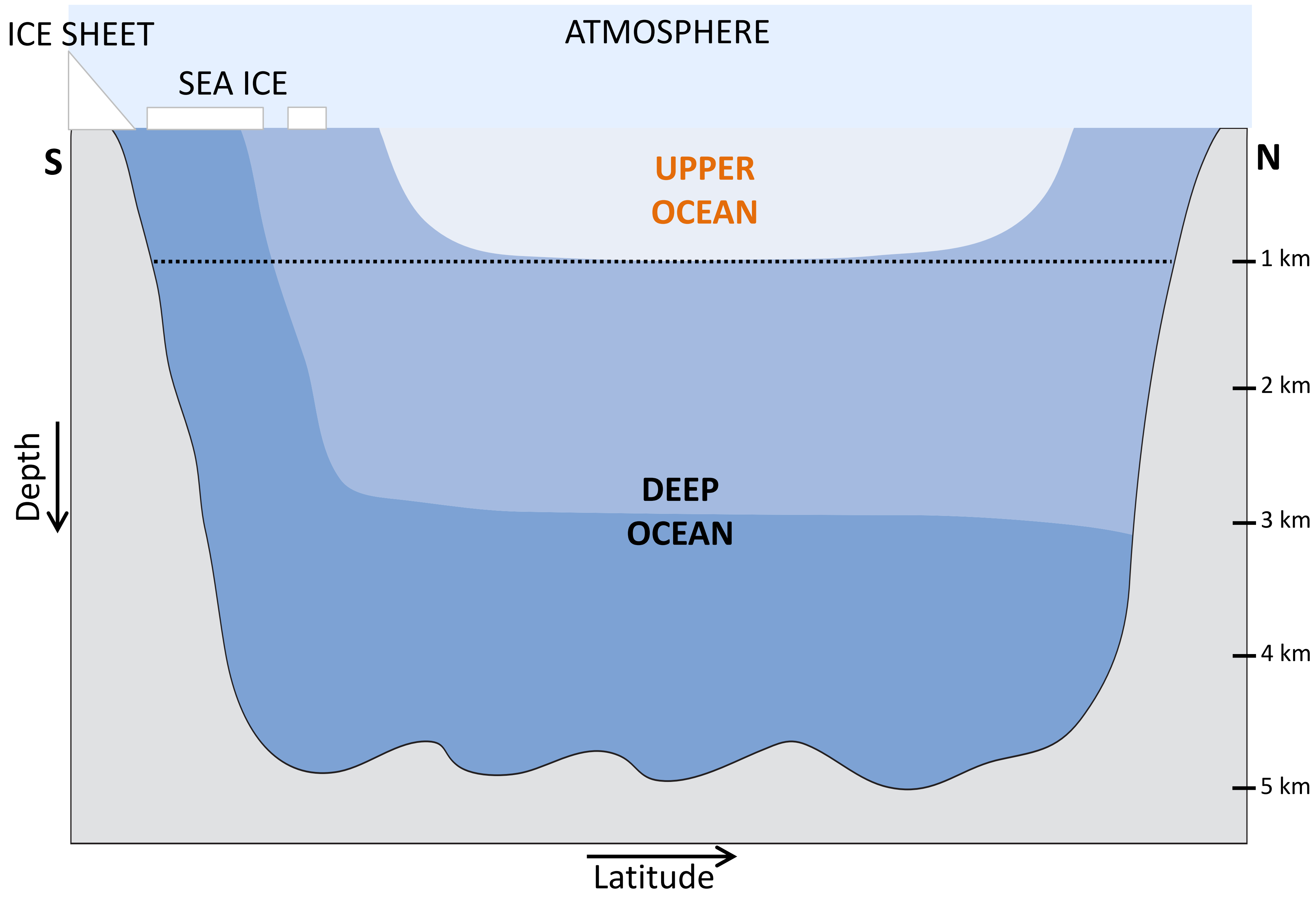


Where does warming go?

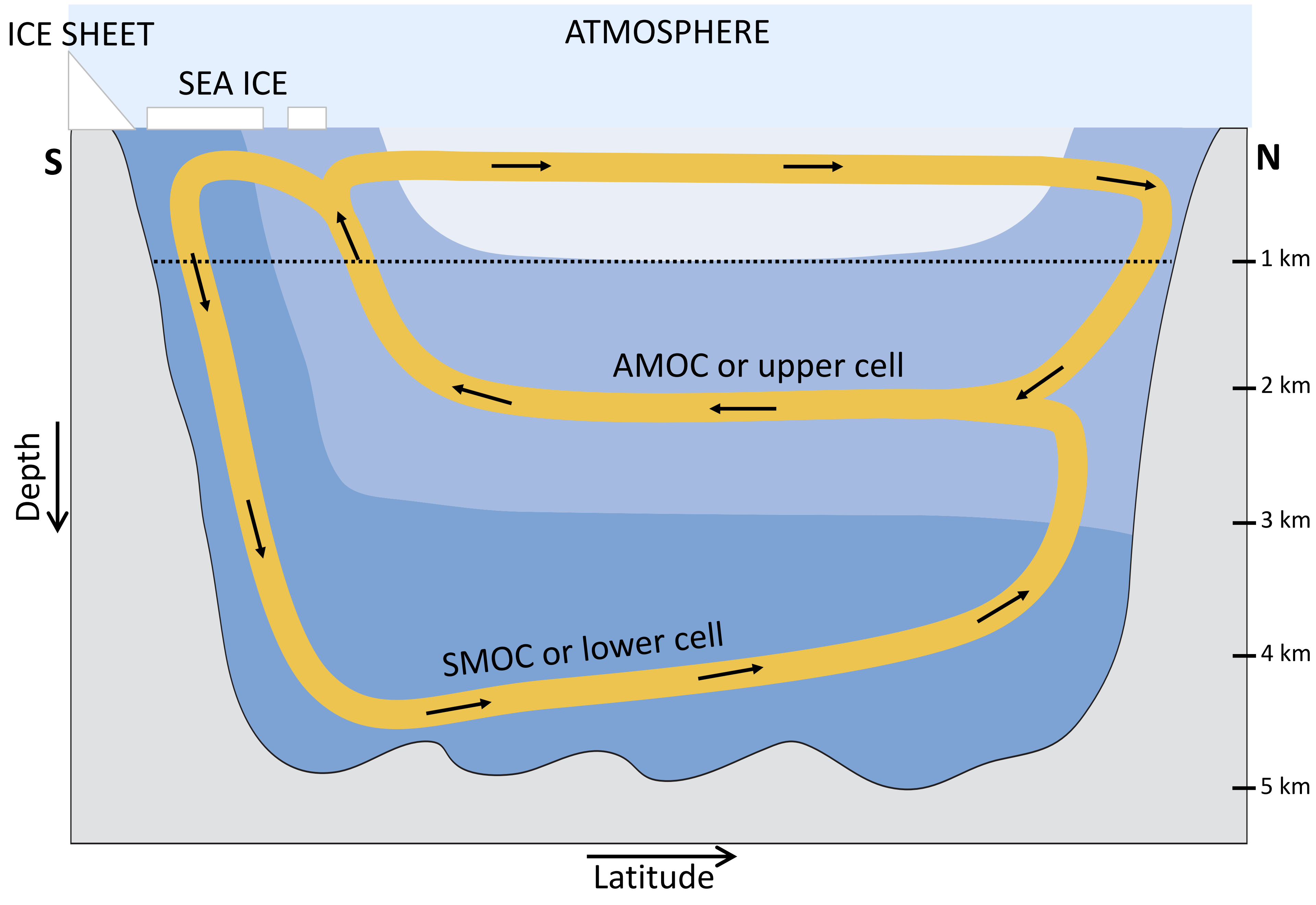


Arias *et al*. 2022

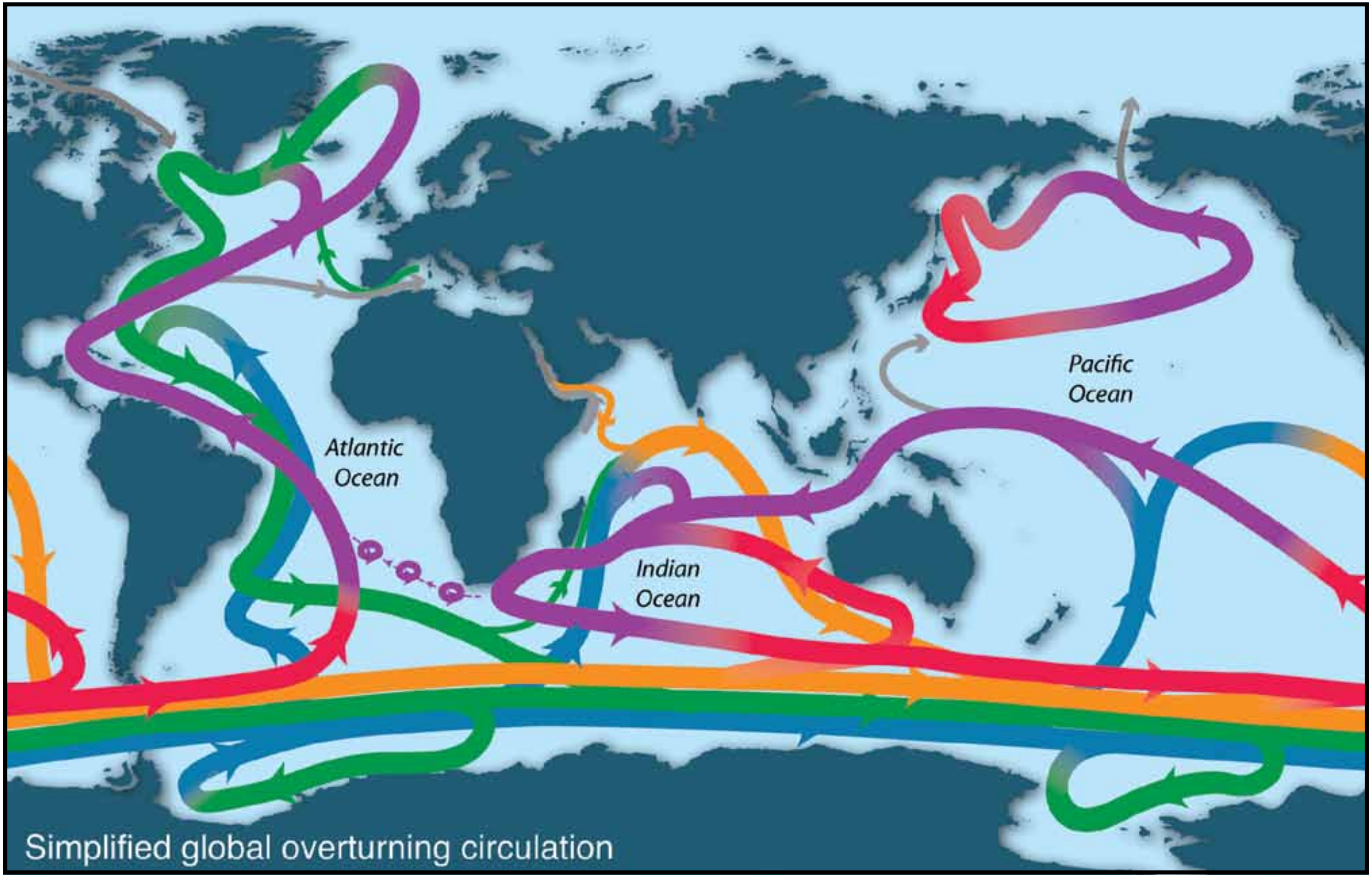
The ocean's layering



The overturning circulation links the surface to the abyss

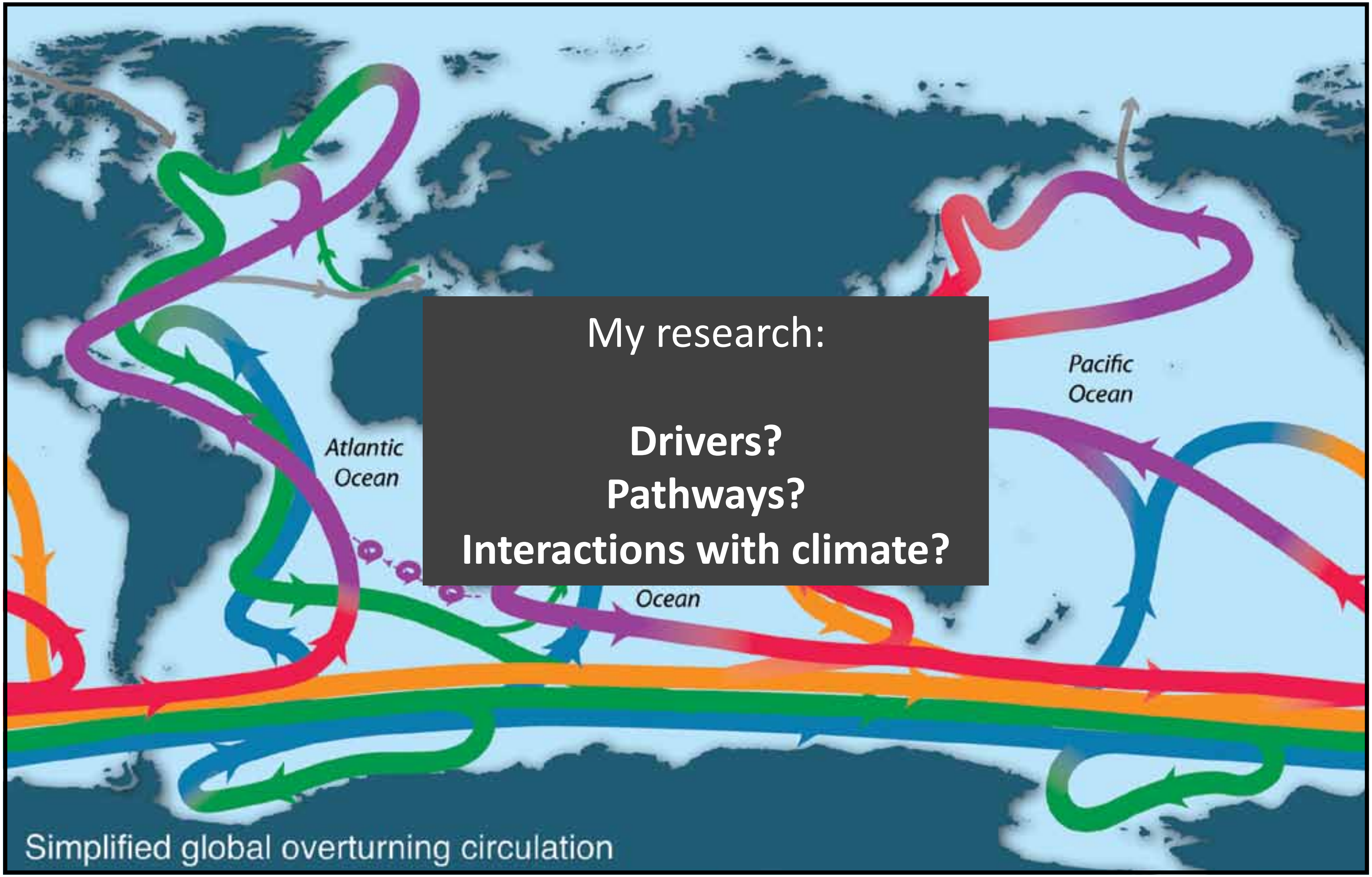


A complex and turbulent 3D circulation



Talley 2013

A complex and turbulent 3D circulation

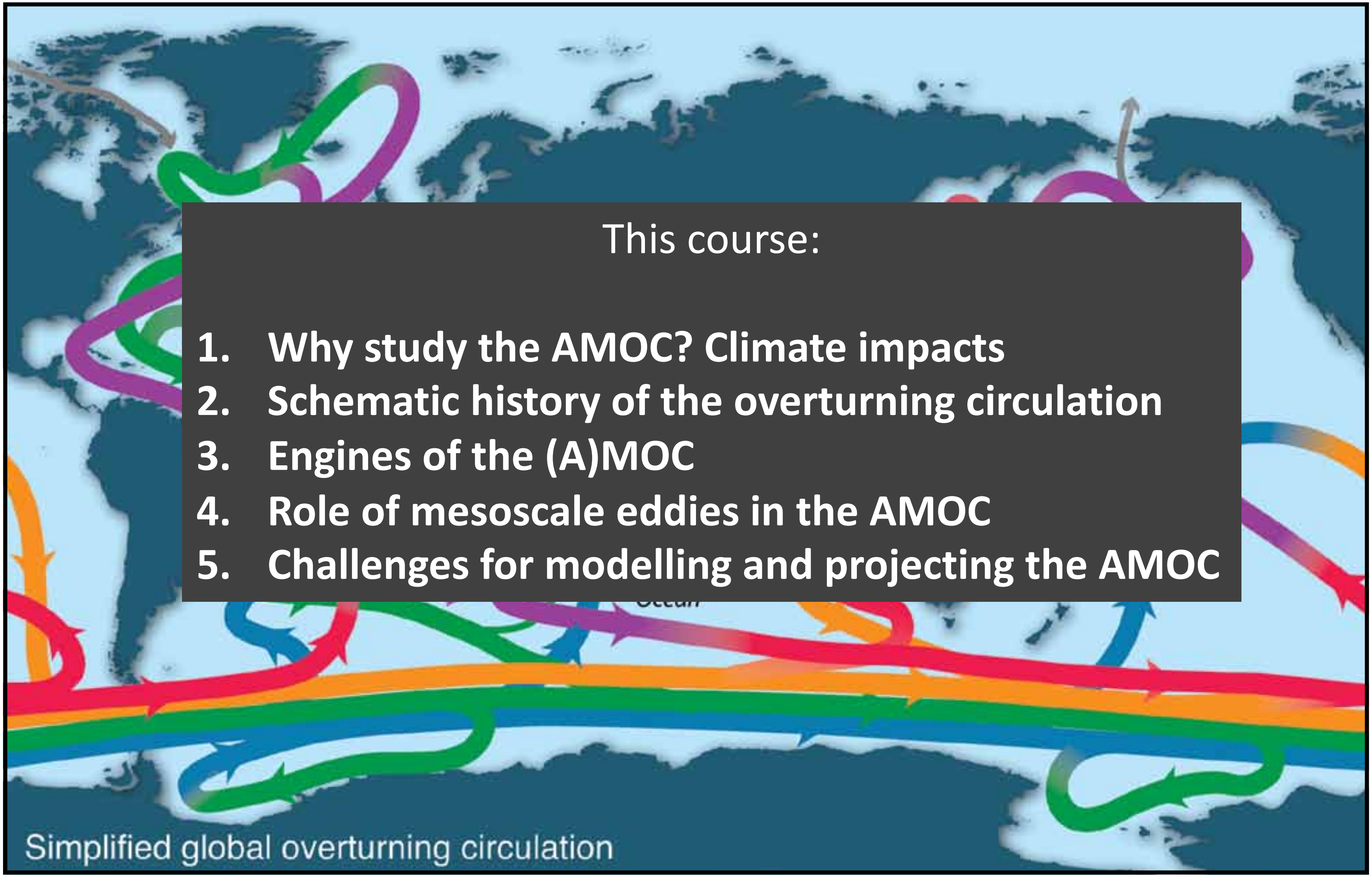


My research:

Drivers?
Pathways?
Interactions with climate?

Talley 2013

A complex and turbulent 3D circulation



This course:

1. Why study the AMOC? Climate impacts
2. Schematic history of the overturning circulation
3. Engines of the (A)MOC
4. Role of mesoscale eddies in the AMOC
5. Challenges for modelling and projecting the AMOC

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Part 1. Climate impacts

- Northward heat transport
- Downward heat transport
- Upward heat transport
- Water cycle changes

Part 1. Climate impacts

- **Northward heat transport**
- Downward heat transport
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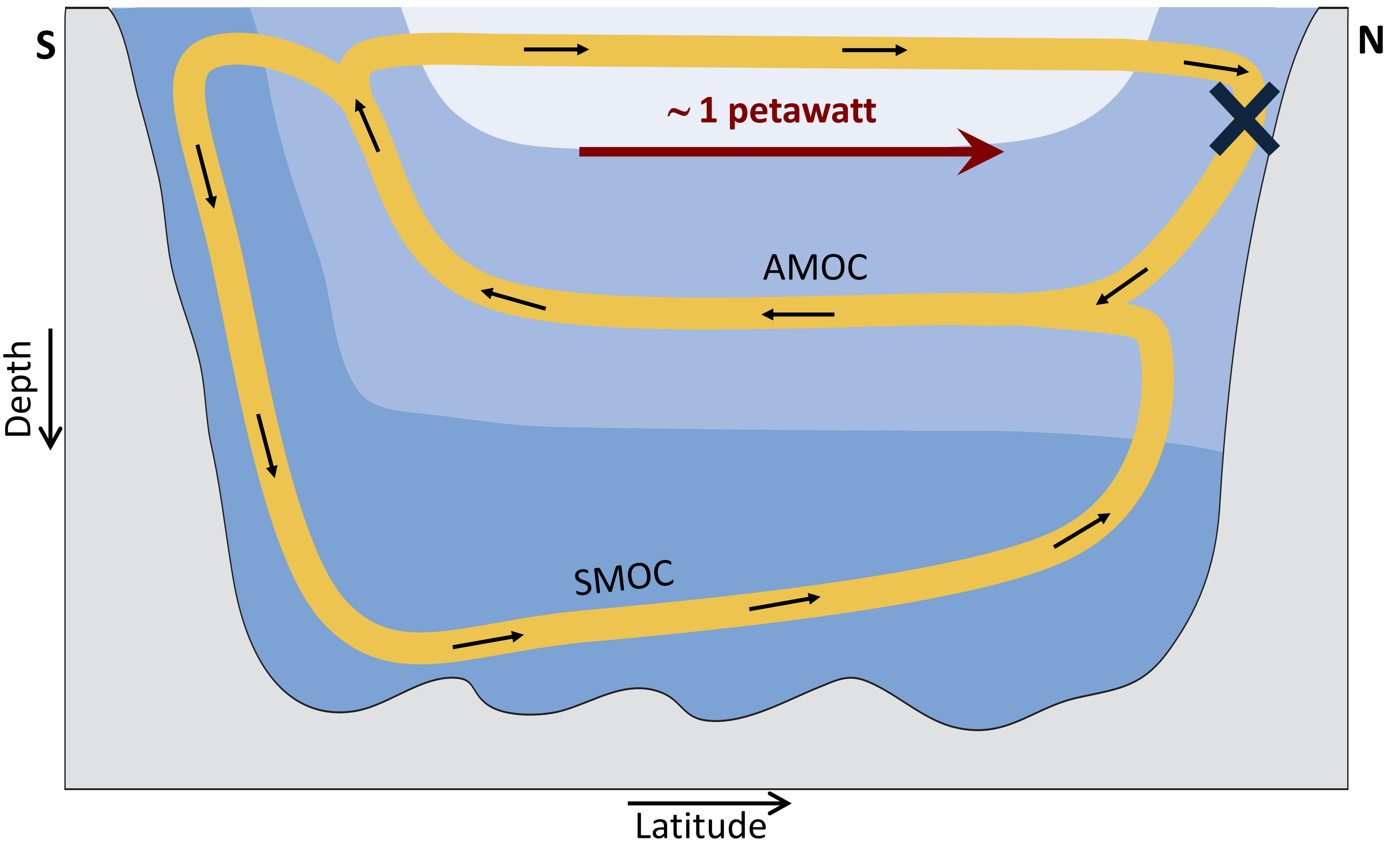
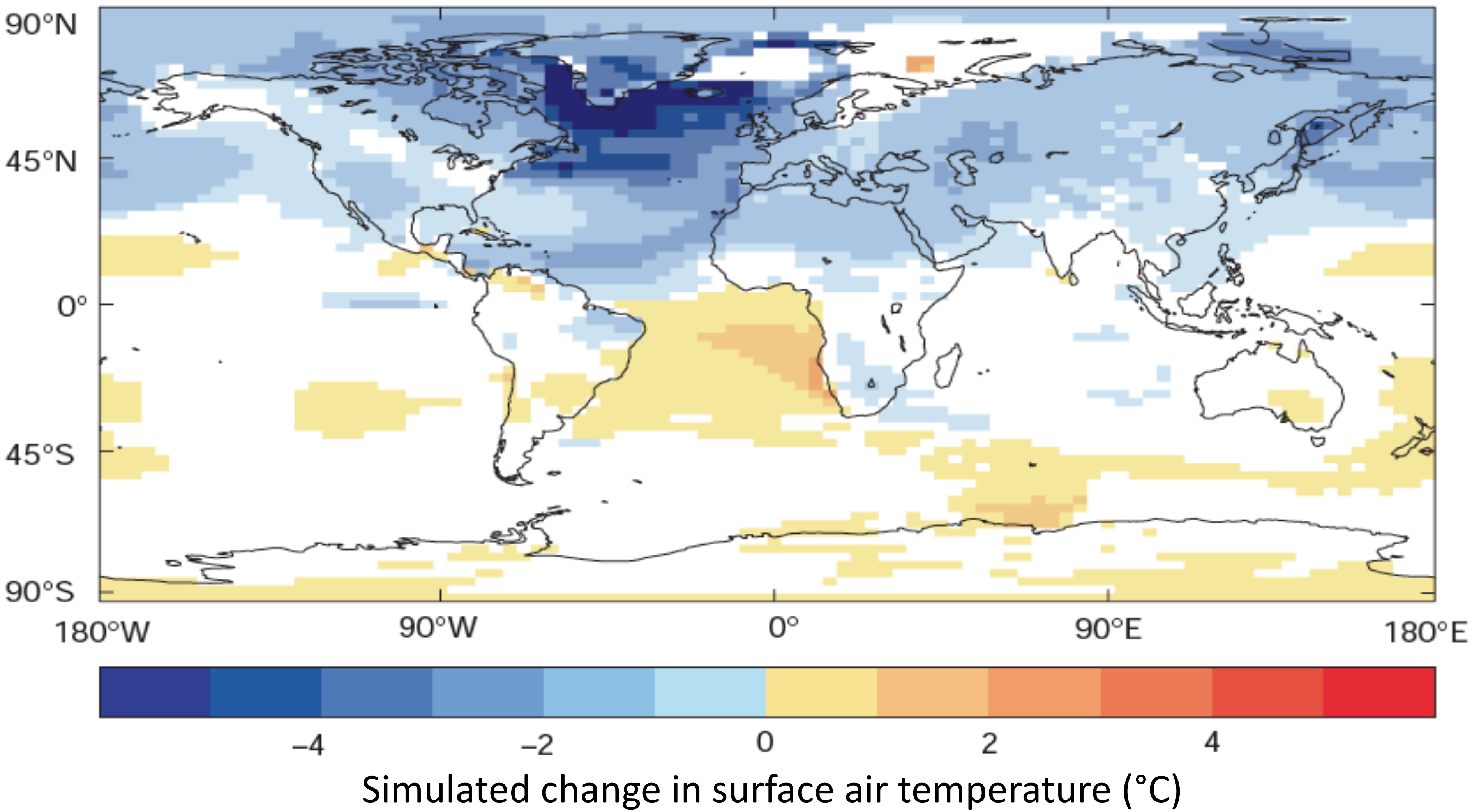
The fear of a collapse of the AMOC

The AMOC transports heat from the southern to the northern hemisphere



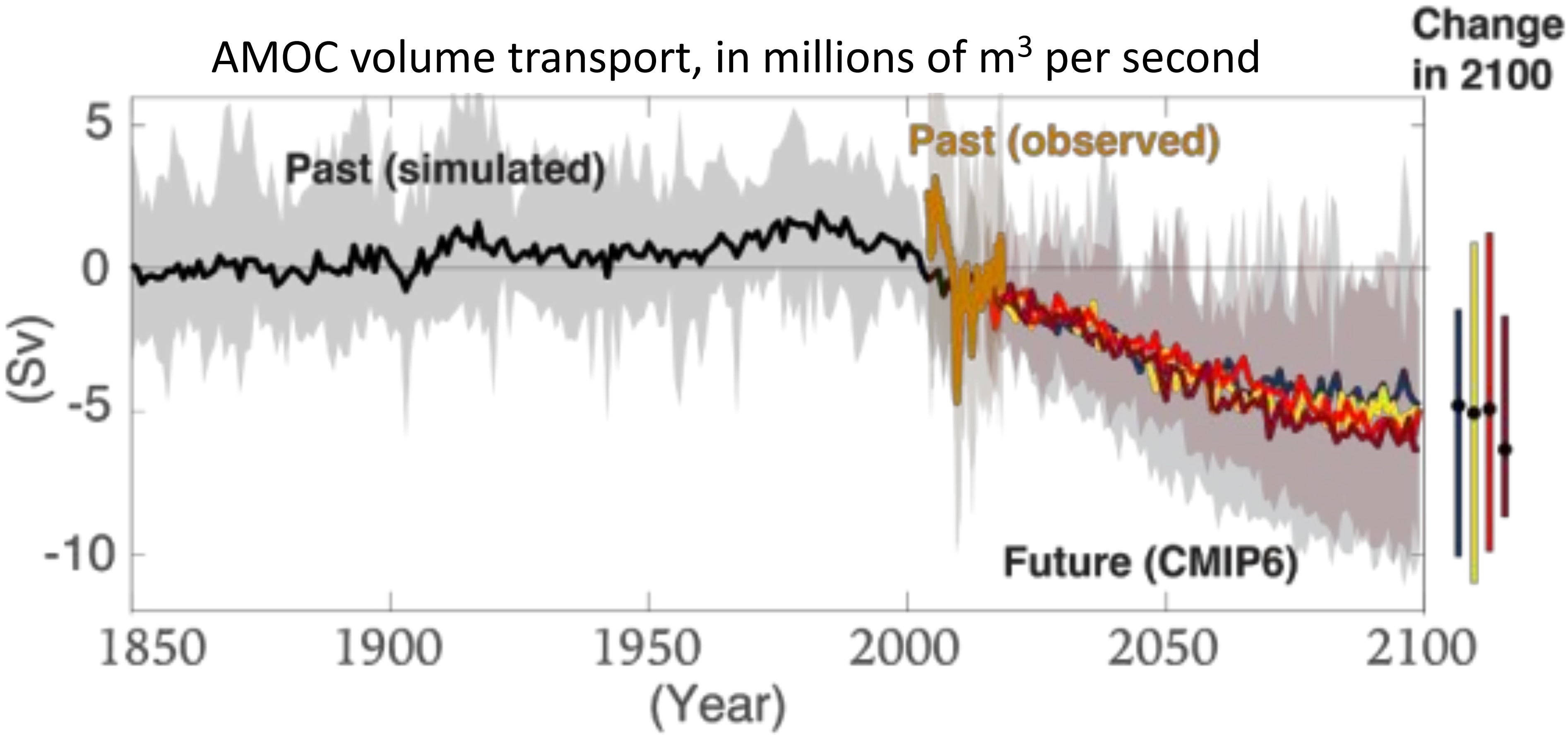
Potential impact of a collapse of the AMOC



Vellinga & Wood 2002


LE JOUR D'APRÈS
THE DAY AFTER TOMORROW

Progressive slowdown according to climate models

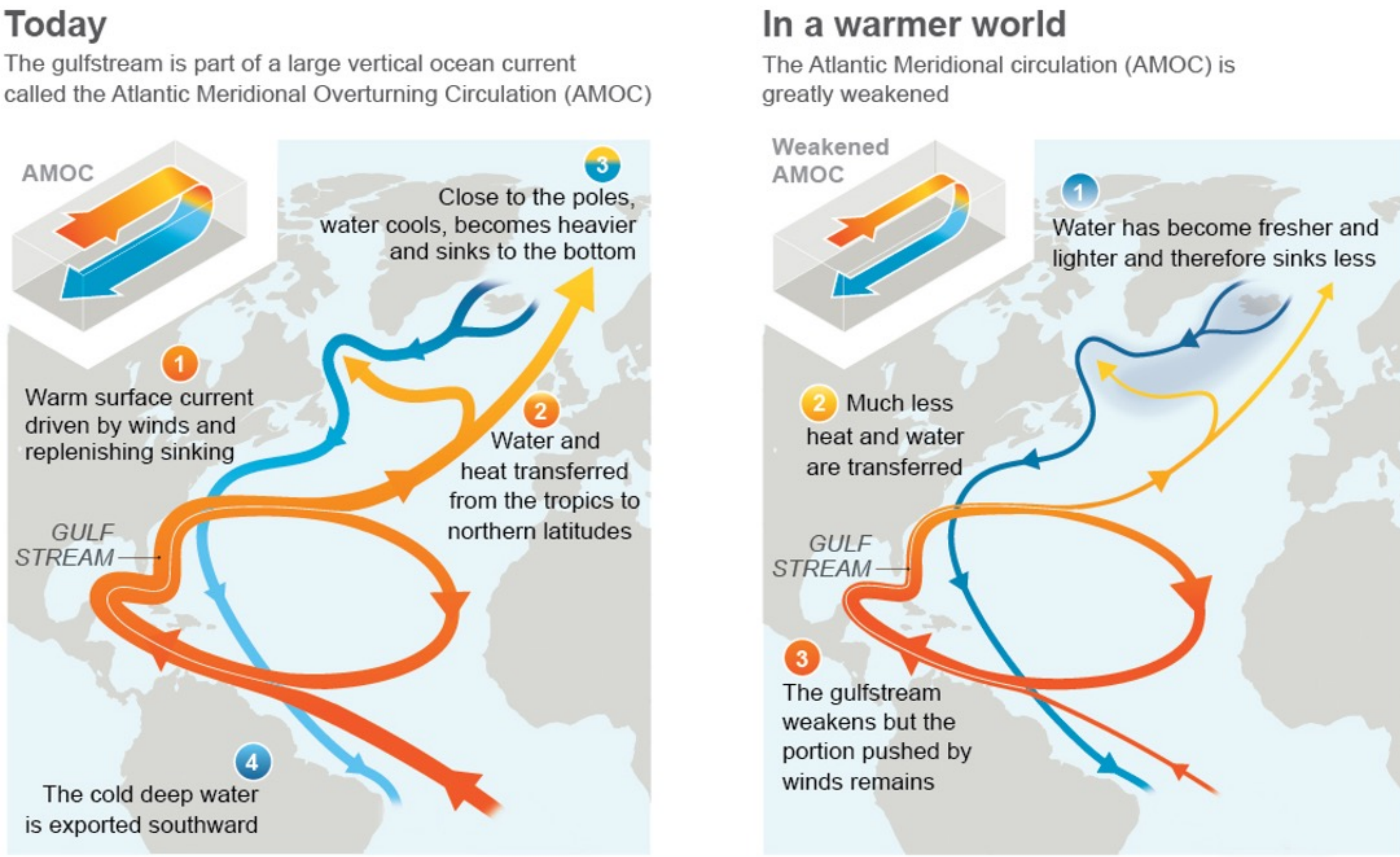


This projected slowdown has a limited impact on warming in Europe.

However, it can alter transport of heat and carbon into the deep ocean, modify weather and precipitation regimes in some regions, ...

Fox-Kemper *et al*. 2022

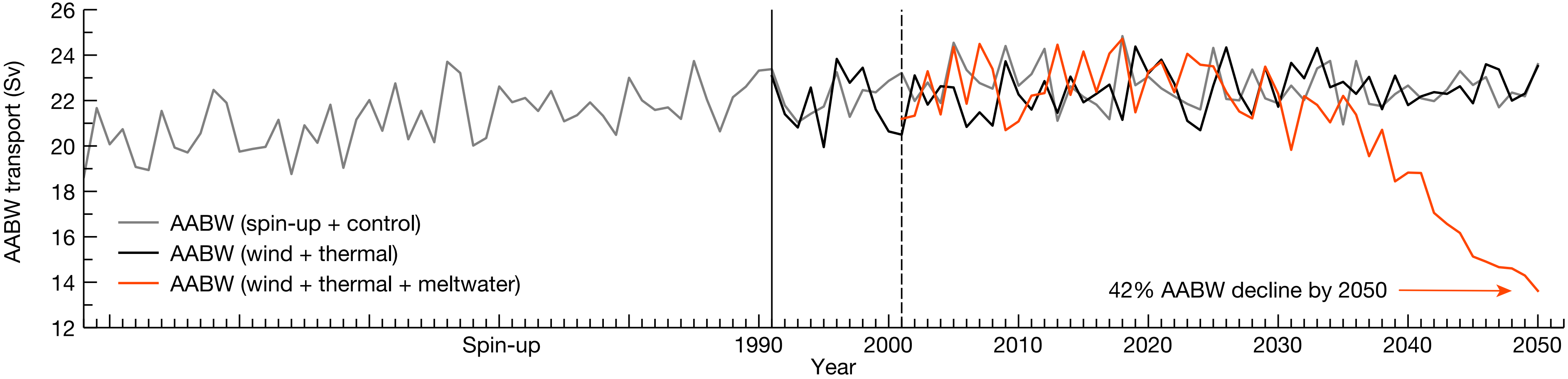
Link between the AMOC and the Gulf Stream



Fox-Kemper *et al*. 2022

Fear now turns to the SMOC

SMOC volume transport, in millions of m^3 per second



Melting of the Antarctic ice sheet could hamper the formation and sinking of dense waters around Antarctica.

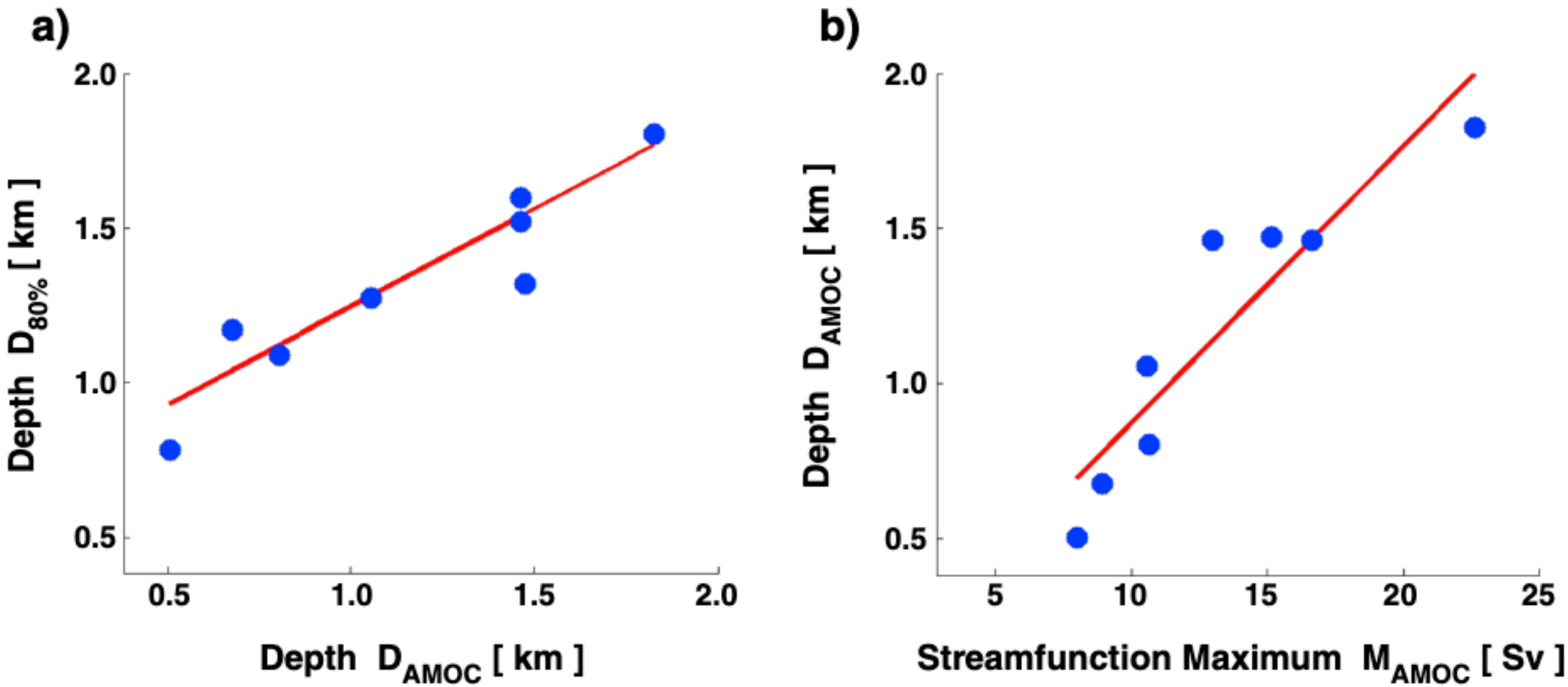
This could facilitate the access of warm subsurface waters to the ice sheet, and thereby trigger a positive feedback.

Li *et al*. 2023

Part 1. Climate impacts

- Northward heat transport
- **Downward heat transport**
- Upward heat transport
- Water cycle changes

A stronger AMOC goes with deeper heat storage



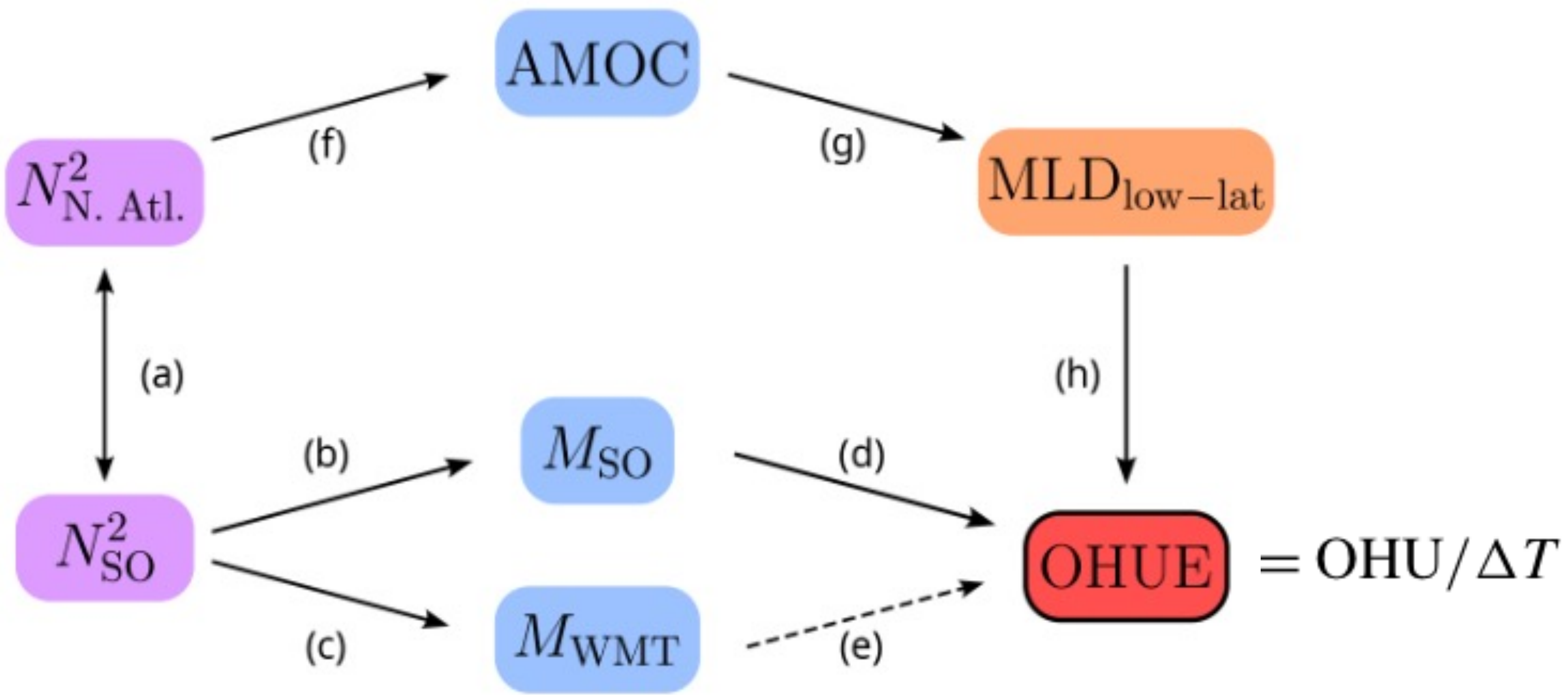
"We find that the rate of heat sequestration in the ocean interior is strongly correlated with the depth of heat penetration within climate models, which, in turn, appears to be regulated by the vertical extent and strength of the AMOC cell."

Kostov *et al*. 2014

Correlation is not causation

Analysis of CMIP6 models suggests that AMOC correlates with Southern Ocean stratification and subduction, which in turn control Ocean Heat Uptake Efficiency (OHUE).

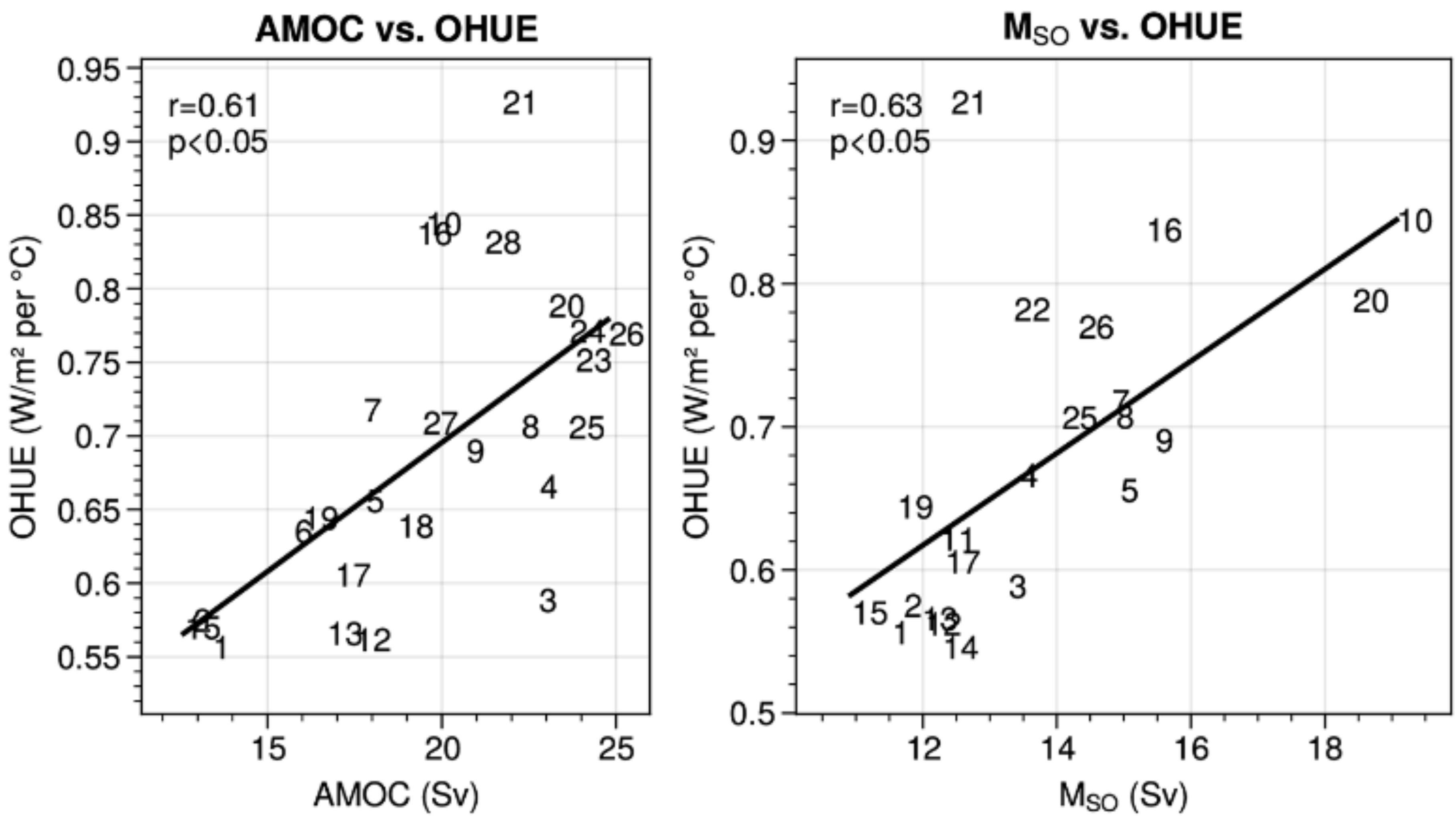
OHUE = global ocean heat gain / global mean surface warming



Vogt *et al*. 2025a

AMOC and Southern Ocean upper cell versus OHUE

Latest generation of climate models shows strongest correlation between OHUE and Southern Ocean upper cell strength.



Vogt *et al*. 2025a

Part 1. Climate impacts

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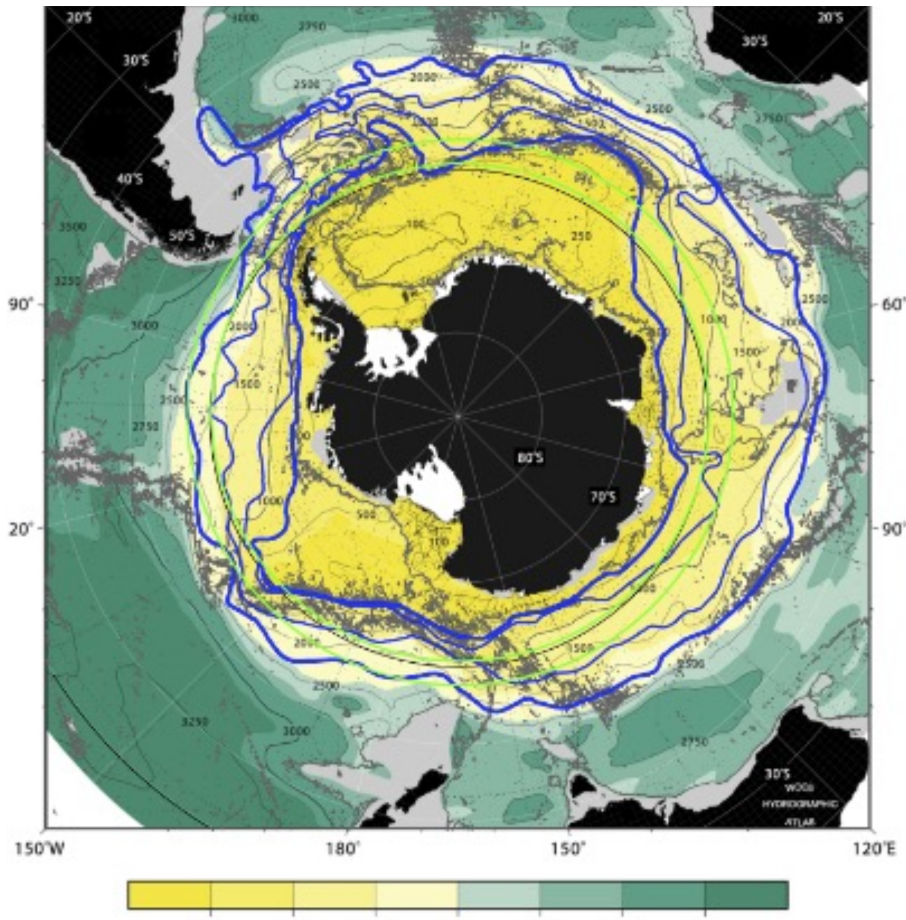
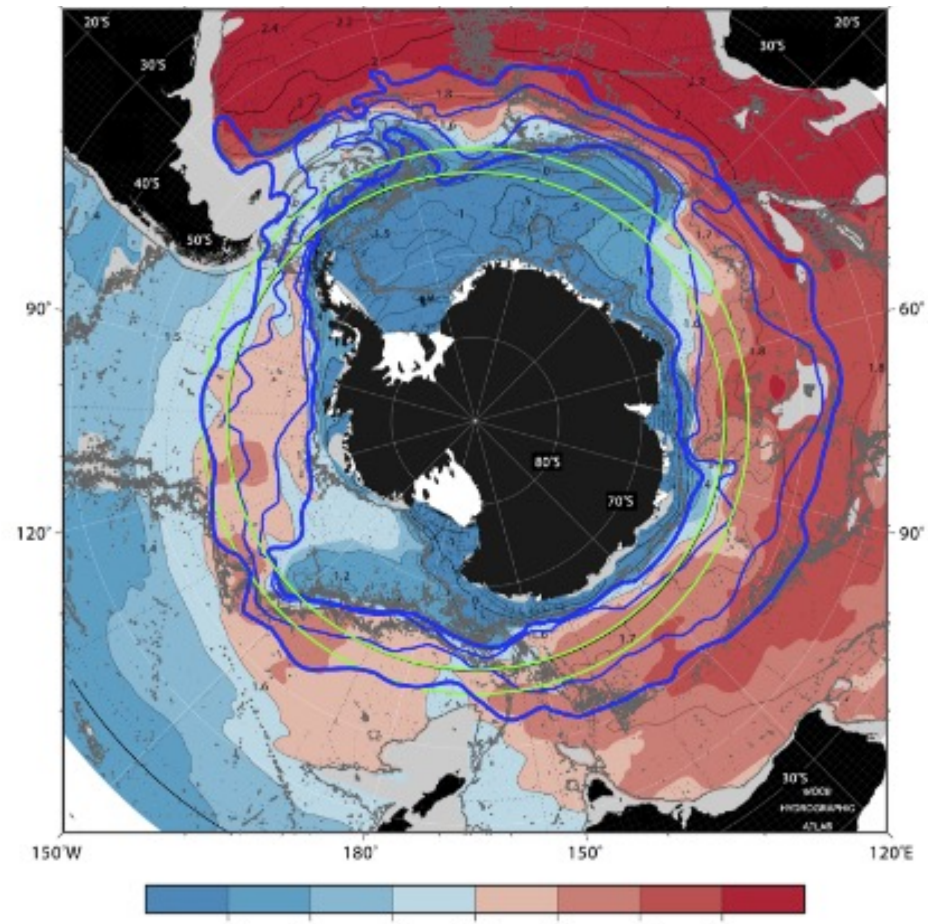
- Water cycle changes

AMOC brings heat to the upper Southern Ocean

Properties following the core density of the southward AMOC branch



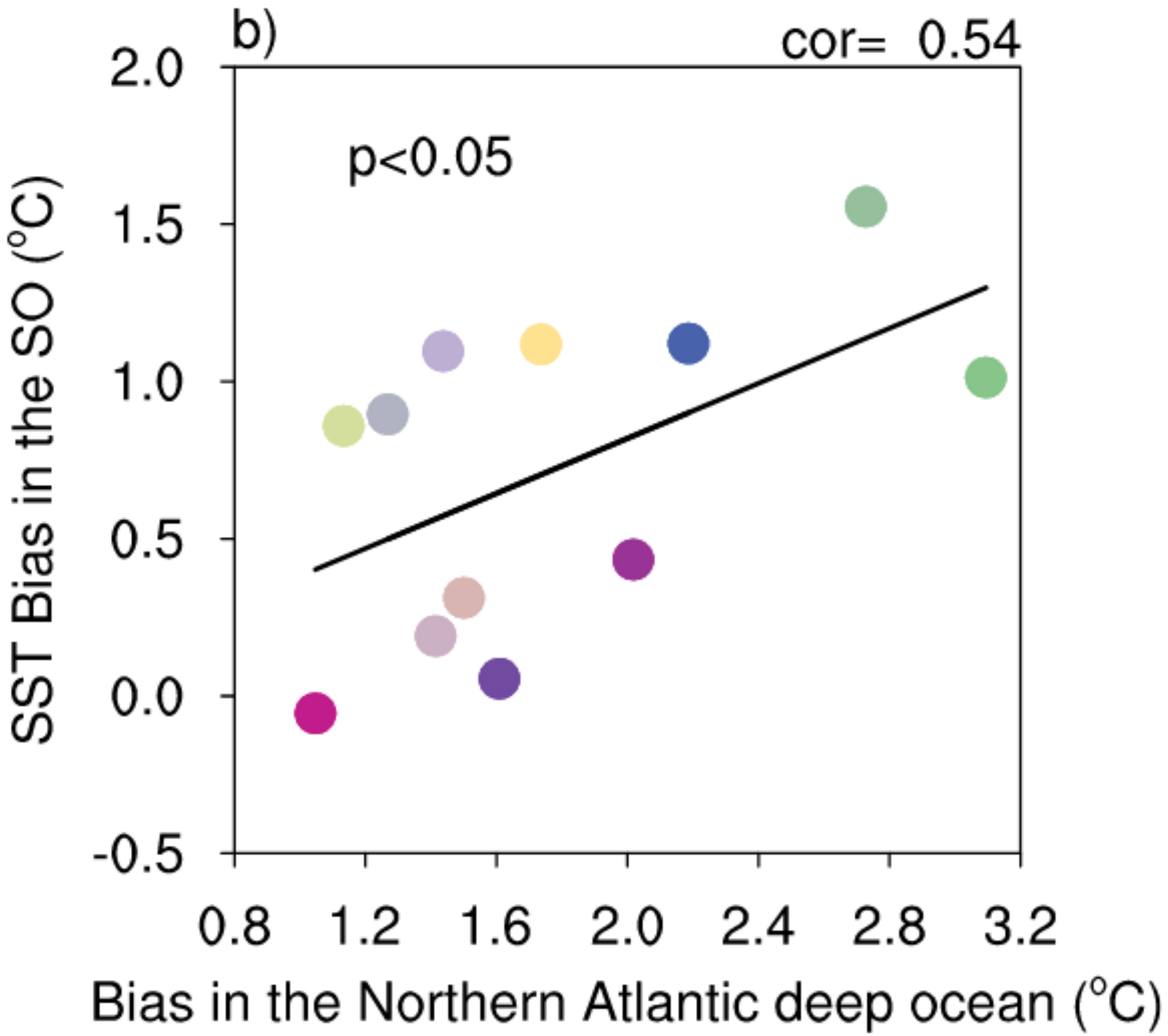
Depth (m)



Temperature (°C)

Tamsitt *et al*. 2017

AMOC brings heat to the upper Southern Ocean

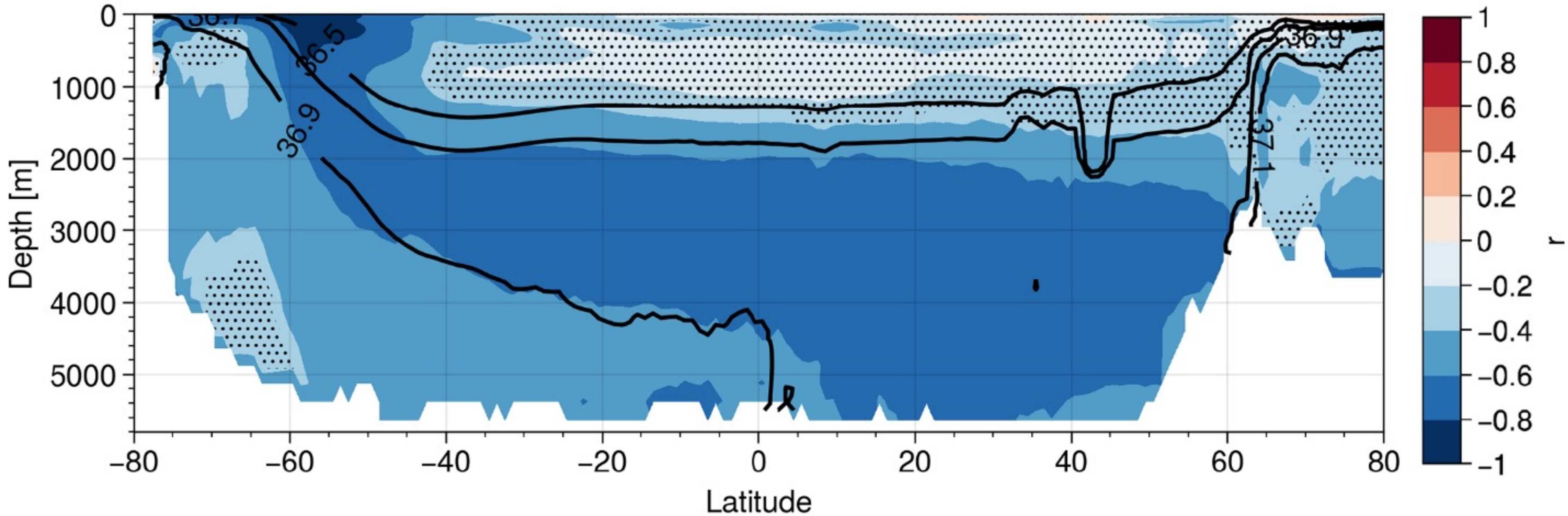


Deep North Atlantic temperature correlates with Southern Ocean sea surface temperature (SST) in CMIP6 models.

Luo *et al*. 2023

Upwelling heat affects Antarctic sea ice and SST

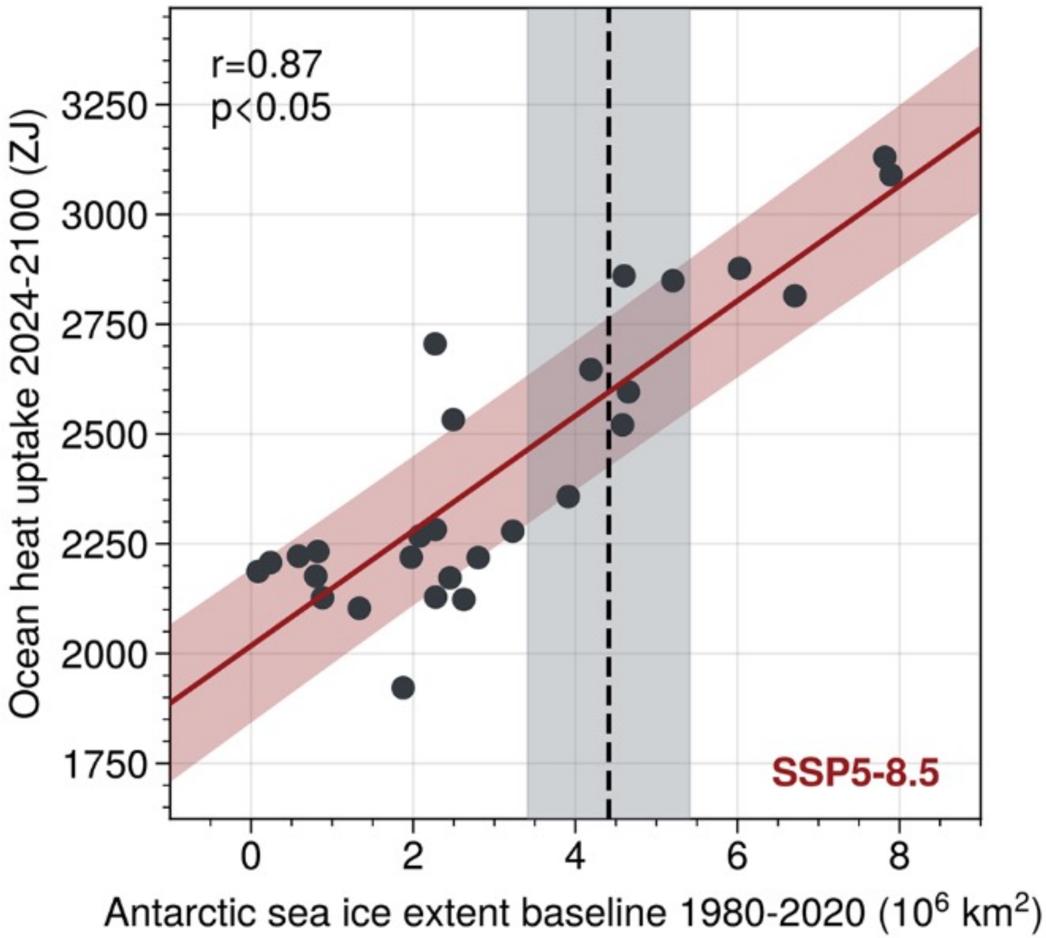
Inter-model correlation between Antarctic sea ice extent and zonal-mean ocean temperature, in the preindustrial state.



- ➢ Deep ocean temperatures in the density range of upwelling North Atlantic deep water influence Antarctic sea ice coverage and Southern Ocean SST.
- ➢ In turn, Antarctic sea ice extent and Southern Ocean SST precondition projected future warming.

Vogt *et al*. 2025b

Antarctic sea ice as a predictor of future warming

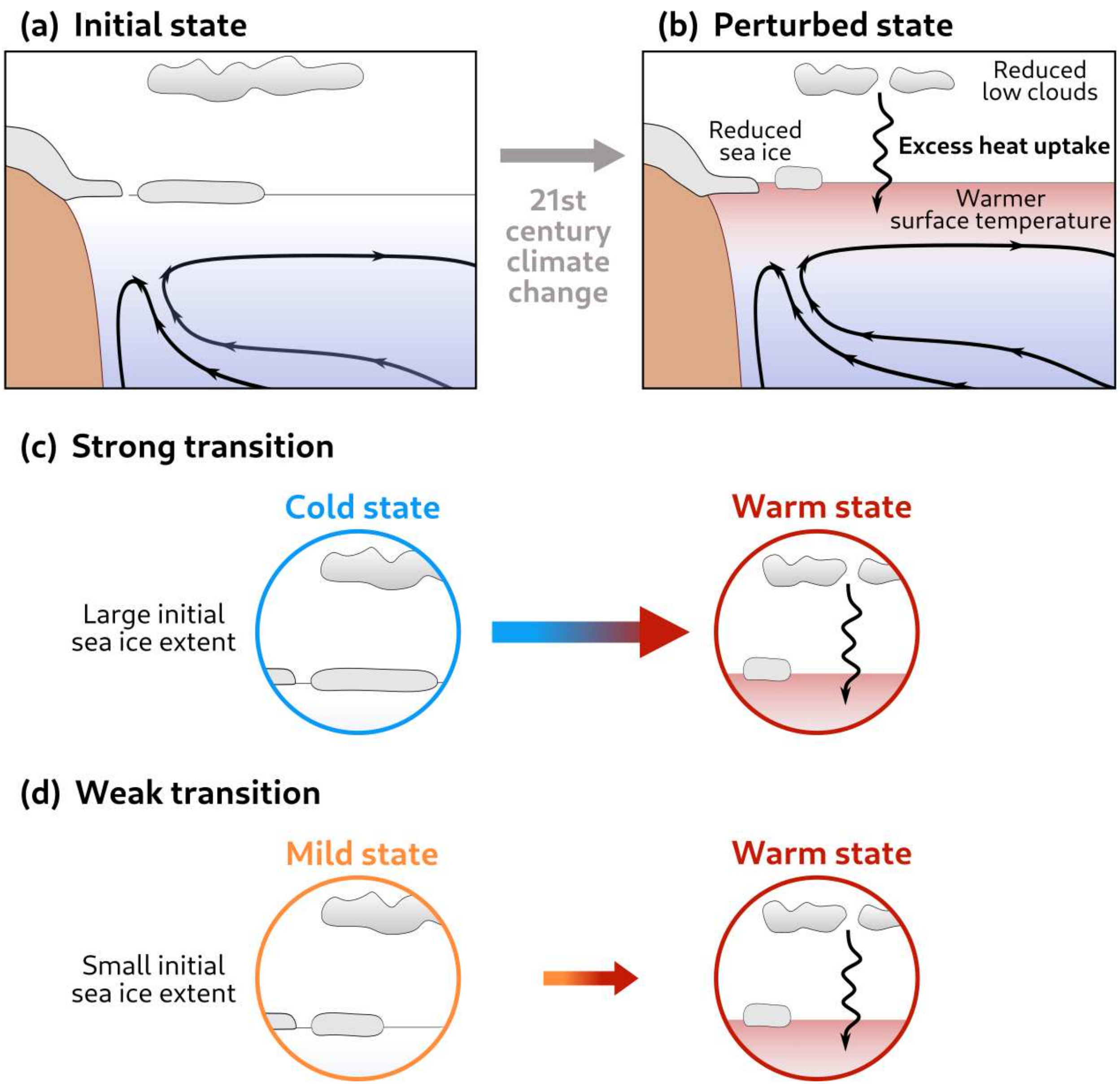


Future ocean warming versus present-day Antarctic sea ice extent in CMIP6 models.

- Future warming correlates with baseline Antarctic sea ice extent.
- Observed extent of Antarctic sea ice allows to constrain and refine projections of future ocean warming.

Vogt *et al*. 2025b

Cold initial state has more potential for warming



Vogt *et al.* 2025b

Part 1. Climate impacts

- Northward heat transport
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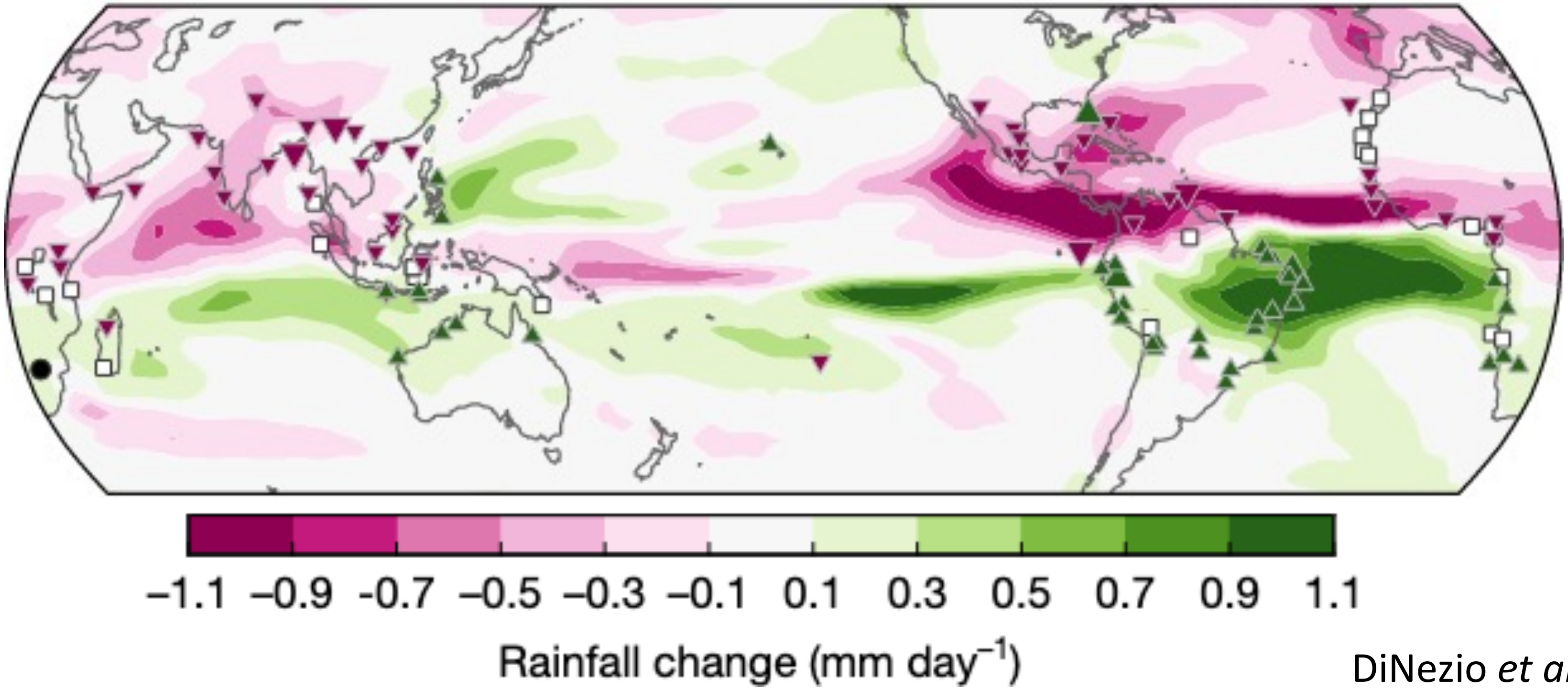
- **Water cycle changes**

Weakened AMOC impacts tropical rainfall

- AMOC changes impacts North Atlantic SST all the way to the equator. This in turn affects rainfall via dynamic and thermodynamic changes in the atmosphere (shifts of the Inter-Tropical Convergence Zone).
- Models and proxies suggest that a weaker AMOC leads to wetting south of the equator and drying north of the equator.



DiNezio *et al*. 2025

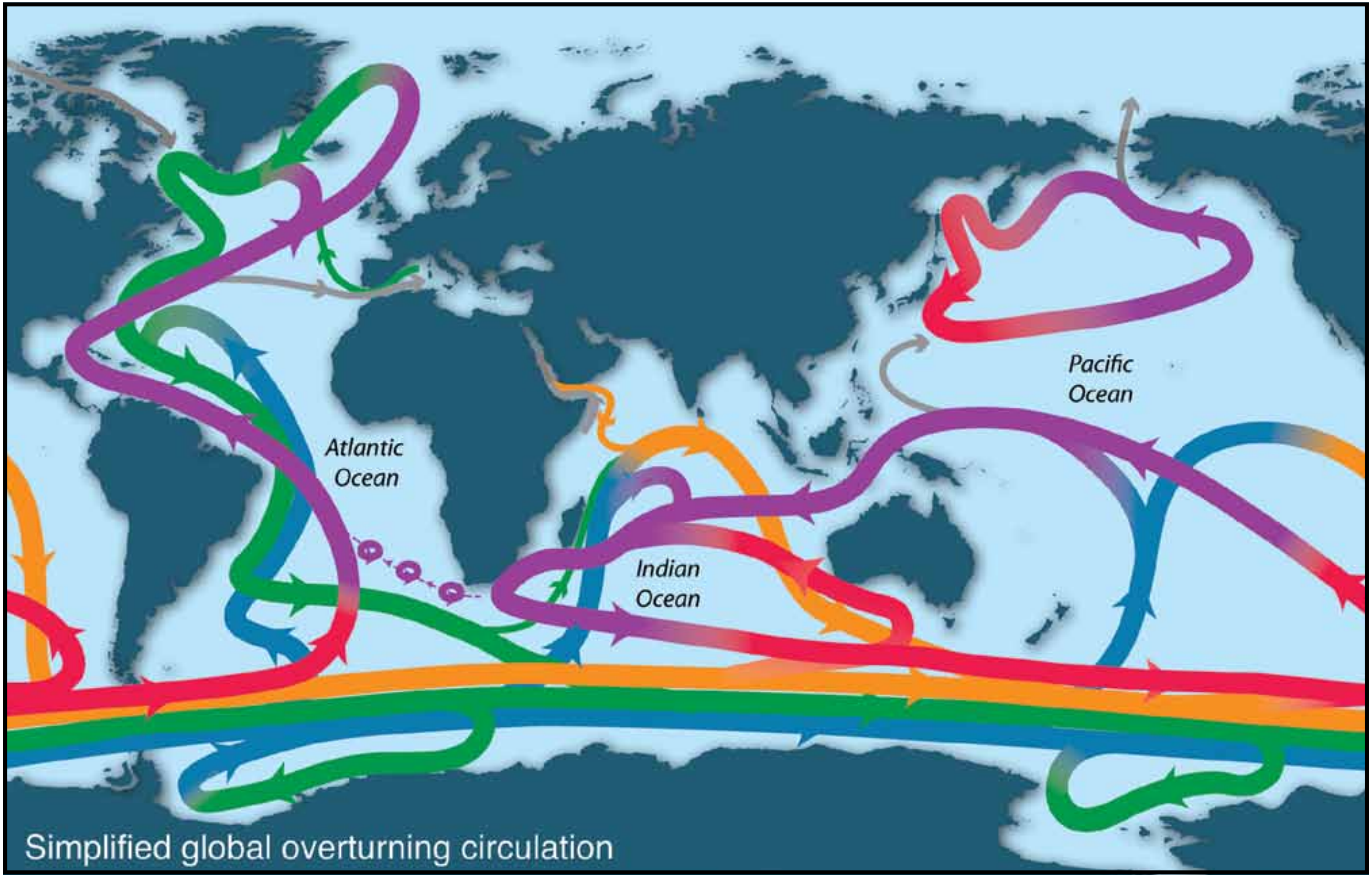
Conclusions

- The AMOC redistributes heat globally.
- It also redistributes carbon and nutrients, affecting ocean carbon storage and marine ecosystems.
- It contributes to shape rainfall across the global tropics.
- Impact on European climate perhaps overstated.
- Future gradual slowdown is expected. Highly uncertain due to incomplete understanding and model limitations.

Part 2. Schematic history of the overturning circulation

from 1750 to 2013

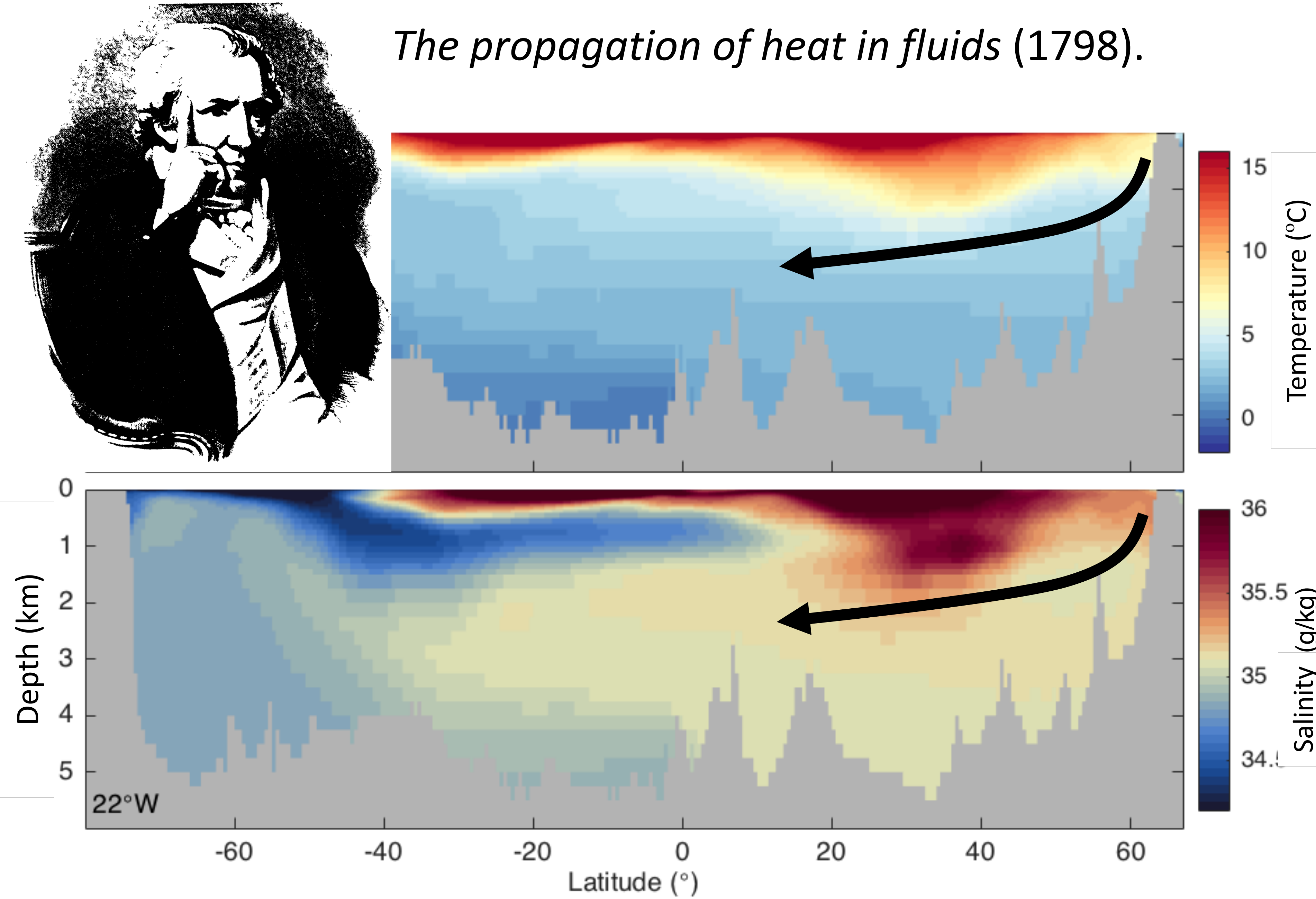
How did we discover this complex circulation?



Talley 2013

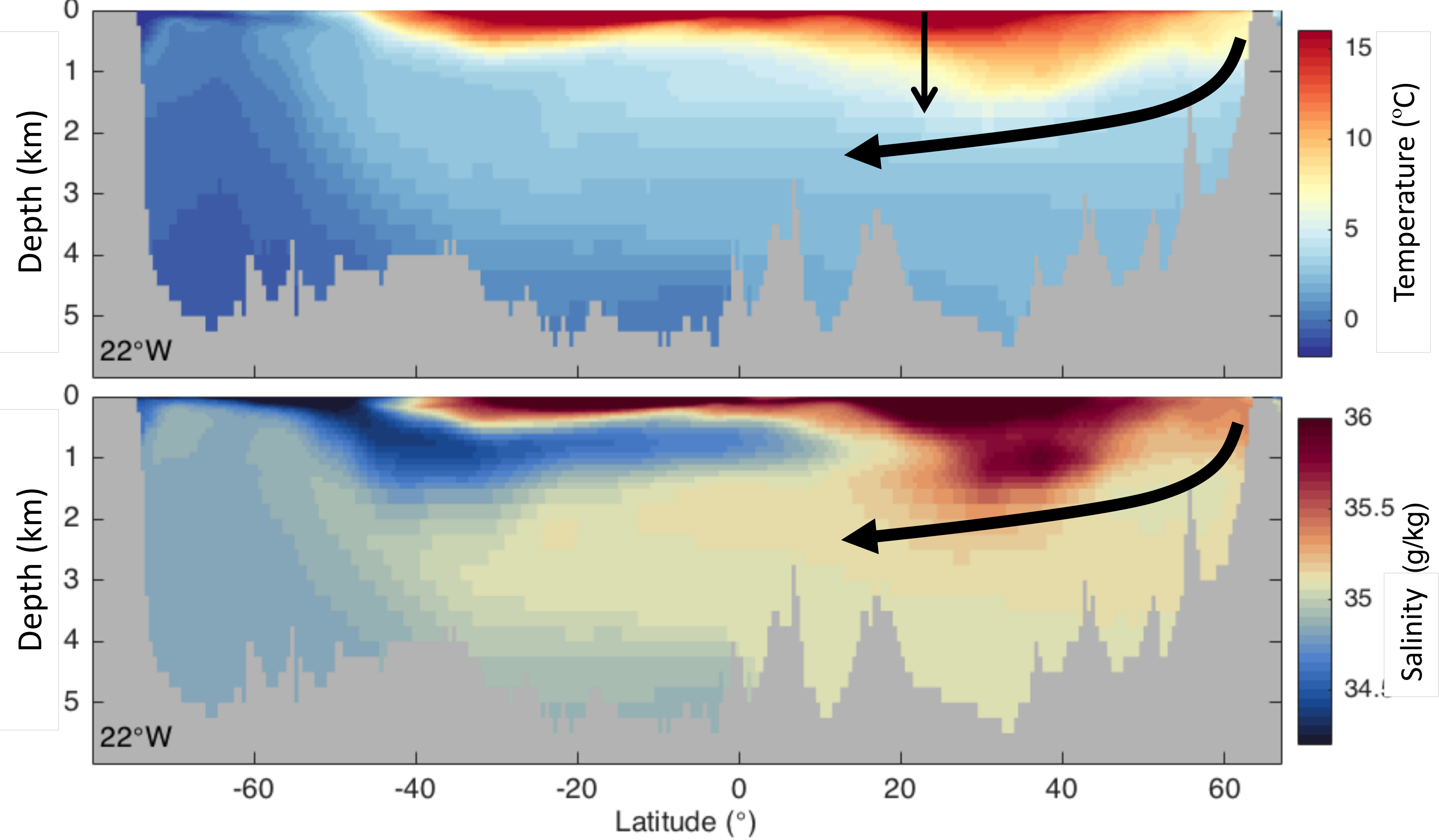
Benjamin Thomson (1798)

The propagation of heat in fluids (1798).



Benjamin Thomson (1798)

Captain Ellis (1750) : T ~ 10 ℃



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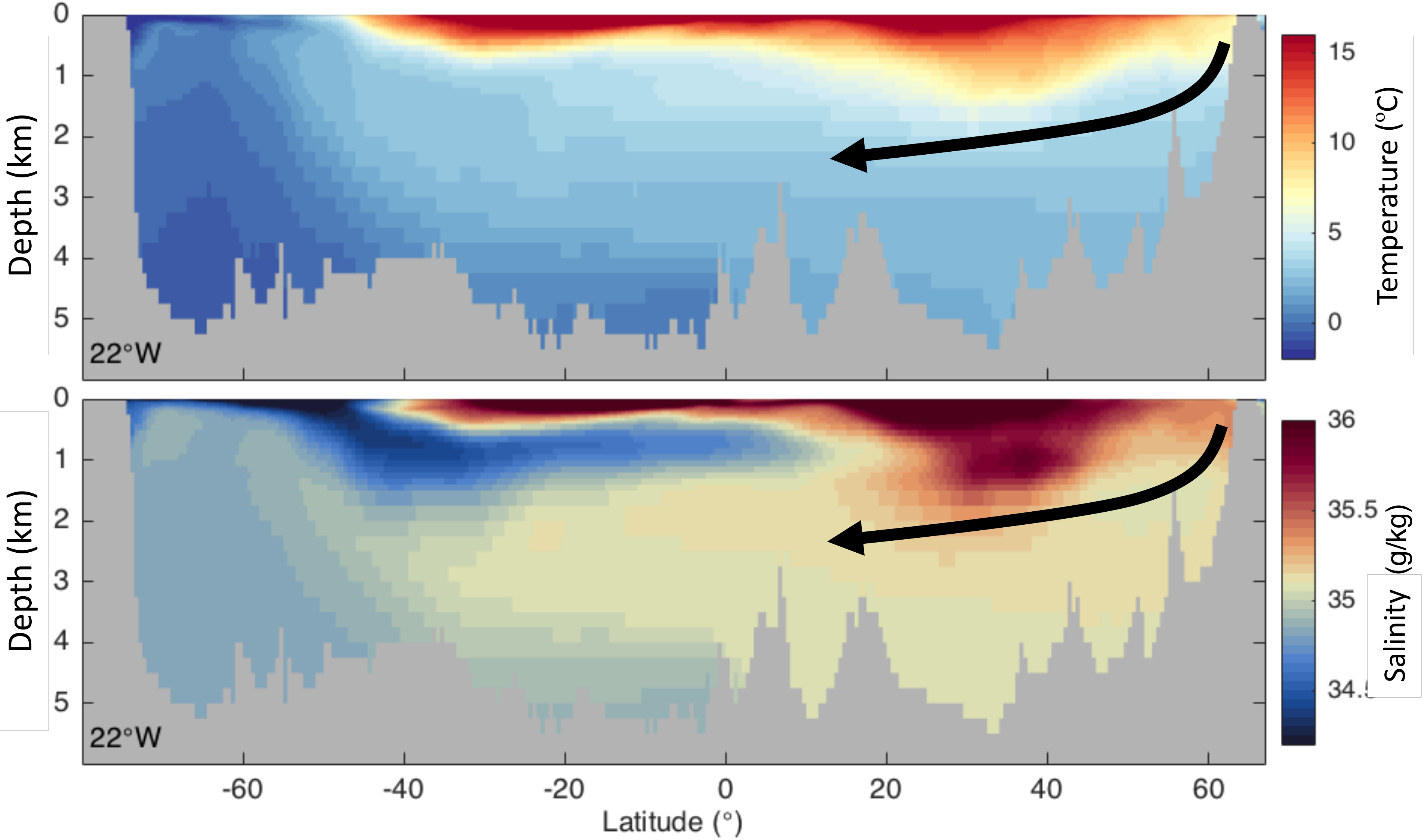
Circulation is not measured but deduced from tracers.



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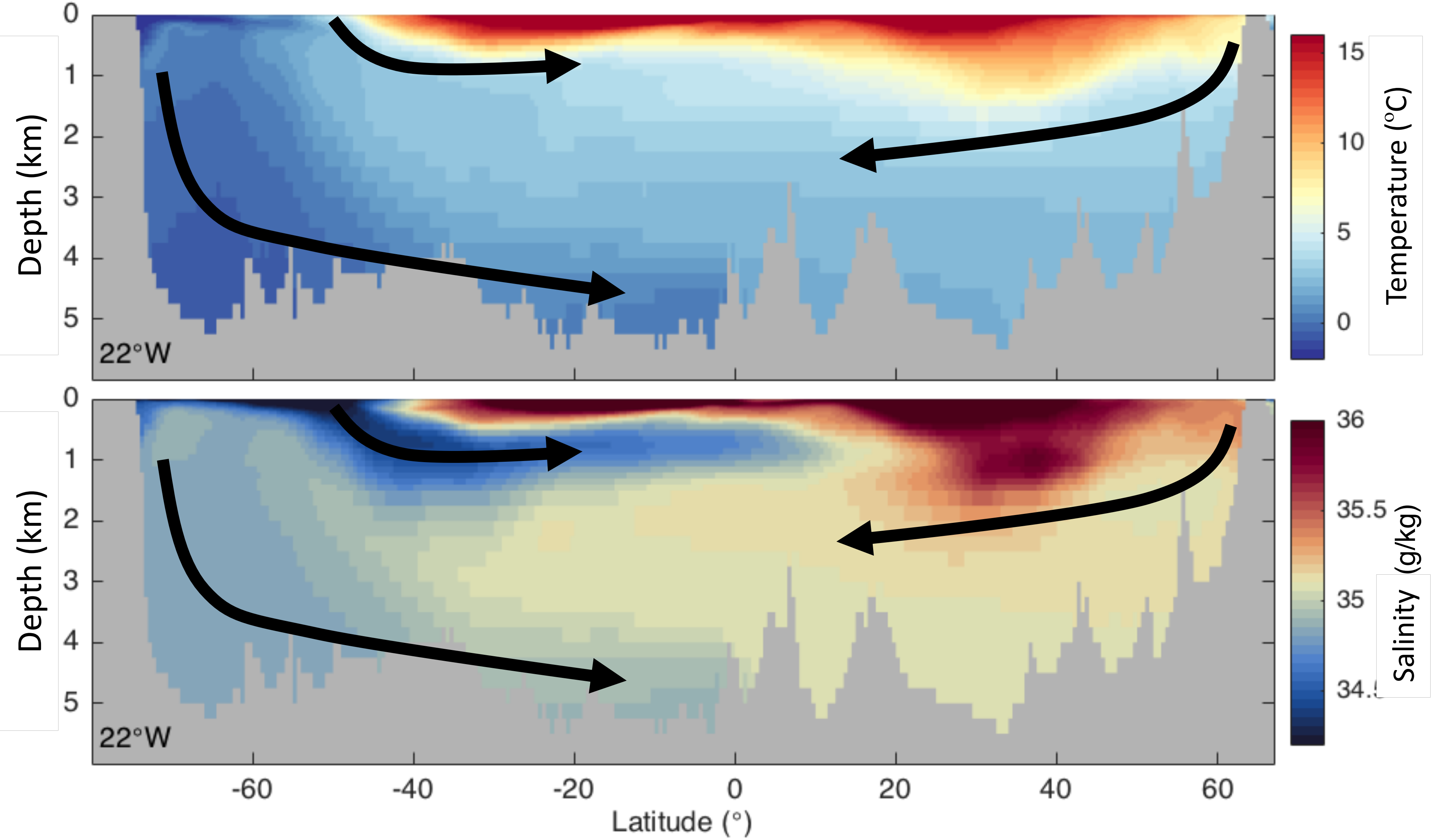

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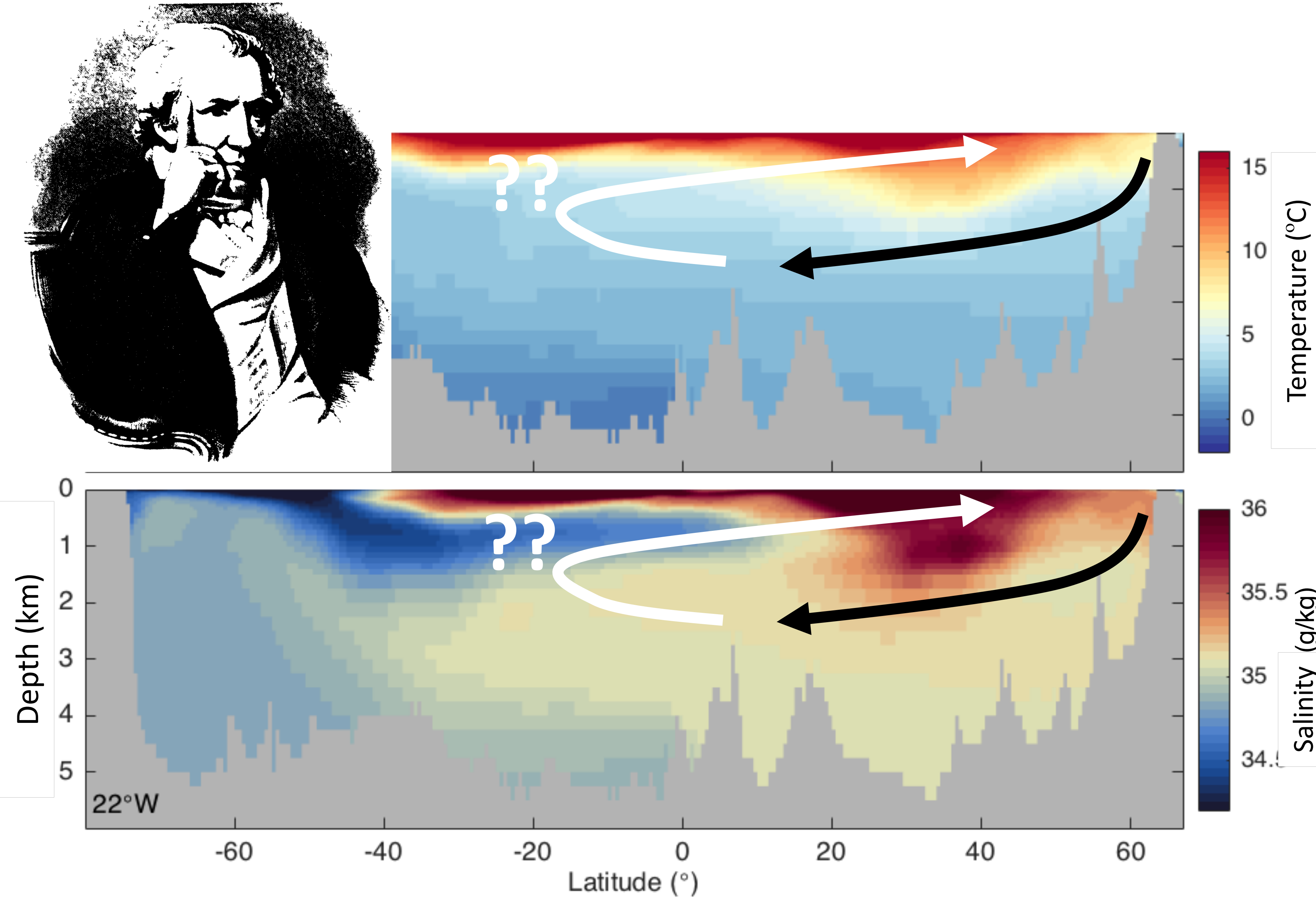
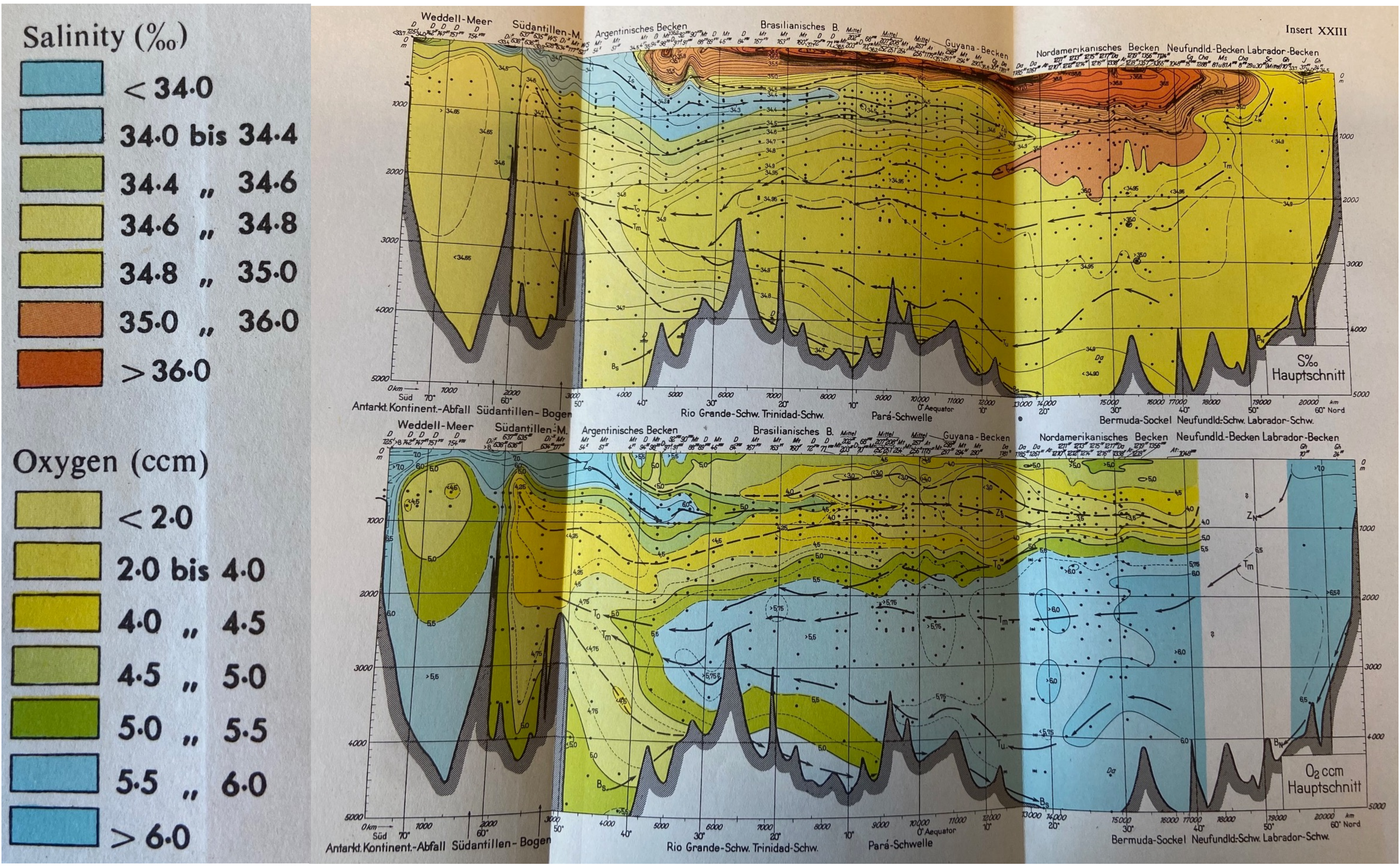
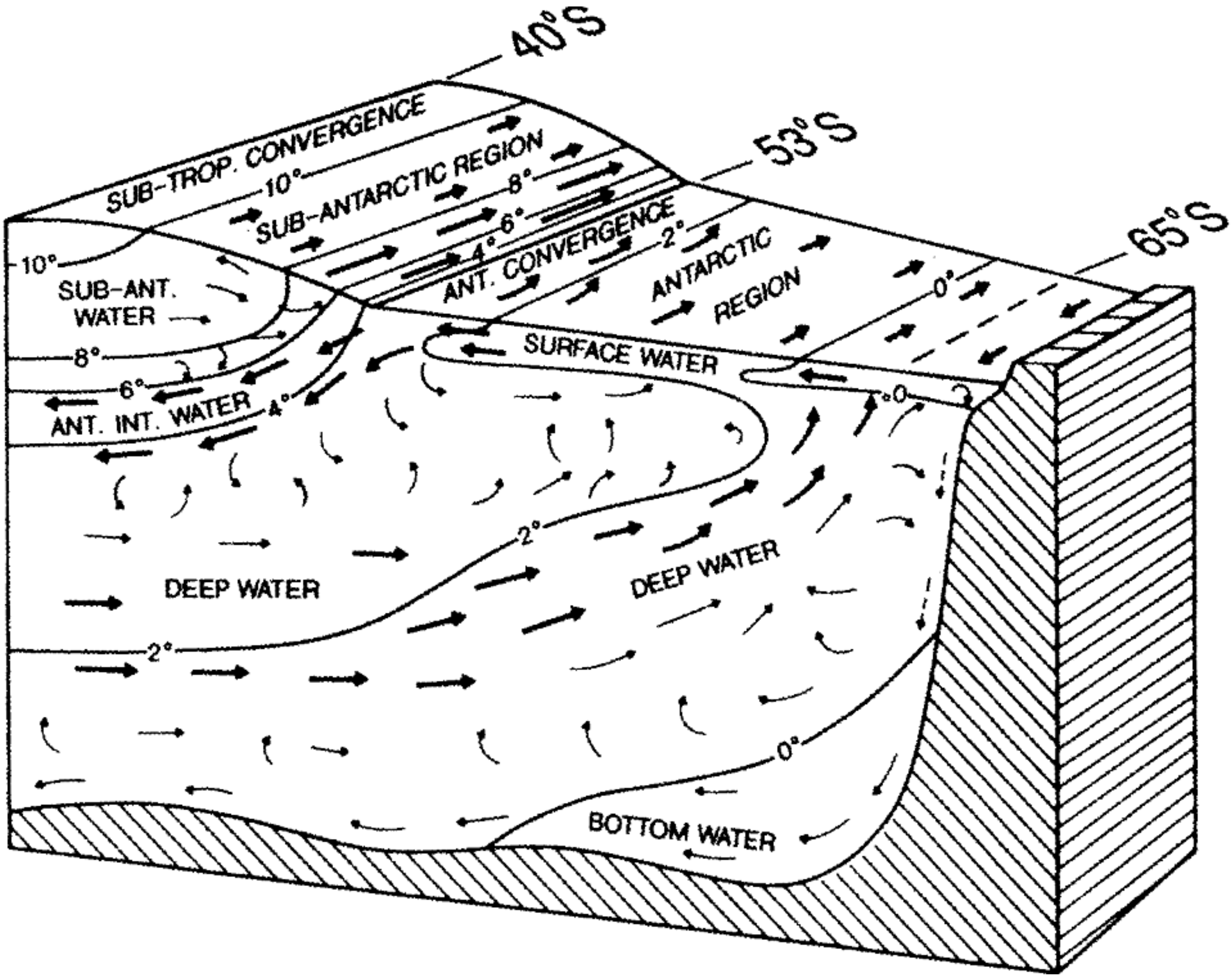


Wüst (1935)


Salinity (‰)
< 34.0
34.0 bis 34.4
34.4 „ 34.6
34.6 „ 34.8
34.8 „ 35.0
35.0 „ 36.0
> 36.0
Oxygen (ccm)
< 2.0
2.0 bis 4.0
4.0 „ 4.5
4.5 „ 5.0
5.0 „ 5.5
5.5 „ 6.0
> 6.0
Insert XXIII
Weddell-Meer
Südantillen-M.
Argentinisches Becken
Brasilianisches B.
Guyana-Becken
Nordamerikanisches Becken
Neufundld.-Becken
Labrador-Becken
S‰ Hauptschnitt
O2 ccm Hauptschnitt
Antarkt. Kontinent-Abfall
Südantillen-Bogen
Rio Grande-Schw.
Trinidad-Schw.
Pará-Schwelle
0° Aequator
Bermuda-Sockel
Neufundld-Schw.
Labrador-Schw.
Süd
60° Nord

Deacon (1937), Sverdrup (1942)



Stommel (1958)

The abyssal circulation

(*Received* 18 *February*, 1958)

« It seems likely that the low temperature of deep waters in the world ocean is maintained in the face of downward diffusion of heat from the warm surface layers by a very slow upward component of velocity in the deep water. »

Circulation and stratification are maintained by mixing of deep waters with lighter waters. Mathematically:

$$\omega\,\partial_z\gamma = \partial_z(K_\perp\,\partial_z\gamma)$$

Diapycnal velocity   Diffusivity   Density

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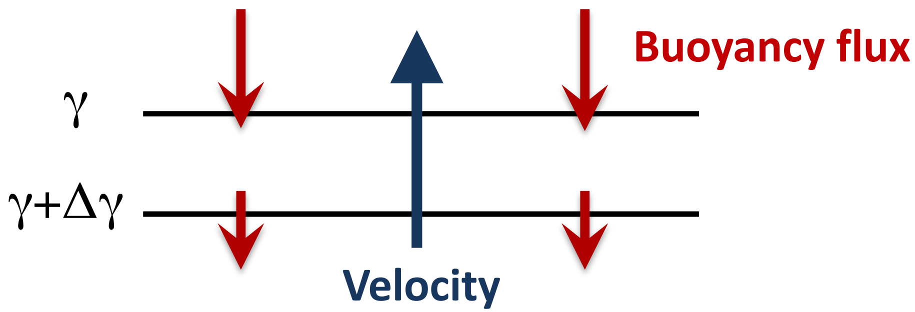


Munk (1966)

Abyssal recipes

WALTER H. MUNK*

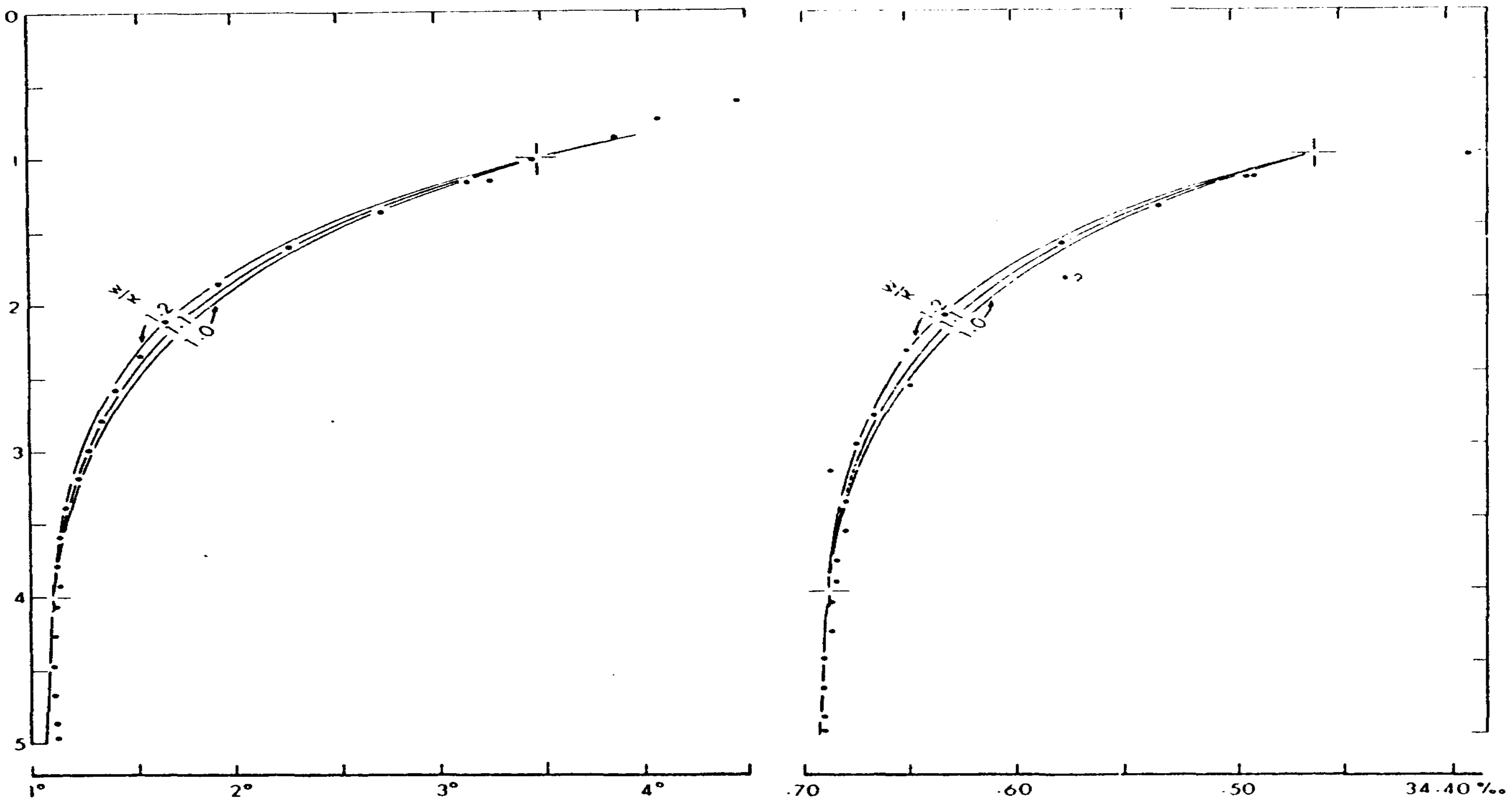


Fig. 3. Potential temperature and salinity as functions of depth (km) at station *Calcofi* 1964: ≠ 60·190, 33° 17′N, 132° 42·5′W (salinity at depth 1859 m was questioned in the original observations). Curves labeled w/κ (in units km^{-1}) are based on equation (1).

Munk (1966)

Abyssal recipes

WALTER H. MUNK*

(*Received* 31 *January* 1966)

Abstract—Vertical distributions in the interior Pacific (excluding the top and bottom kilometer) are not inconsistent with a simple model involving a constant upward vertical velocity $w \approx 1{\cdot}2$ cm day^{-1} and eddy diffusivity $\kappa \approx 1{\cdot}3$ cm^2 sec^{-1}. Thus temperature and salinity can be fitted by exponential-like solutions to $[\kappa \cdot d^2/dz^2 - w \cdot d/dz]\, T, S = 0$, with $\kappa/w \approx 1$ km the appropriate "scale height."

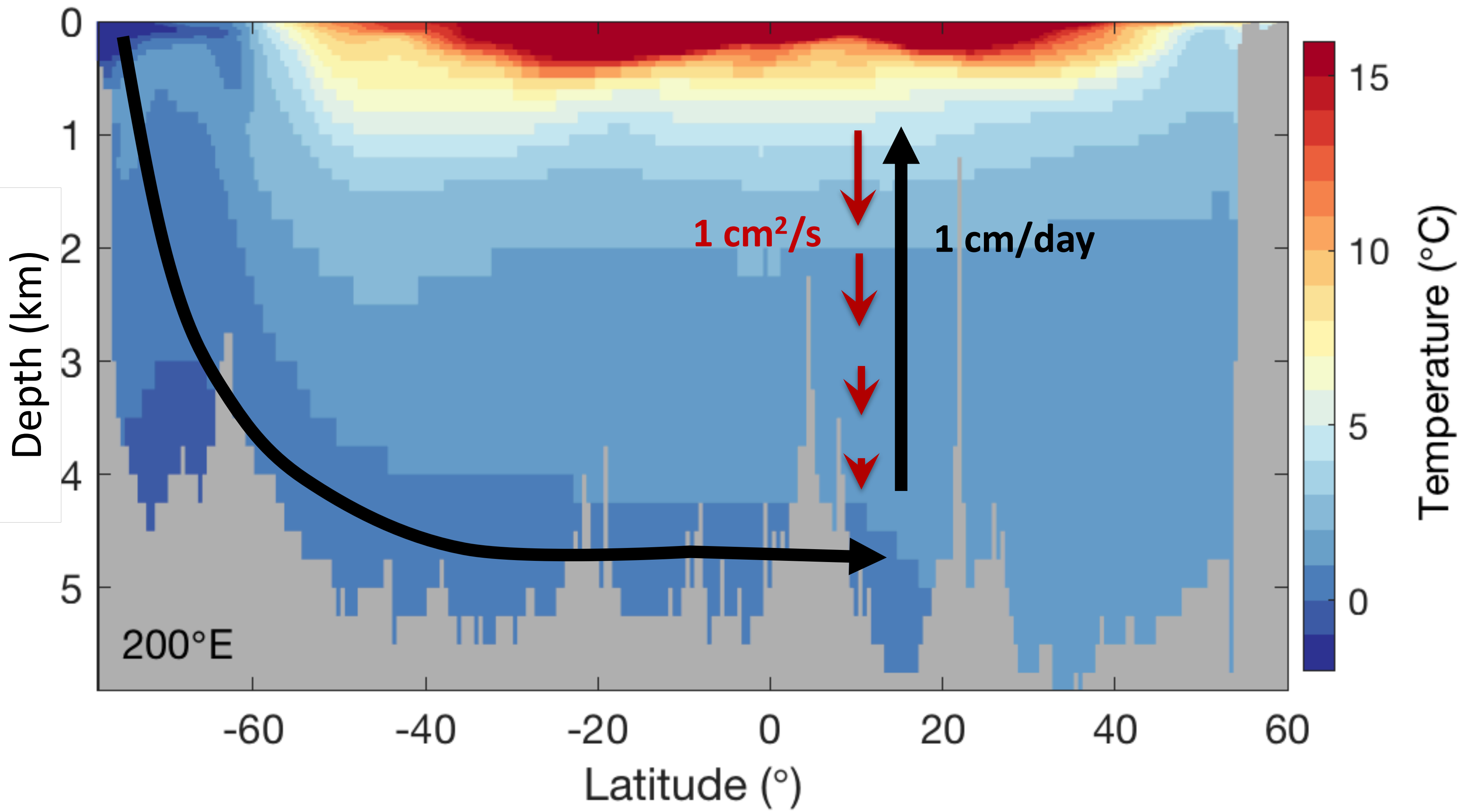
$$\omega\, \partial_z \gamma = \partial_z (K_\perp\, \partial_z \gamma)$$

$$\omega(z) = K_\perp\, \partial_{zz}\gamma / \partial_z \gamma \approx \text{constant}$$

Munk (1966)

Abyssal recipes

Walter H. Munk*

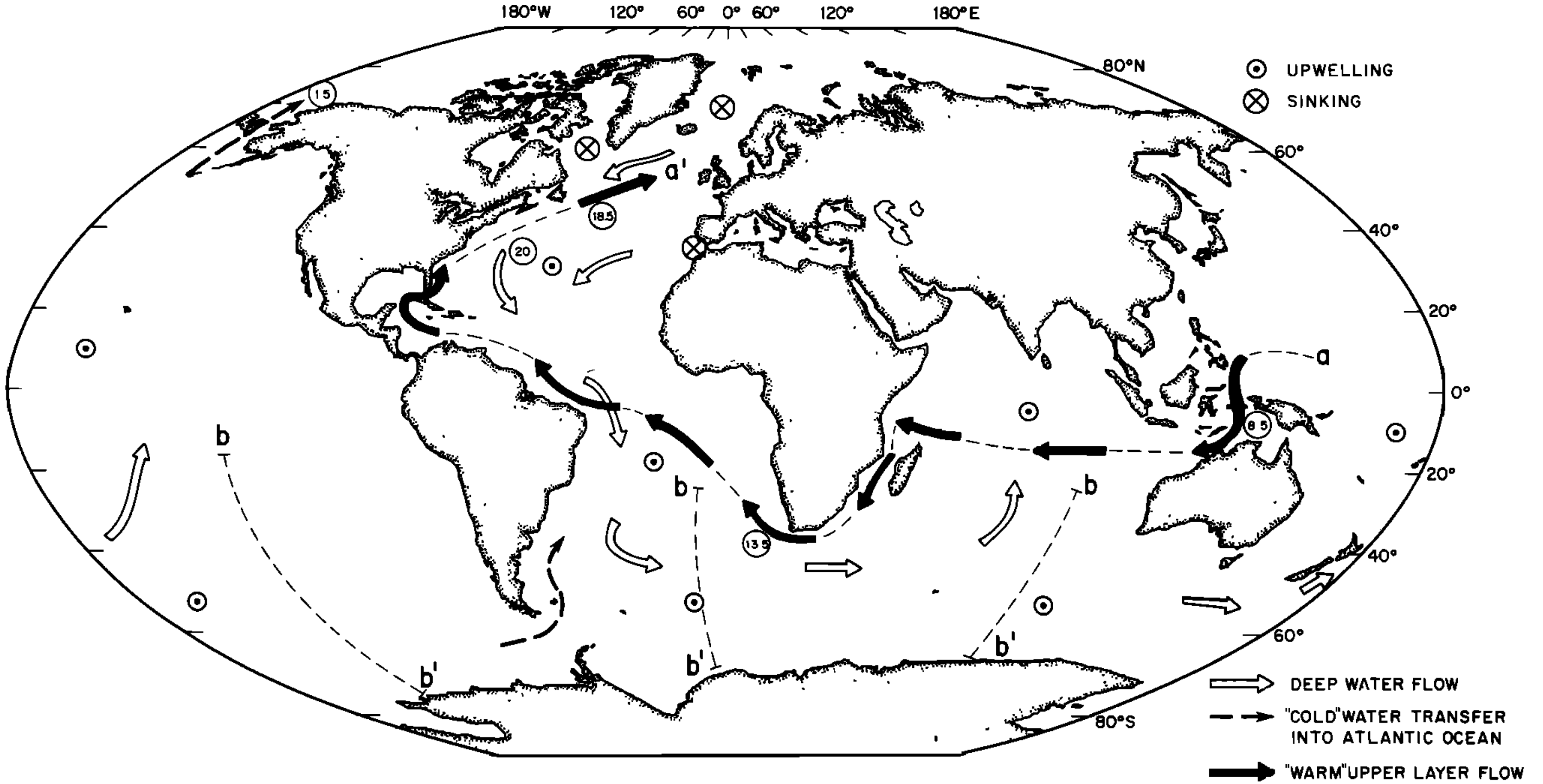


Gordon (1986)

Interocean Exchange of Thermocline Water

Arnold L. Gordon

Lamont-Doherty Geological Observatory of Columbia University, Palisades, New York



The biggest chill (1987).

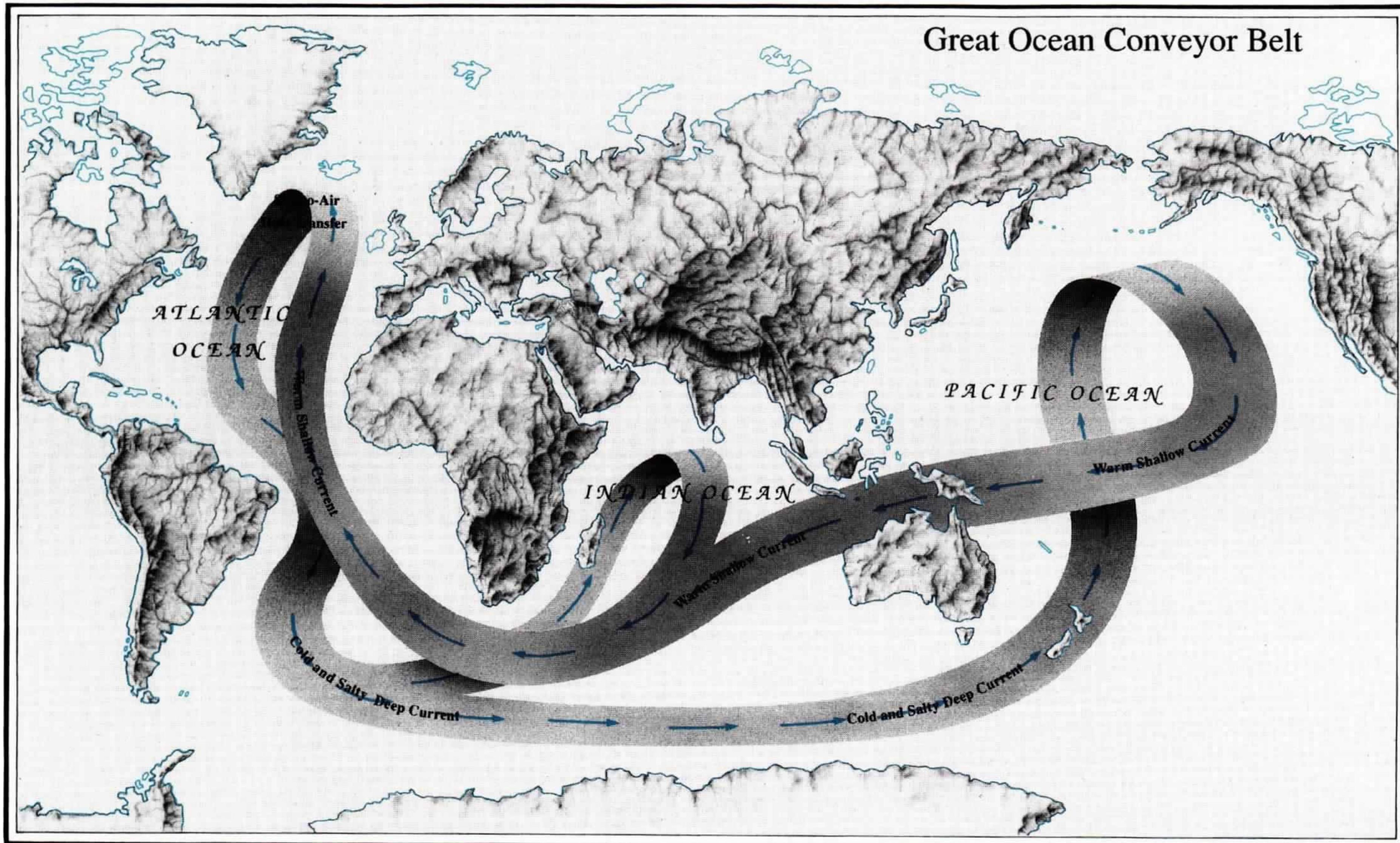
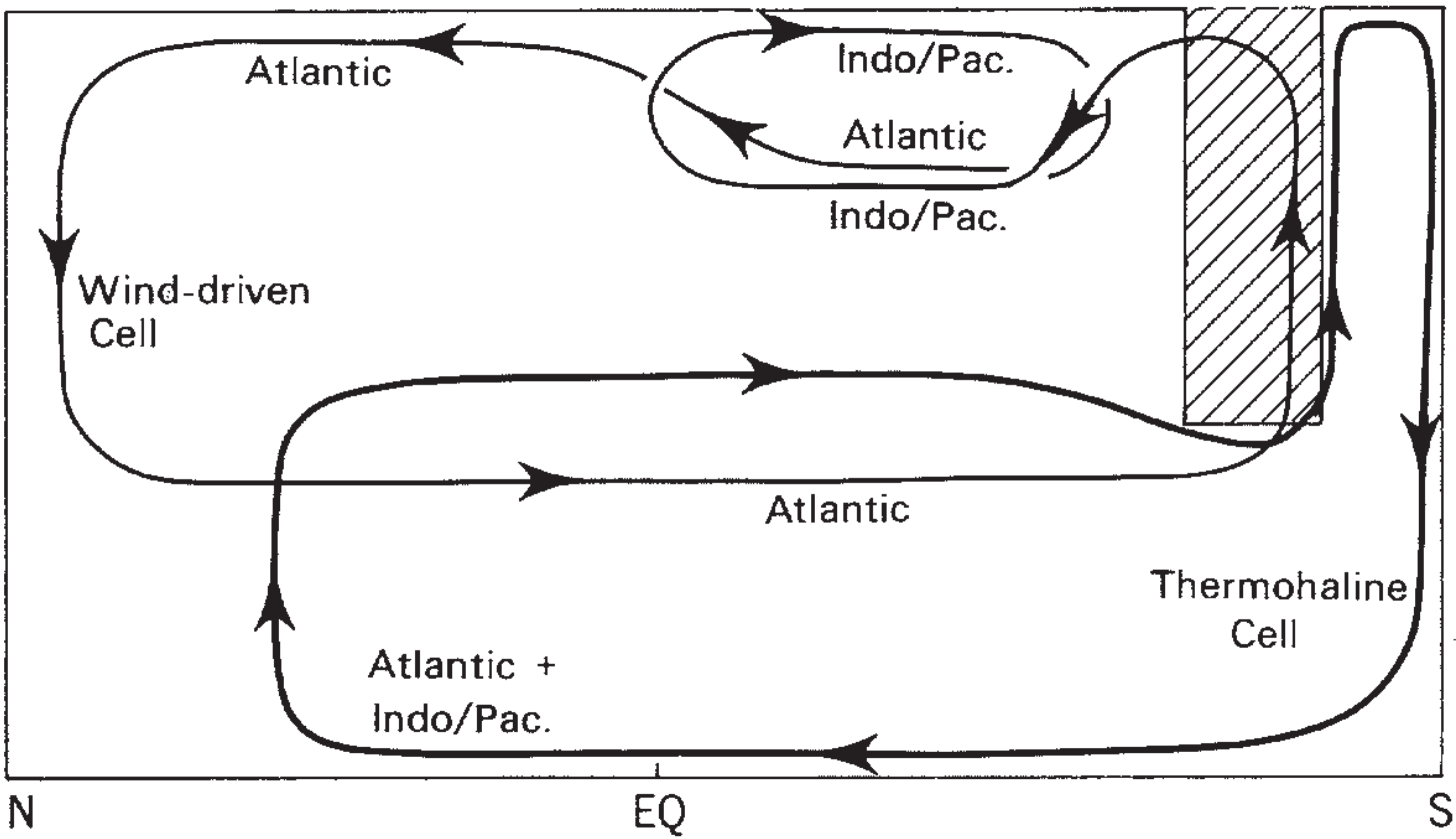


Fig. 1: The great ocean conveyor logo (Broecker, 1987). (Illustration by Joe Le Monnier, Natural History Magazine.)

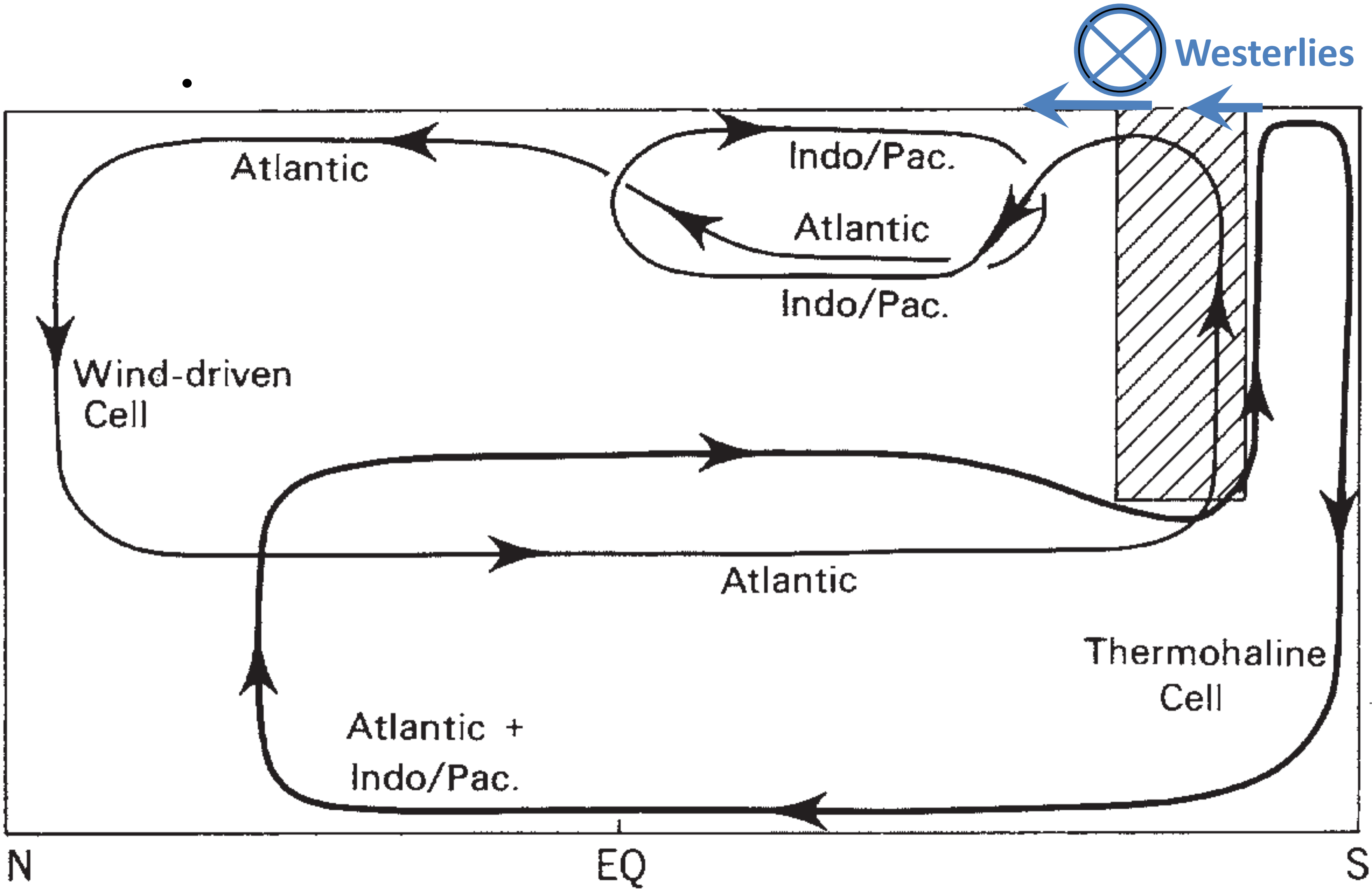
Toggweiler & Samuels (1993)

- Two cells.
- Pivot role of the Southern Ocean.



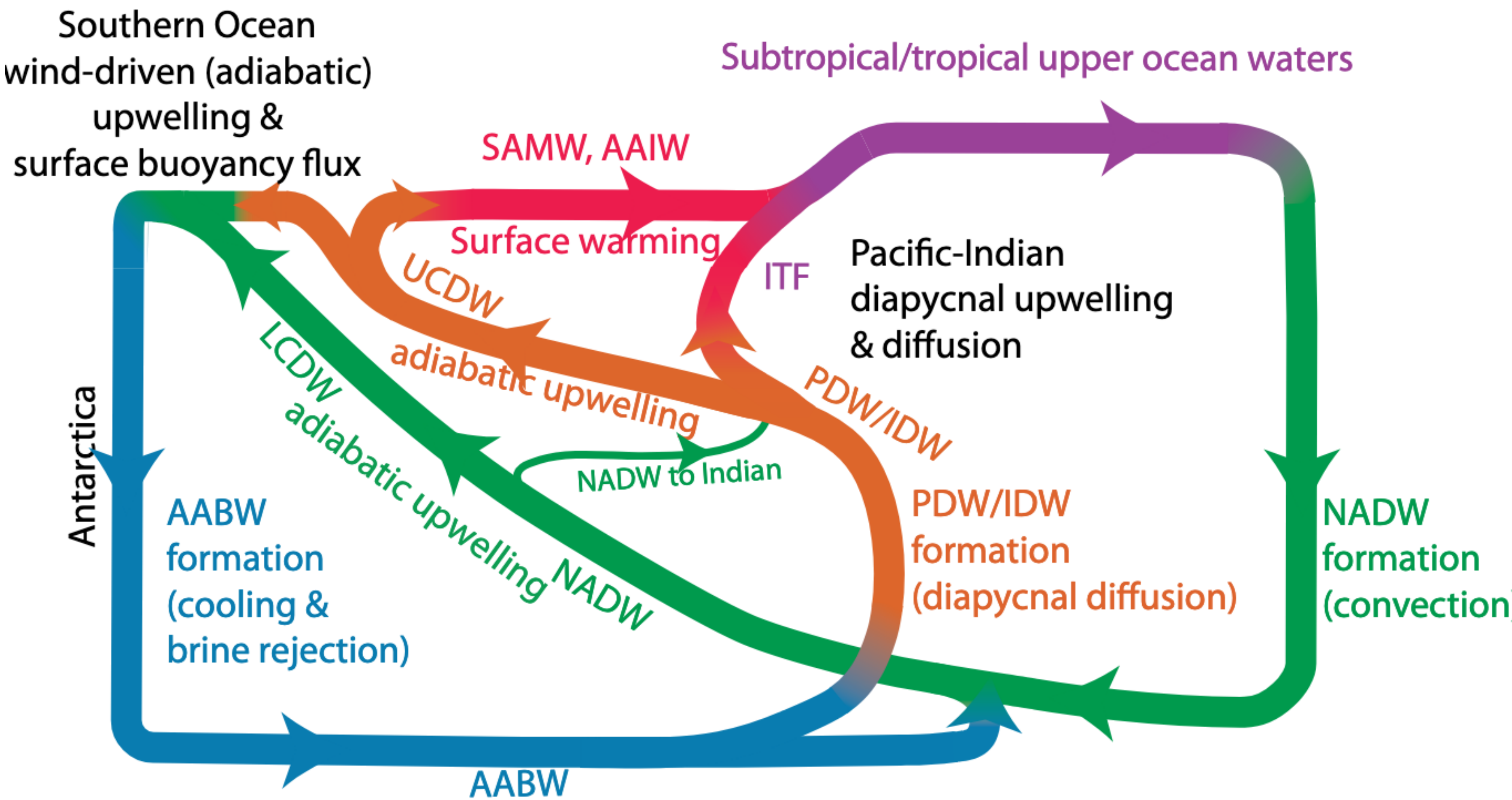
Toggweiler & Samuels (1993)

In the re-entrant channel: $\oint v\,dx = -\frac{1}{\rho f}\oint \partial_x p\,dx = 0$



Talley (2013)

- Two imbricated cells: figure-of-eight circulation.



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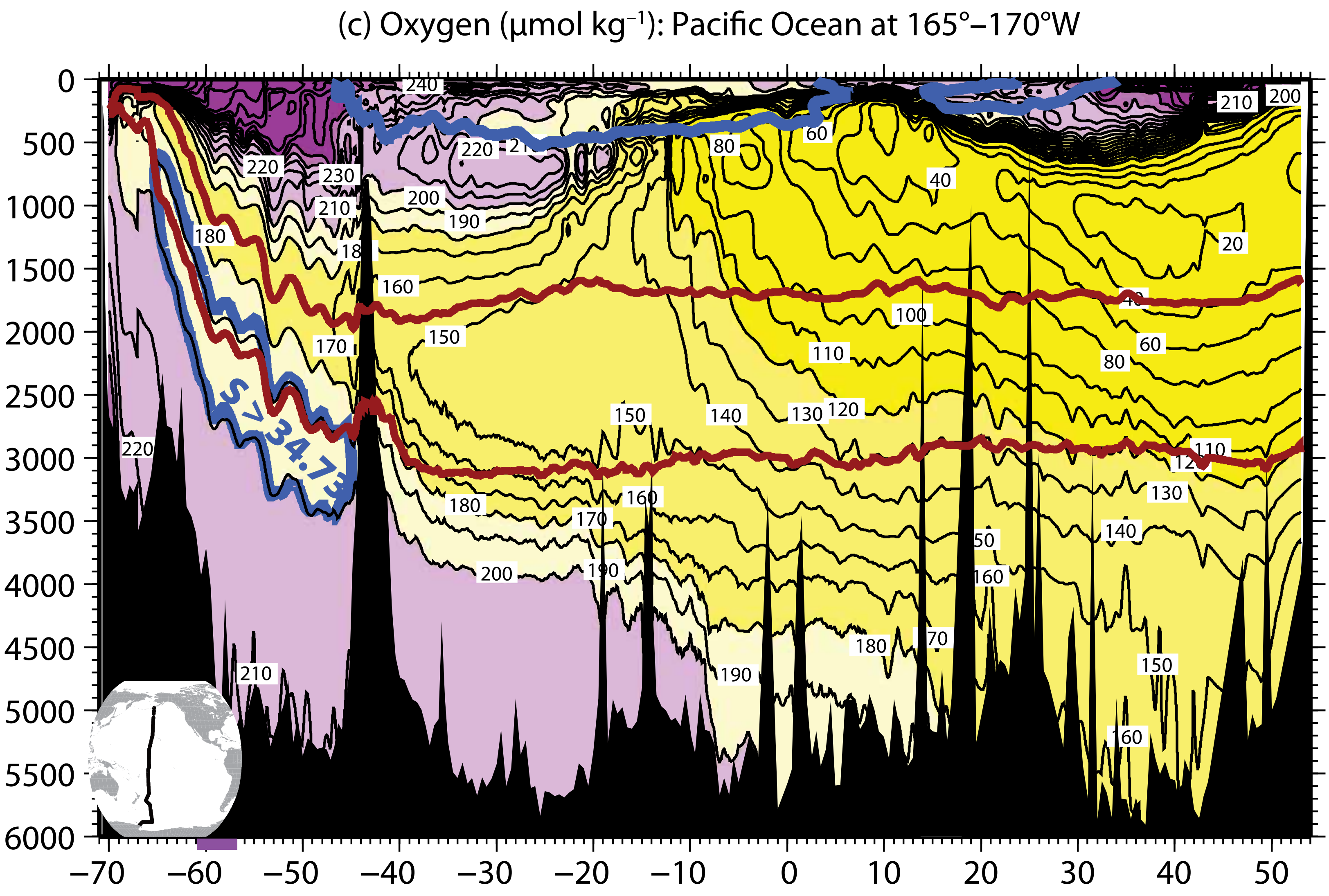

Talley (2013)

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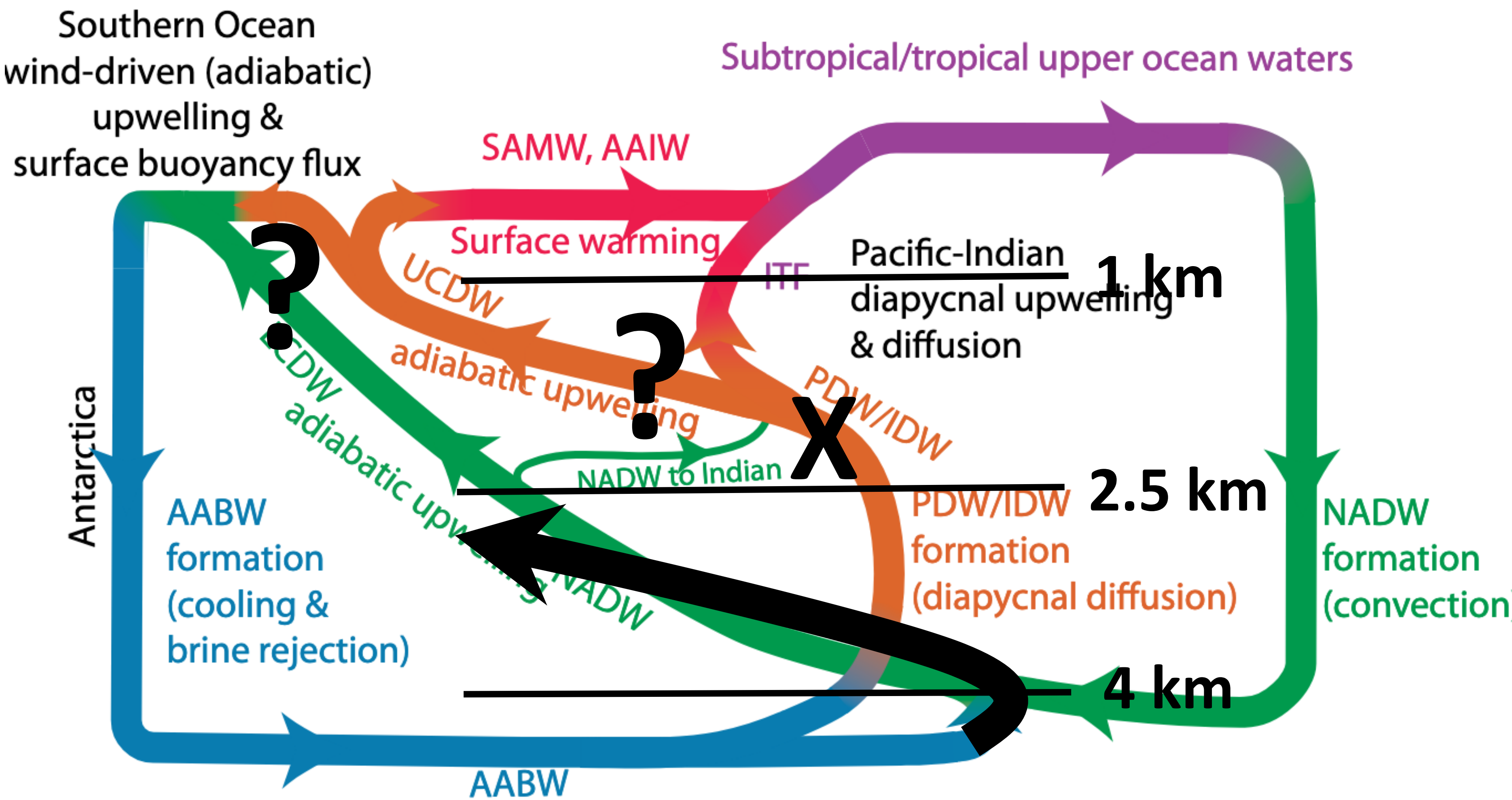
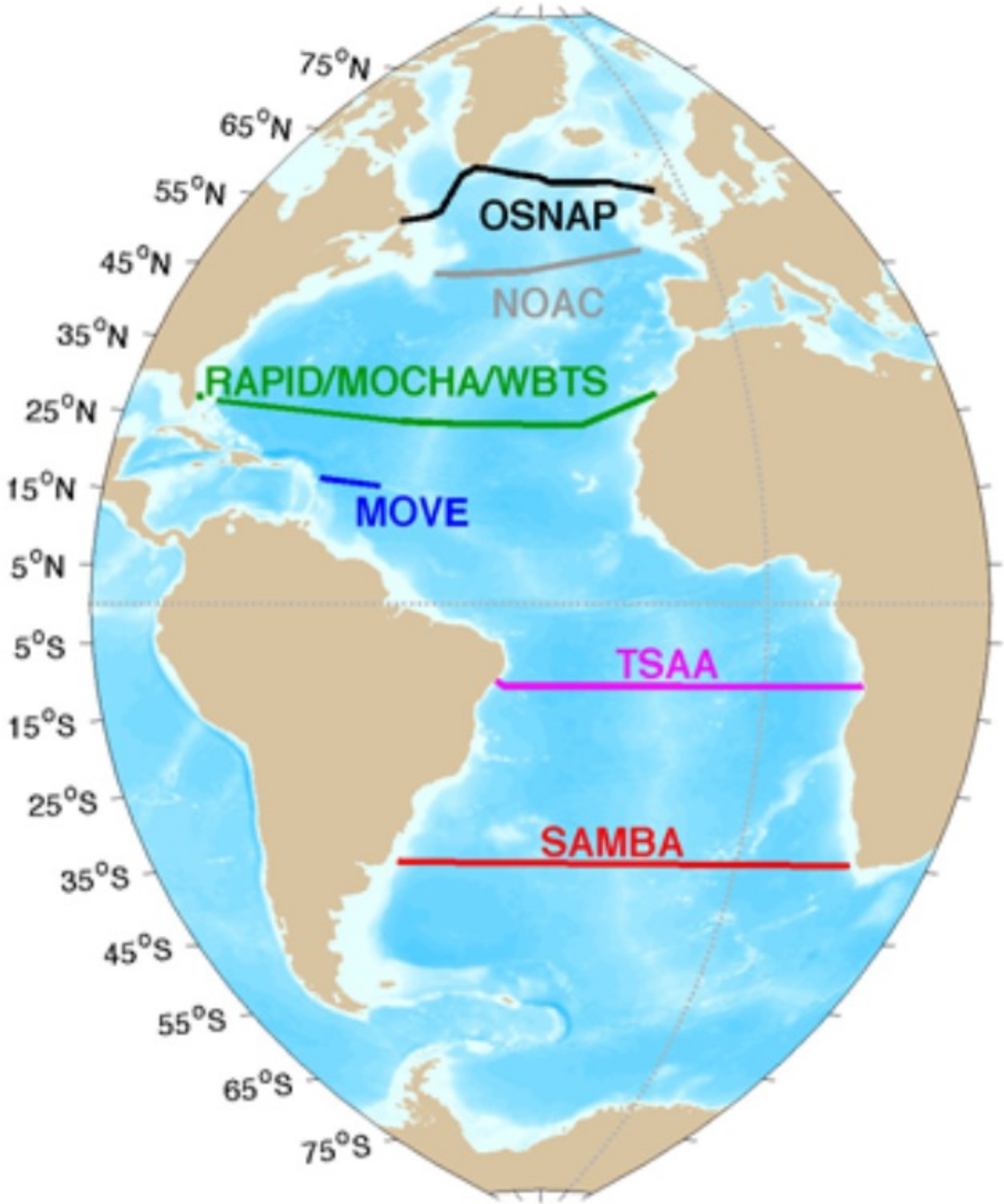


Beyond schematics: monitoring the AMOC

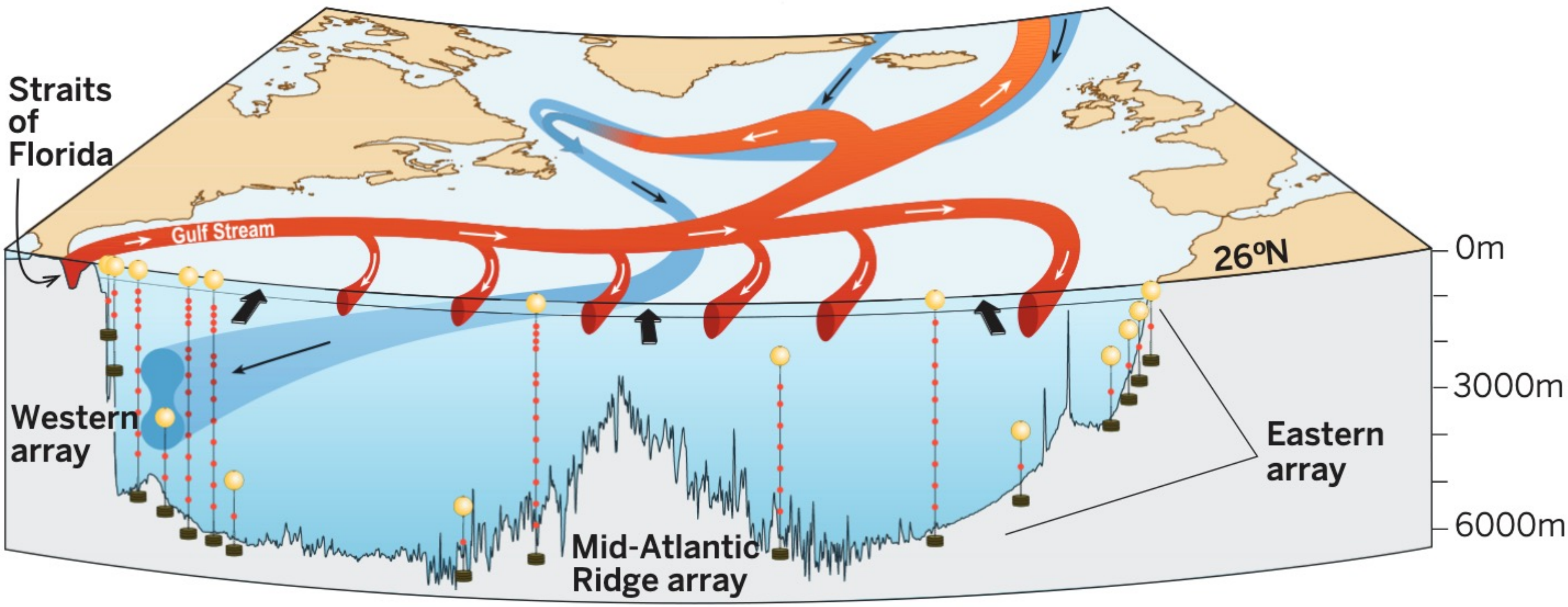


Existing mooring arrays that help to measure the strength of the AMOC.

Srokosz & Danabasoglu 2019

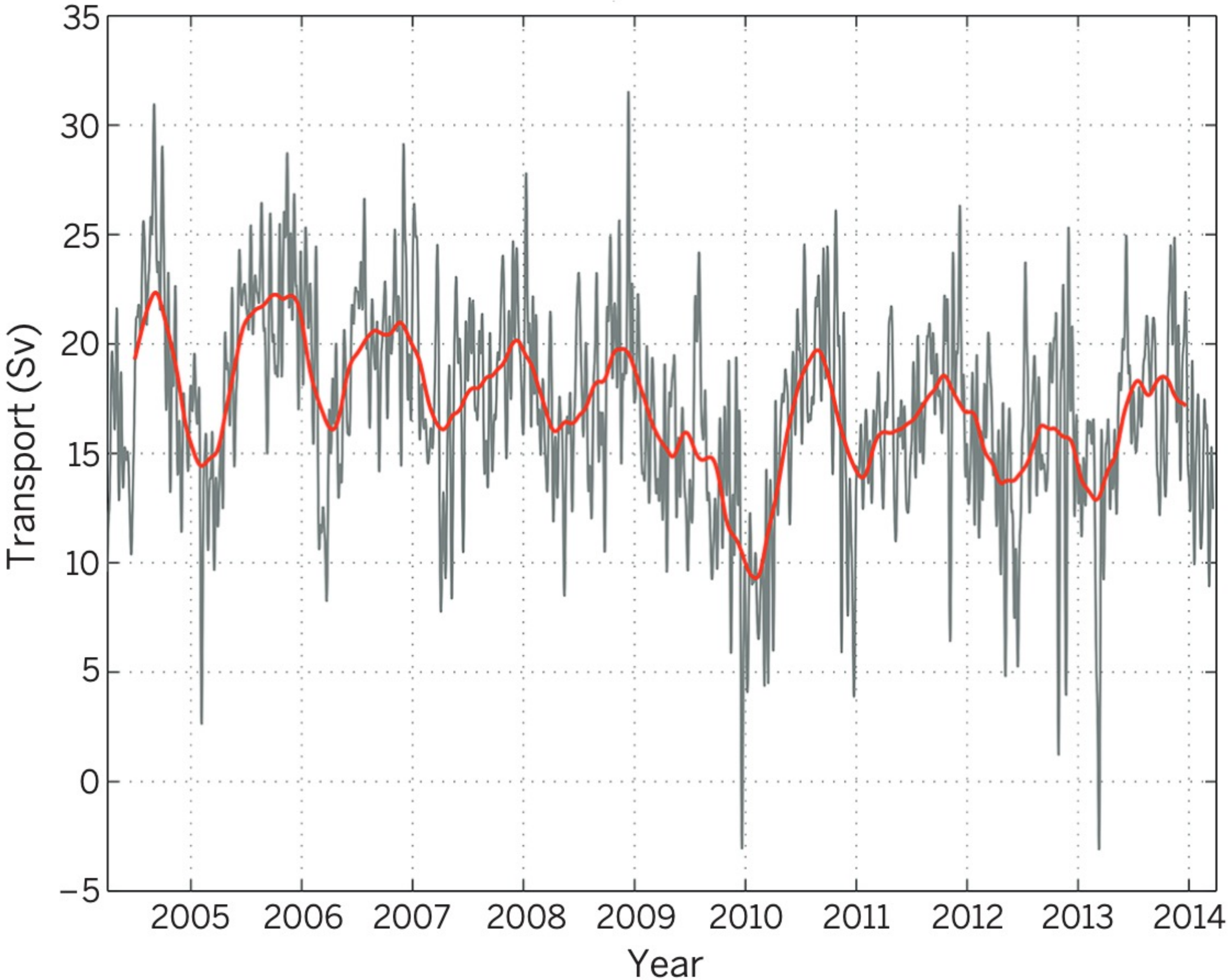
Beyond schematics: monitoring the AMOC

The RAPID array.



Srokosz & Bryden 2015

Beyond schematics: monitoring the AMOC

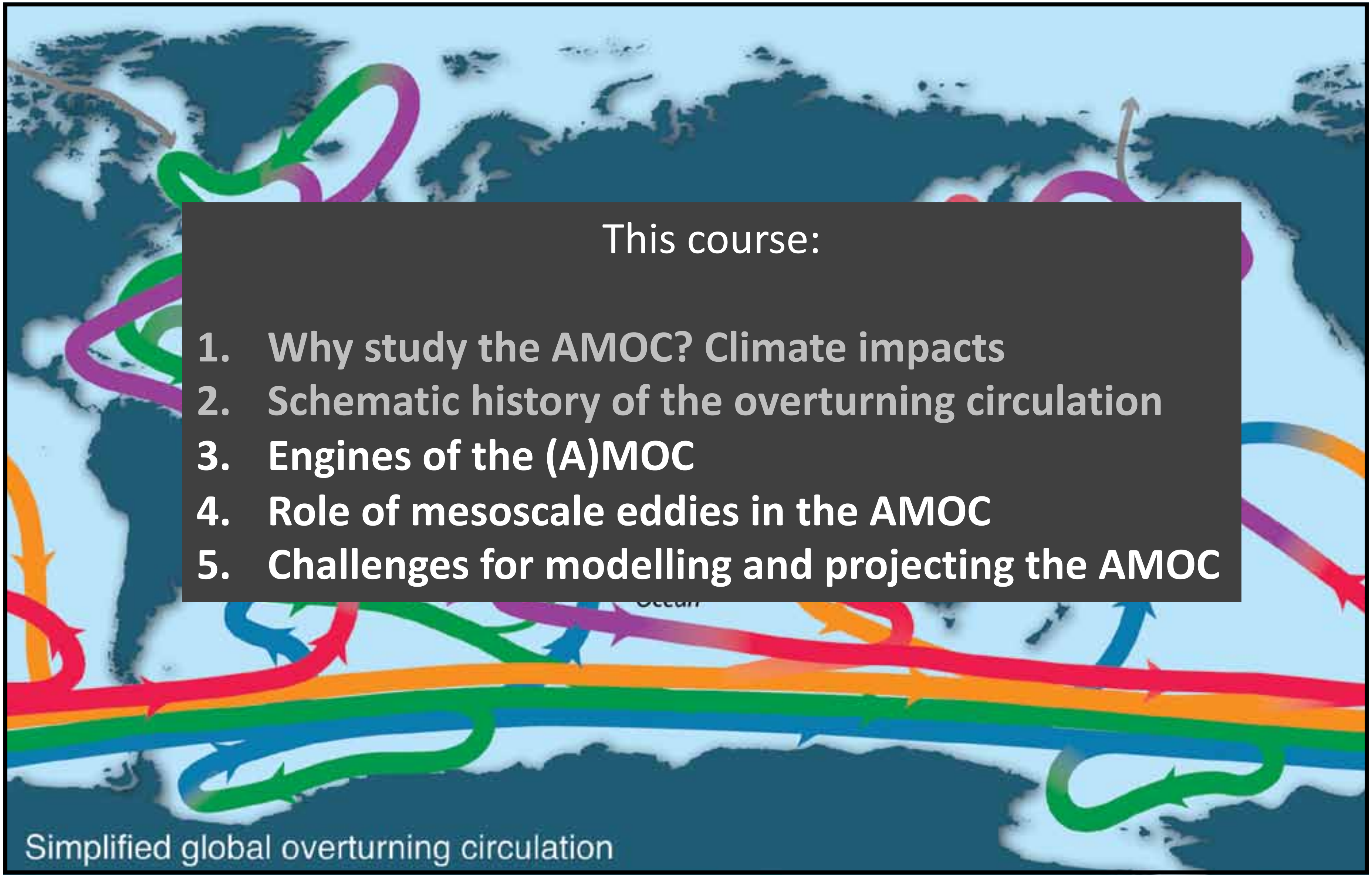


Srokosz & Bryden 2015

Conclusions

- Conveyor belt schematics are idealized and sometimes misleading yet have an immense impact on thinking about the overturning.
- Overturning pathways are largely deduced from tracer distributions, through heuristic or inverse methods.
- Uncertainties in these pathways and their associated volume transports remain huge.
- AMOC is connected to SMOC, and is not restricted to the Atlantic basin. Impossible to understand the AMOC without looking at return pathways in other basins.

A complex and turbulent 3D circulation



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4. Role of mesoscale eddies in the AMOC
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Talley 2013

Part 3. Engines of the (A)MOC

- **Overview**
- **Why do (deep) ocean currents exist?**
- **Role of North Atlantic surface density gain**
- **Role of mixing and geothermal heating**
- **Role of Southern Ocean winds**

Part 3. Engines of the (A)MOC

- **Overview**
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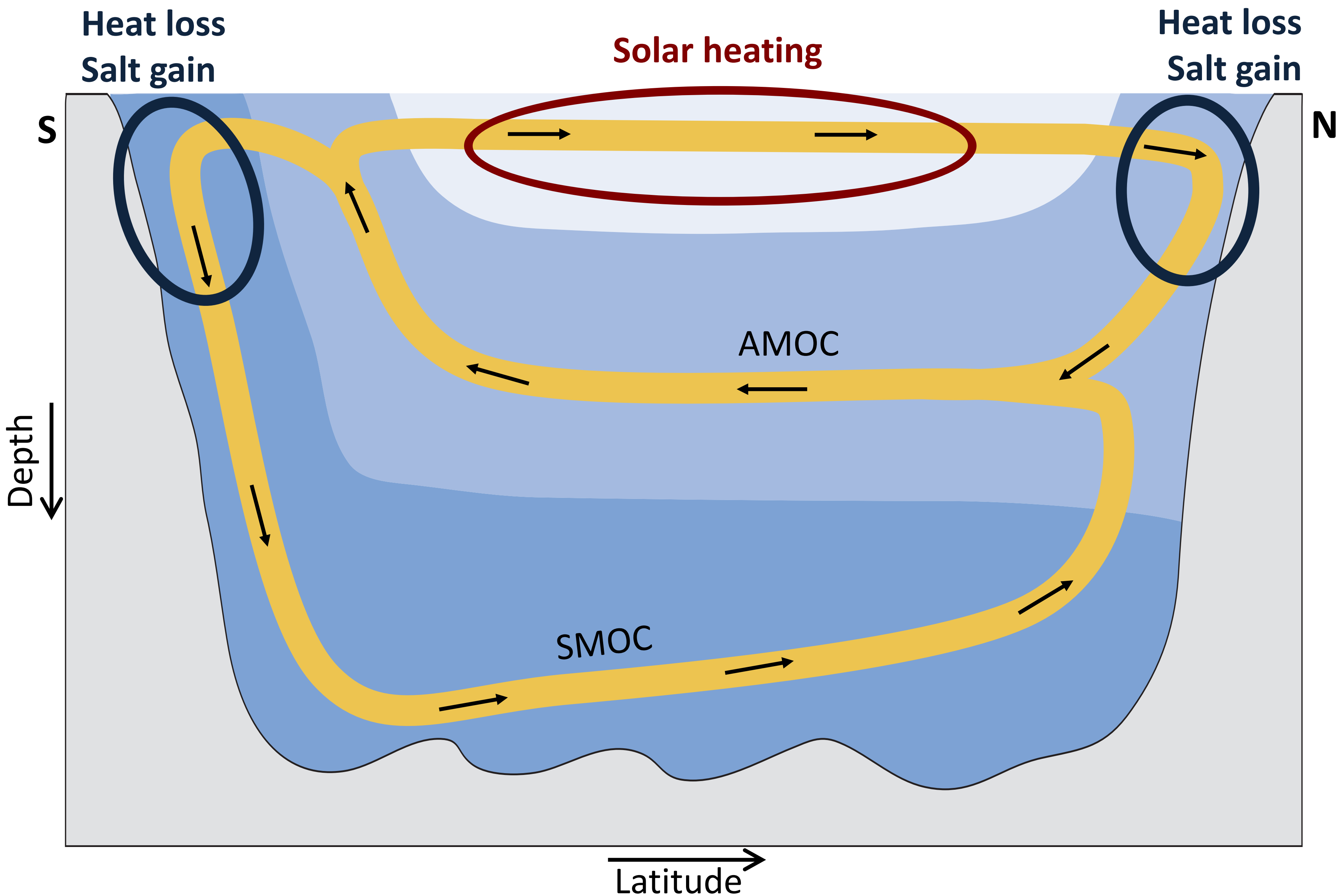
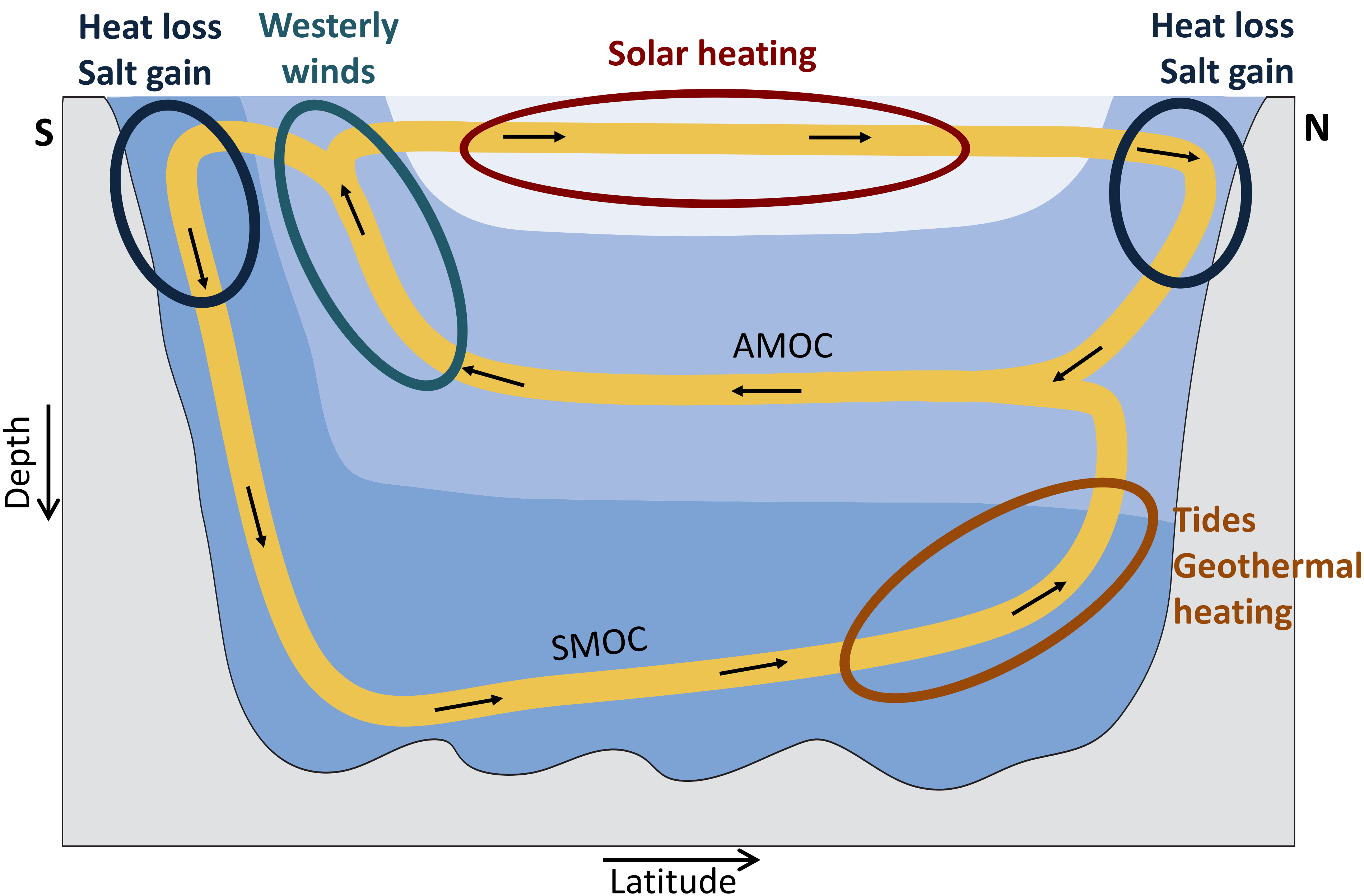
Engines of the overturning circulation (1/2)



Engines of the overturning circulation (2/2)



Part 3. Engines of the (A)MOC

- Overview
- **Why do (deep) ocean currents exist?**
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Taking a step back

Ocean currents come from…

1. The wind’s action on the ocean surface

2. Exchanges of water and heat at the surface

3. Geothermal heating

4. Gravitational pull of the Moon and Sun

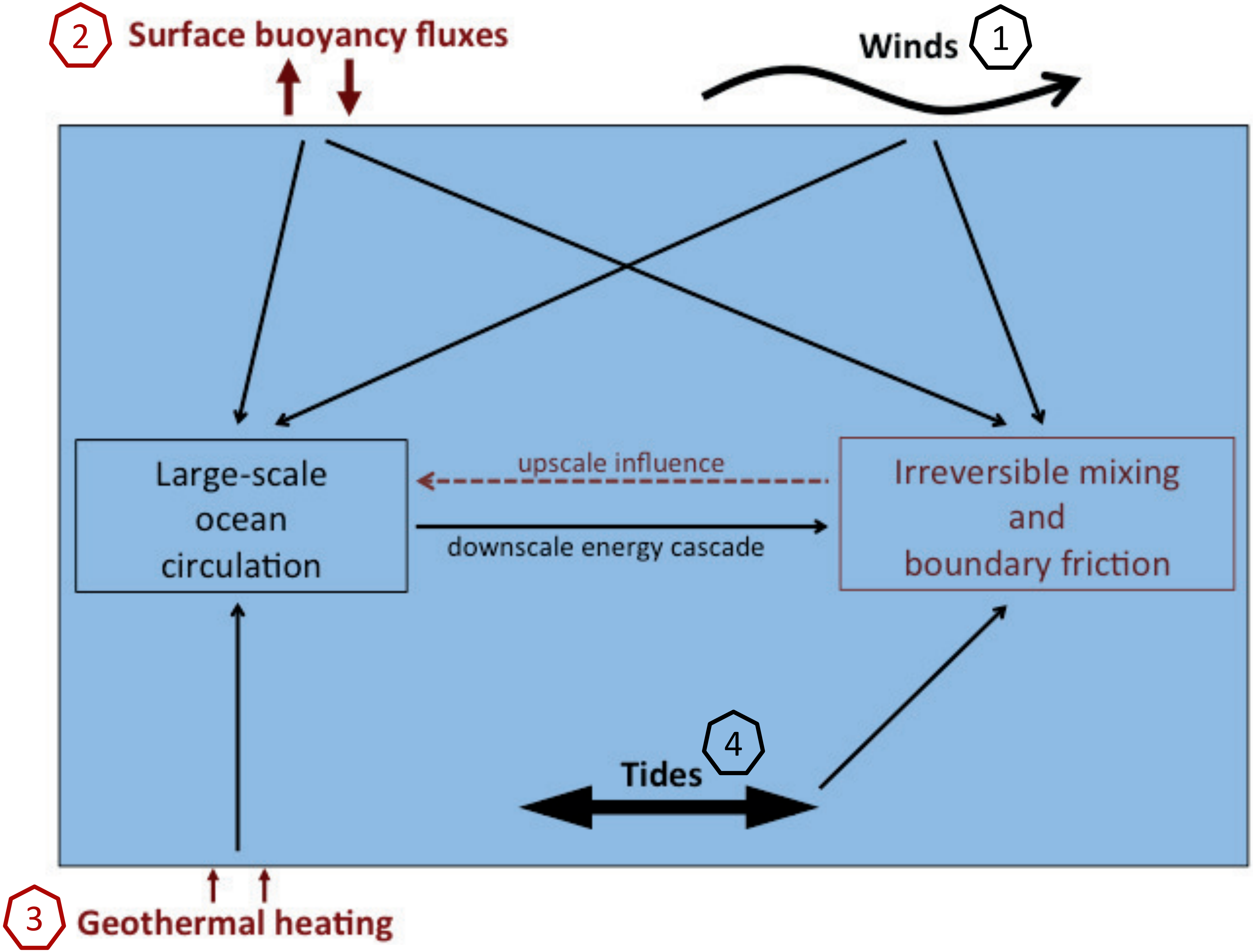
Taking a step back

Ocean currents come from…

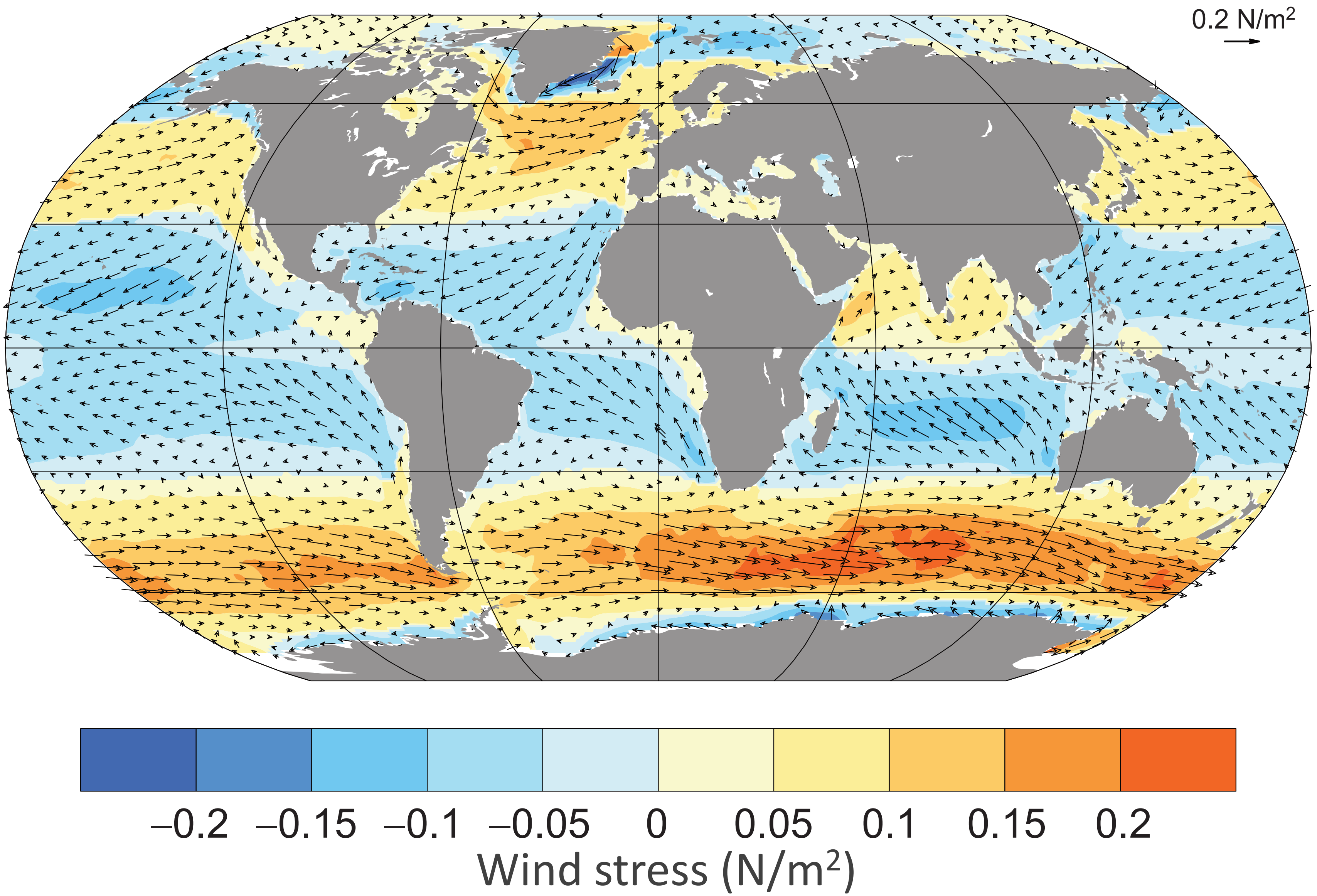
1+2. Latitudinal contrasts in solar heating

3. Geothermal heating

4. Gravitational pull of the Moon and Sun

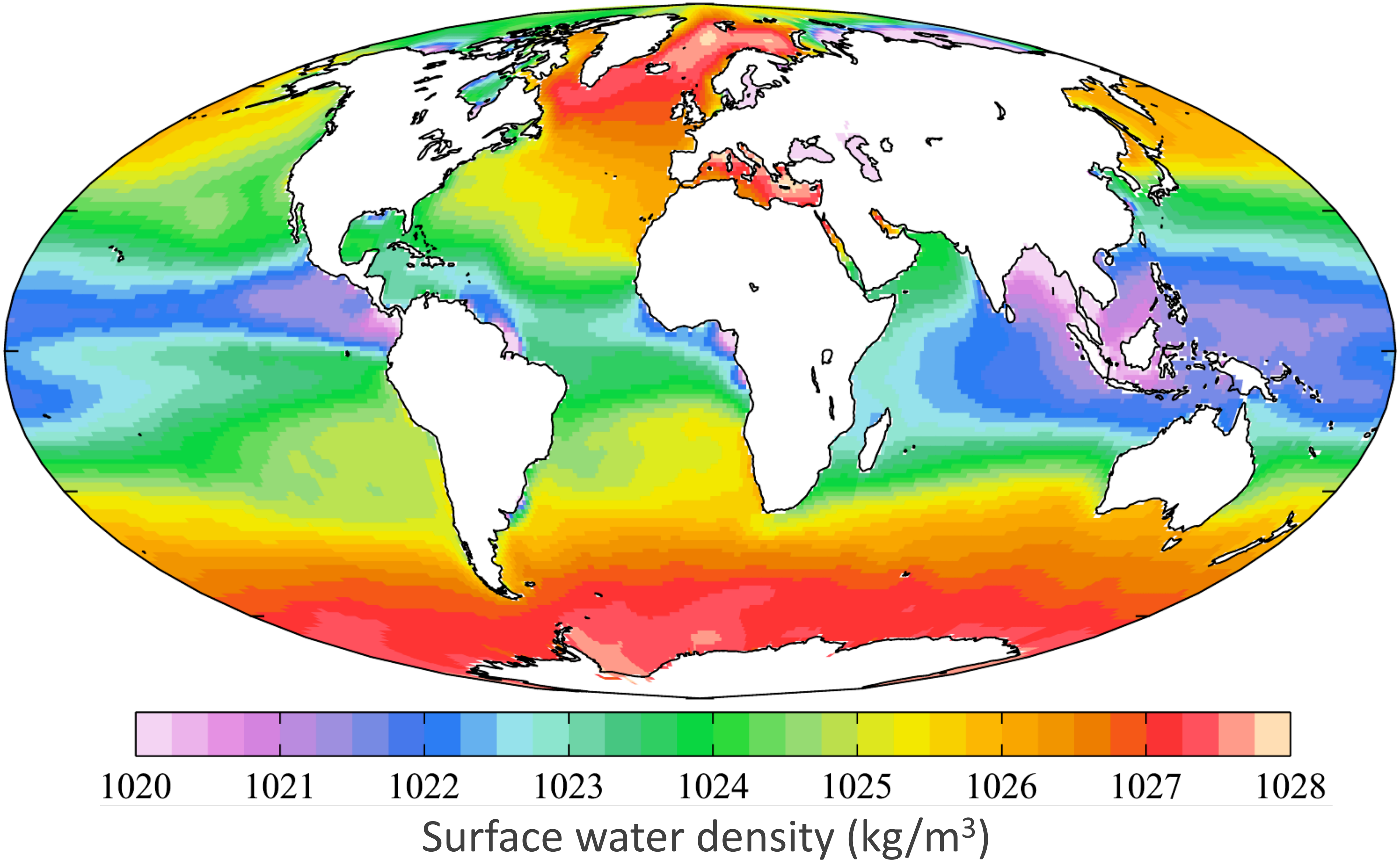

2
Surface buoyancy fluxes
Winds
1
Large-scale
ocean
circulation
upscale influence
downscale energy cascade
Irreversible mixing
and
boundary friction
4
Tides
3
Geothermal heating

1. The wind's action on the ocean surface



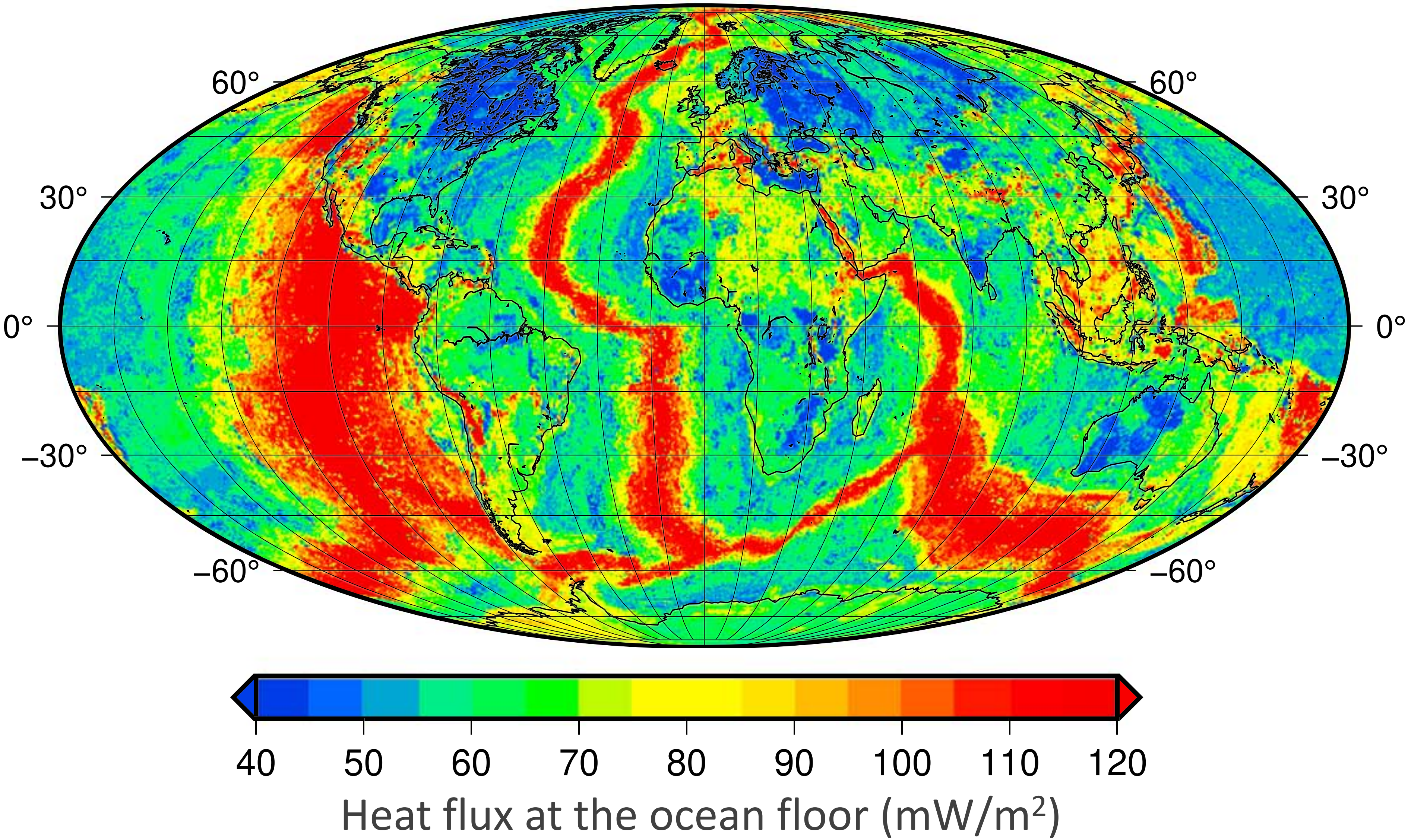
Source : Ocean circulation and climate, 2014

2. Exchanges of water and heat at the surface



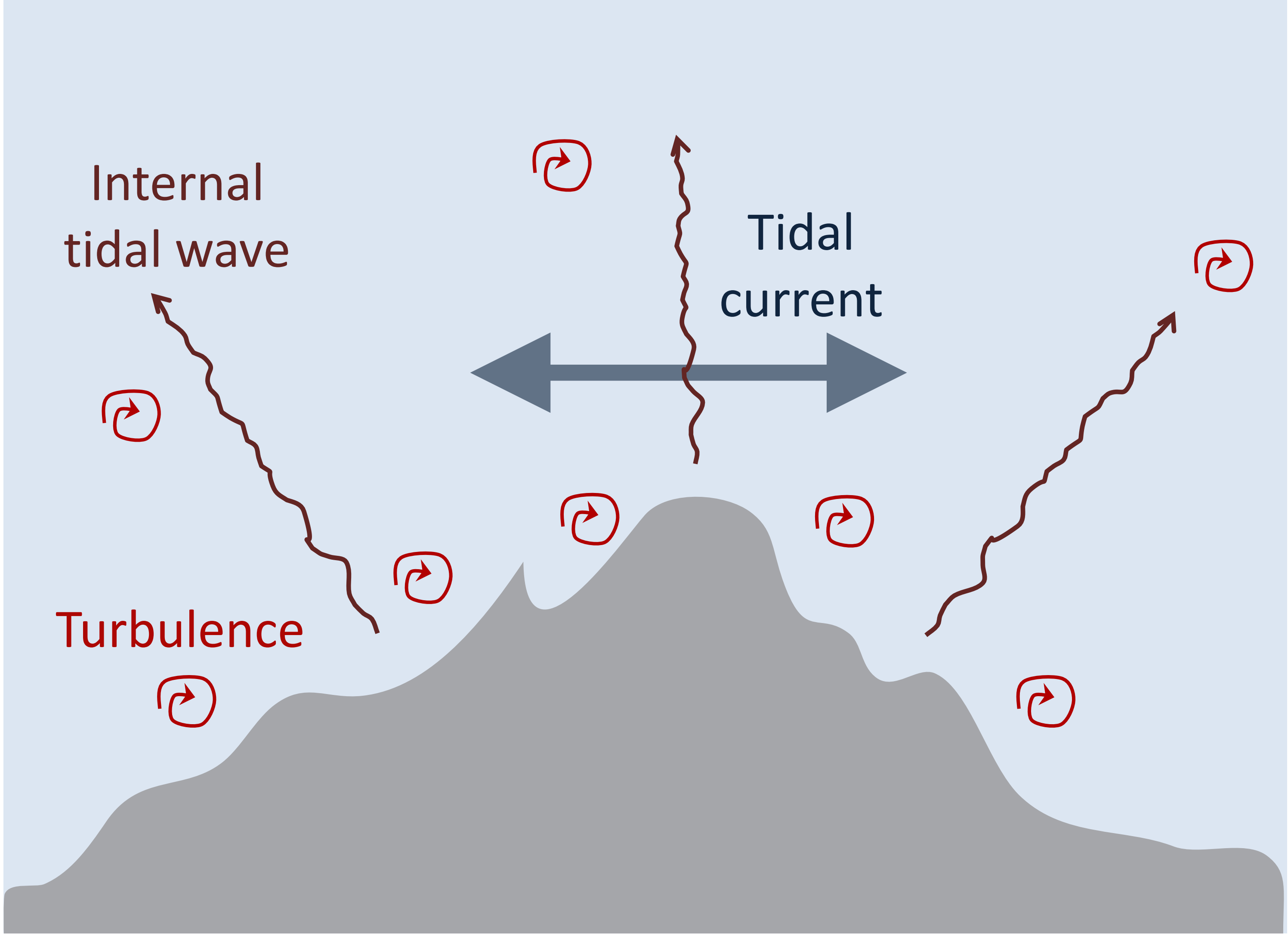
Source : World Ocean Atlas

3. Geothermal heating



Source : Lucazeau 2019

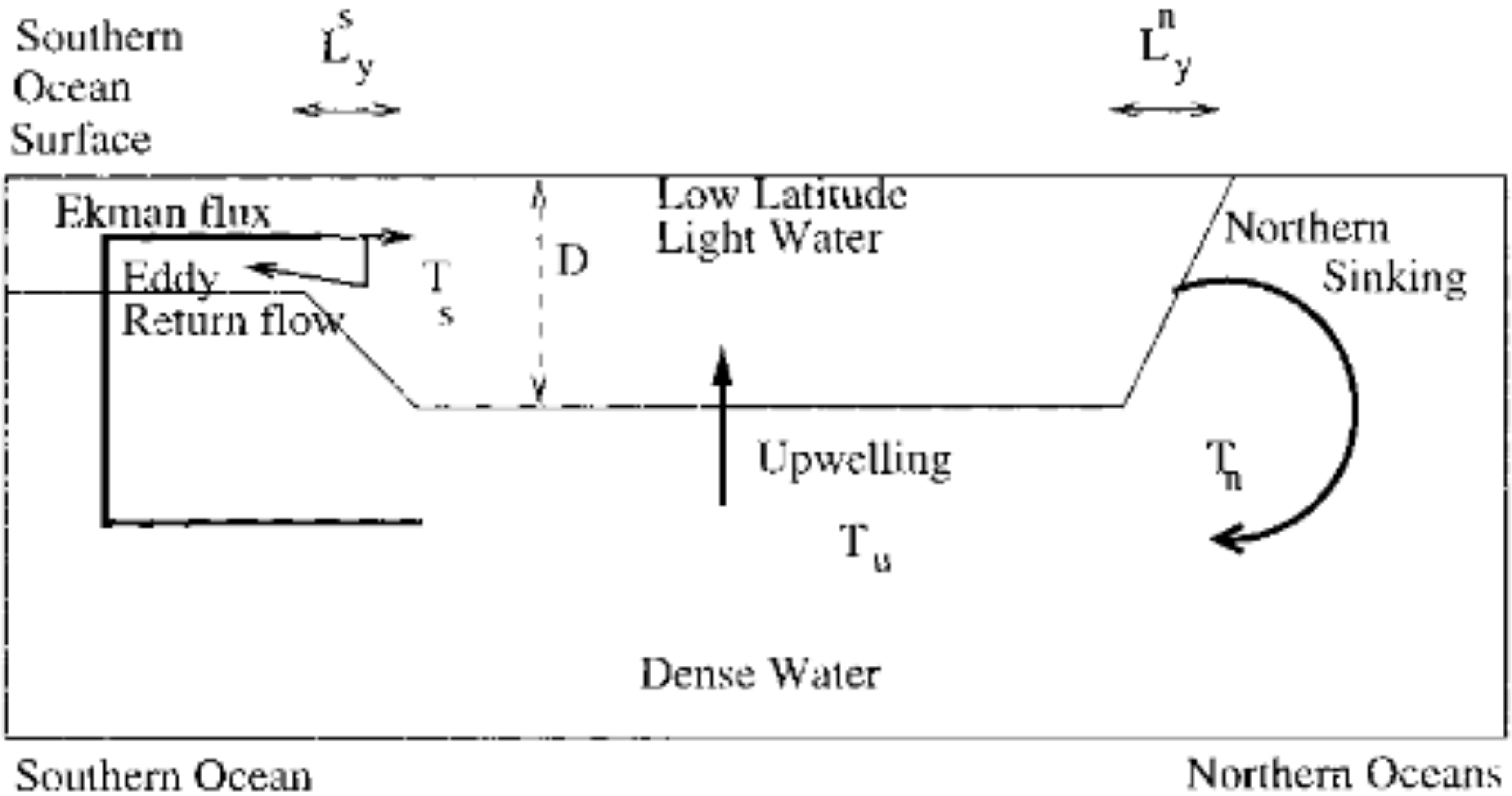
4. Gravitational pull of the Moon and Sun



Part 3. Engines of the (A)MOC

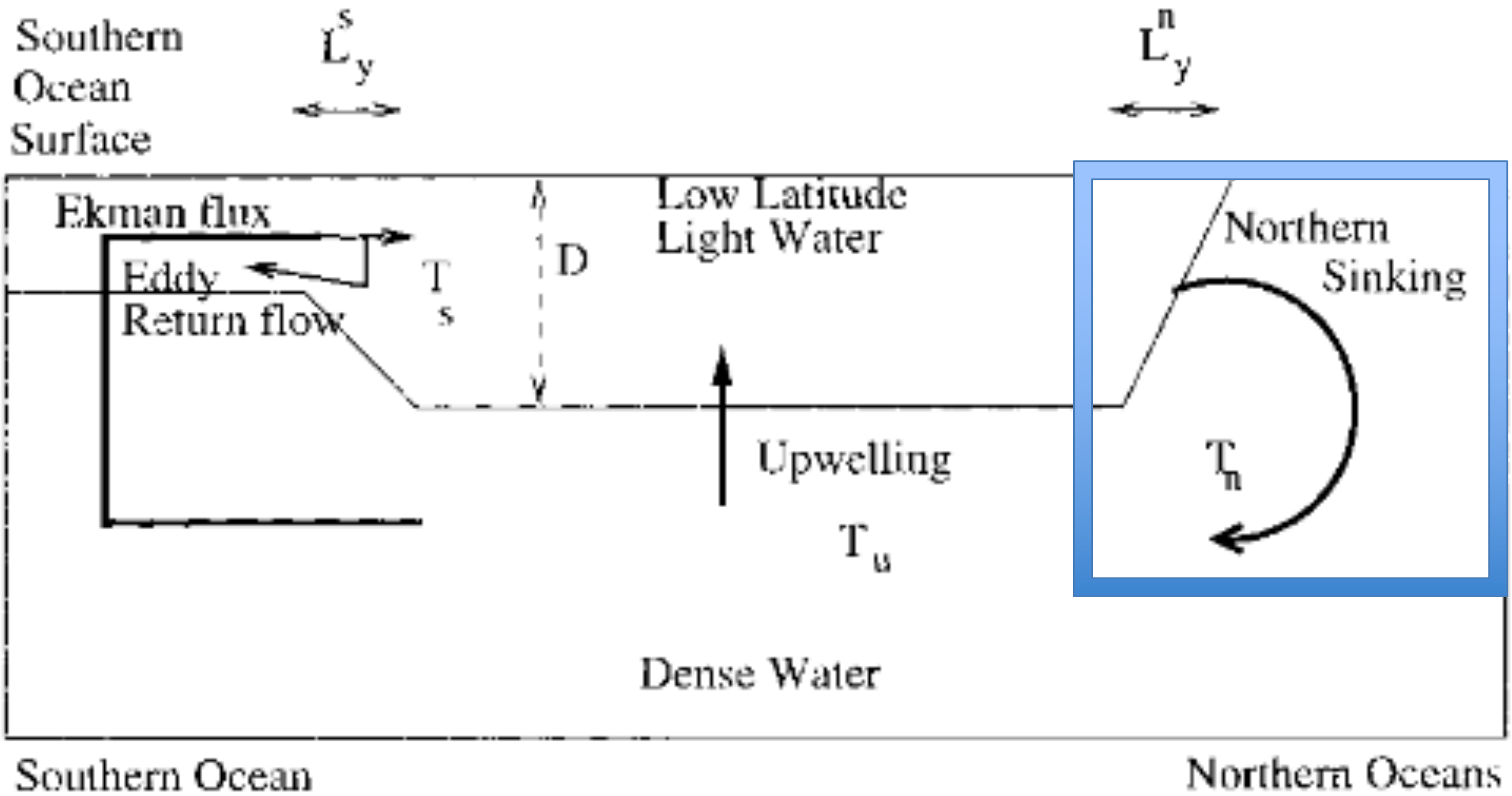
- Overview
- Why do (deep) ocean currents exist?
- **Role of North Atlantic surface density gain**
- Role of mixing and geothermal heating
- Role of Southern Ocean winds

A simple mass budget



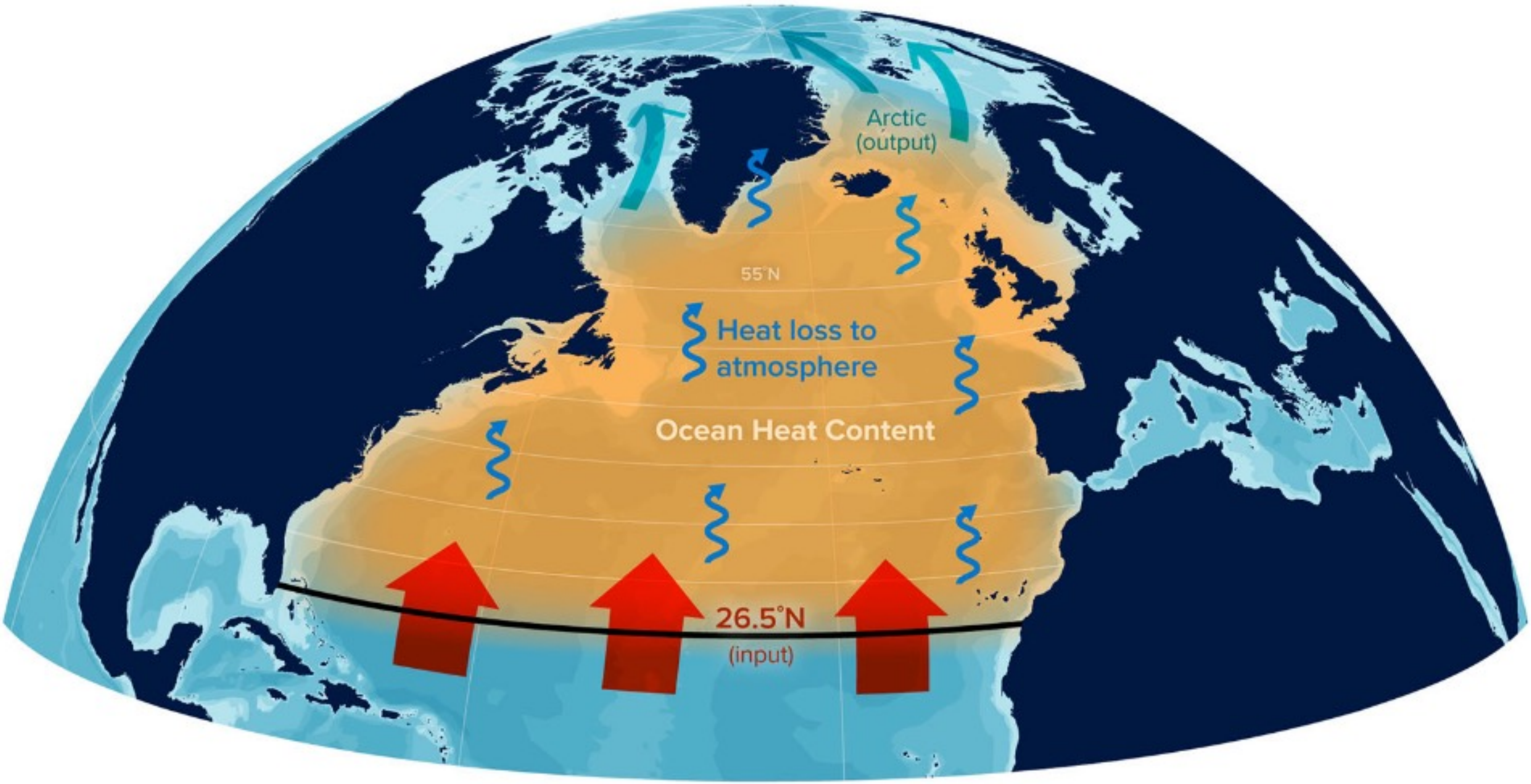
Gnanadesikan 1999

A simple mass budget



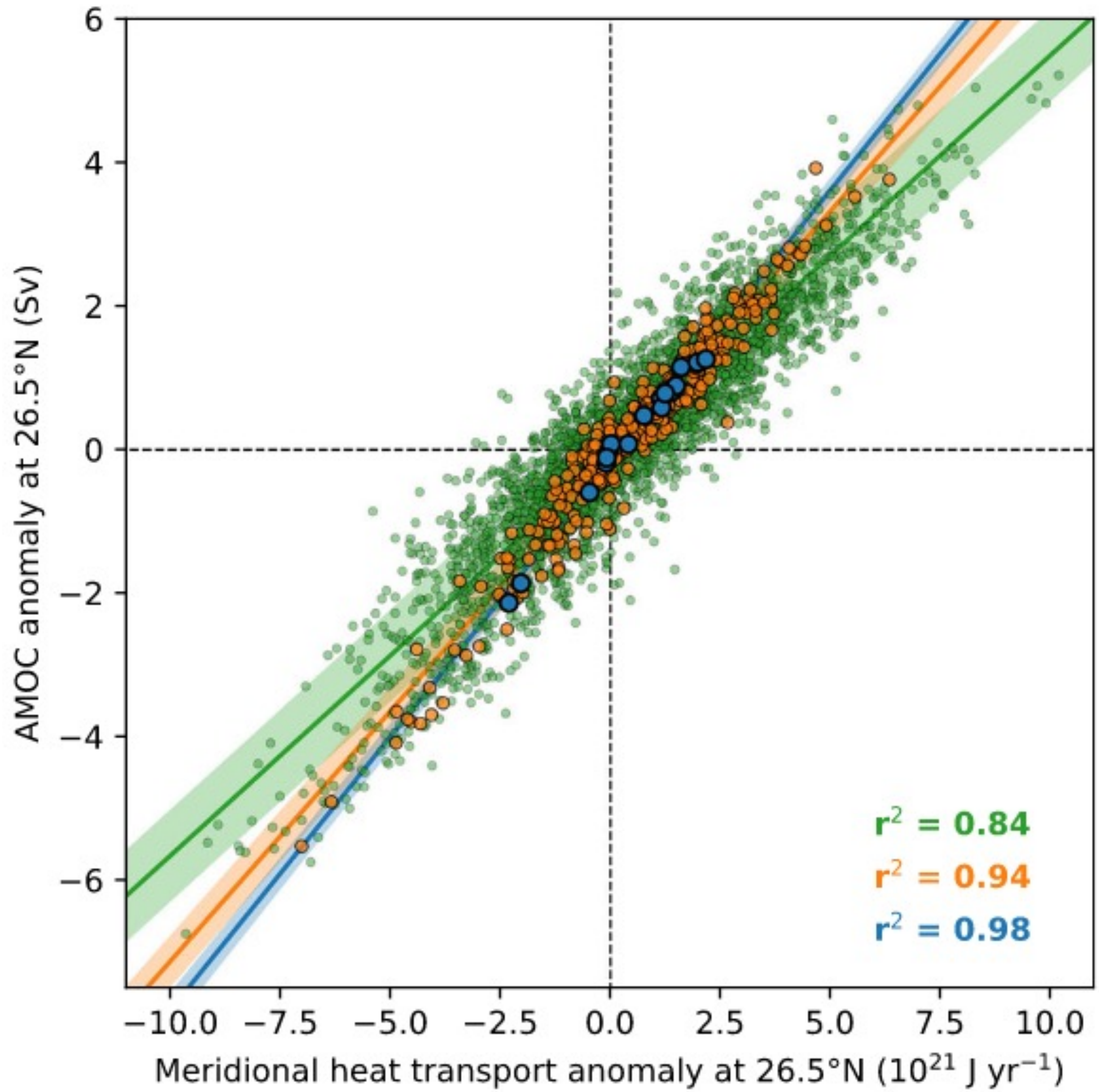
Gnanadesikan 1999

A heat budget to constrain the mass budget



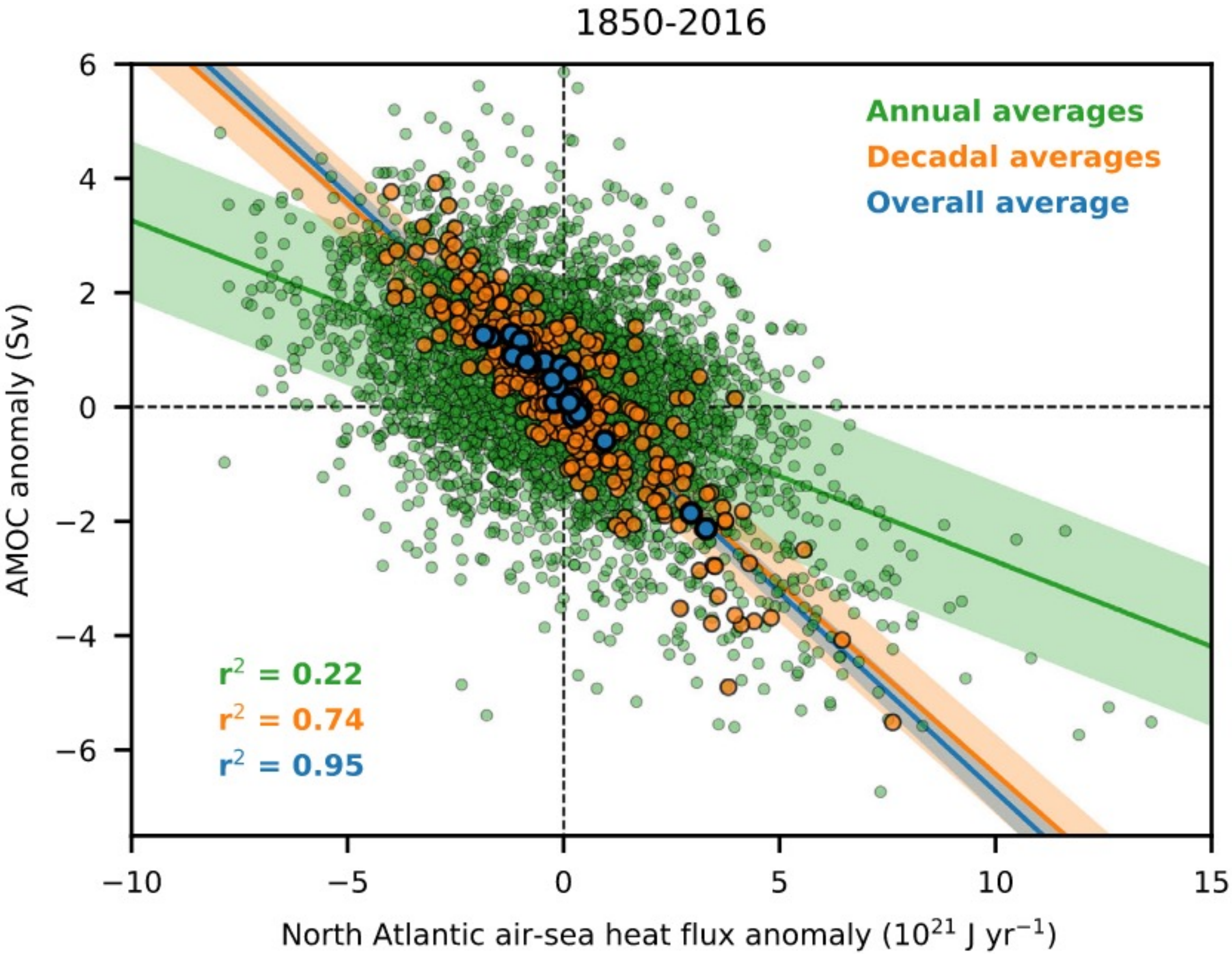
Terhaar *et al*. 2024

Meridional heat transport vs AMOC



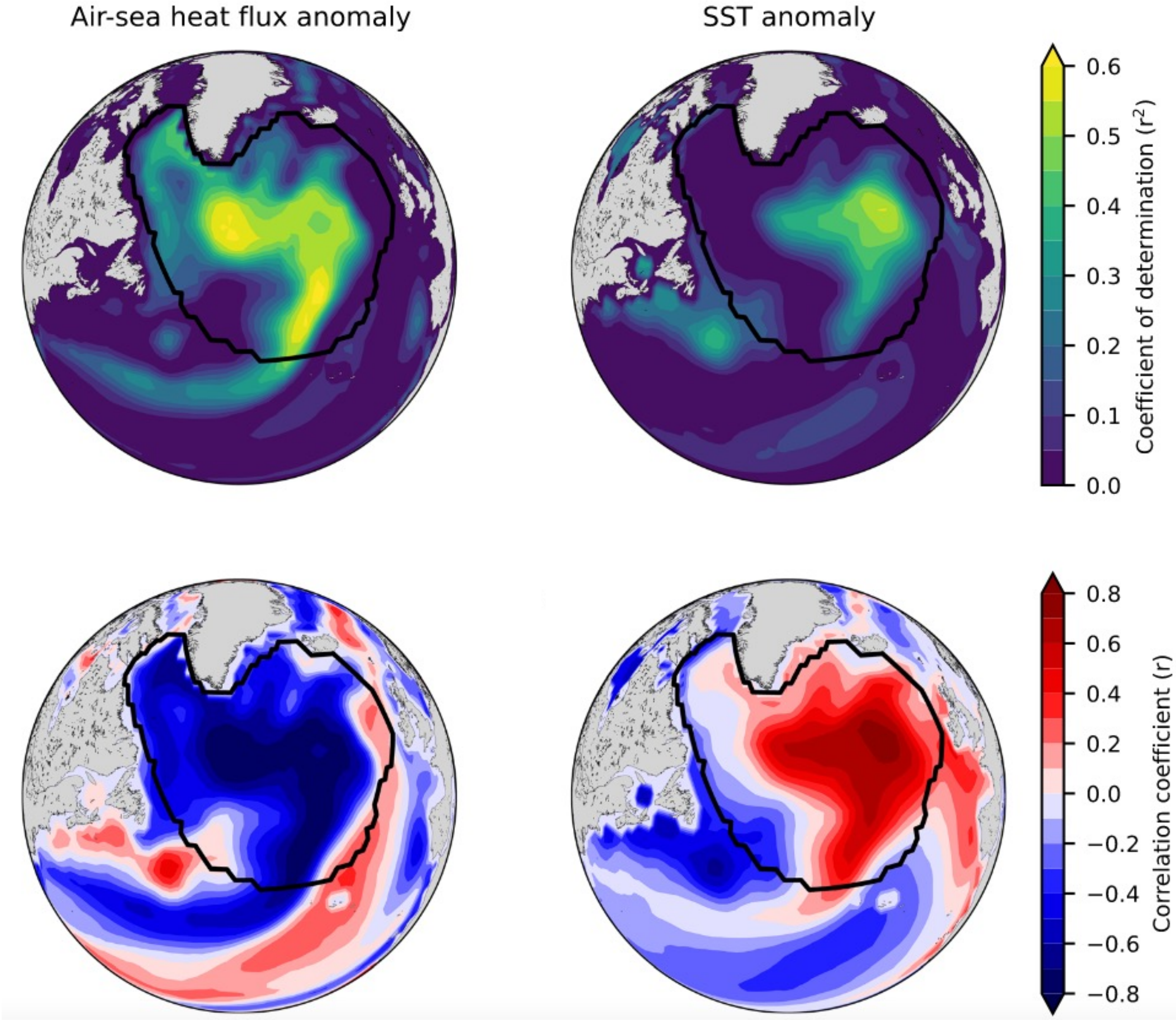
Terhaar *et al*. 2024

Surface heat loss in the North Atlantic vs AMOC



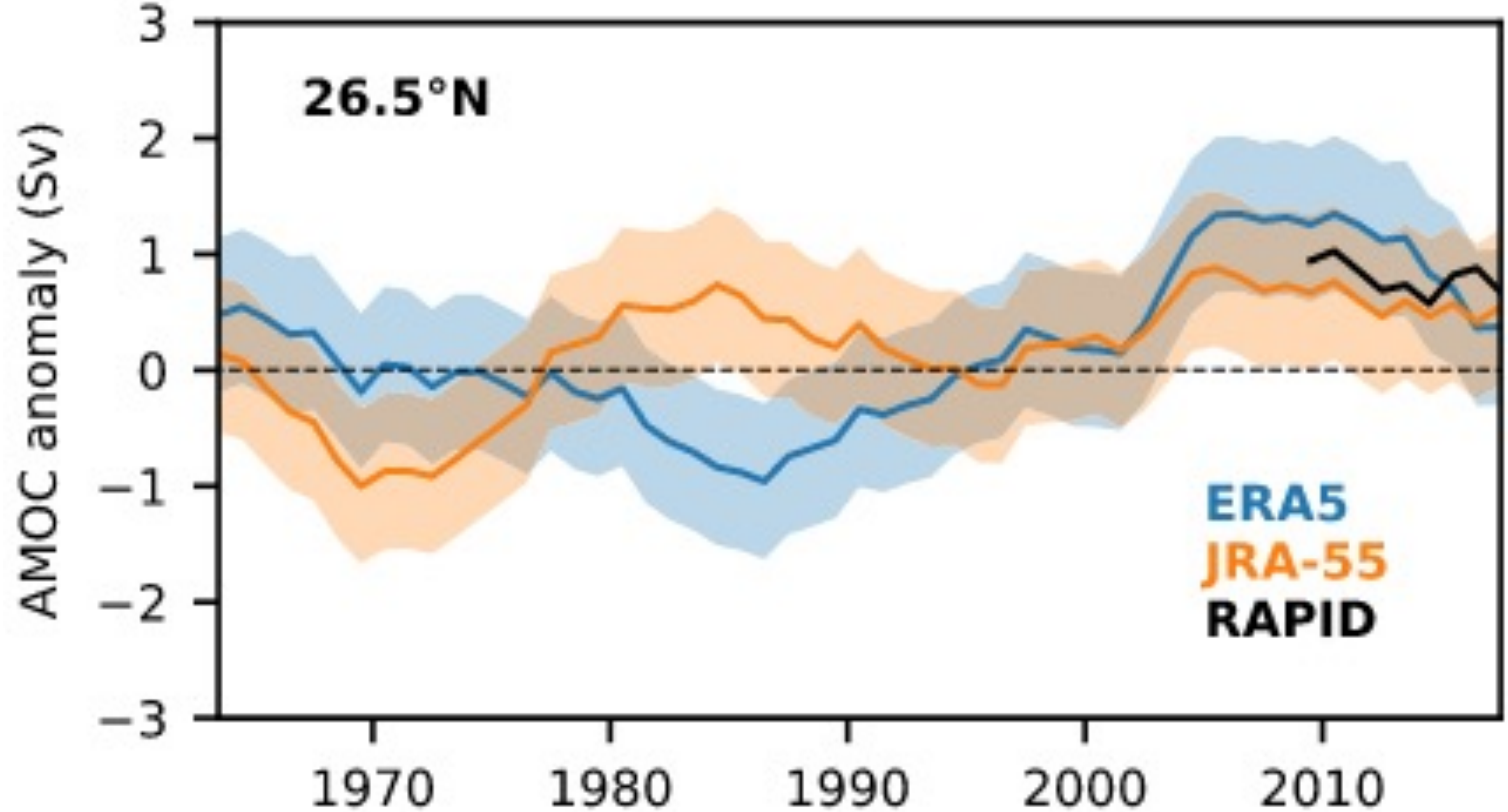
Terhaar *et al*. 2024

Two AMOC proxies



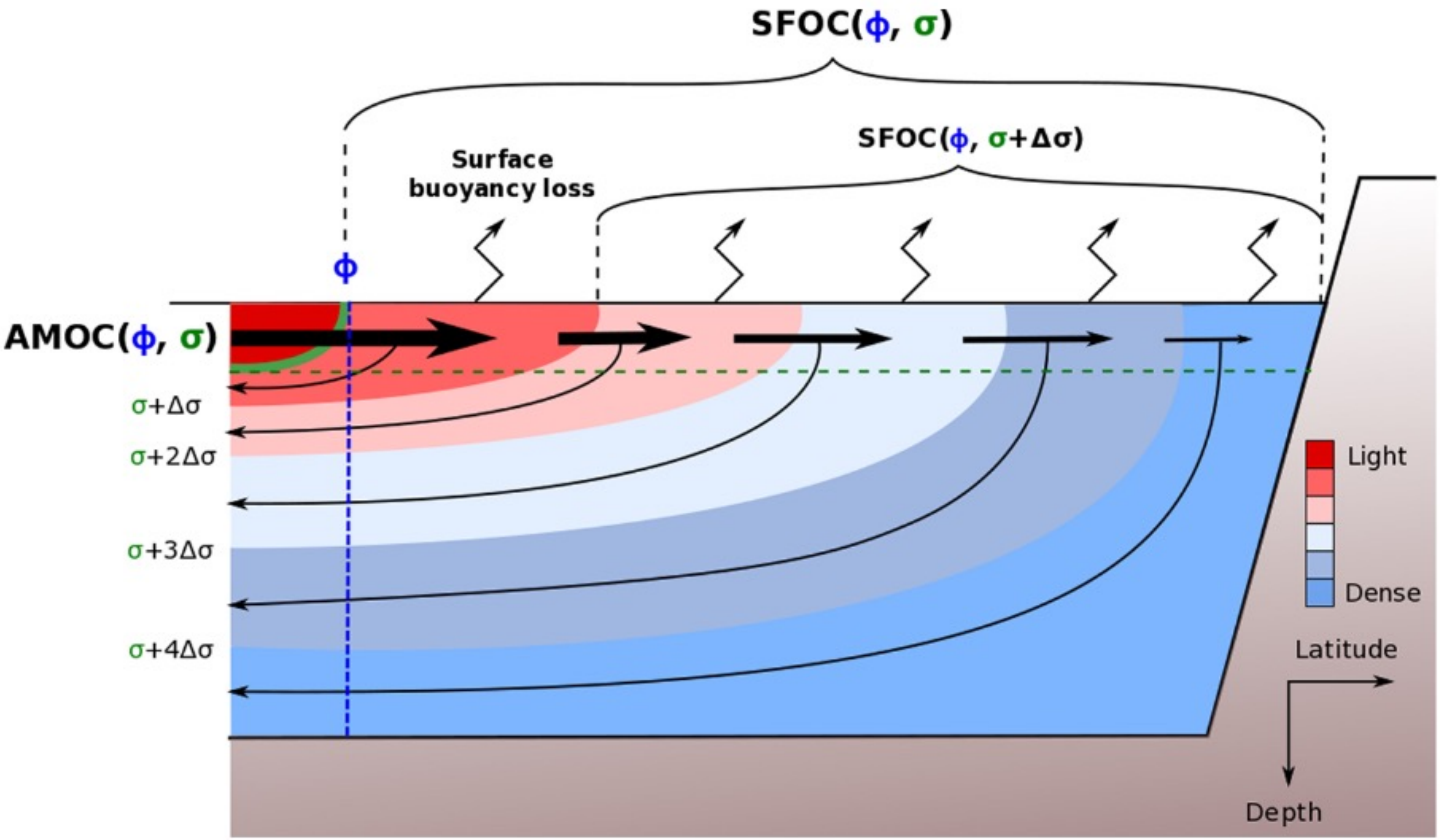
Terhaar *et al*. 2024

AMOC reconstruction based on air-sea heat flux



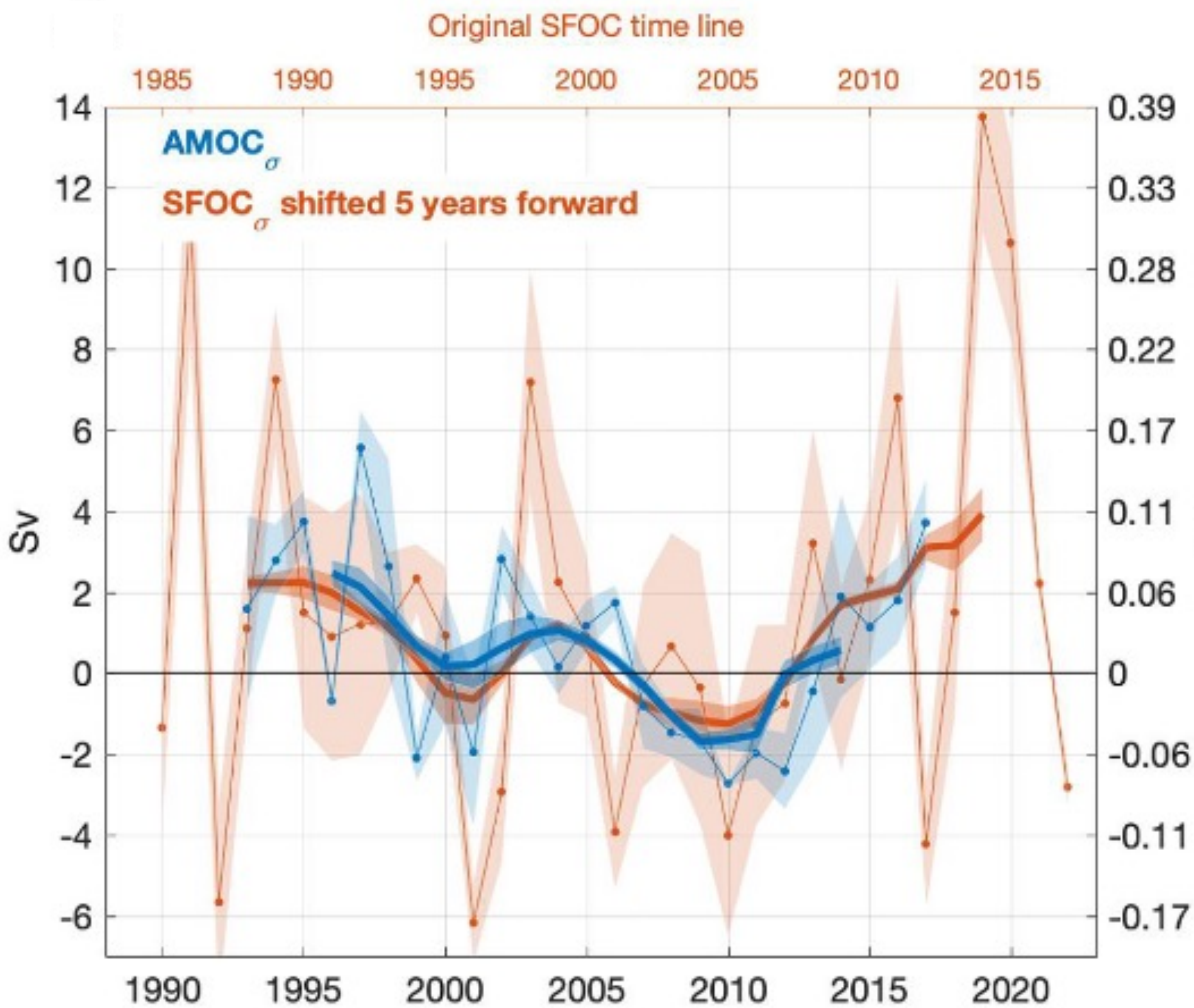
Terhaar *et al*. 2024

Now with in density space with observations



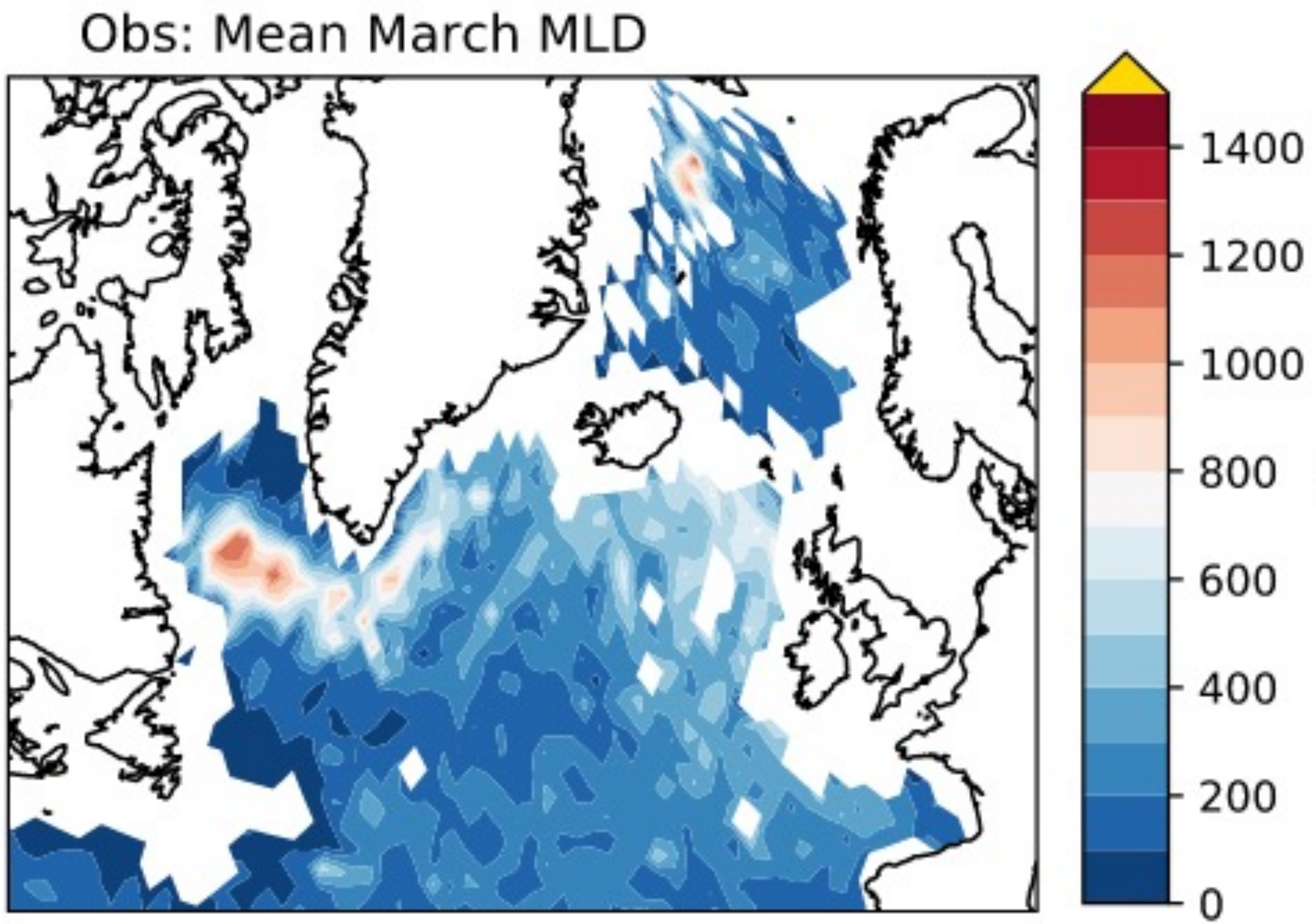
Desbruyères *et al*. 2019

Now in density space with observations



Desbruyères *et al*. 2019

Debate: does deep convection drive the AMOC?



Yeager *et al*. 2021

Debate: does deep convection drive the AMOC?

Observations say NO (Pickart and Spall 2007, Lozier et al. 2019, Zou et al. 2020)

- No clear link between Labrador Sea convection and AMOC.

Theory says NO (Marshall and Schott 1999, Waldman et al. 2018)

- Open-ocean convection does not imply net sinking.

Models say YES (Danabasoglu et al. 2014, Robson et al. 2014)

- Labrador Sea convection intensity usually tracks AMOC intensity.

Compromise: deep convection linked to the AMOC

Deep convection is usually a signature of strong surface buoyancy loss (density gain), and a region of dense water formation.

- Labrador Sea convection causes only moderate dense water formation; this is overestimated in climate models.

Complex dynamical processes (restratification by turbulence, interactions with topography) ultimately cause net sinking in the North Atlantic and carry dense water to deep boundary currents.

- Climate models poorly represent these dynamics, and often fail to capture Nordic Seas overflows.

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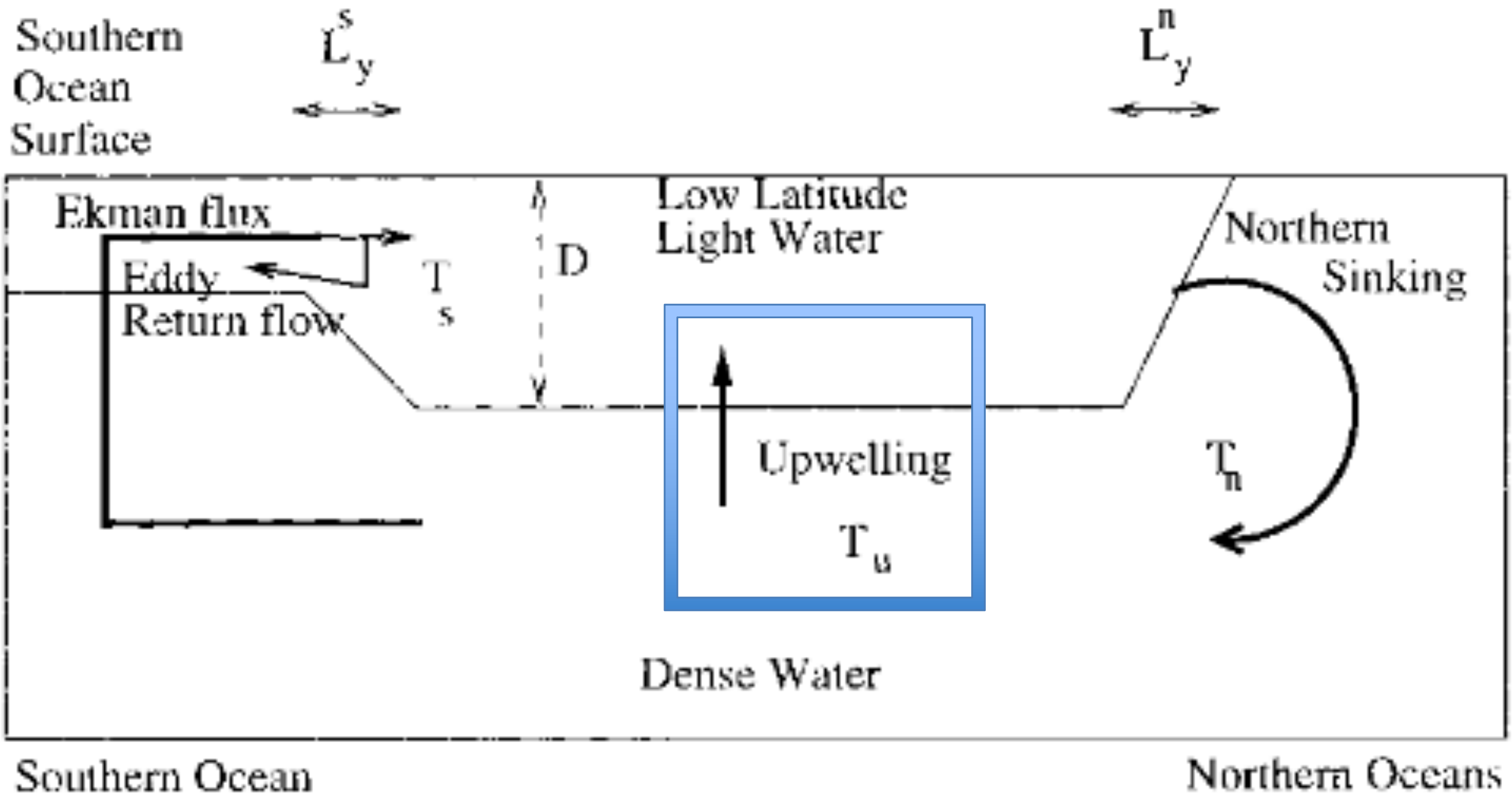
- **Role of mixing and geothermal heating**
- Role of Southern Ocean winds

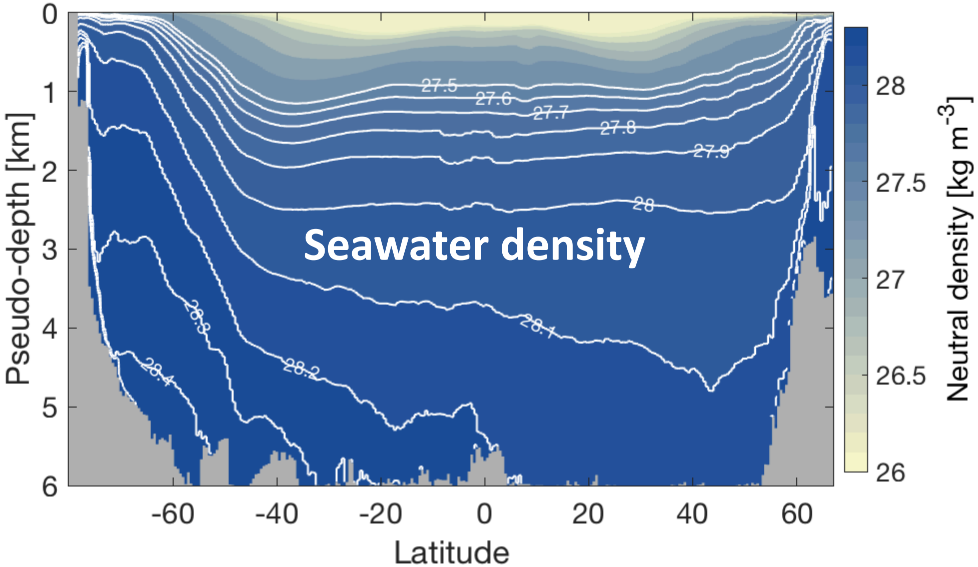
A simple mass budget



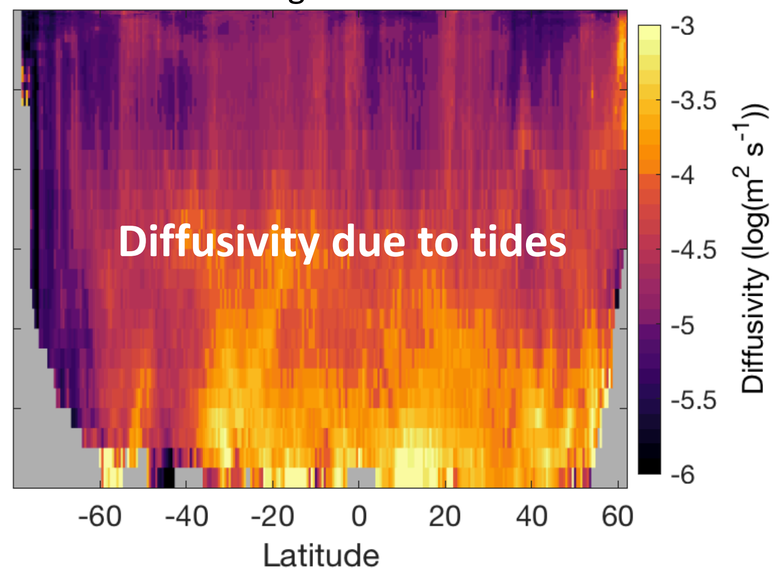
Gnanadesikan 1999

Density balance in the deep ocean

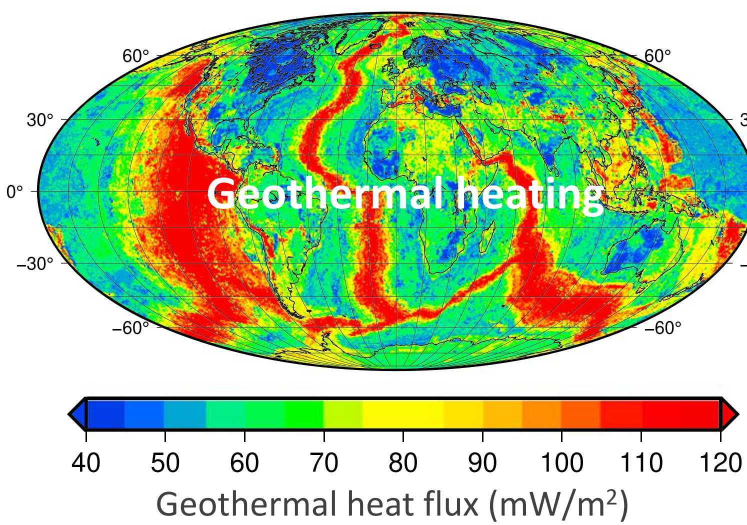
Gouretski & Koltermann 2004



de Lavergne *et al.* 2020



Lucazeau 2019



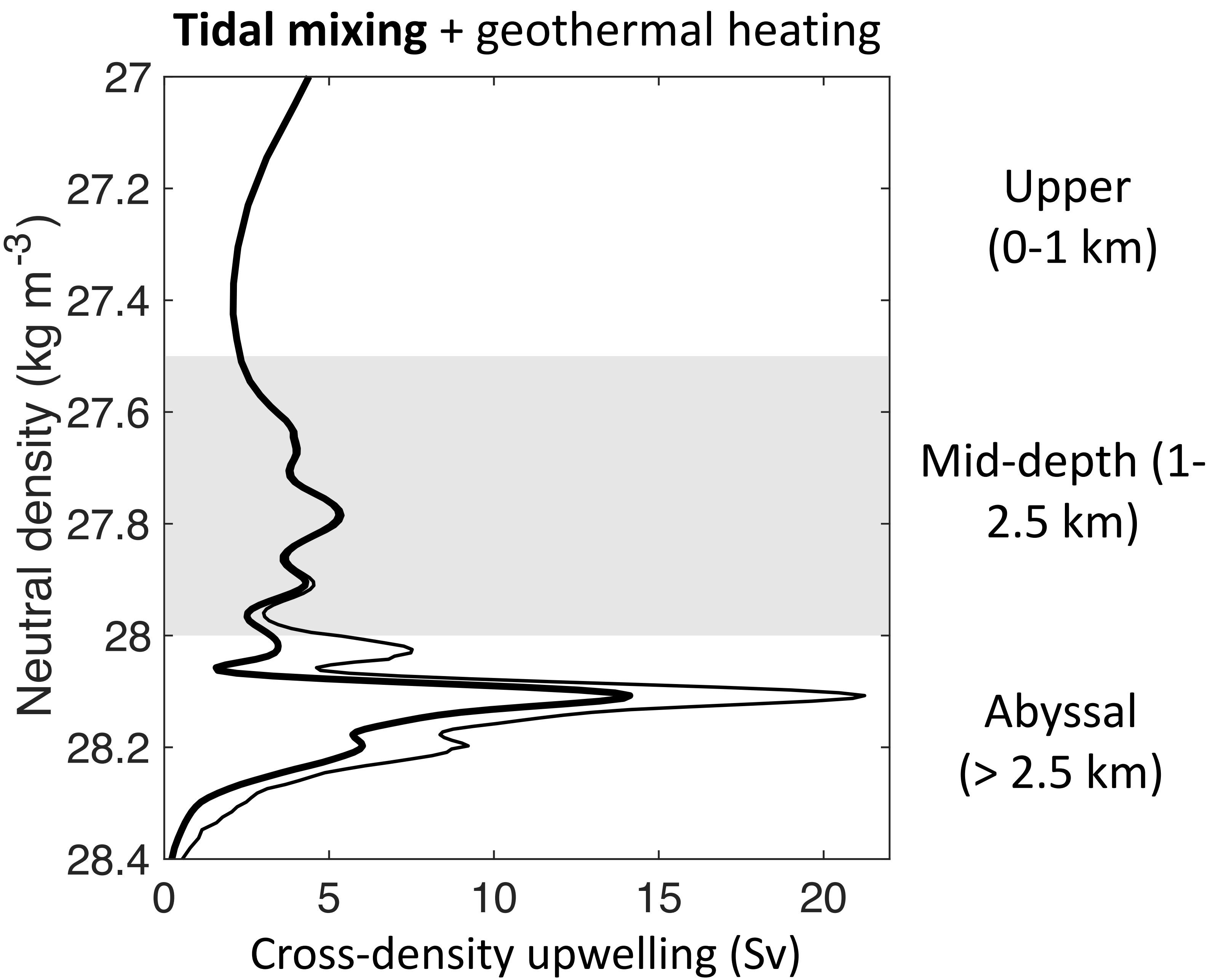
Density balance:

$$\omega\,\partial_z\gamma = \partial_z(K_\perp \partial_z\gamma)$$

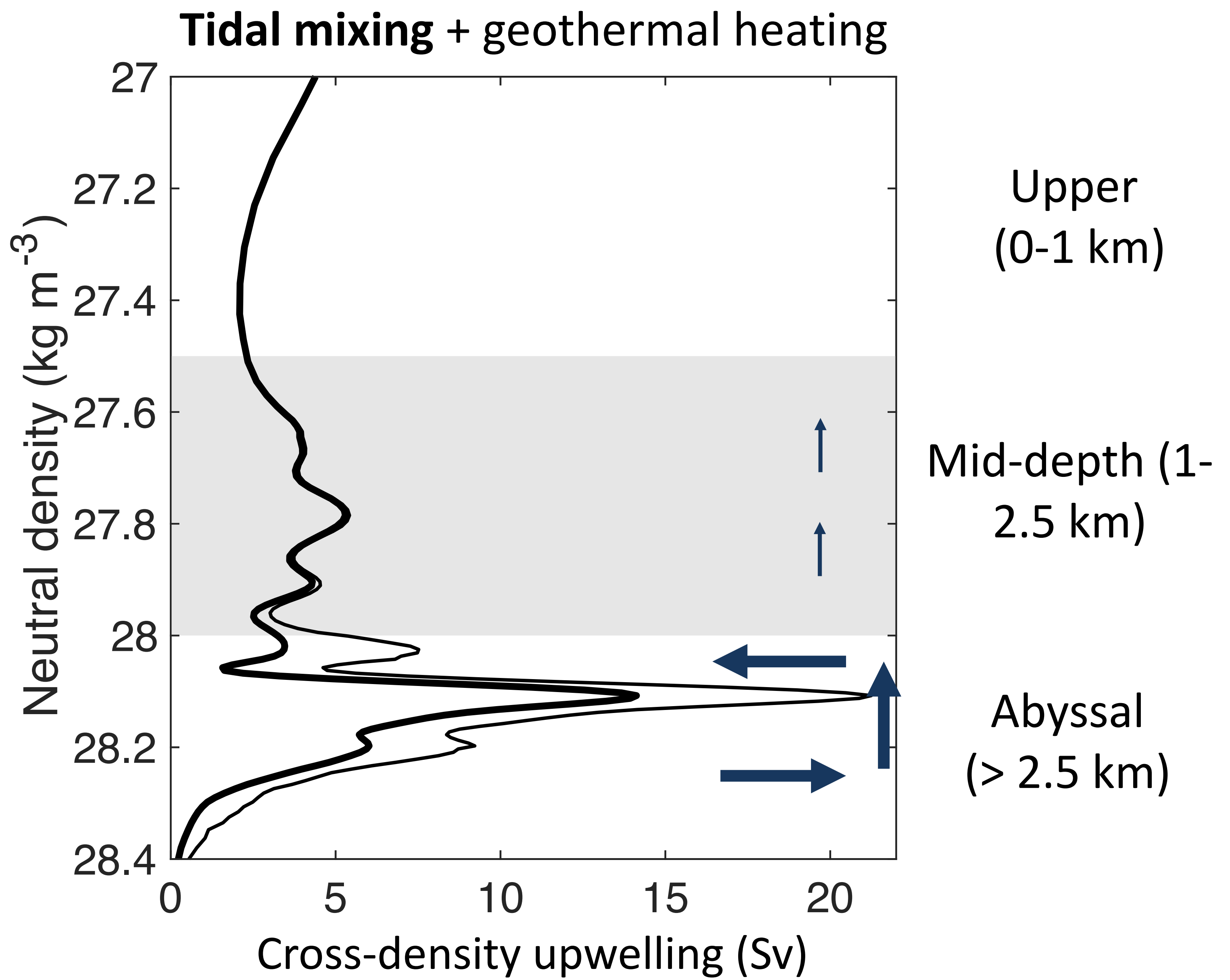
<=>

$$\boxed{\omega} = \boxed{\partial_\gamma(K_\perp \partial_z\gamma)}$$

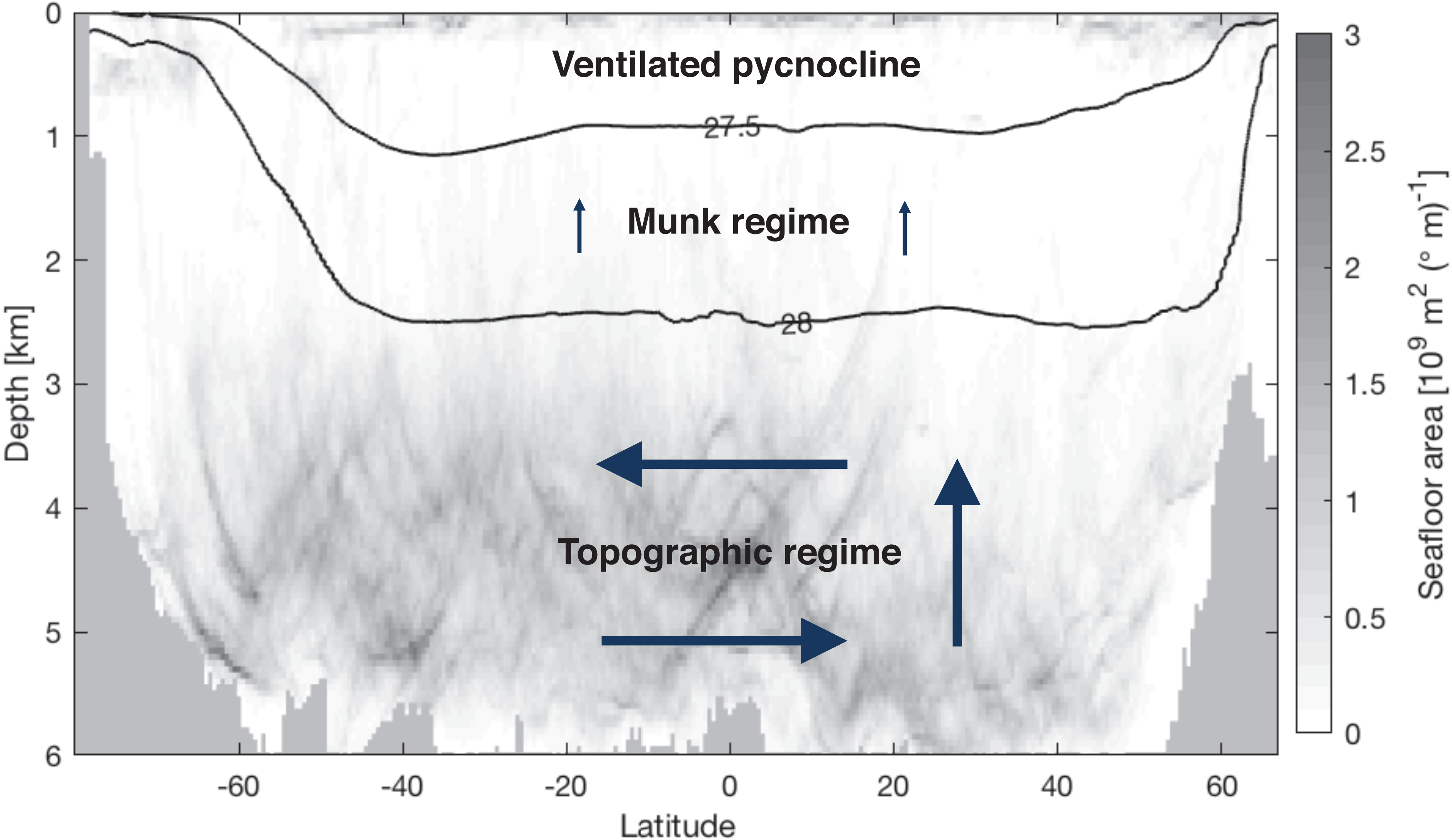
Application to global ocean



Application to global ocean

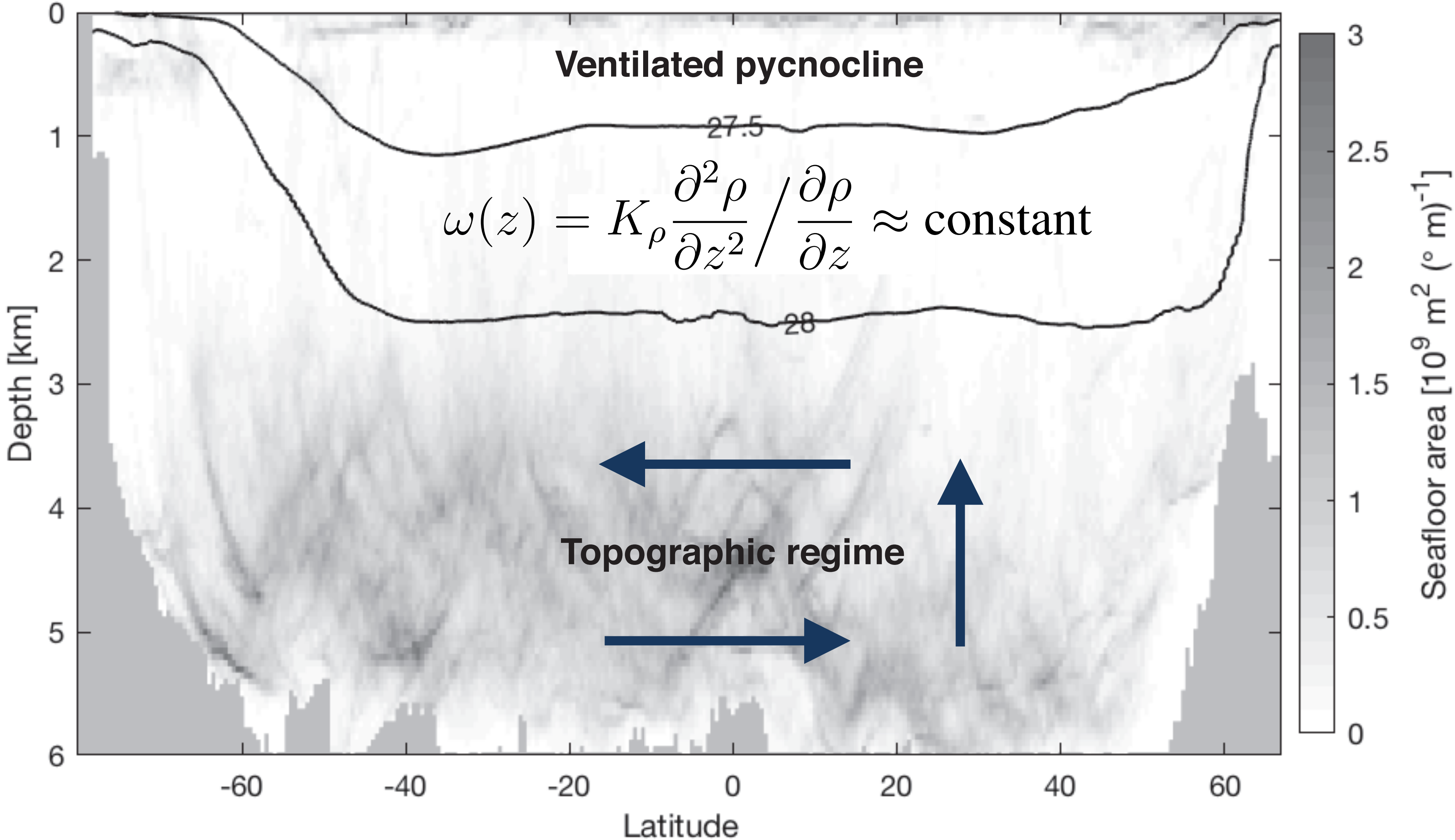


Three ocean regimes



de Lavergne *et al*. 2022

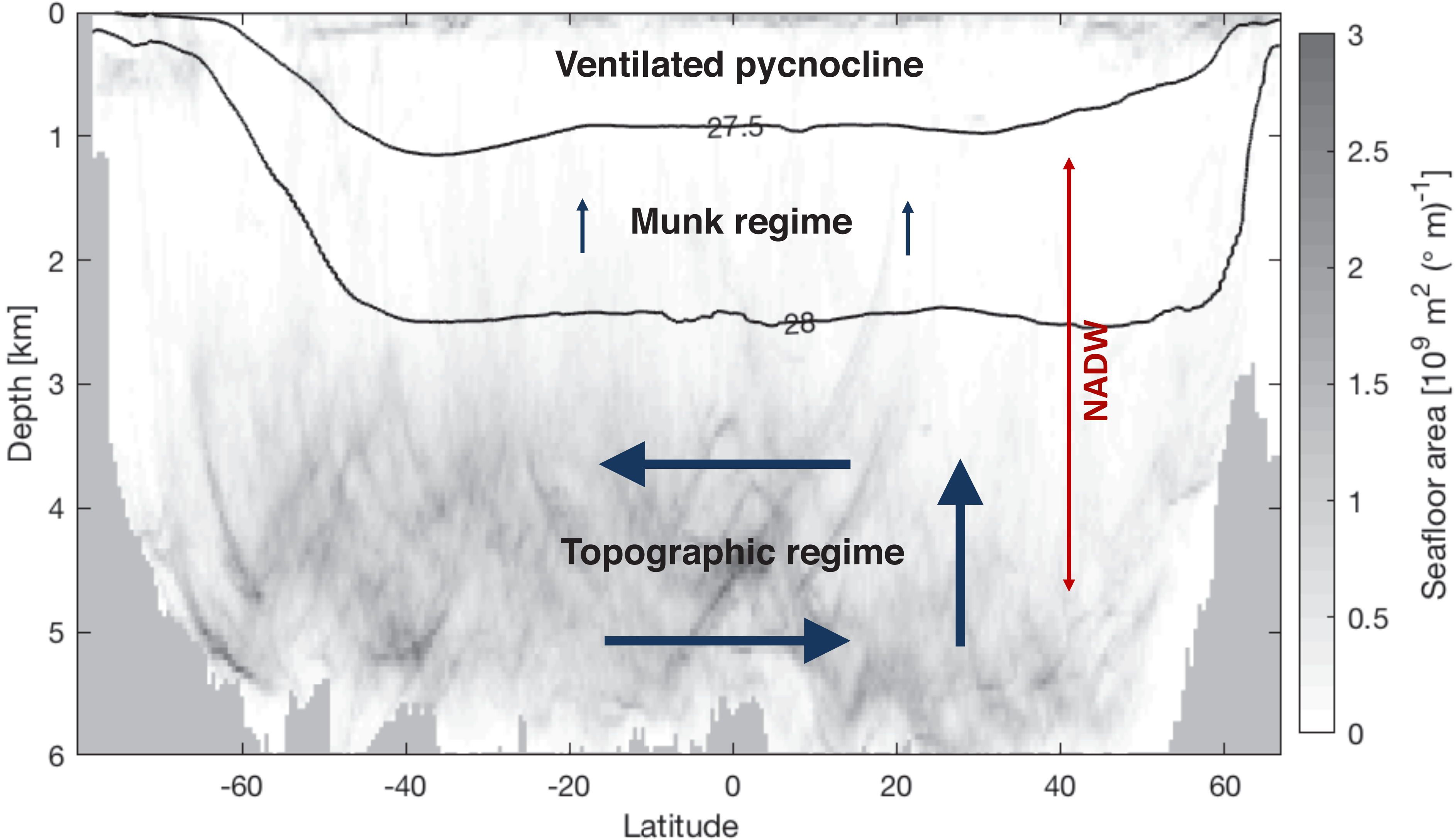
Three ocean regimes



$$\omega(z) = K_\rho \frac{\partial^2 \rho}{\partial z^2} \Big/ \frac{\partial \rho}{\partial z} \approx \text{constant}$$

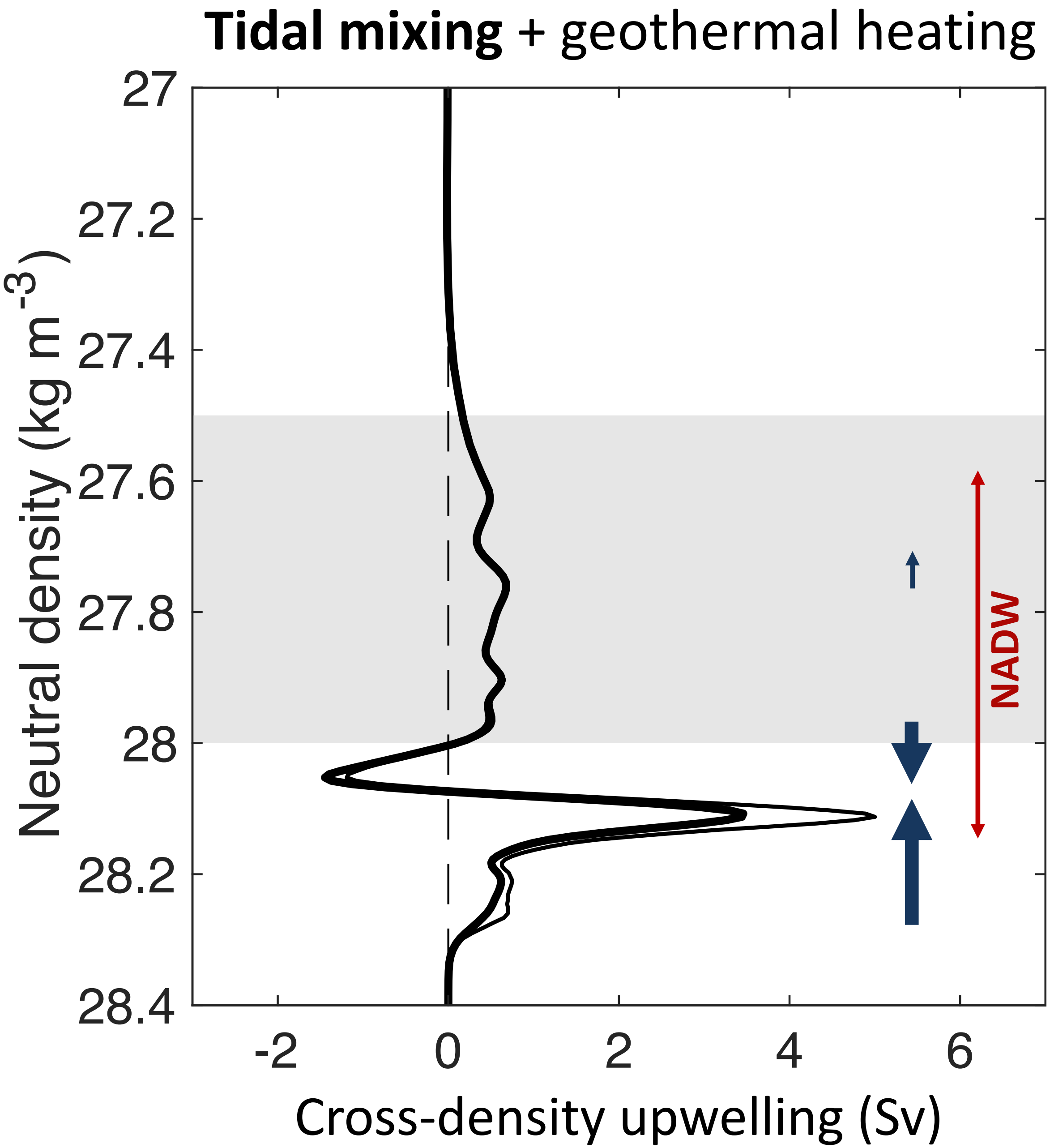
de Lavergne *et al*. 2022

Three ocean regimes



de Lavergne *et al*. 2022

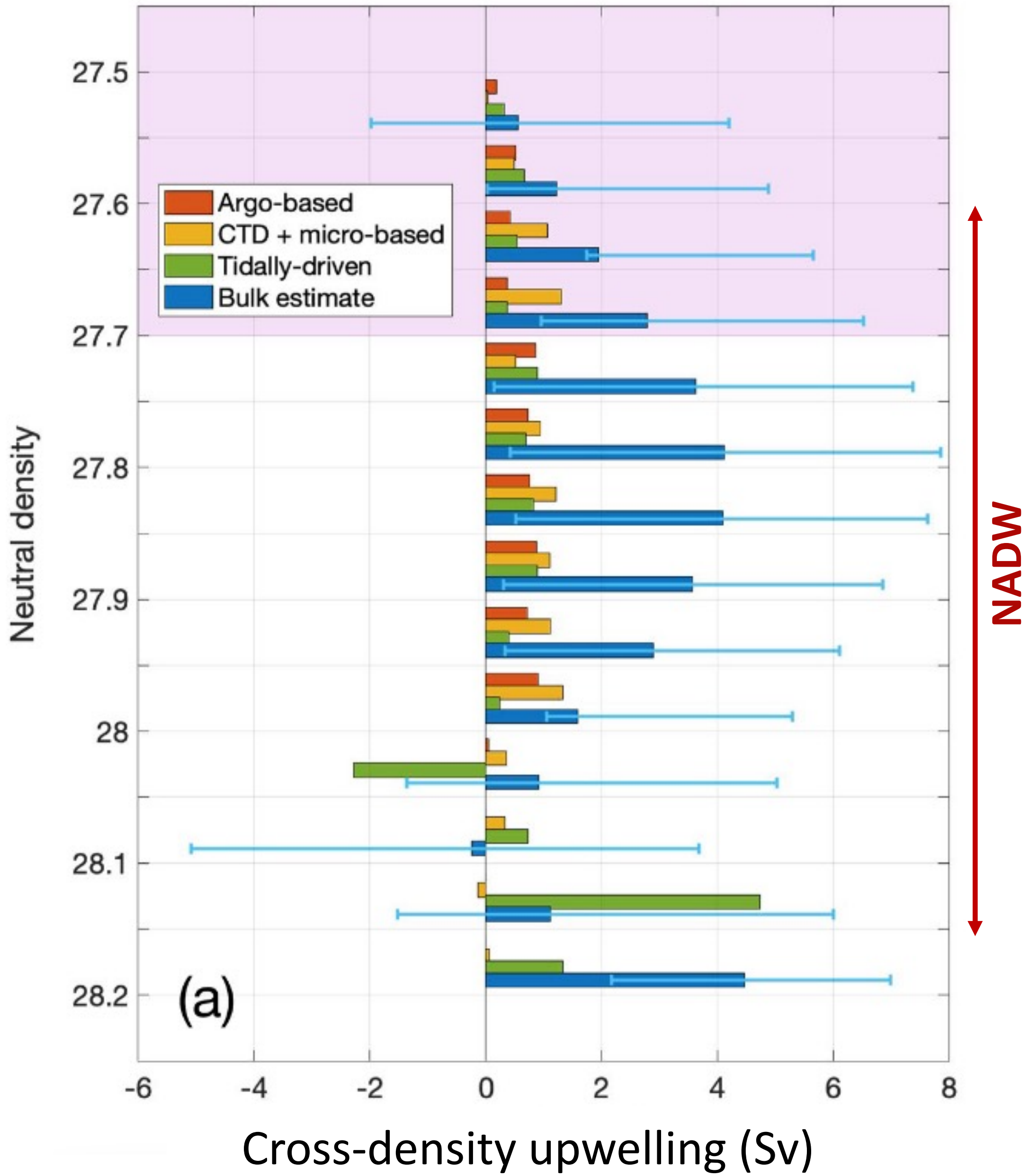
Application to Atlantic ocean (32°S-60°N)



Little-to-no upwelling to pycnocline

NADW homogenization

Applications to Atlantic ocean (32°S-60°N)

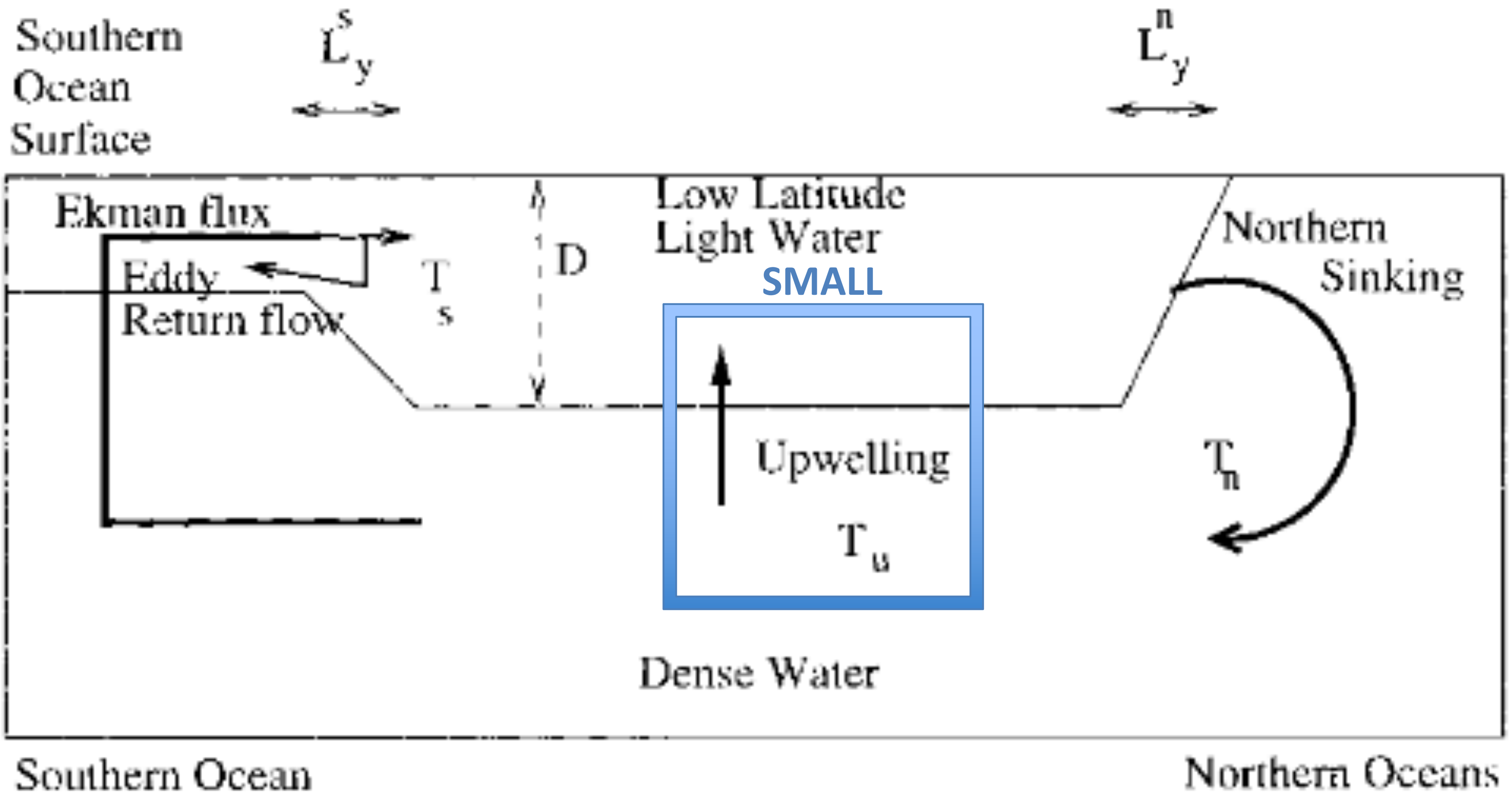


Four different mixing estimates yield a range of upwelling values.

Most likely, upwelling through Atlantic pycnocline is about 10% of AMOC strength.

Cimoli *et al.* 2023

A simple mass budget



Gnanadesikan 1999

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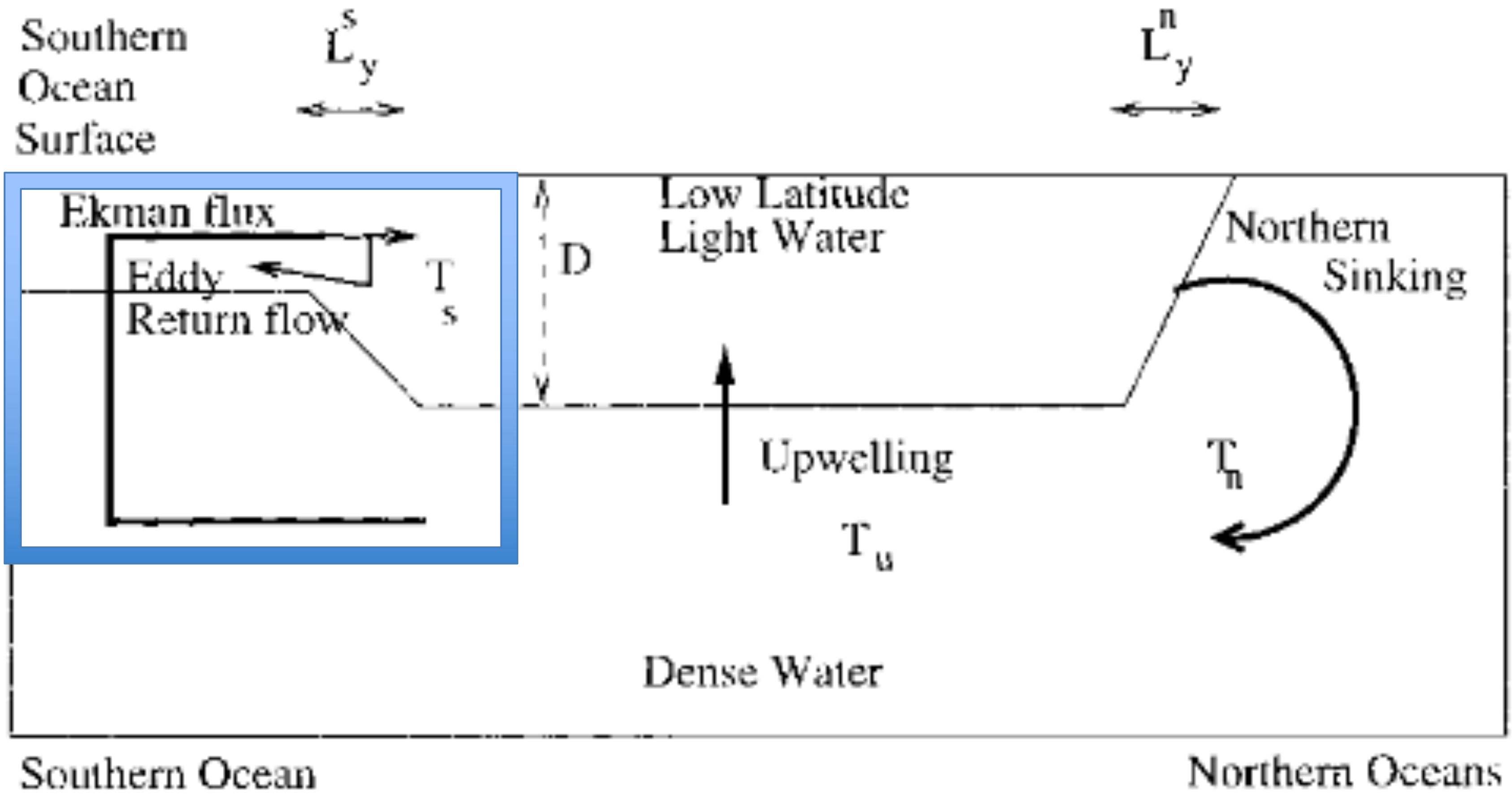
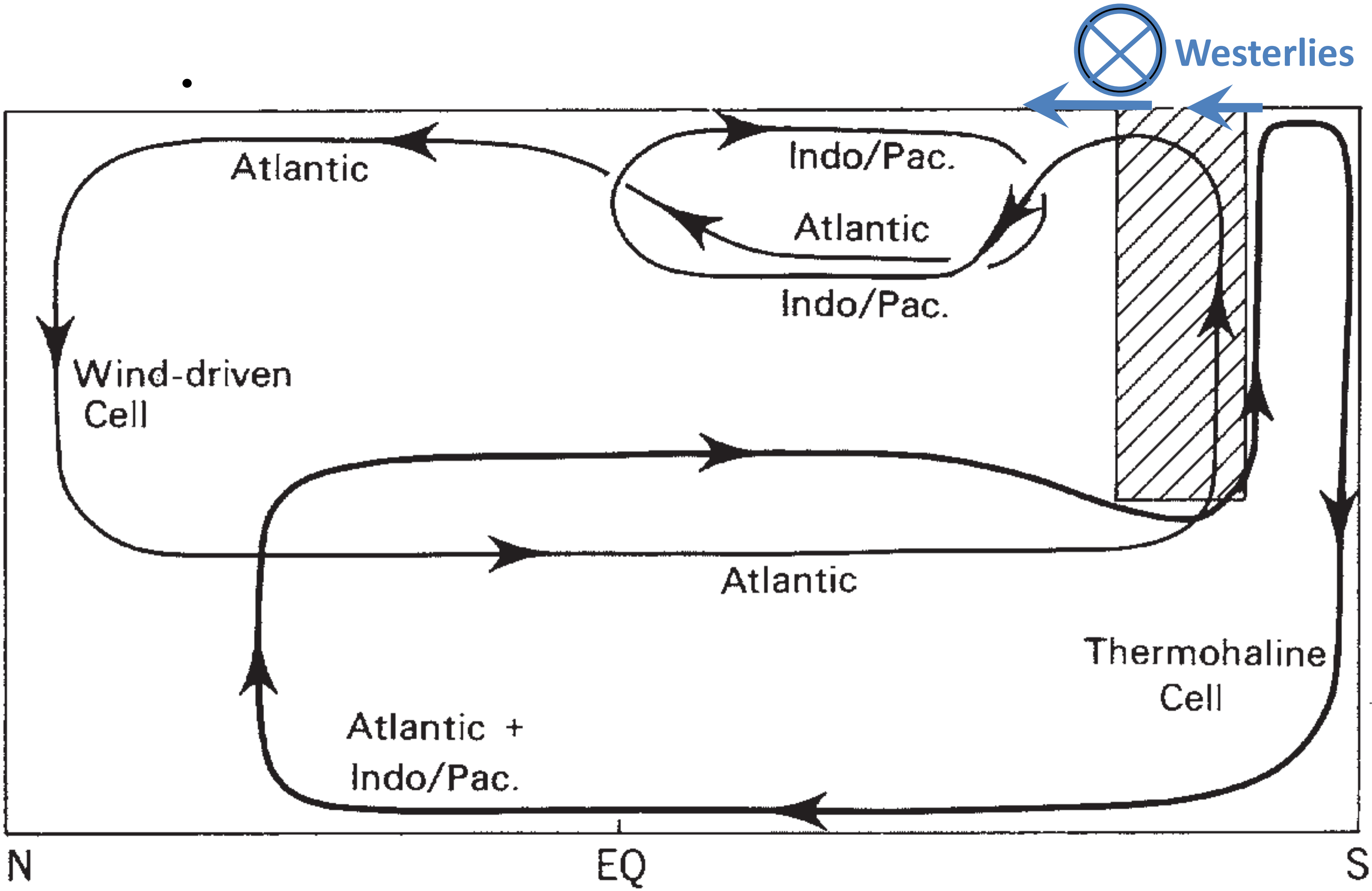


Gnanadesikan 1999

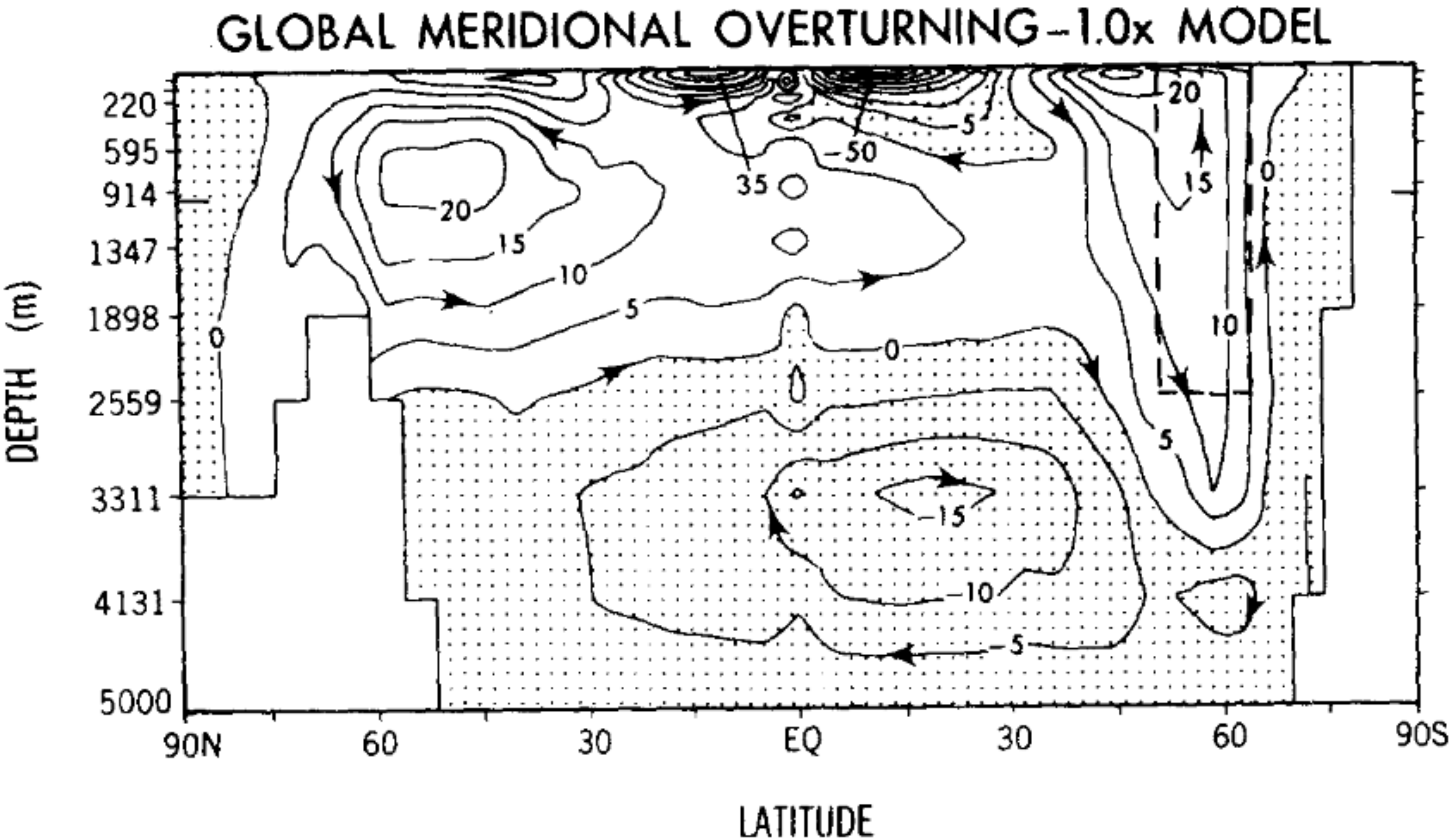
Toggweiler & Samuels (1993, 1995, 1998)

In the re-entrant channel: $\oint v\,dx = -\frac{1}{\rho f}\oint \partial_x p\,dx = 0$

•



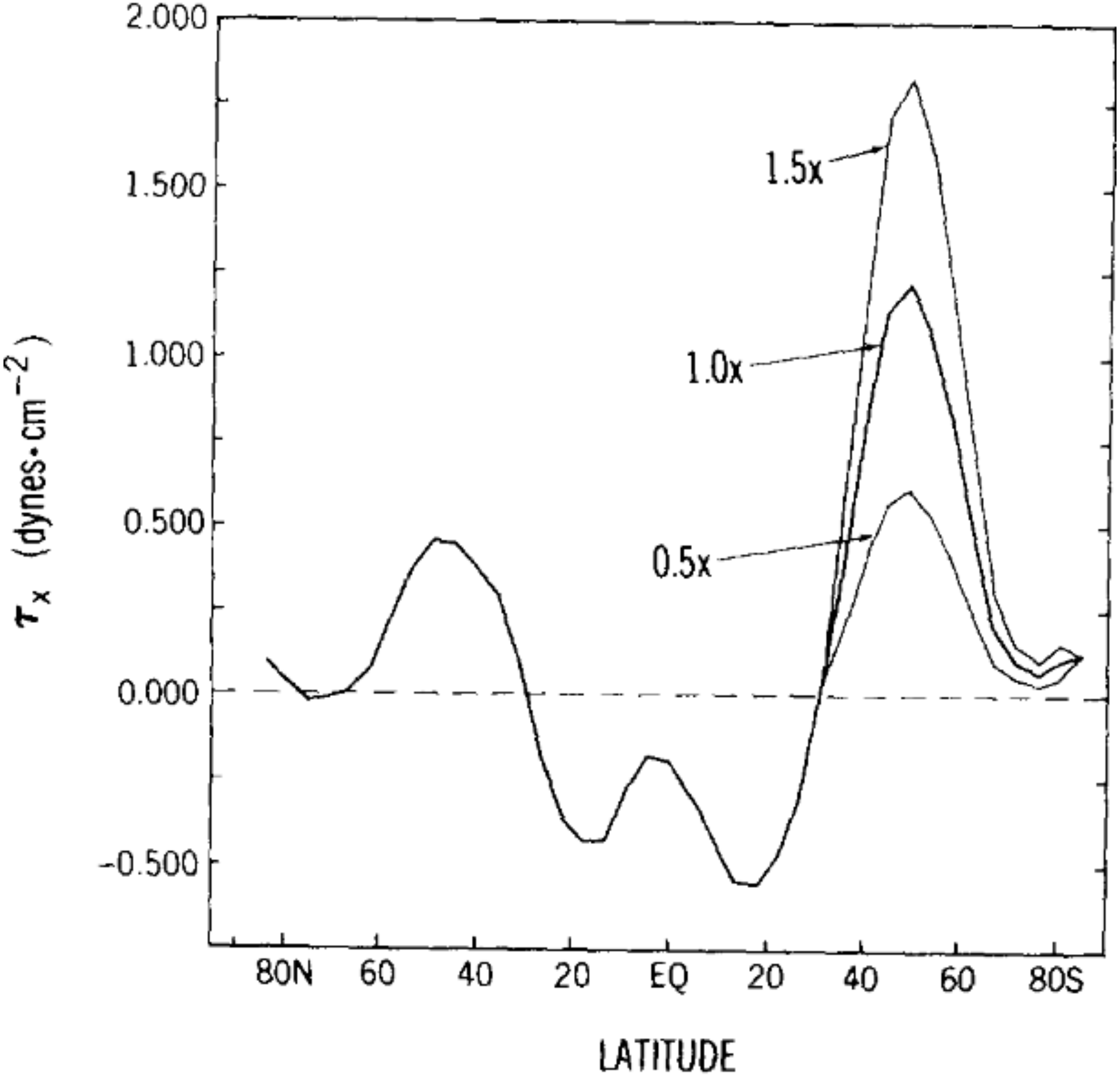
Meridional overturning streamfunction in an ocean model



$$\psi(y,z) = \int_{bottom}^{z} \int v(x,y,z')dx\, dz'$$

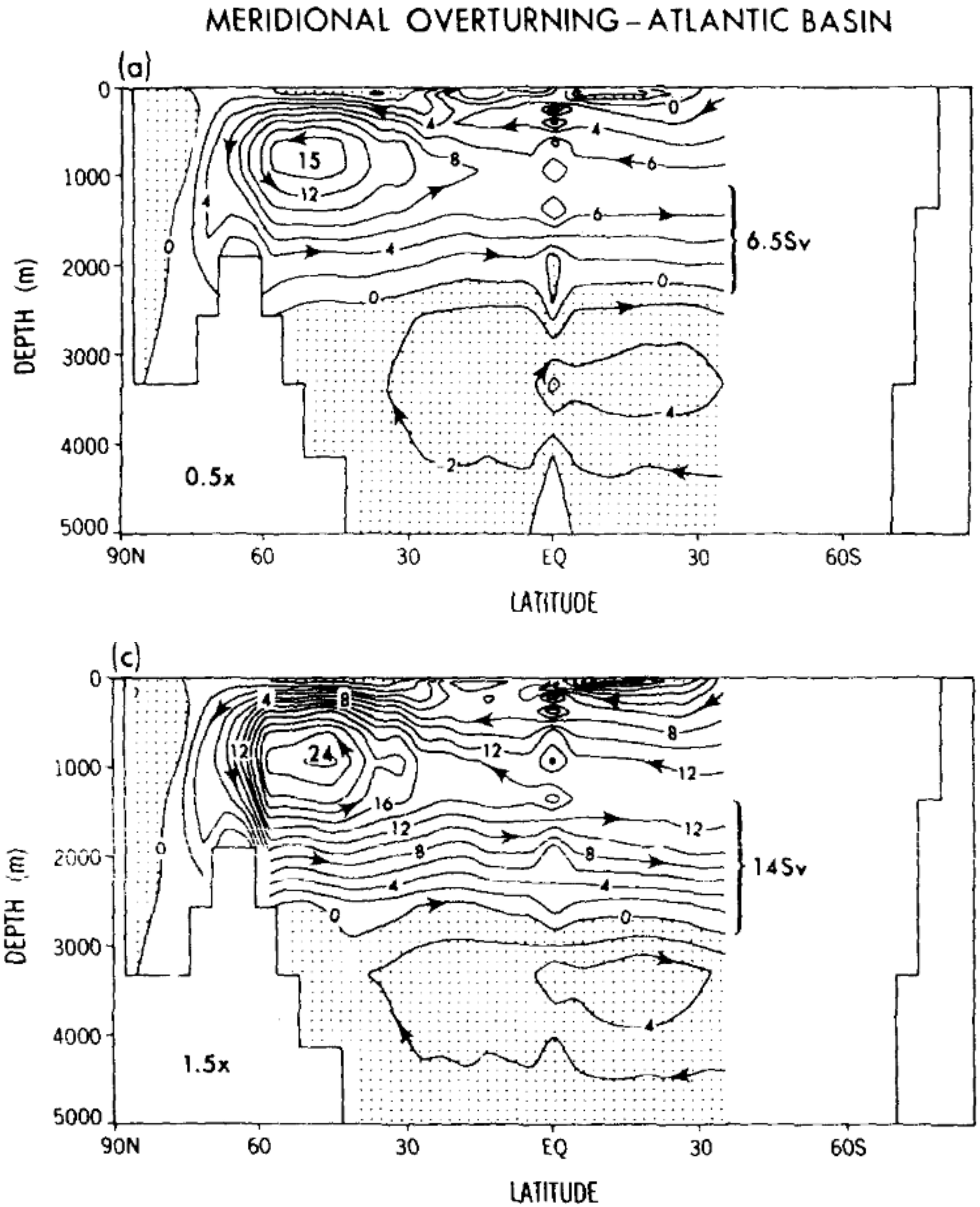
Toggweiler & Samuels 1995

Modified southern westerlies



Toggweiler & Samuels 1995

Impact of modified westerlies on the AMOC



50% decrease of winds: 6.5 Sv upwell in the Southern Ocean

50% increase of winds: 14 Sv upwell in the Southern Ocean

Toggweiler & Samuels 1995

Part 4. Role of mesoscale eddies in the AMOC

- **Eddy compensation and residual overturning in the Southern Ocean**
- **Do Southern Ocean eddies reinforce or damp the AMOC?**
- **An illustration of eddy compensation sensitivity**

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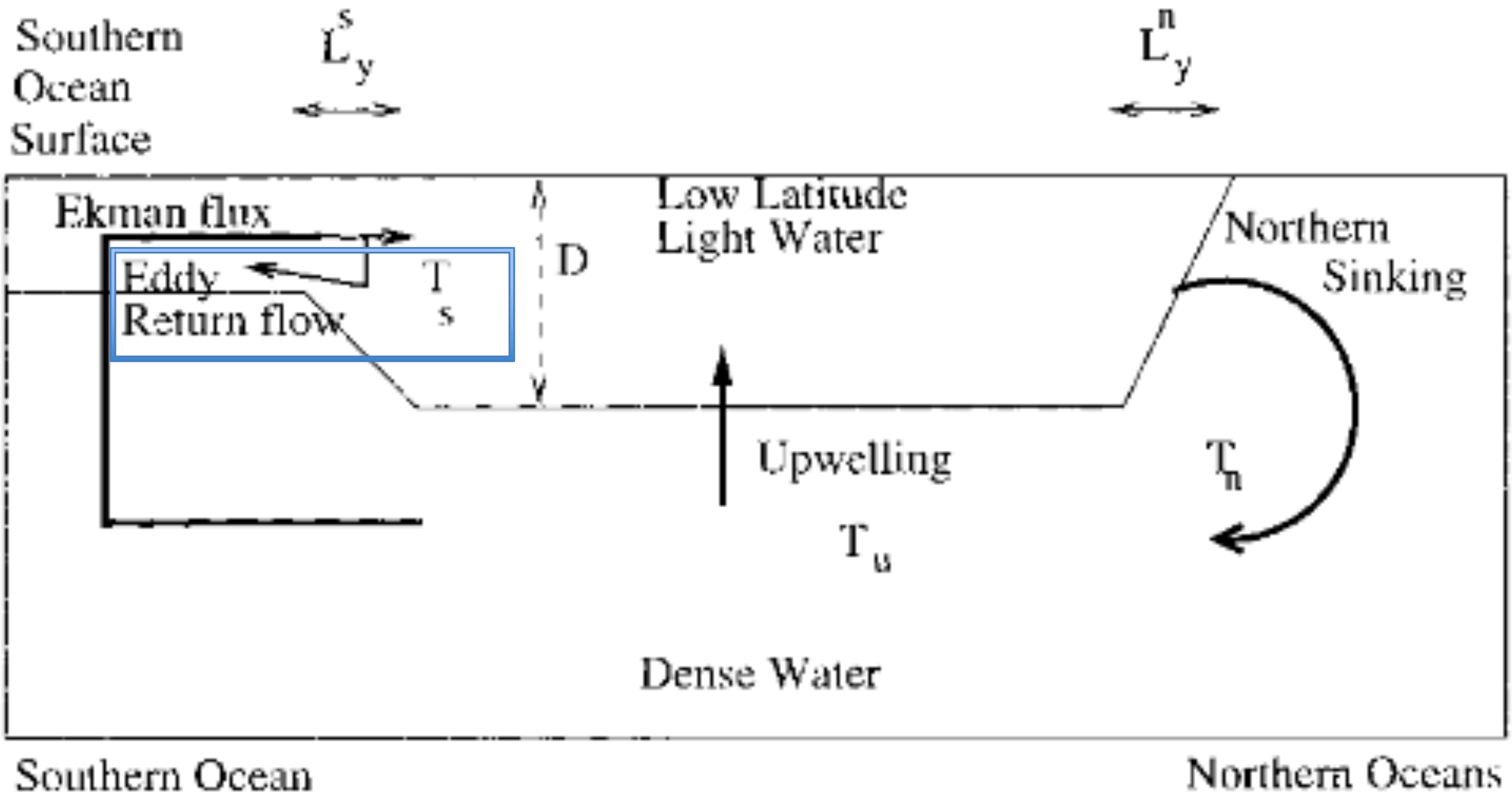
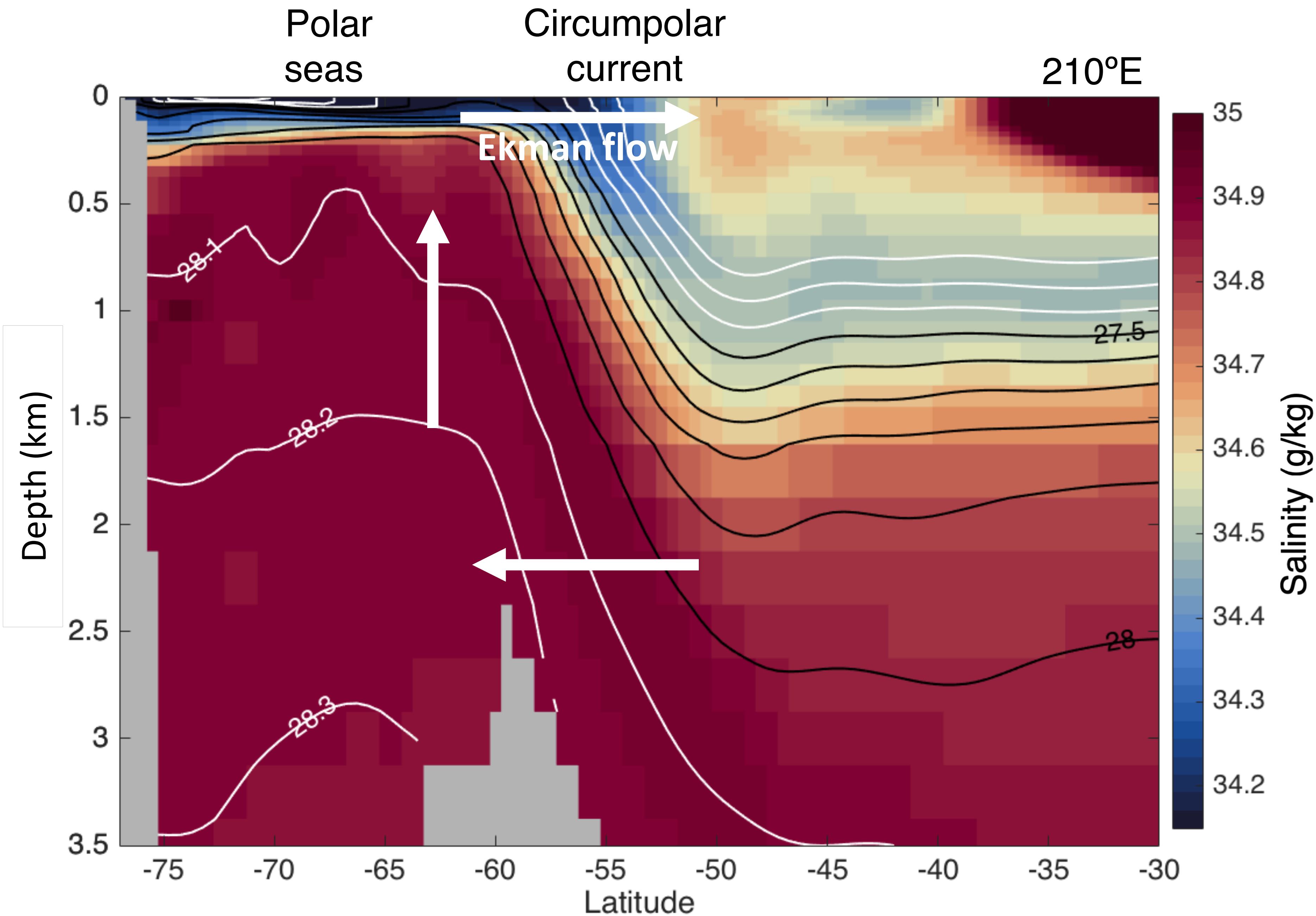
A missing ingredient: geostrophic turbulence

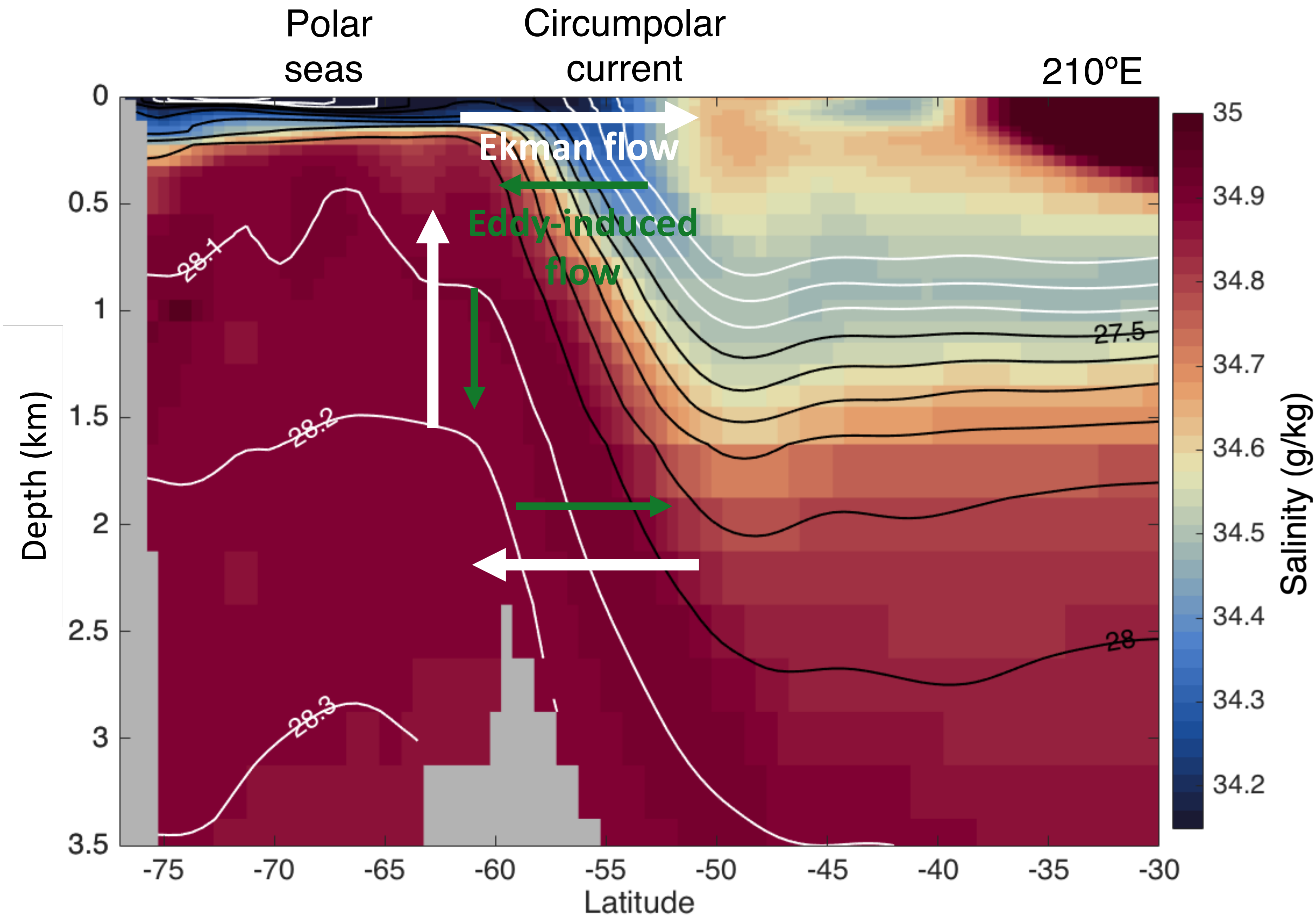


Marshall 1997, Gnanadesikan 1999, Marshall & Speer 2012

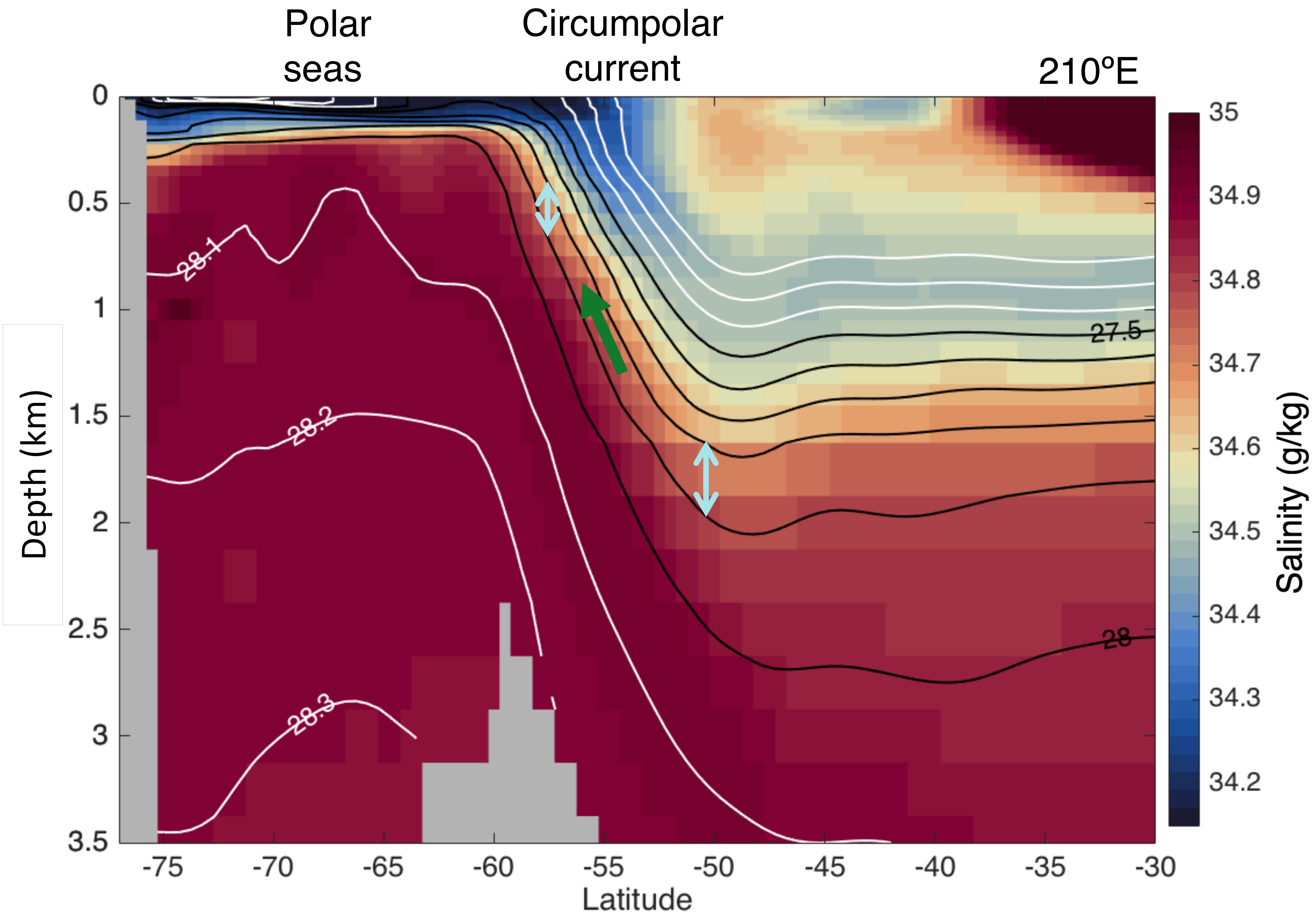
The wind-driven Ekman cell steepens isopycnals



Baroclinic instability kicks in to restore stratification



Eddy-induced flow conceptualized as thickness diffusion



In equations

$$\overline{vh} = \underbrace{\bar{v}\bar{h}}_{\substack{\text{mean transport} \\ \overline{\psi}}} + \underbrace{\overline{v'h'}}_{\substack{\text{eddy transport} \\ \psi^*}} = \underbrace{v_{\text{res}}\bar{h}}_{\substack{\text{residual transport} \\ \psi_{\text{res}}}}$$

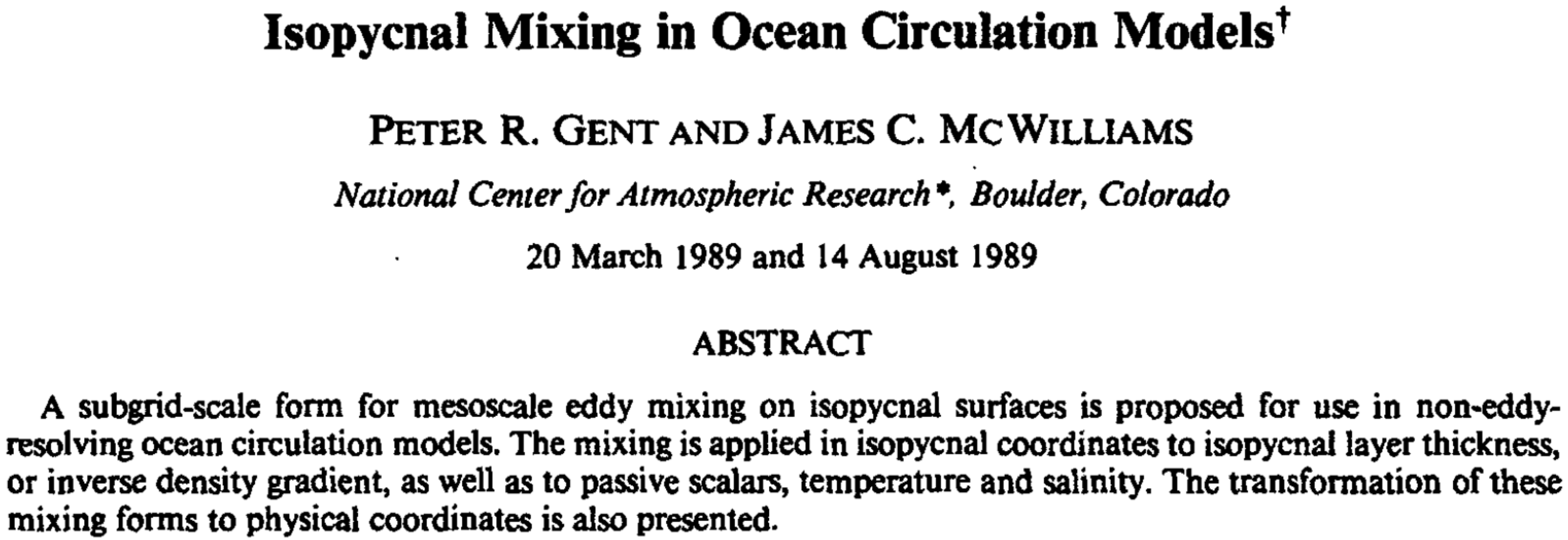
In the re-entrant channel (55-60°S, 0-2 km), below the Ekman layer and above topographic ridges, only mesoscale eddies can generate net meridional mass transport in isopycnal layers:

$$\overline{vh} = \underbrace{\overline{v'h'}}_{\substack{\text{eddy transport} \\ \psi^*}} \simeq -K\frac{\partial \bar{h}}{\partial y}$$

K is the Gent-McWilliams coefficient for eddy-induced transport.

Gent & McWilliams 1990, McDougall & McIntosh 2001, Marshall & Speer 2012

In equations


Isopycnal Mixing in Ocean Circulation Models†

PETER R. GENT AND JAMES C. MCWILLIAMS

National Center for Atmospheric Research, Boulder, Colorado*

20 March 1989 and 14 August 1989

ABSTRACT

A subgrid-scale form for mesoscale eddy mixing on isopycnal surfaces is proposed for use in non-eddy-resolving ocean circulation models. The mixing is applied in isopycnal coordinates to isopycnal layer thickness, or inverse density gradient, as well as to passive scalars, temperature and salinity. The transformation of these mixing forms to physical coordinates is also presented.

”The proposal is to mix isopycnal layer thickness, or inverse density gradient, along isopycnal surfaces.”

- Equivalent to downgradient diffusion of planetary potential vorticity along isopycnals (neglecting a β term).
- Equivalent to vertical diffusion of momentum (with diffusivity $K\,\frac{f^2}{N^2}$).

Gent & McWilliams 1990, Rhines & Young 1982, Gent *et al.* 1995

Application to observed hydrography (1/2)

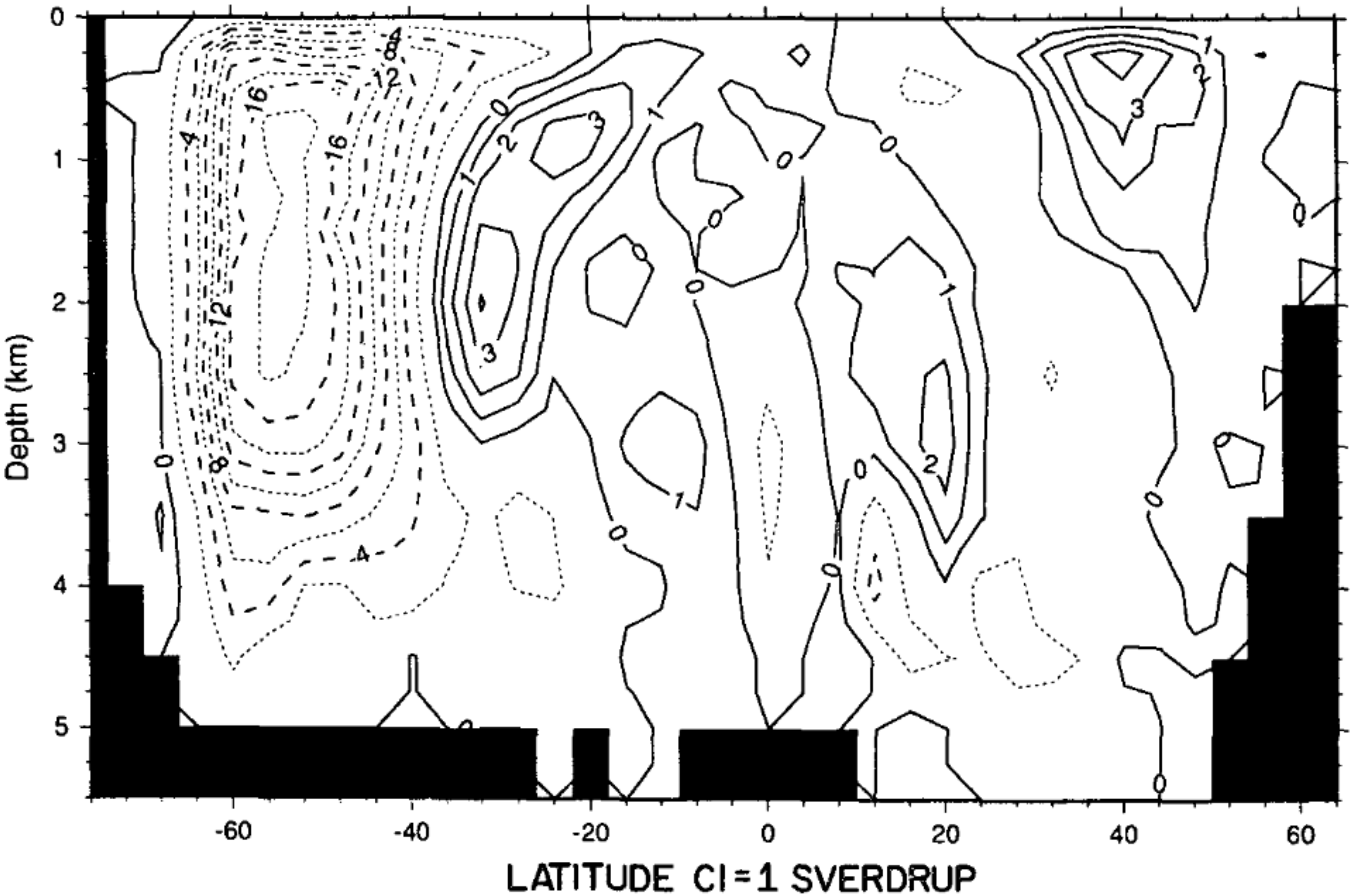


FIG. 6. Zonally averaged meridional overturning streamfunction $\int \kappa\rho_y/\rho_z dx$ in Sverdrups calculated from Levitus (1982) data where the average is over all ocean basins: $\kappa = 10^3\ m^2\ s^{-1}$ and is constant.

Gent *et al*. 1995

Application to observed hydrography (2/2)

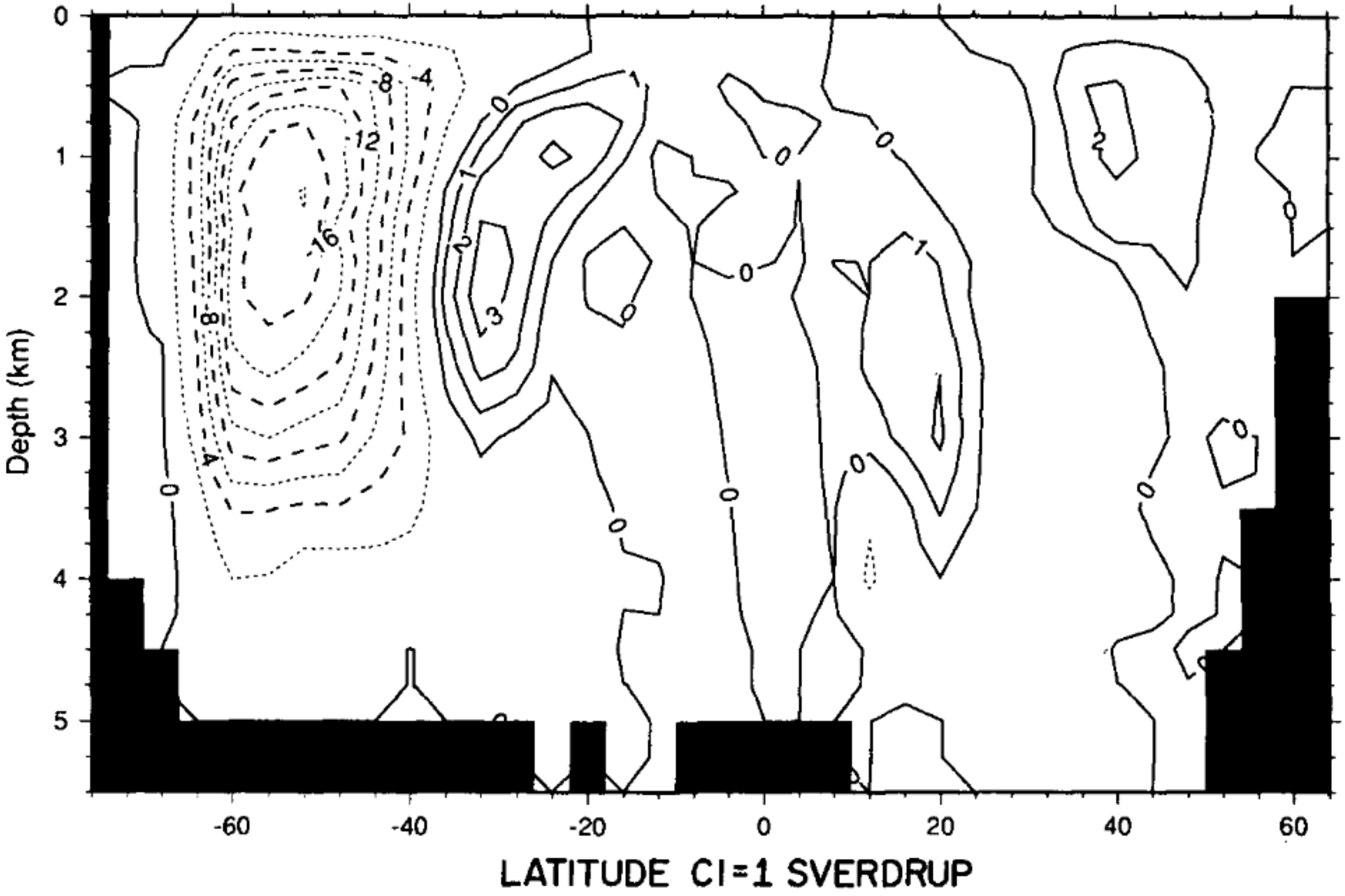


FIG. 7. Zonally averaged meridional overturning streamfunction in Sverdrups as in Fig. 6 but for κ with a first baroclinic mode profile.

Gent *et al*. 1995

Problem: how to specify the Gent-McWilliams coefficient?

Everything depends on K and implementation details:

- Transition from isopycnal to horizontal flow in the surface boundary layer.
- At the boundaries, ψ^* needs to be zero.

- K varies in 3D. It depends not only on eddy properties but also on the mean flow and topography (via suppression effects).

- K is very hard to diagnose from observations, eddying models or data-assimilating models.

=> Challenges for parameterization in climate models

Gent & McWilliams 1990, Ferrari *et al*. 2010, Ferrari & Nikurashin 2010

Part 4. Role of mesoscale eddies in the AMOC

- Eddy compensation and residual overturning in the Southern Ocean
- **Do Southern Ocean eddies reinforce or damp the AMOC?**
- An illustration of eddy compensation sensitivity

The devil is in the details

The conundrum:

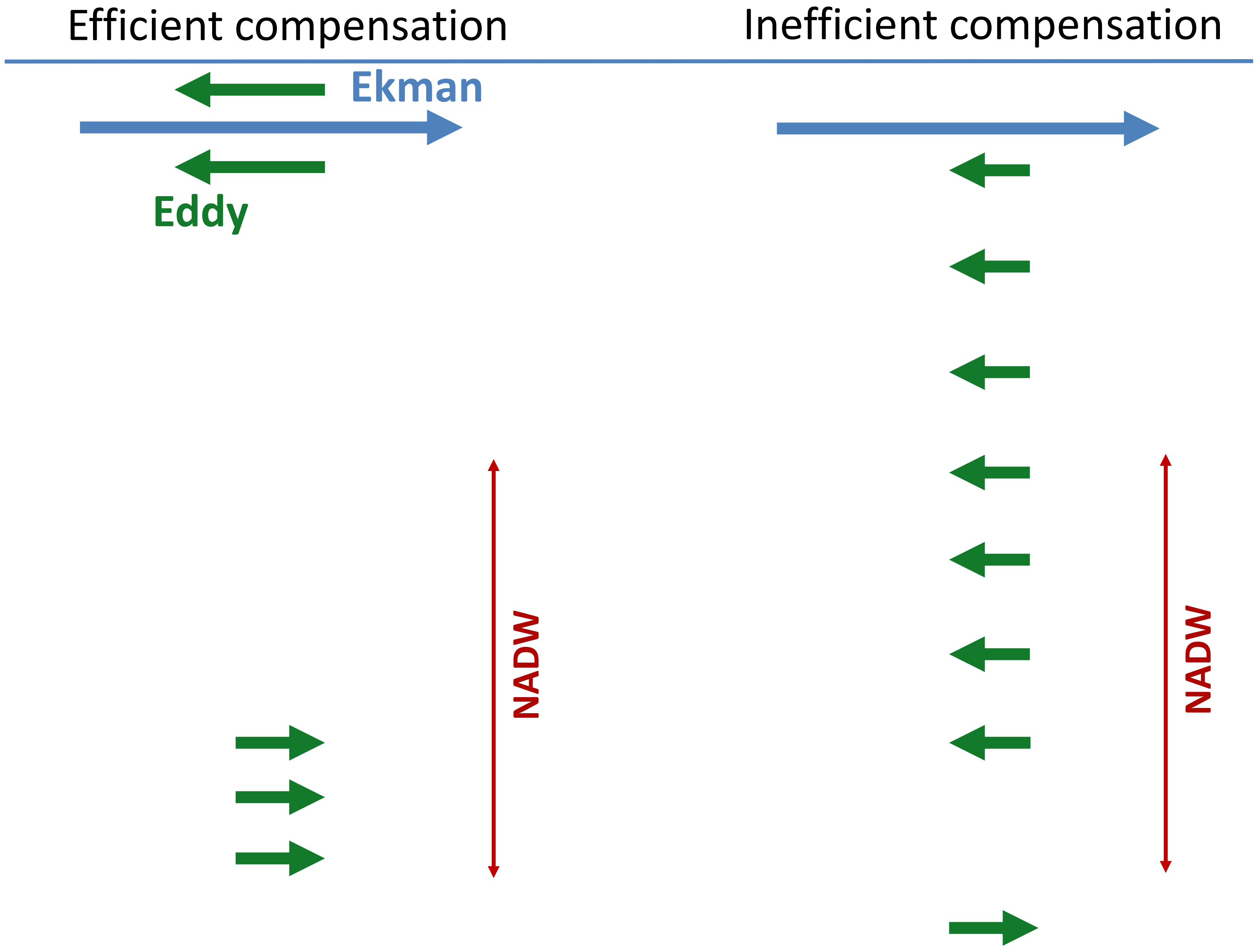
- Gnanadesikan (1999) sees the eddy-driven circulation as offsetting the Ekman circulation (thus causing downwelling).
- Marshall and Speer (2012) argue that eddies cause upwelling of mid-depth waters.

Do eddies cause more downwelling or upwelling of NADW?

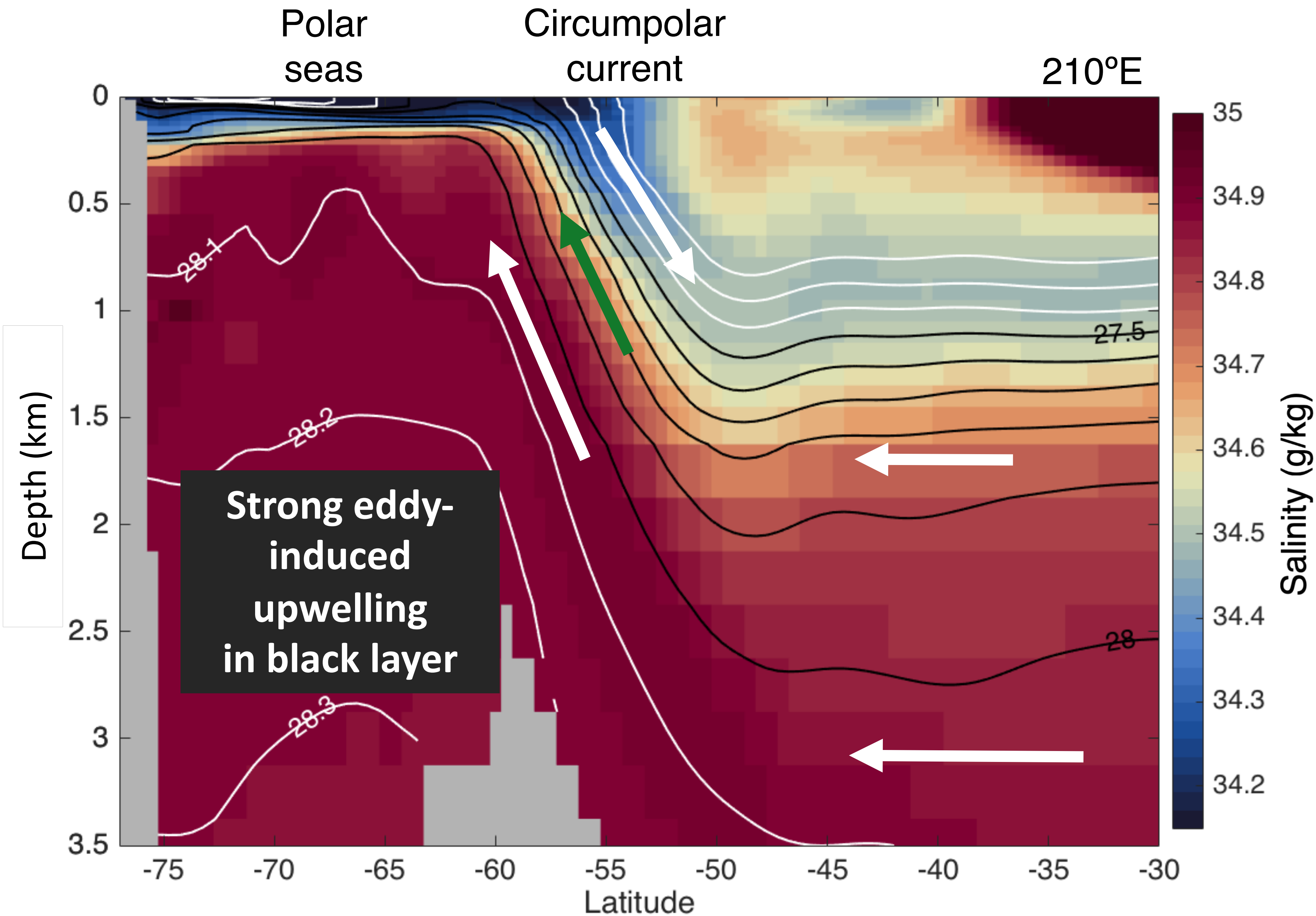
The answer depends on the depth range of the eddy-induced southward flow, which itself depends on the vertical profile of K and the treatment of the surface boundary layer.

Consequence: depending on parameterization choices and simulated ocean states, mesoscale eddies can either reinforce or damp the AMOC in climate models!

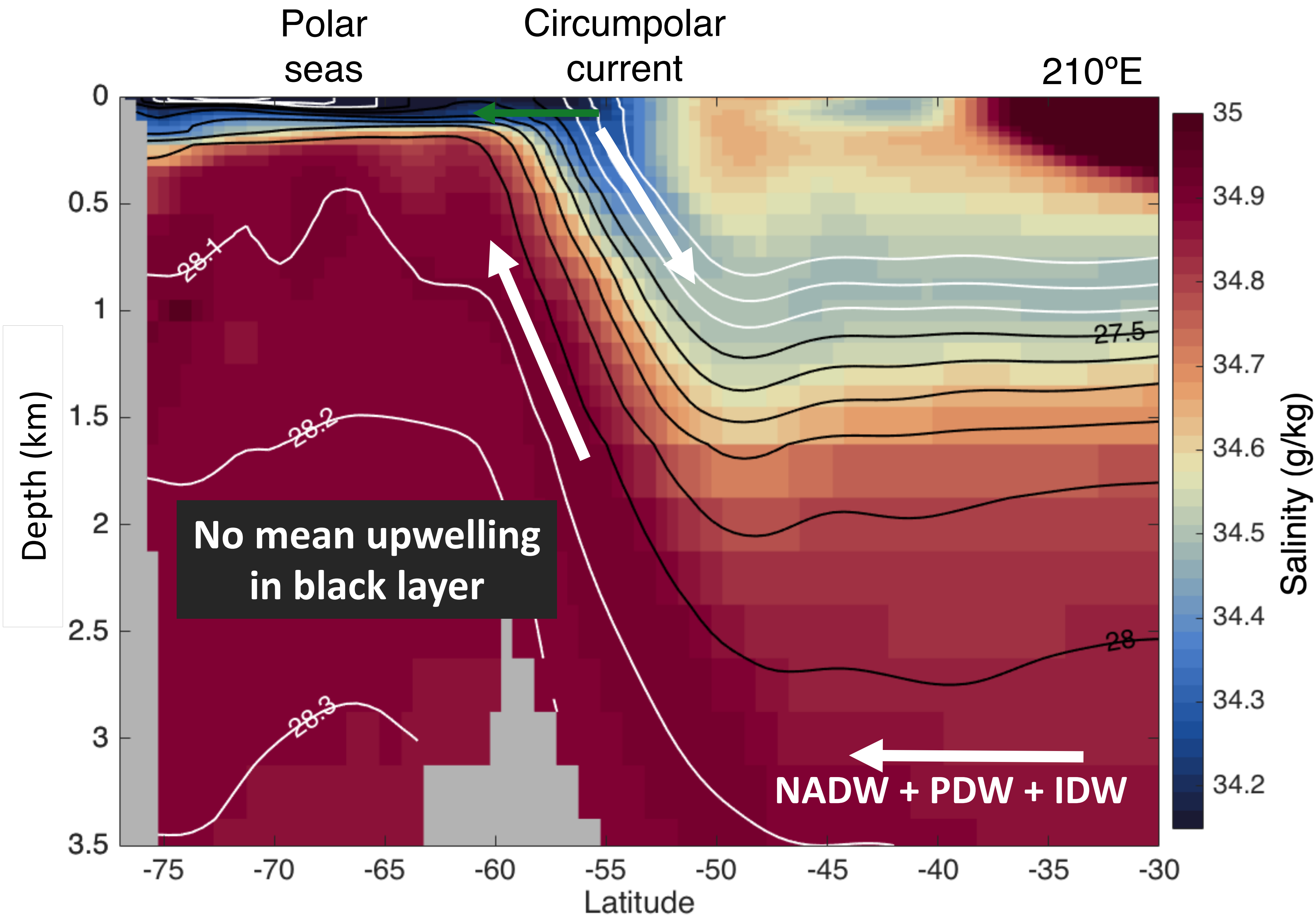
The devil is in the details



Current view: eddies upwell mid-depth waters



My hypothesis: eddies against Ekman and AMOC



Evidence from observations and theory

A dynamical barrier to meridional transport exists within the black layer (neutral density = 27.5-28):

- Closed circumpolar contours of potential vorticity along black isopycnals

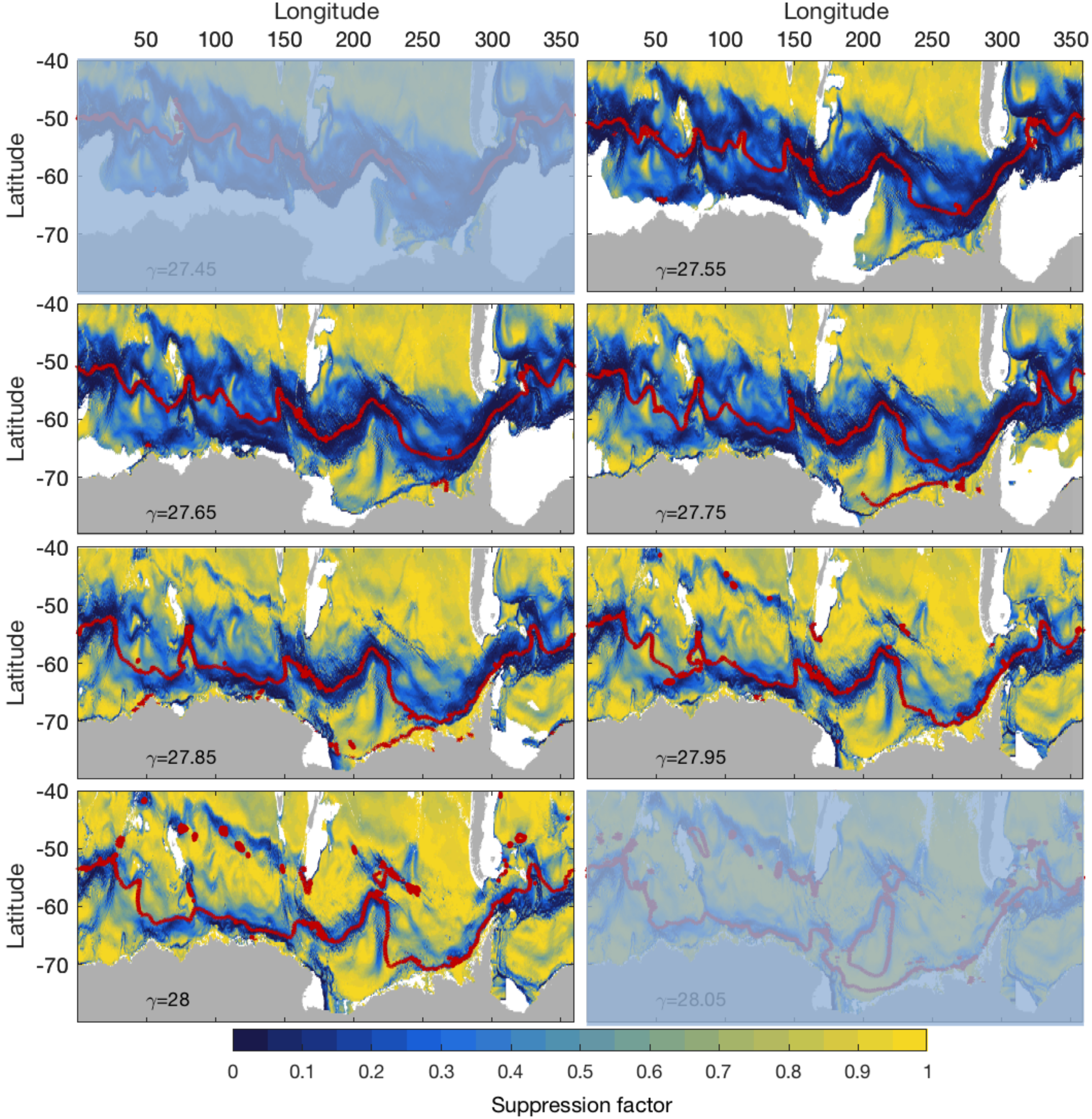
  => mean geostrophic flow follows these contours

- Swift eastward currents suppress meridional mixing by mesoscale eddies

  => turbulent geostrophic flow inefficient at fluxing water up

The Antarctic Circumpolar Current core does not promote upwelling along its steep isopycnals but instead acts as a barrier to meridional mass transport.

Evidence from observations and theory

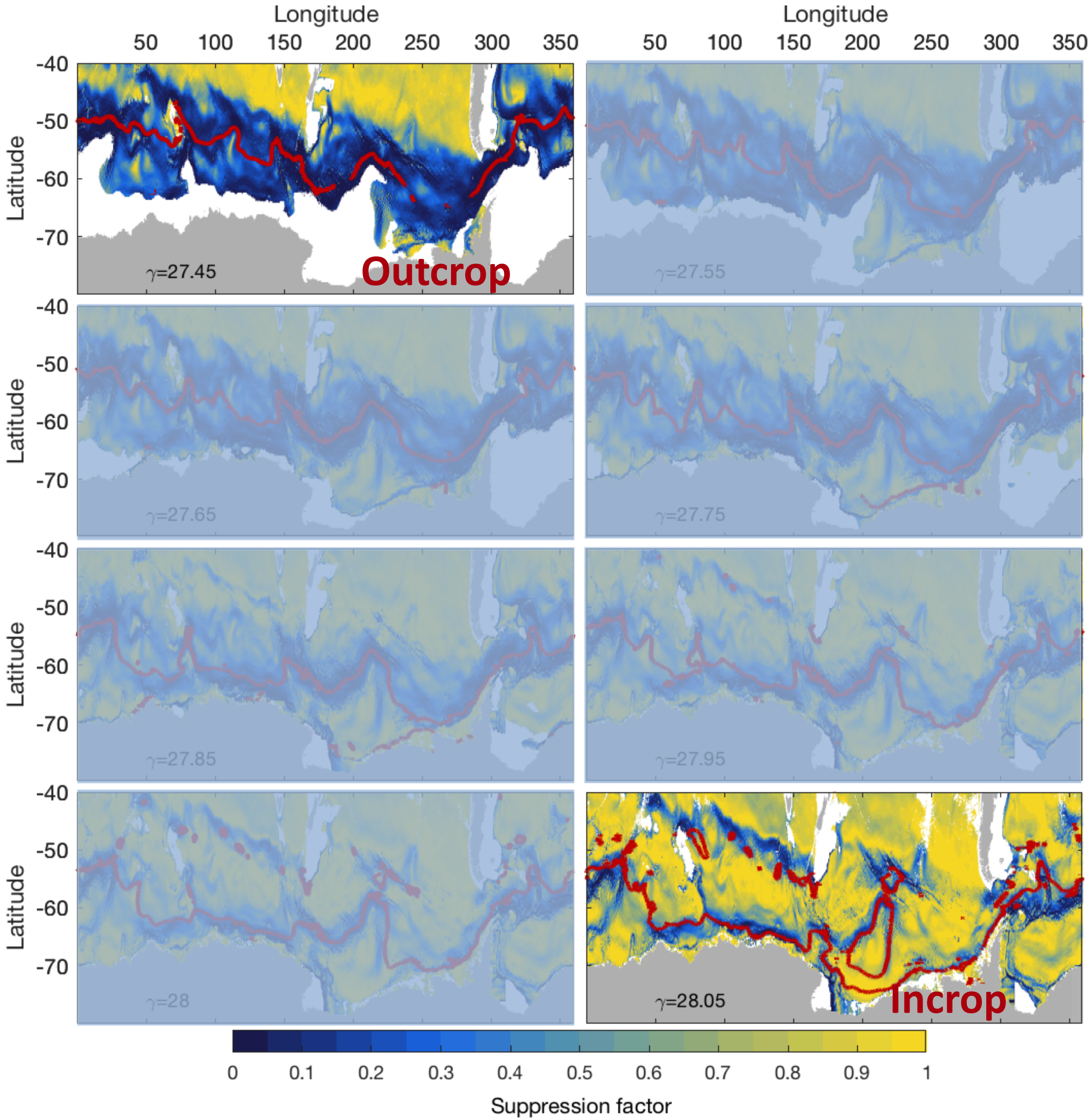


Hydrography from Gouretski (2018).

Red contours:
Selected isocontour of potential vorticity (=f/h) along isopycnal (e.g., Zika *et al*. 2009).

Shading:
Suppression factor (Ferrari & Nikurashin 2010) calculated from hydrography following Groeskamp *et al*. (2020).

Evidence from observations and theory



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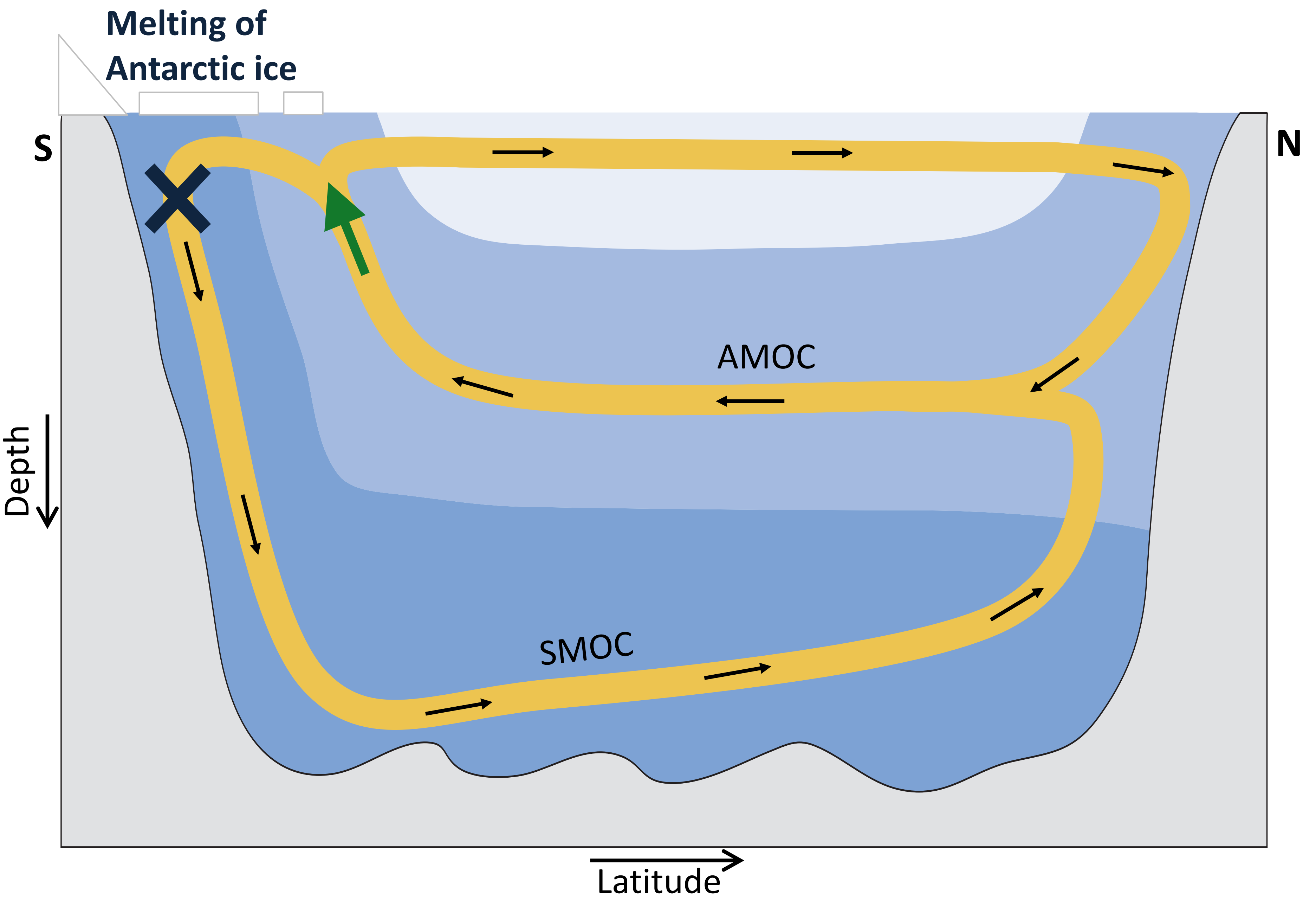
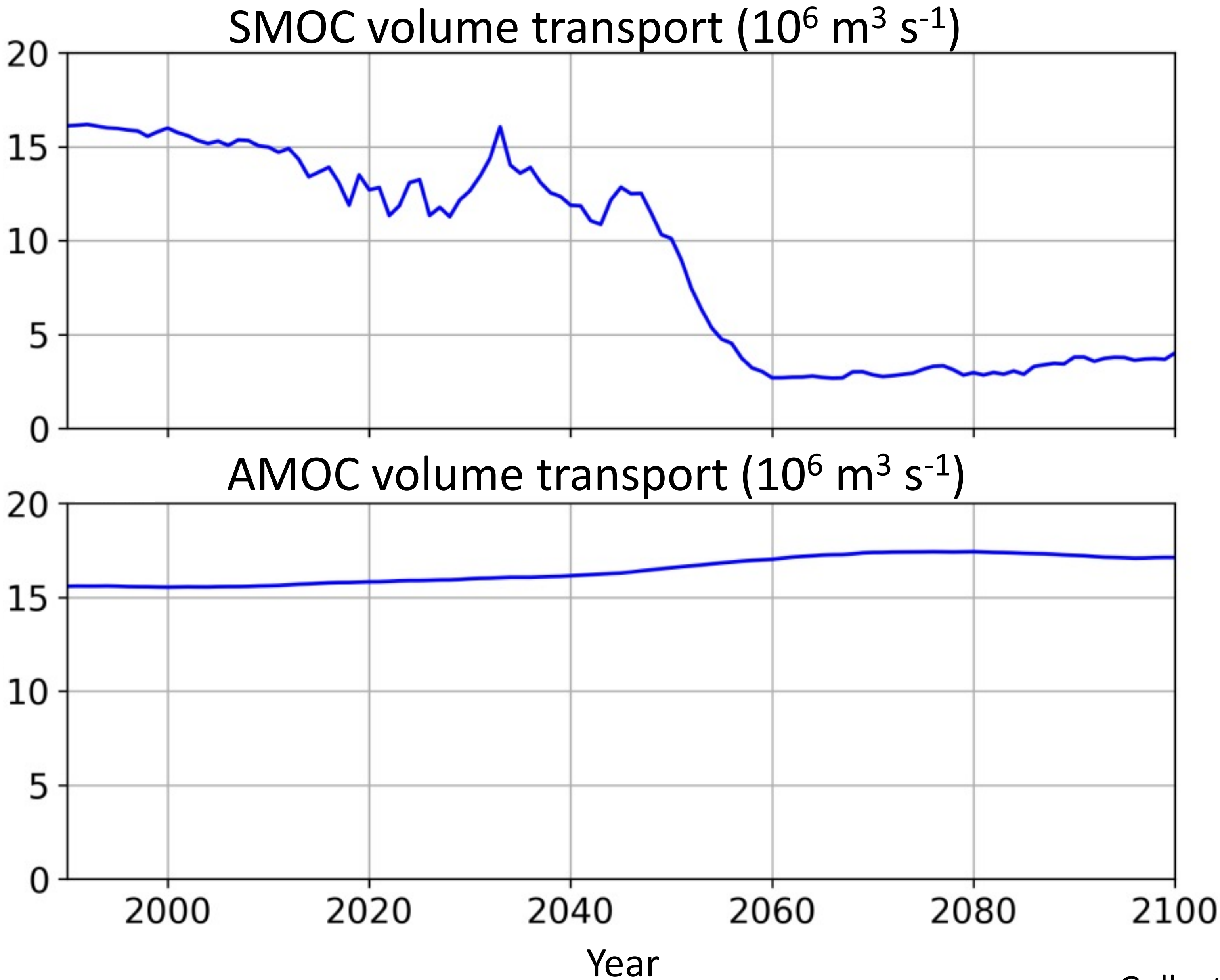
A study of Antarctic meltwater impacts on the MOC

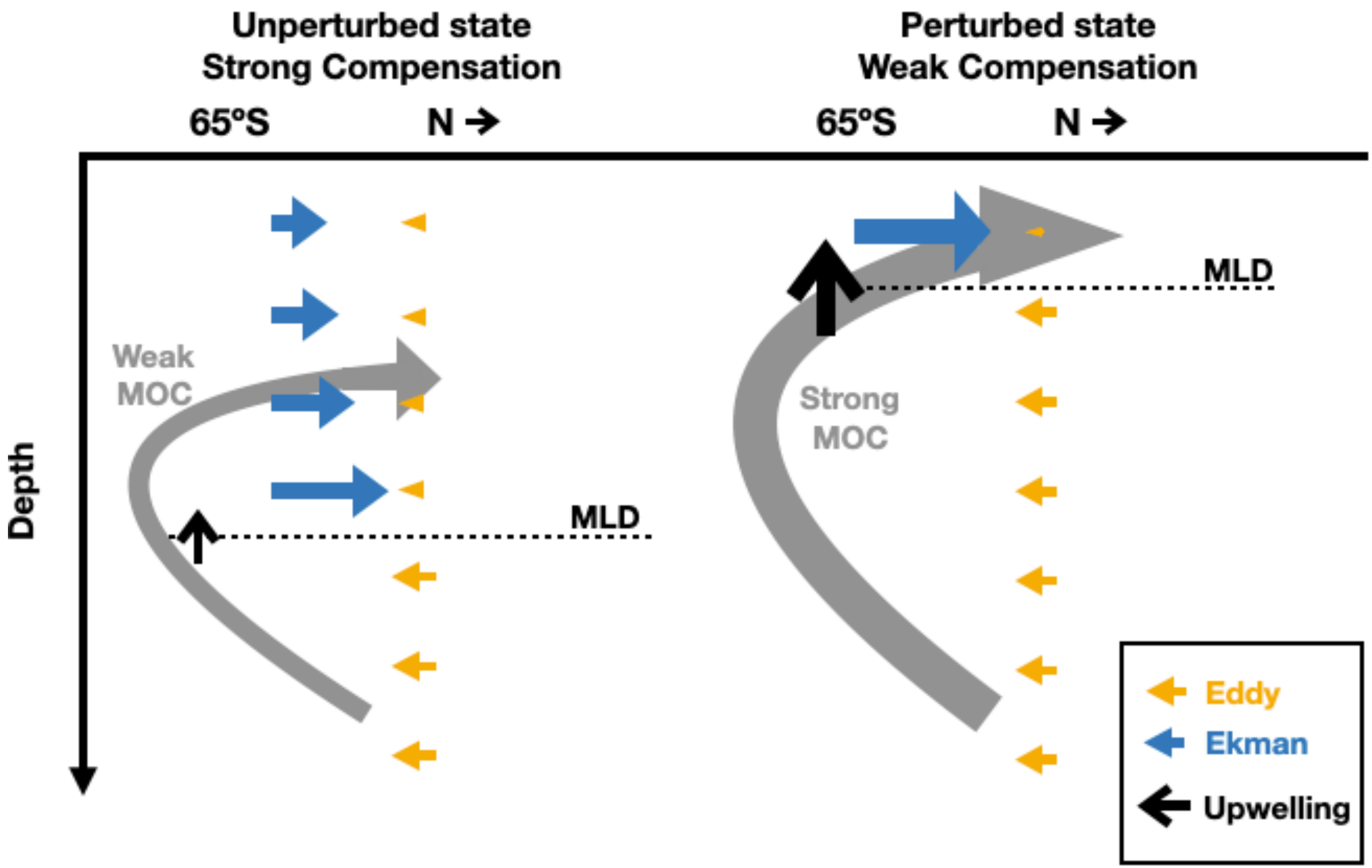


Results: SMOC collapse, AMOC increase!



Gulk *et al*. 2025

Meltwater separates Ekman and eddy-induced flows



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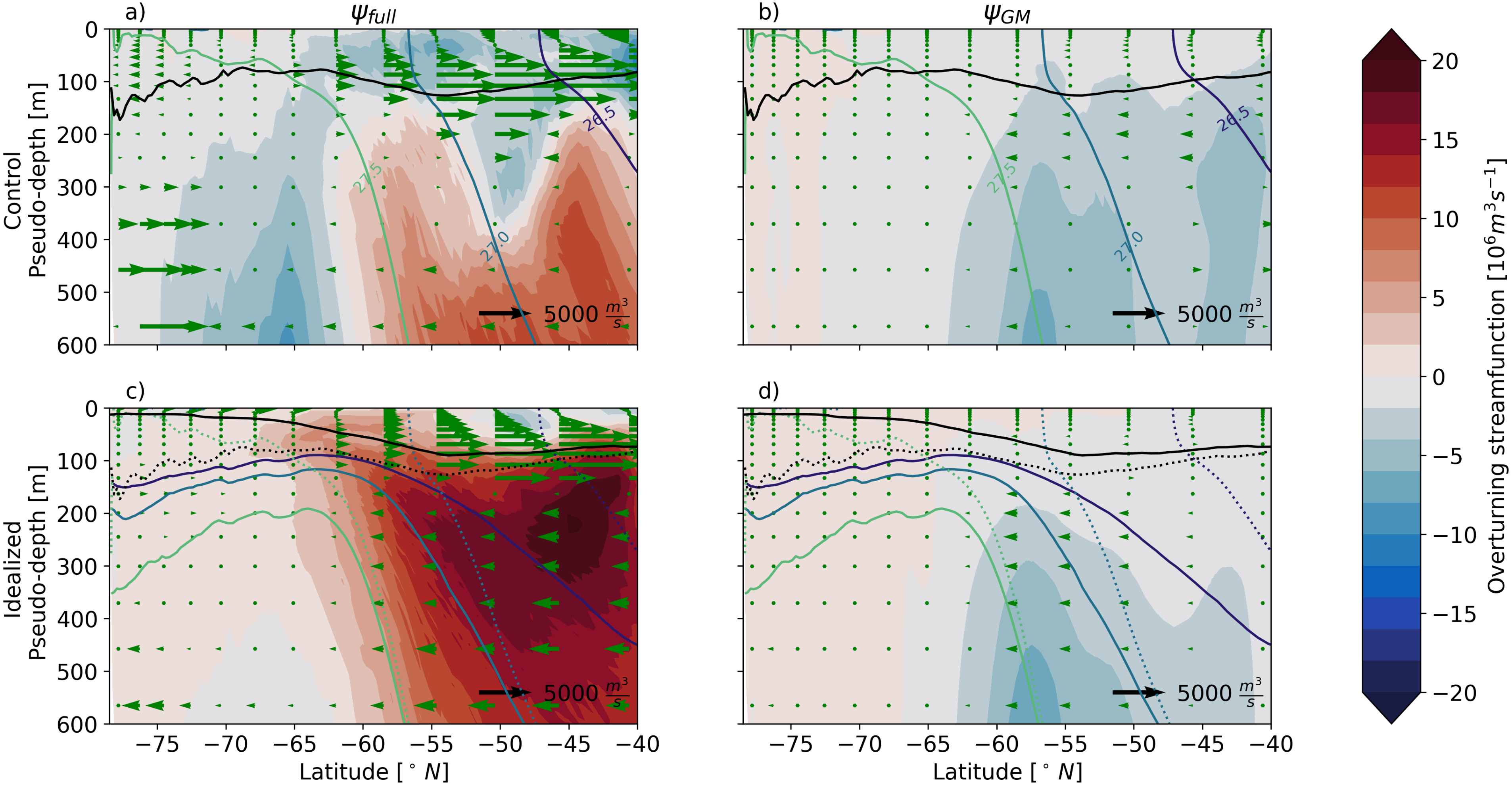
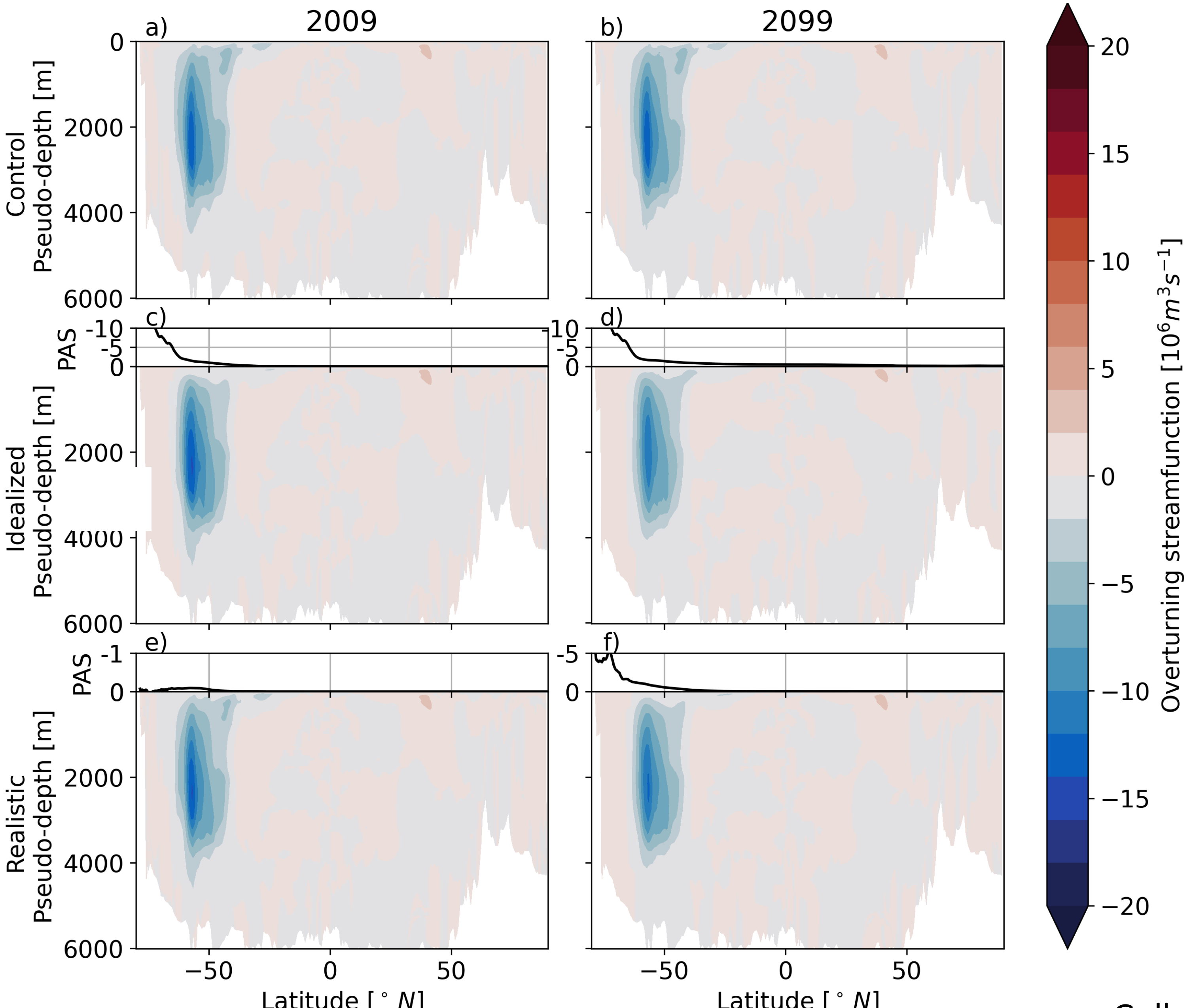


Gulk *et al.* 2025

Eddy-induced overturning is rather stable



Gulk *et al.* 2025

Conclusions

- Eddy compensation is the counteracting effect of mesoscale eddies on wind-driven overturning in the Southern Ocean.
- Eddy-induced circulation is poorly constrained from observations, and parameterized in most climate models.
- Parameterization choices can lead to opposite impacts on the mean-state AMOC, or to different responses to perturbations.
- Observations and theory needed, notably to constrain magnitude and vertical structure of K including suppression effects.

Part 5. Challenges for modelling and projecting the AMOC

- **Overturning pathways are debated and different across climate models**
- **Climate models struggle to accurately represent downwelling and upwelling**
- **Interactions with ice sheets are unrealistic but could be key**

Part 5. Challenges for modelling and projecting the AMOC

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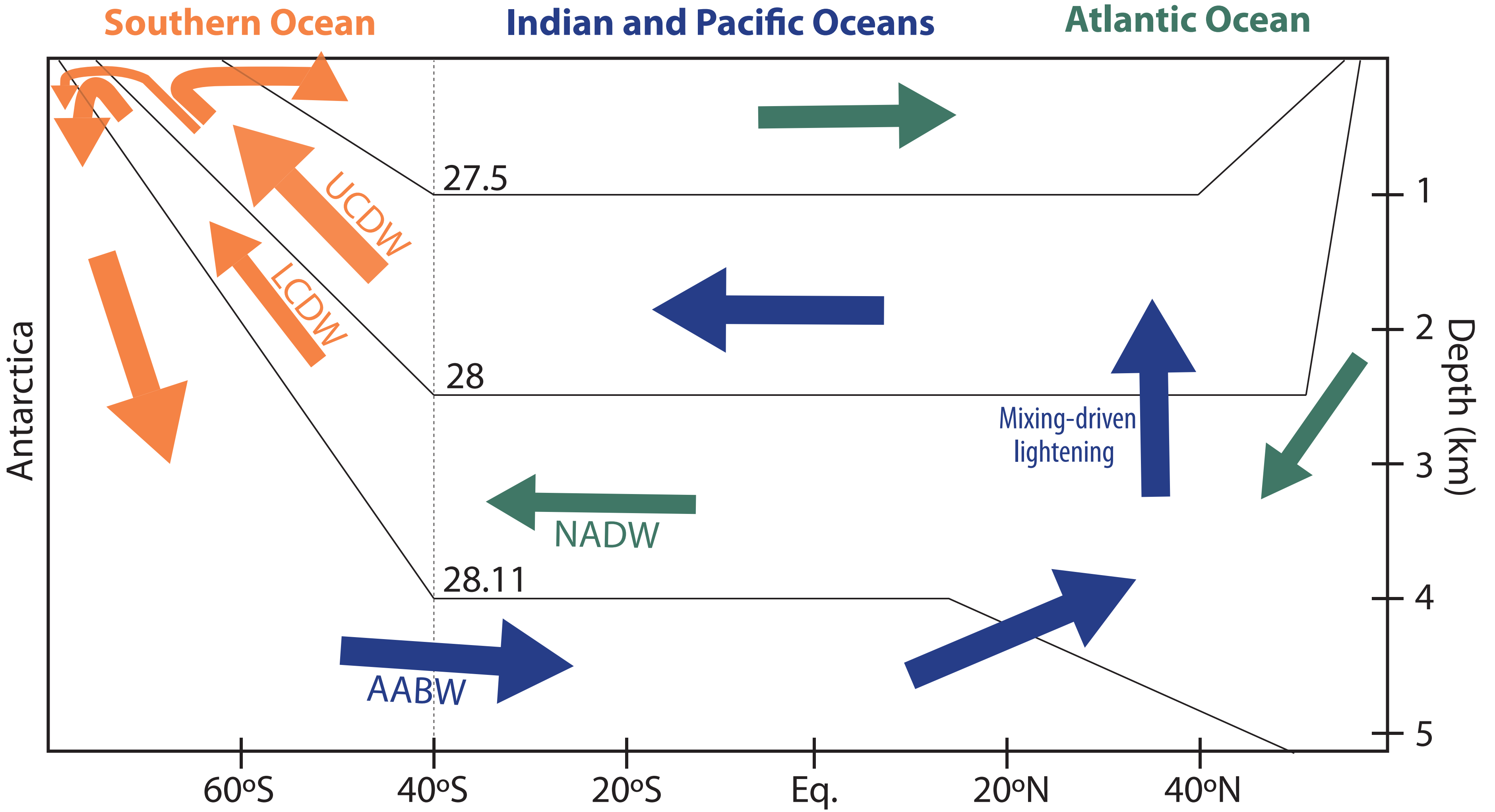
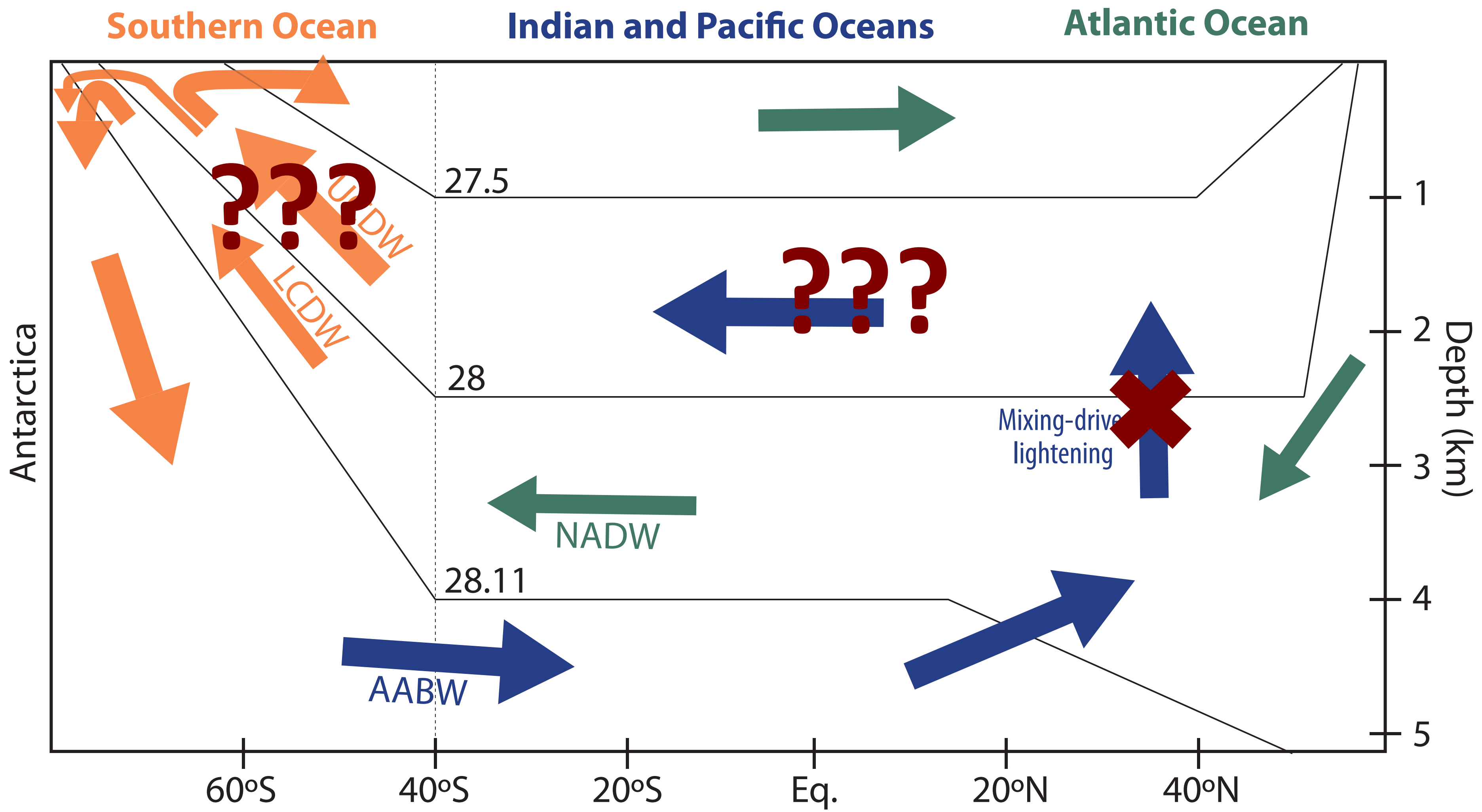
- Interactions with ice sheets are unrealistic but could be key

The figure-of-eight overturning

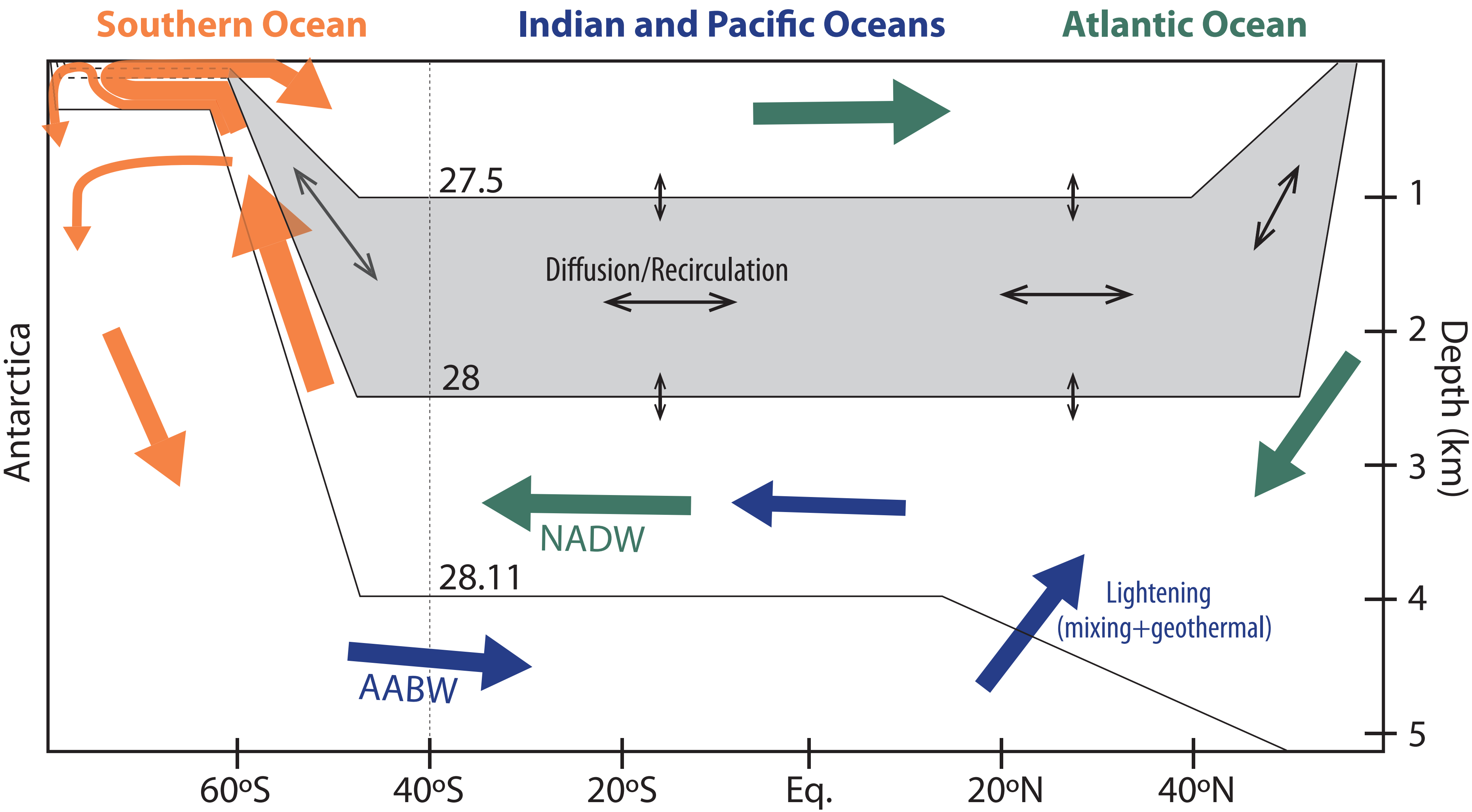


Talley 2013

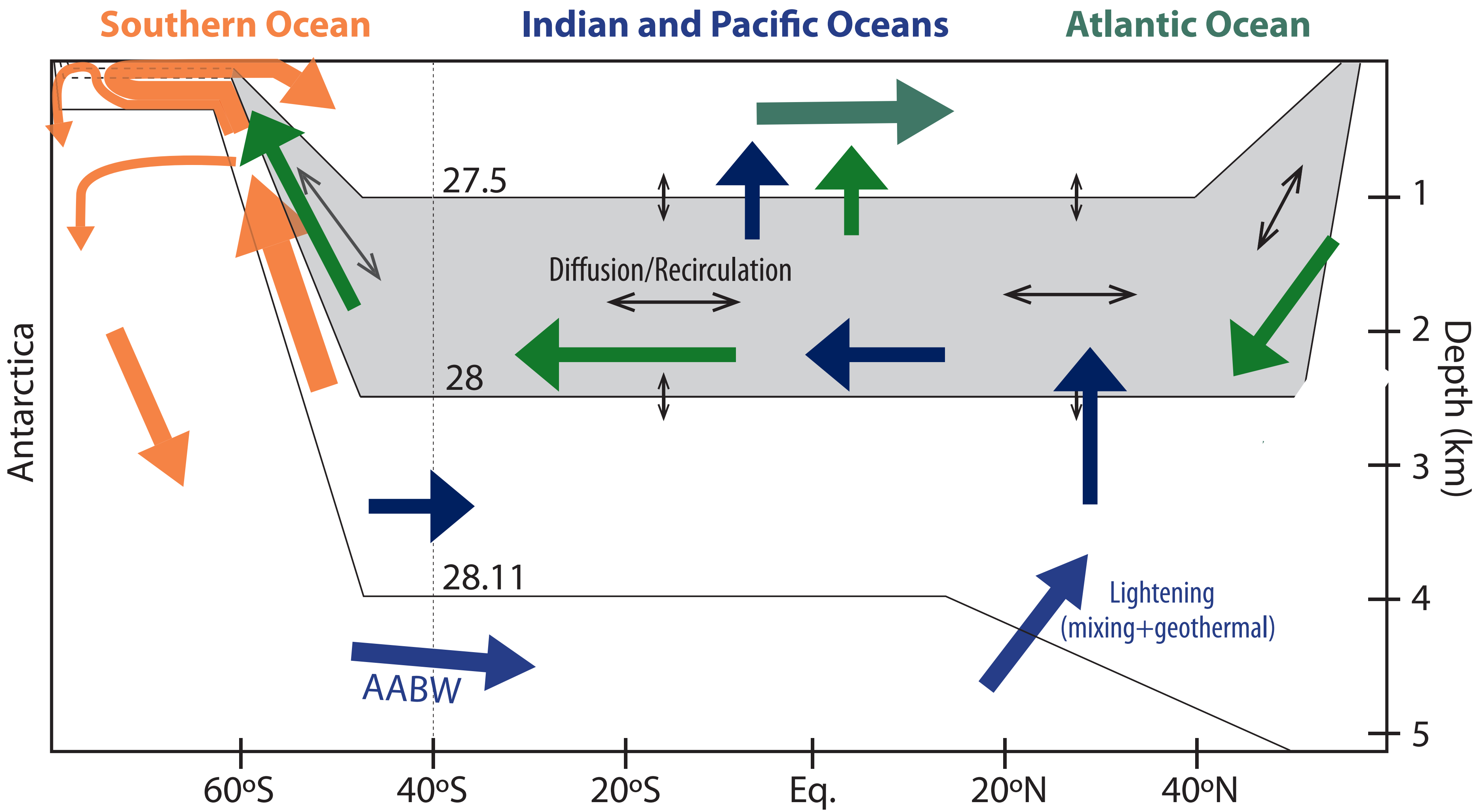
Not enough deep mixing



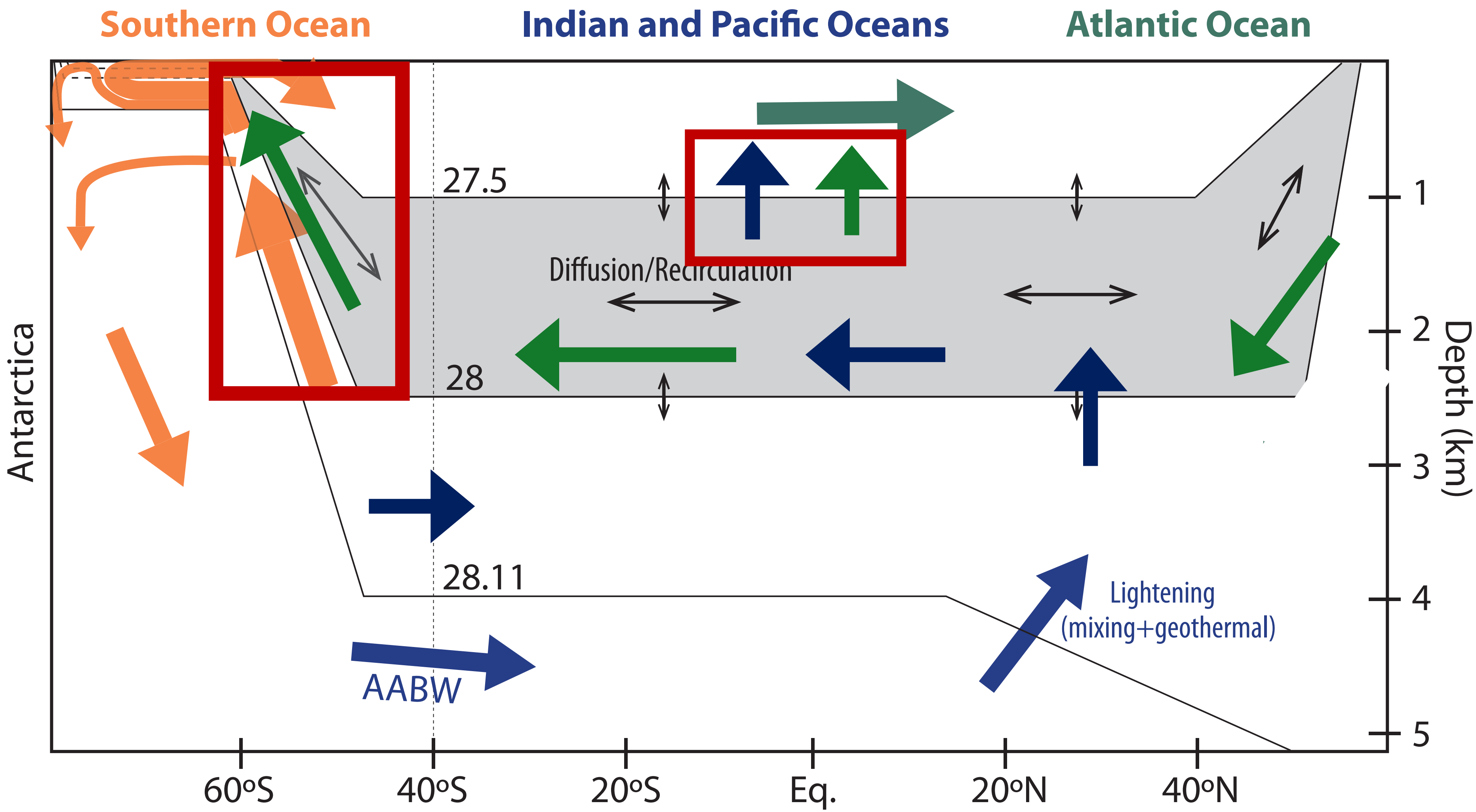
Hypothesis: a layer largely excluded from overturning



Typical climate models: southward flow biased shallow

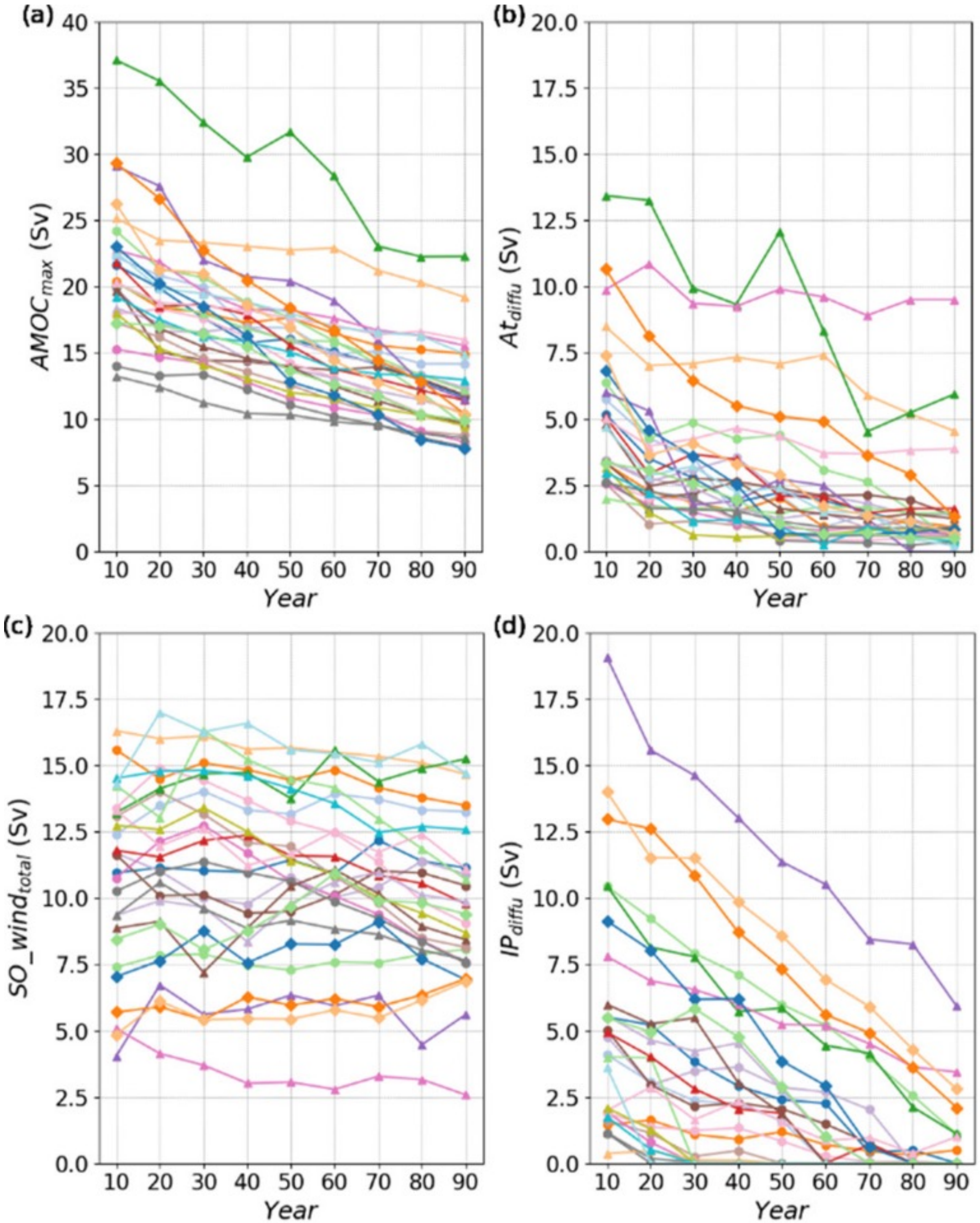


Variable proportion of low-latitude vs SO upwelling...



Baker *et al.* 2023

…affects predicted future AMOC slowdown



Variable overturning strength, decline and return pathways in CMIP6 climate models.

The return pathway via diffusive upwelling in the Indian-Pacific drops most under future warming.

Southern Ocean wind-driven upwelling is most stable.

Baker *et al.* 2023

Need for a robust observational reference

"Our findings indicate that by 2100, under a high greenhouse gas emission scenario, the AMOC will weaken by 29%–61%.

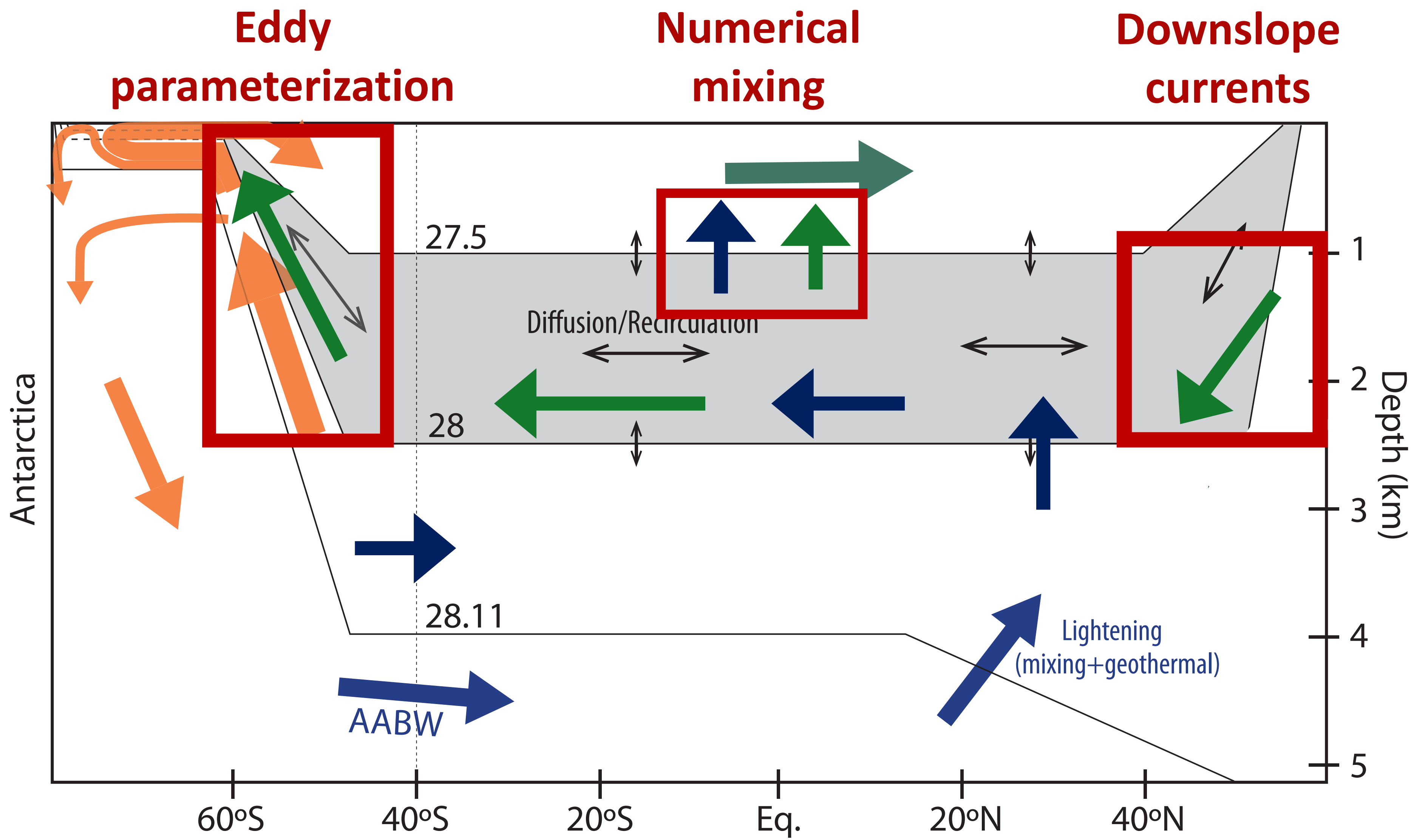
This highlights the importance of reducing differences between observational estimates of the ocean's overturning pathways to reduce uncertainty in future AMOC weakening and to improve the representation of these pathways in climate models."

Baker *et al*. 2023

Part 5. Challenges for modelling and projecting the AMOC

- Overturning pathways are debated and different across climate models
- **Climate models struggle to accurately represent downwelling and upwelling**
- Interactions with ice sheets are unrealistic but could be key

Challenges: downslope currents, eddies and numerical mixing



Slow ongoing progress

- New eddy parameterizations that are energetically and observationally constrained (Mak et al. 2022, Torres et al. 2025)

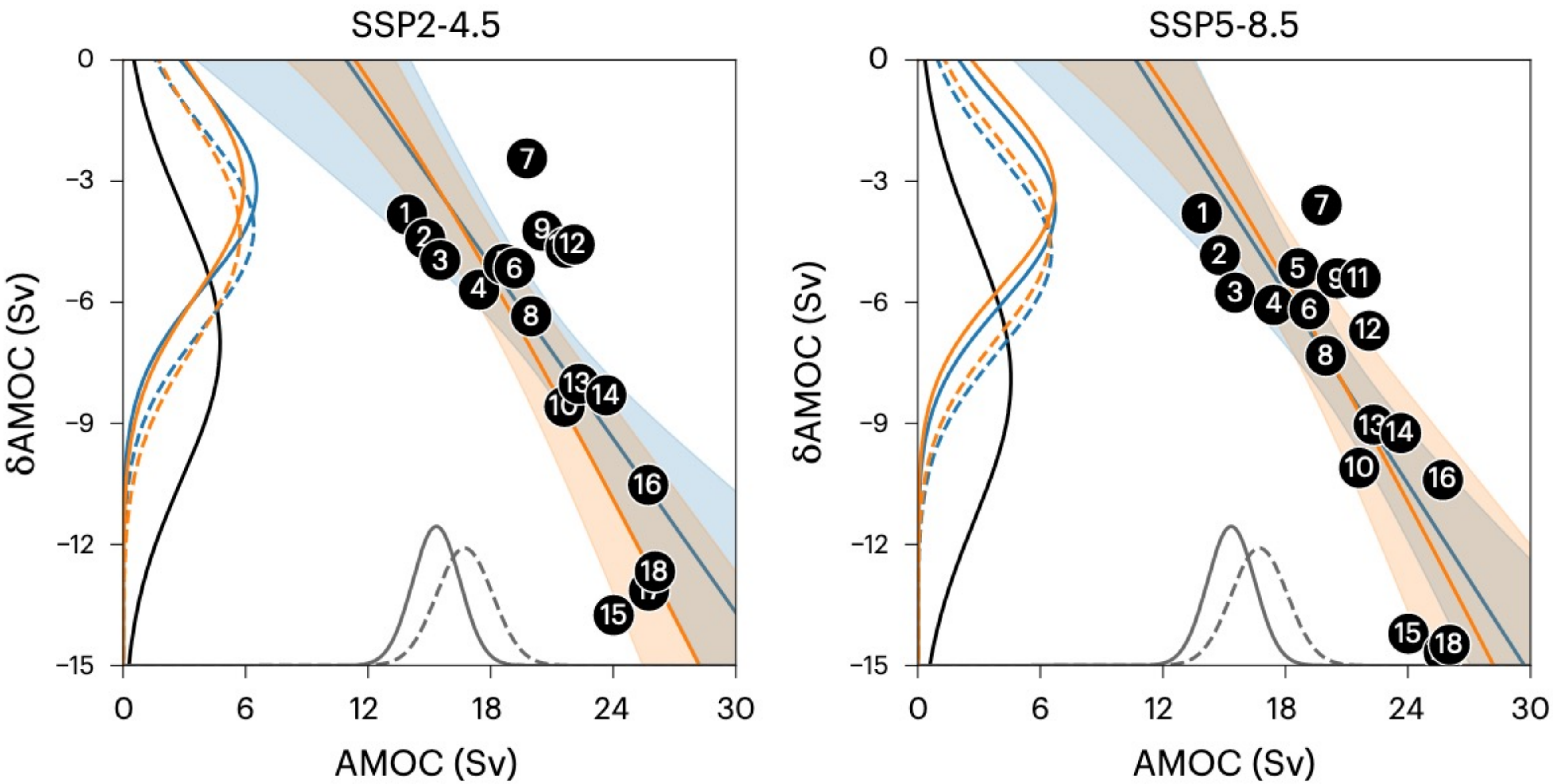
- Vertical coordinates and advection schemes allowing reduced numerical mixing and improved downslope currents (Griffies et al. 2020, 2025)

- New representations of topography (Nasser 2023)

- New 'EDMF' convection schemes that better capture penetrative convective plumes (Giordani et al. 2020)

- Better atmospheric models…

Alternative: emergent constraints



- ”By incorporating observational constraints, we conclude that the AMOC will experience limited weakening of about 3–6 Sv (about 18–43%) by the end of this century, regardless of emissions scenario.”
- “The uncertainty in 21st century AMOC weakening and the propensity to predict substantial AMOC weakening can be attributed primarily to climate model biases in accurately simulating the present-day ocean stratification.”

Bonan *et al*. 2025

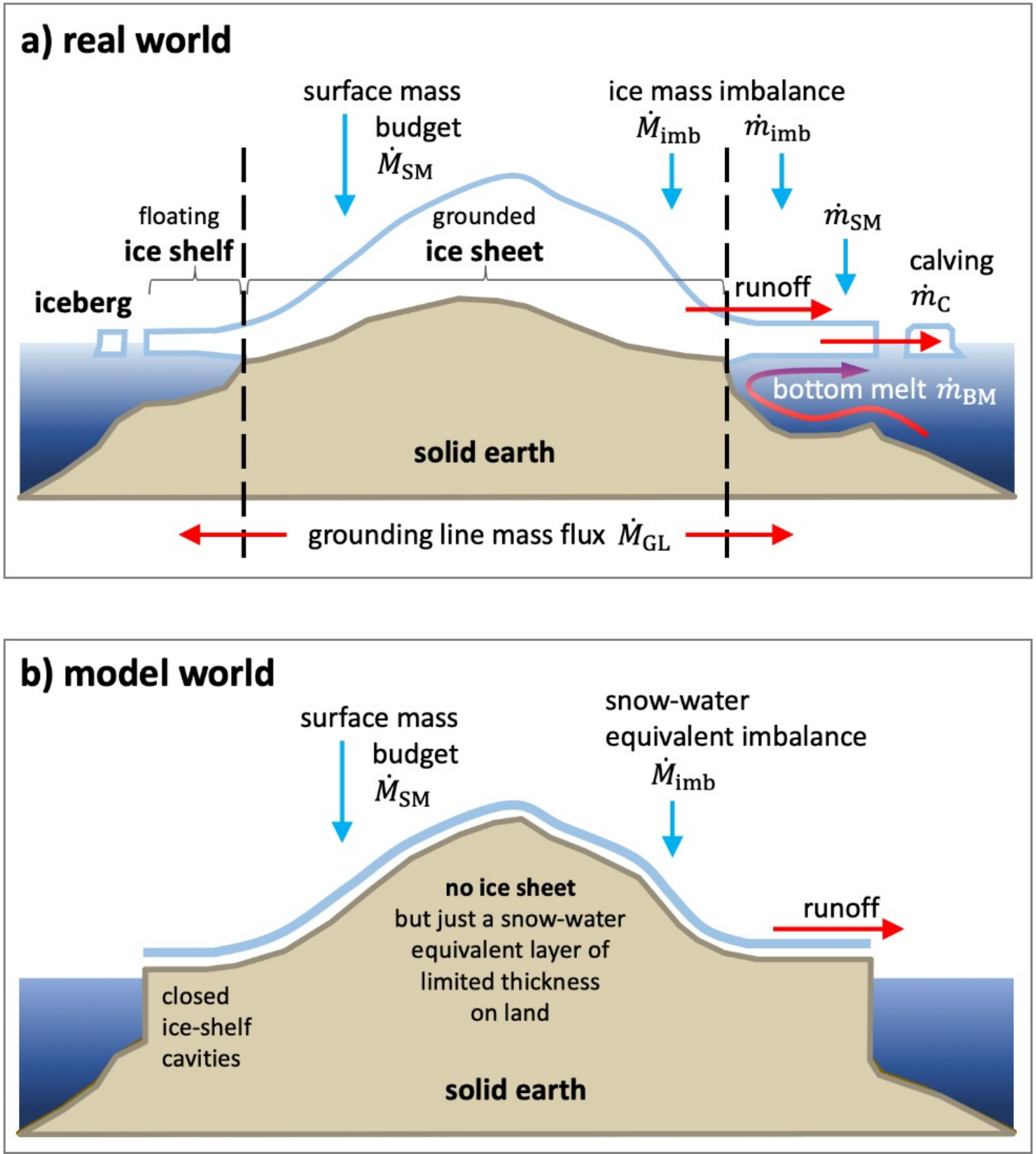
Part 5. Challenges for modelling and projecting the AMOC

- Overturning pathways are debated and different across climate models

- Climate models struggle to accurately represent downwelling and upwelling

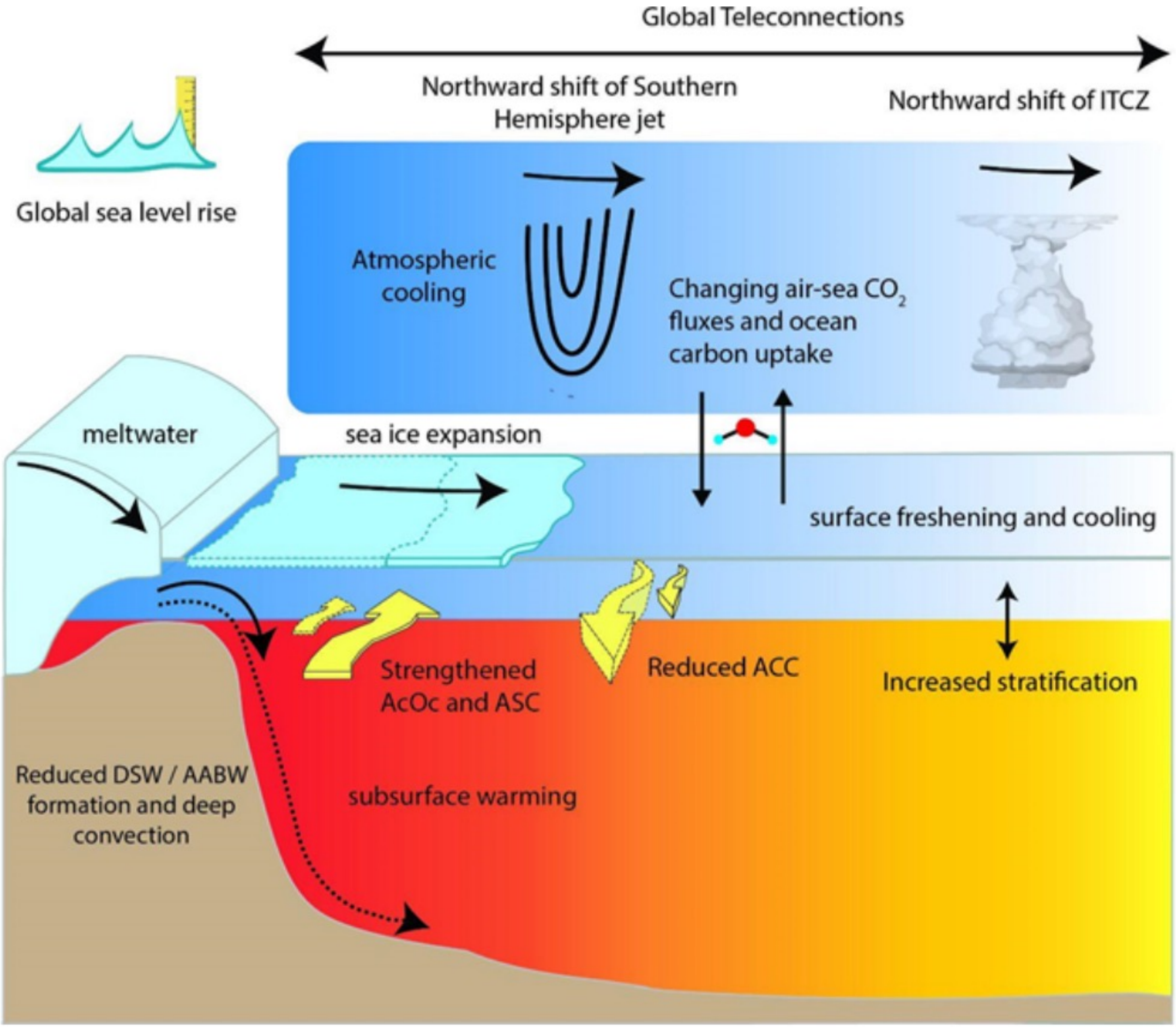
- **Interactions with ice sheets are unrealistic but could be key**

No interactive ice sheets in climate models...



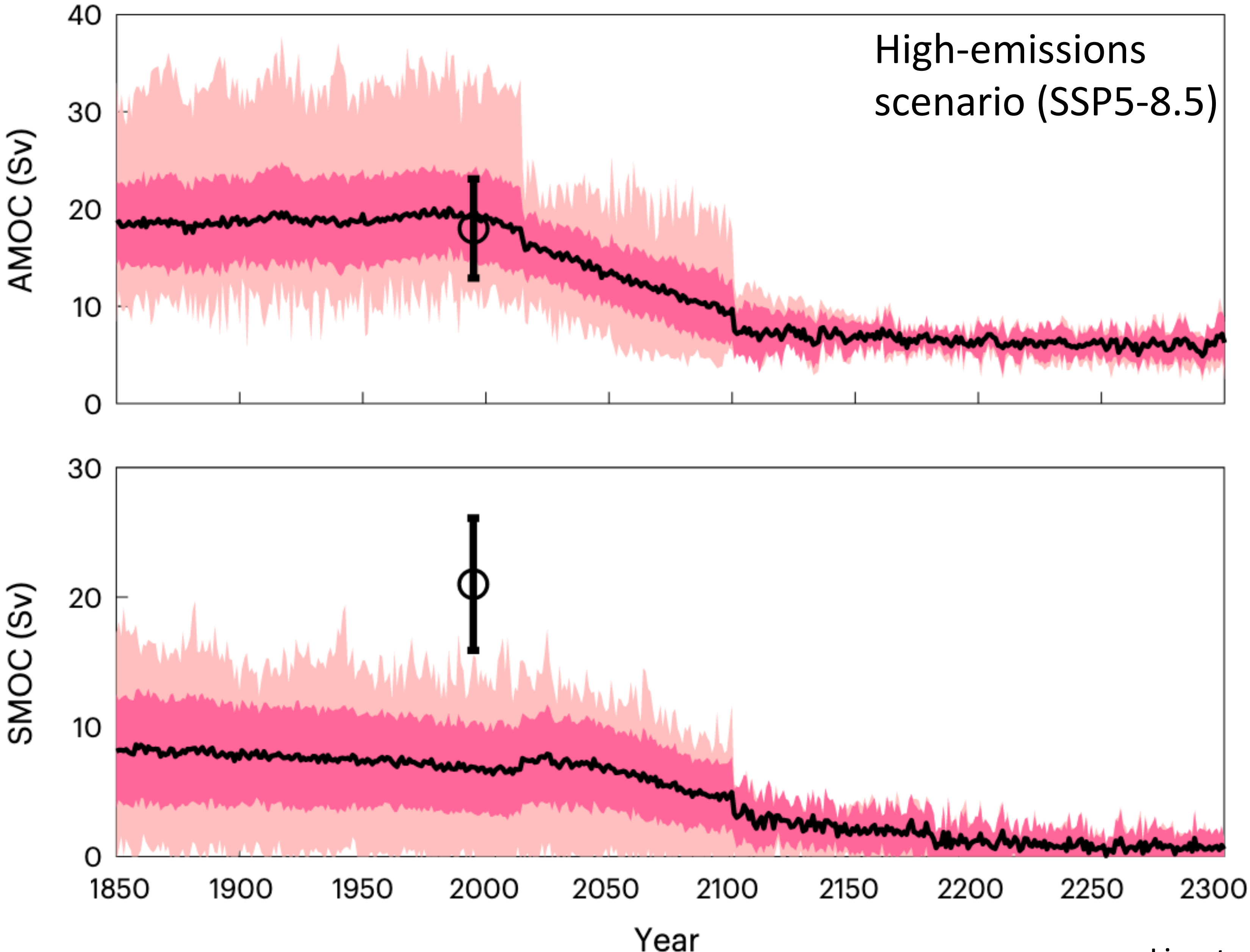
Swart *et al*. 2023

…despite multiple climate impacts



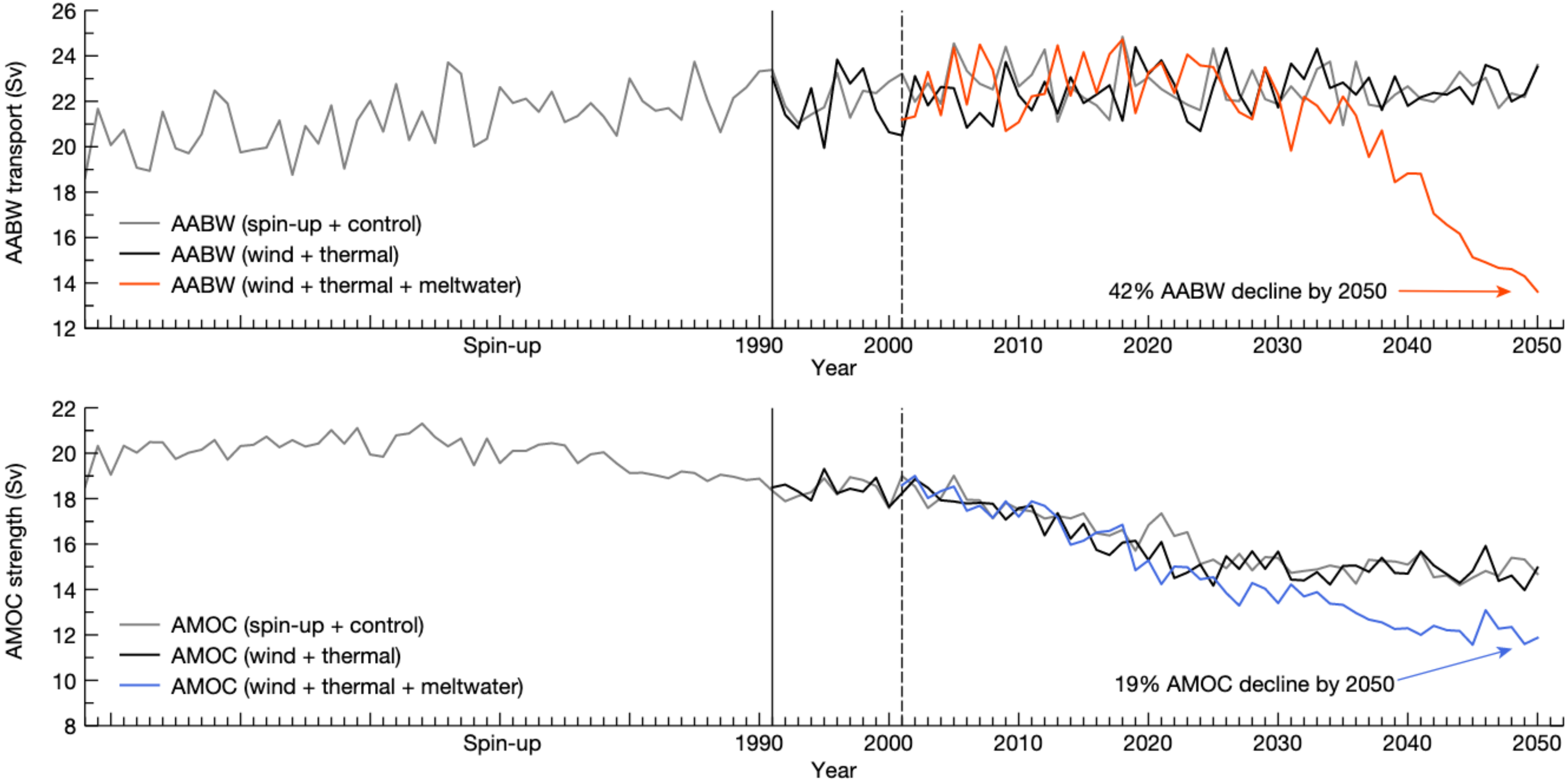
Swart *et al.* 2023

CMIP6 projections without ice sheet mass losses



Liu *et al.* 2023

A projection with Antarctic & Greenland meltwater



➢ The impact of increasing ice sheet melting is likely first-order.

Li *et al*. 2023

Conclusions

- Climate models struggle to represent upwelling and downwelling branches of the AMOC.
- Observational constraints and model improvements both required to reduce uncertainty in AMOC future.
- Interactions with ice sheets must be accounted for.
- The AMOC is probably more resilient than the SMOC, largely thanks to resilient wind-driven upwelling in the Southern Ocean.