# The AMOC in a Global Context: Insights from Thermodynamics

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# How is the AMOC closed over the global scale?

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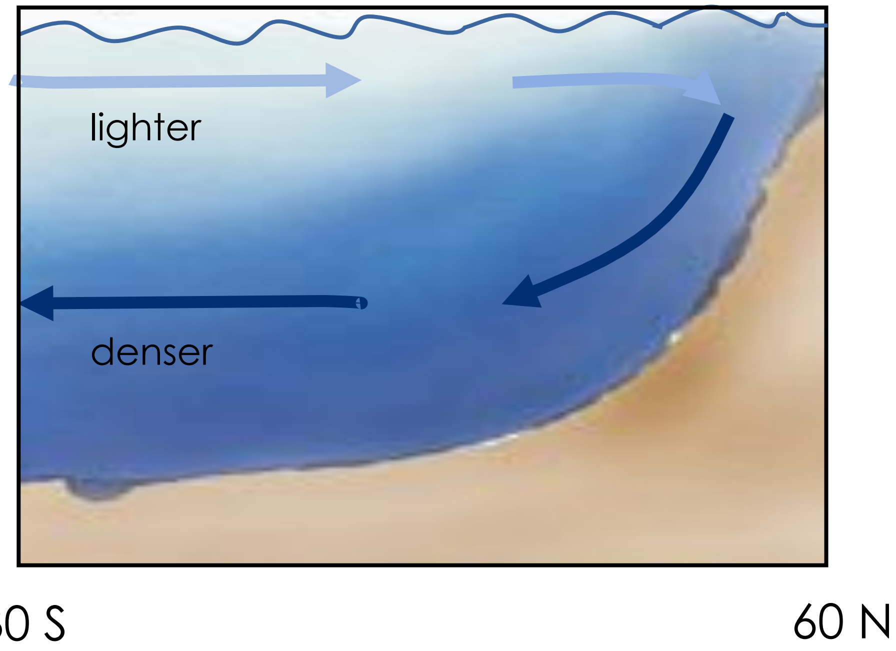
Part One: Discuss different ideas, their evolution, and their inconsistencies.

Part Two: Use the global buoyancy flux  distribution to constraint the problem and place distinct mechanisms in their global context

# Part One: Closing The AMOC

The overturning circulation that transports tracers- the “residual circulation”- is the movement of water *along and across density classes.*




In the Atlantic, water is moved from lower density classes to higher density classes. Lighter waters flow in, denser waters flow out.

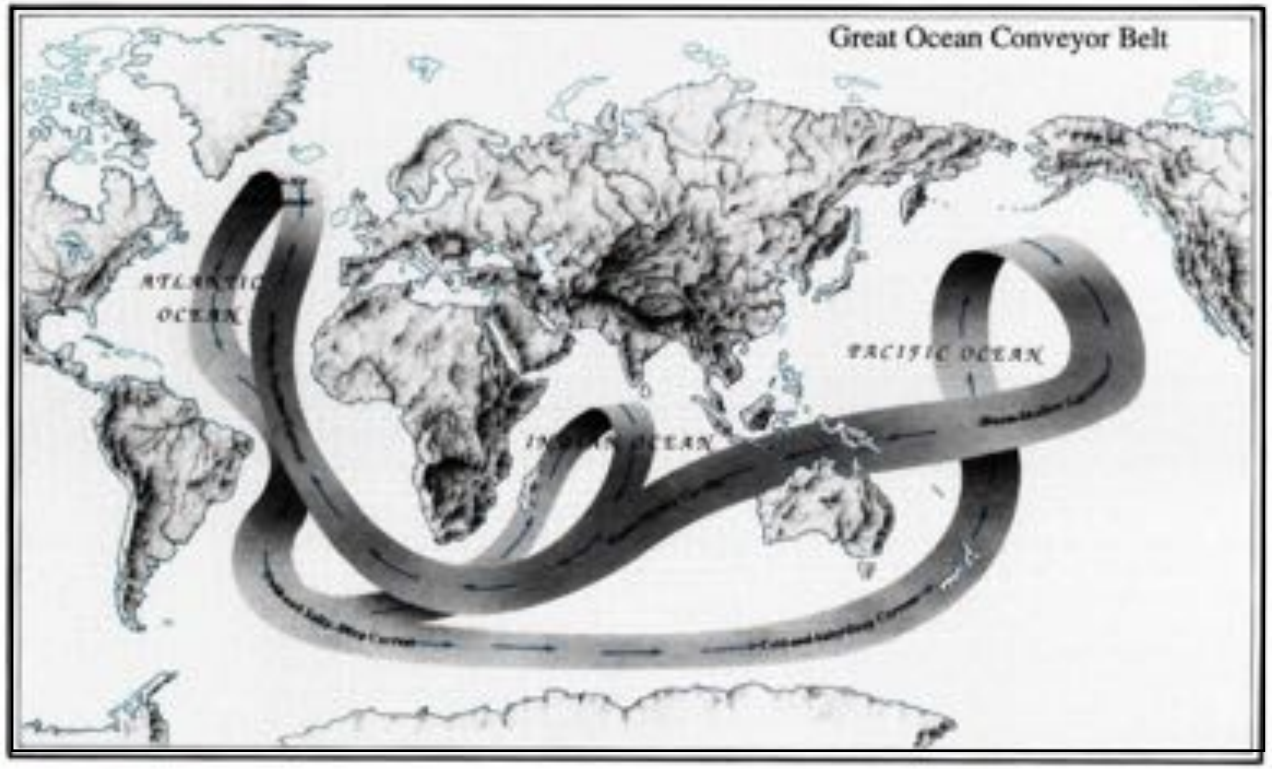
Somehow, somewhere outside of the Atlantic, these dense waters must be made light again.

# The AMOC and the Indo-Pacific

NADW formation is balanced by turbulent downward diffusion of heat through the **tropical and subtropical thermoclines** (e.g. Robinson and Stommel 1959, Stommel and Arons, 1959a,b, Munk 1966, Welander, 1971).

This diffusive upwelling occurs primarily in the **Indo-Pacific** (e.g. Gordon, 1986, Broecker, 1987), returning to the Atlantic along the **"warm route."**

Except… the required mixing rates are not observed!



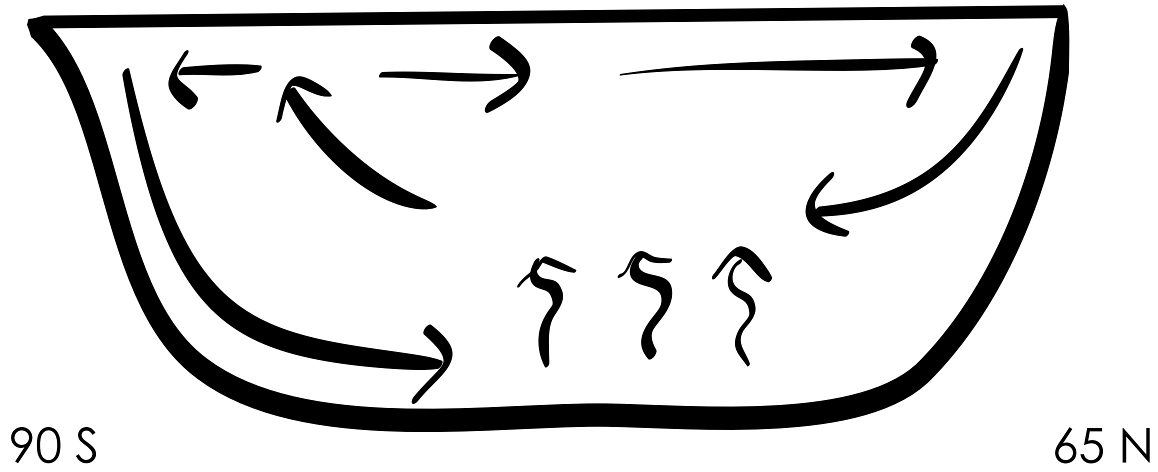

Broecker's Conveyor Belt

# The AMOC and the Southern Ocean

Toggweiler and Samuels (1995): NADW's **adiabatic**, wind-driven pathway to the **Southern Ocean** surface and return to the Atlantic via the **"cold route"** (e.g. Rintoul, 1991),

This is supported by inverse modelling studies *(Rintoul, 1991, Macdonald and Wunsch 1996; Ganachaud 2000, Sloyen and Rintoul, 2001)*.

The global Meridional Overturning Circulation

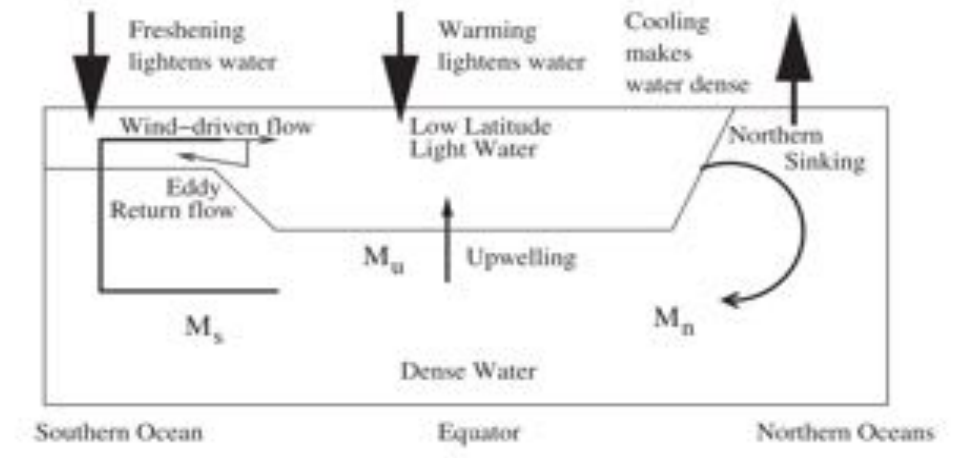



The AMOC and GOC has key meridional asymmetry. Further, it is influenced by processes outside the Atlantic!

# The AMOC and the Southern Ocean:

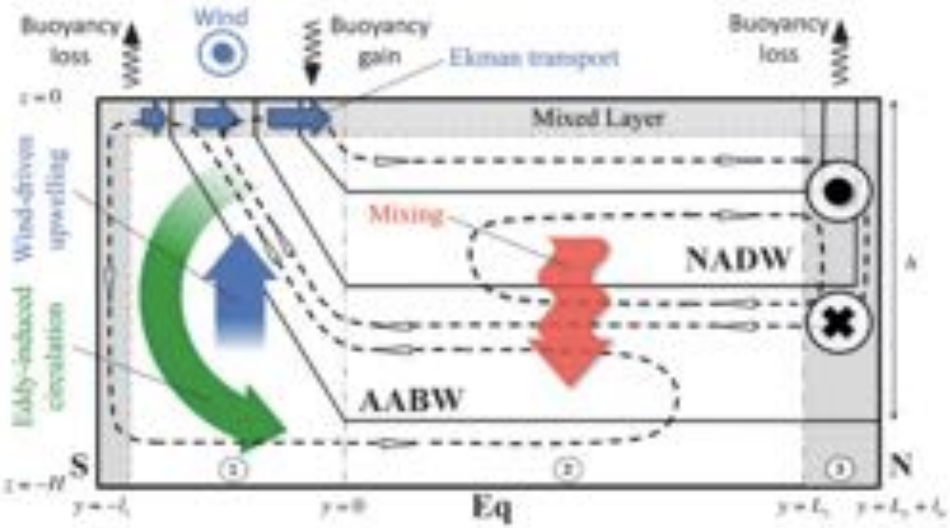
"Basin and Channel" models

Pioneered by Gnanadesikan (1999)




Gnanadesikan, 1999

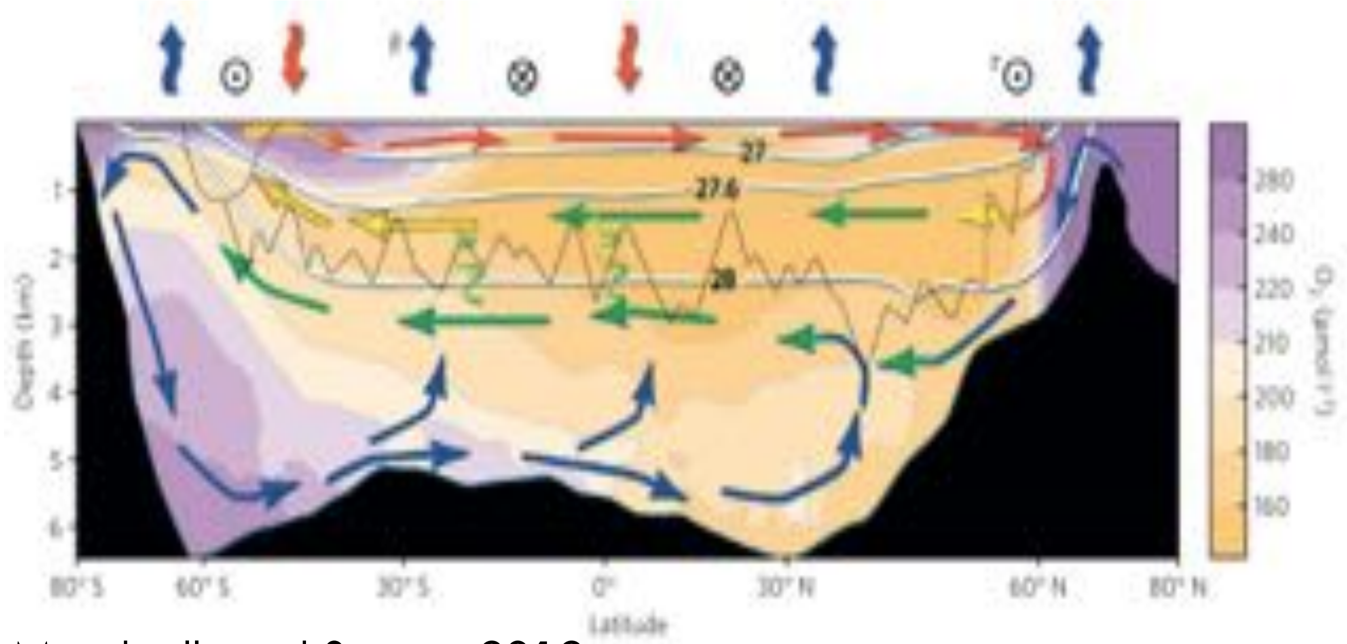
Subsequently, *Wolfe and Cessi, 2011,2015, Haertel and Fedorov, 2012, Shakespeare and Hogg, 2012, Nikurashin and Vallis, 2011, 2012, Munday et al., 2013, Stewart et al., 2014, Cimatoribus et al., 2014, Bell, 2015, among others.*




Nikurashin and Vallis, 2012

Exposed key controls of NADW formation rates, Southern Ocean surface flux pattern, winds, and eddies, and abyssal mixing.

# The Global Meridional Overturning Circulation Paradigm




Marshall and Speer, 2012

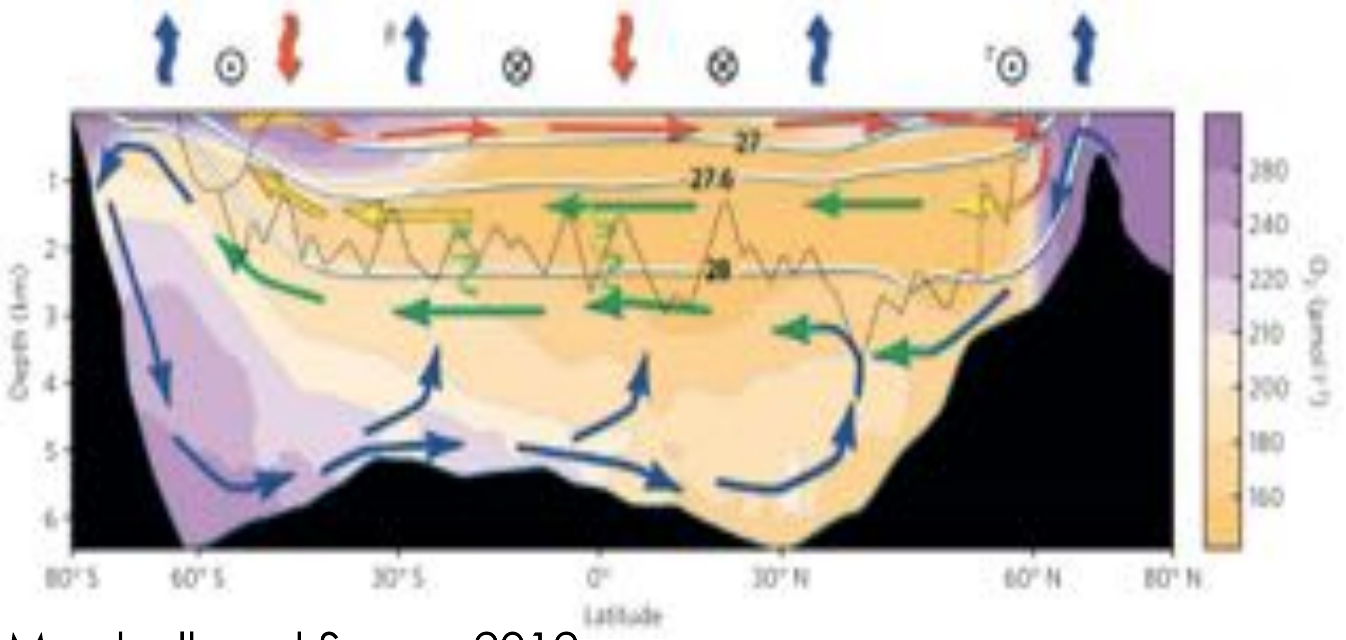
"upwelling pathways and … controlling physical mechanisms have long been debated, but they have now come into clearer focus."

## Unlike earlier theories…

- Little evidence of vigorous mixing across the thermocline; diapycnal mixing occurs primarily in the abyssal ocean.
- The global circulation is controlled by North Atlantic, Southern Ocean, and abyssal processes.
- Glacial interglacial cycles are mediated by North Atlantic and Southern Ocean processes*
- Coupling to Indo-Pacific surface processes is either small or unimportant, and passive.

**e.g. Broeker, 1992, Stocker, 1998, Alley, 2003; Togweiller et al., 2006; Anderson et al., 2009, Watson and Naveria Garabato, 2006, among many others*

# The Only Problem…



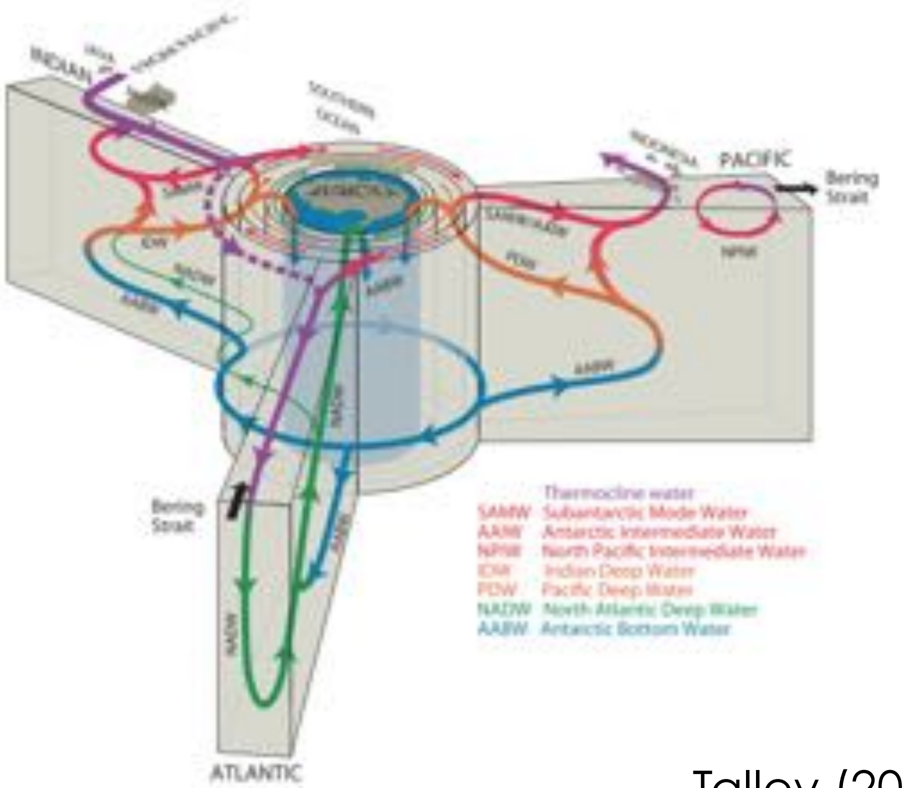
Marshall and Speer, 2012

Other studies support of an equally important *(e.g. Speich et al., 2002)* or *dominant (e.g. Speich et al., 2007, Donners and Drijfort 2004)* "warm route" component.

Further, significant flows through the ITF and into the Atlantic are observed in many estimations (*e.g. Gordon, 1986,1987, Schmitz, 1995, Talley, 1999, 2003, Lumpkin and Speer, 2007, Beal et al., 2011)*

# Accepting a complex Global Overturning Circulation

Talley (2013): the zonal average collapses essential zonal dynamics mediated by the Southern Ocean.




Talley (2013)

Additionally, the role of the "warm" versus "cold" routes depends on SH wind distribution (e.g. Oke and England, 2004) and continental distribution (e.g. Nillson et al. 2013, Cessi and Jones, 2017), suggesting that, currently, the "warm route" dominates.

# Part One Summary (or, where are we now?)

The pathways by which deep waters circulate the ocean, and return to the surface, are compilated, global, and inconsistent across the literature.

The respective roles of zonal, meridional, deep, and upper ocean dynamics as a function of climate state and surface forcing remain unclear.

In an effort to gain a new perspective on global-scale dynamics, and reconcile inconsistencies, let's call upon an relatively unconstrained aspect of the problem in most theories.

the **global** distribution of surface buoyancy fluxes.

# Part Two: Constraints from surface buoyancy flux

Theories of overturning dynamics are largely built within conceptual and modeling frameworks that 1) expect the circulation is sensitive to surface fluxes in the Atlantic and Southern Ocean and interior dynamics and 2) expect the the low latitudes /Indo-Pacific surface to act as a passive, infinite reservoir.

## In Practice, most idealized ocean models:

Relax to (or prescribe) low latitude boundary conditions

Average low latitude flux to one bulk value

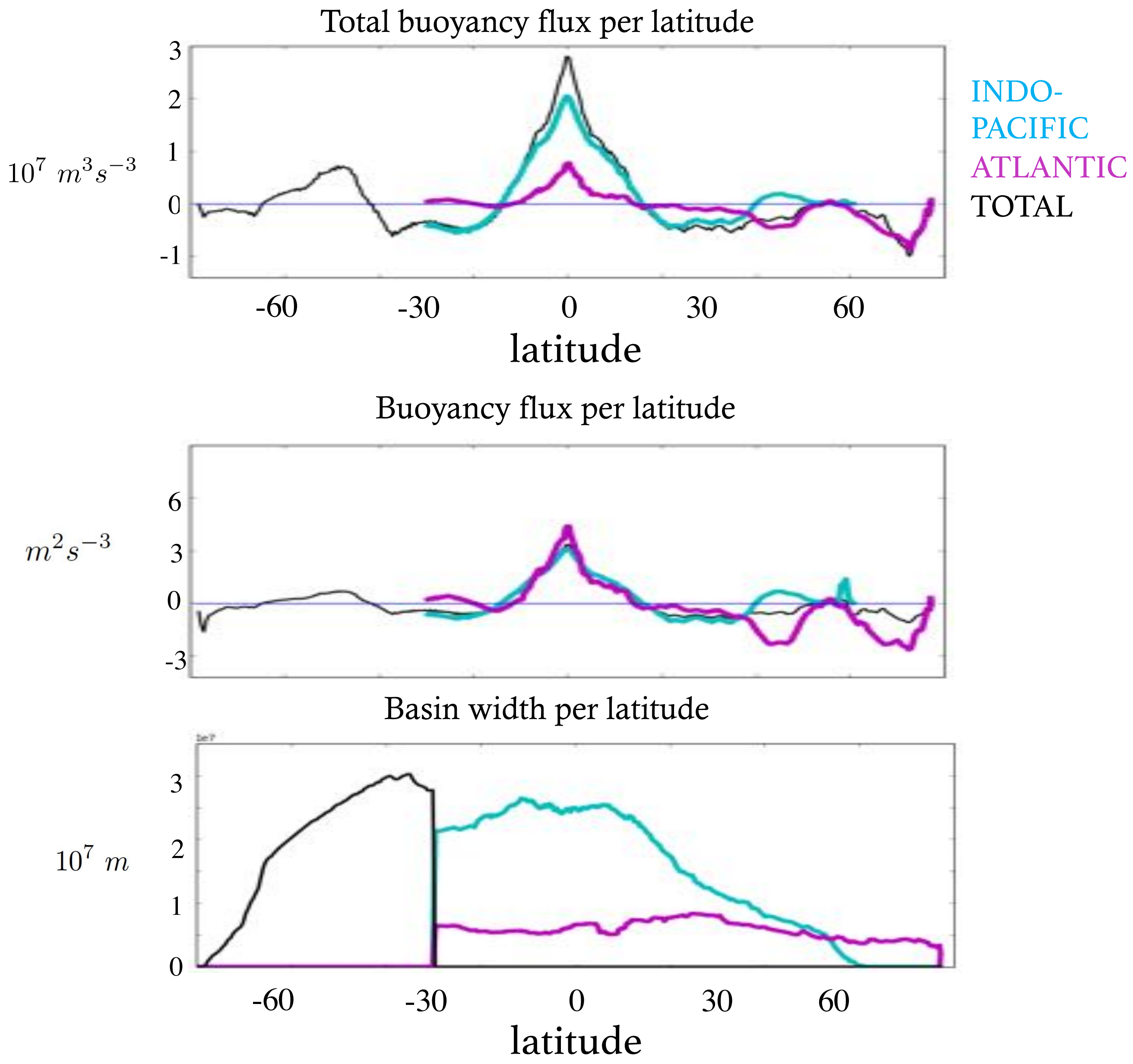
Neglect equatorial gyre circulations

# The Global Surface Buoyancy Flux Distribution

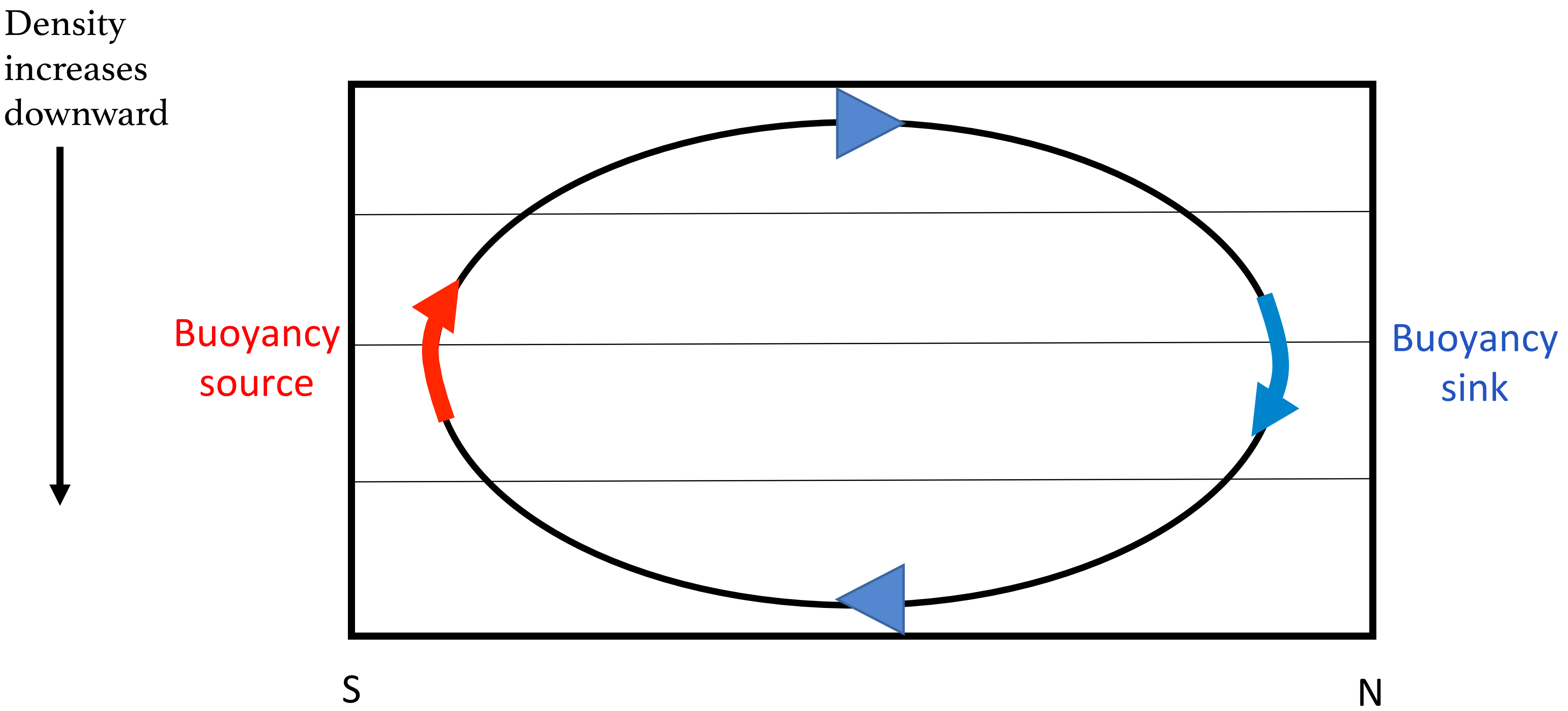
(preindustrial control run in CESM 1.0)

We have a system in which we loose buoyancy from different basins than we gain it.

But we want a constraint on the residual circulation, $\boldsymbol{\Psi}$



# Coupling of volume and buoyancy: Water Mass Transformation



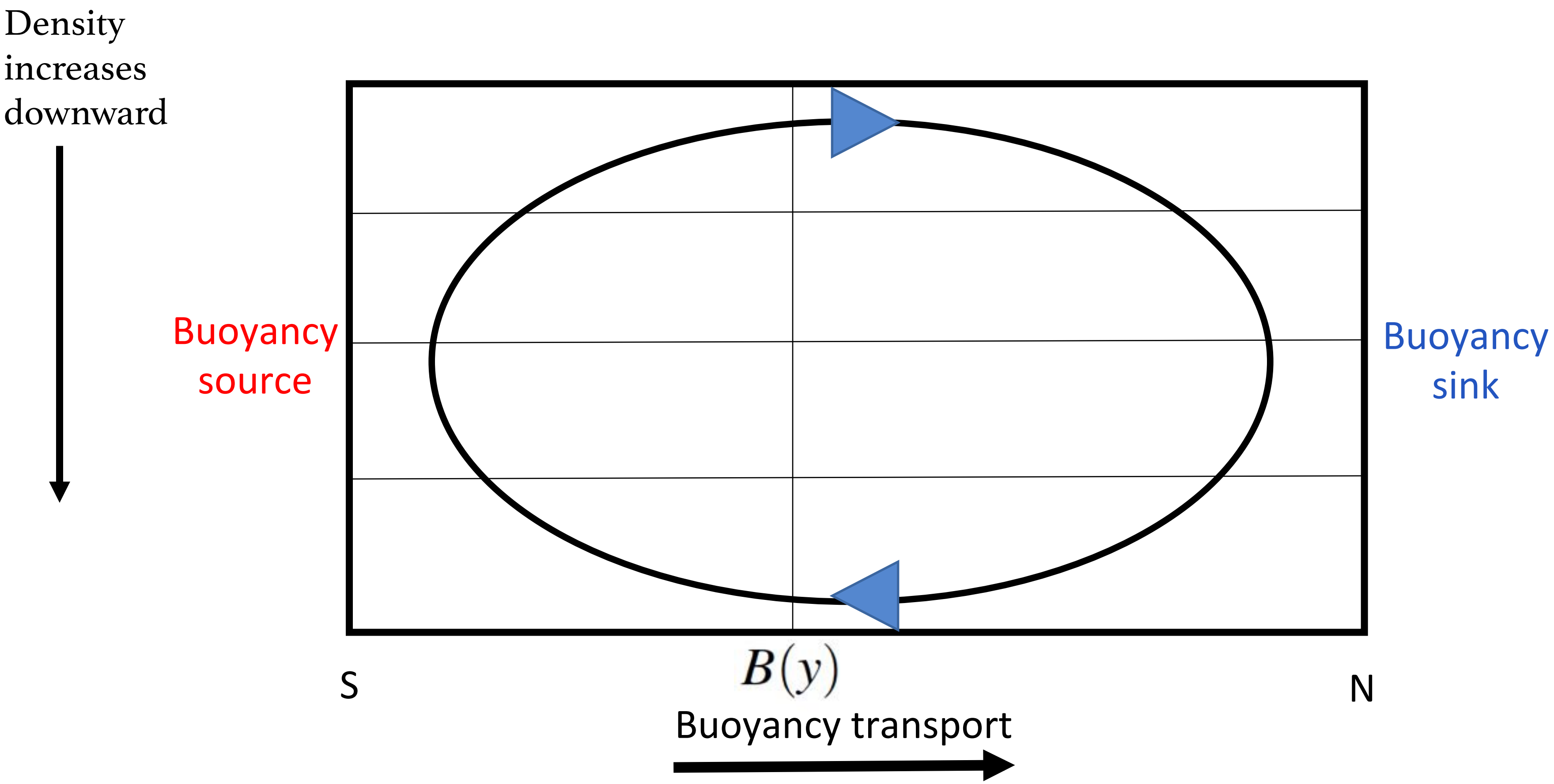

A residual circulation

$$\Psi(y, \sigma)$$

The transport of volume across density classes - "Water Mass Transformation" - requires sources and sinks of buoyancy (e.g. Walin, 1982, Speer and Tziperman, 1992).

(e.g. Speer and Tziperman, 1995, Bryan et al., 1995, Nurser et al. , 1999, Marsh et al., 2000, Radko and Kamenkovich, 2008, Iodicone et al., 2008, Cerovečki et a., 2013, Abernathy et al., 2016, Newsom et al., 2016, among many others).

# Coupling of volume and buoyancy: Buoyancy Transport




A residual circulation must transport buoyancy! This constrains its integrated state.

$$B(y) = -\frac{g}{\rho_0}\int_{\sigma(z=-H)}^{\sigma(z=0)} \Psi(y,\sigma)\,d\sigma$$

*Akin to a Heat or Salinity Function (e.g., Boccaletti et al., 2005, Ferrari and Ferraira, 2011, Zika, 2013, ), but for buoyancy and the residual circulation itself

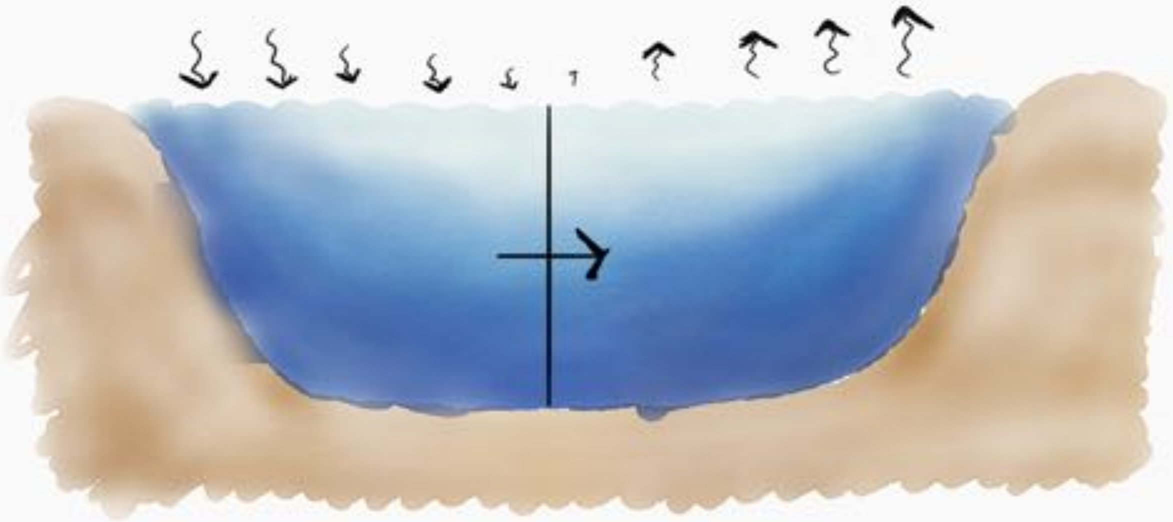
Newsom and Thompson, submitted

# Linking surface buoyancy flux and the GOC

We now have a constraint
on the circulation because

To leading order, what goes in must come out.

(Assuming: steady state, a linear Equation of State,
and neglecting geothermal heating)



Newsom and Thompson, submitted

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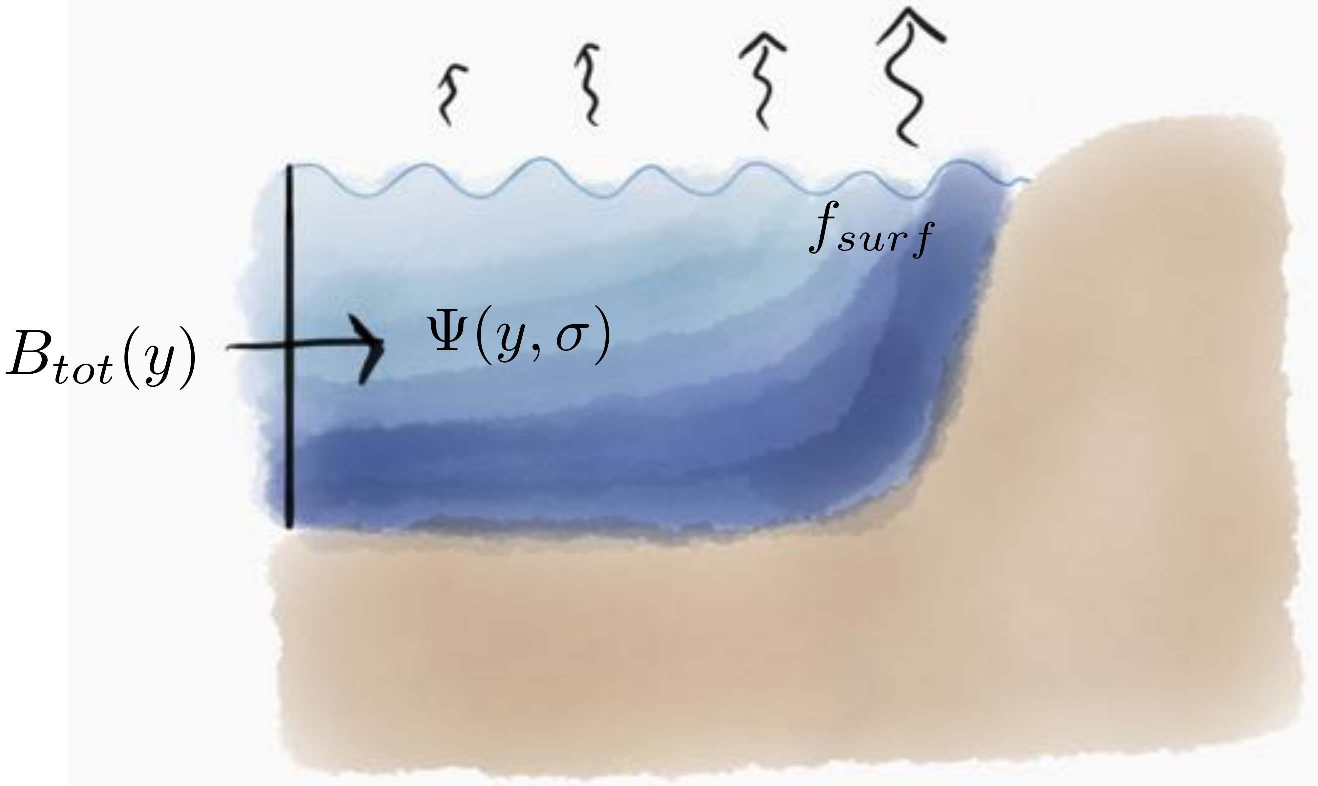


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Northward buoyancy transport — Total surface buoyancy flux — Residual overturning across the full depth

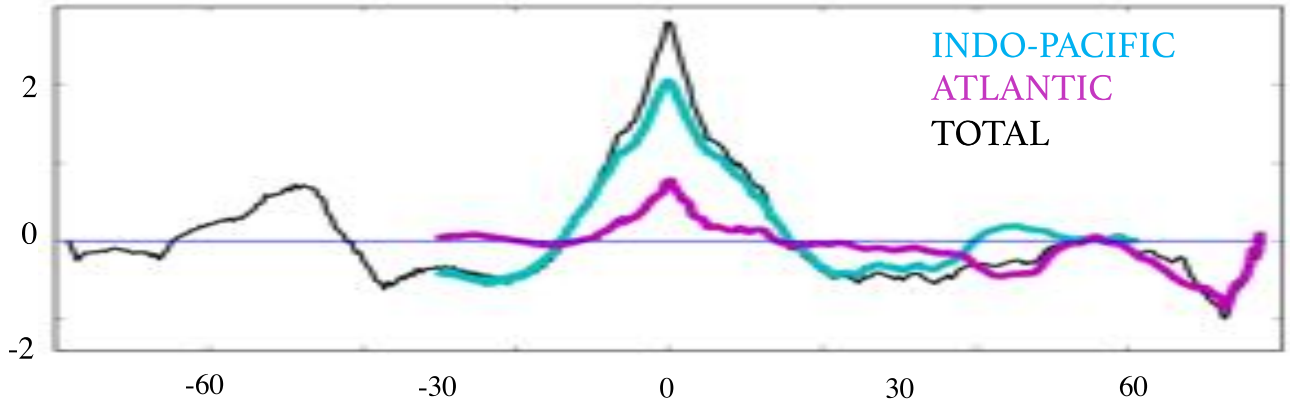
$$B_{tot}(y) = -\int_{90}^{y}\int_{X_E}^{X_W} f_{surf}(x,y)dxdy \quad = -\frac{g}{\rho_0}\int_{\sigma_{max}(y)}^{\sigma_{min}(y)} \Psi(y,\sigma)d\sigma$$

Newsom and Thompson, submitted

# Linking surface buoyancy flux and the GOC

Total buoyancy flux per latitude

$10^7\ m^3 s^{-3}$

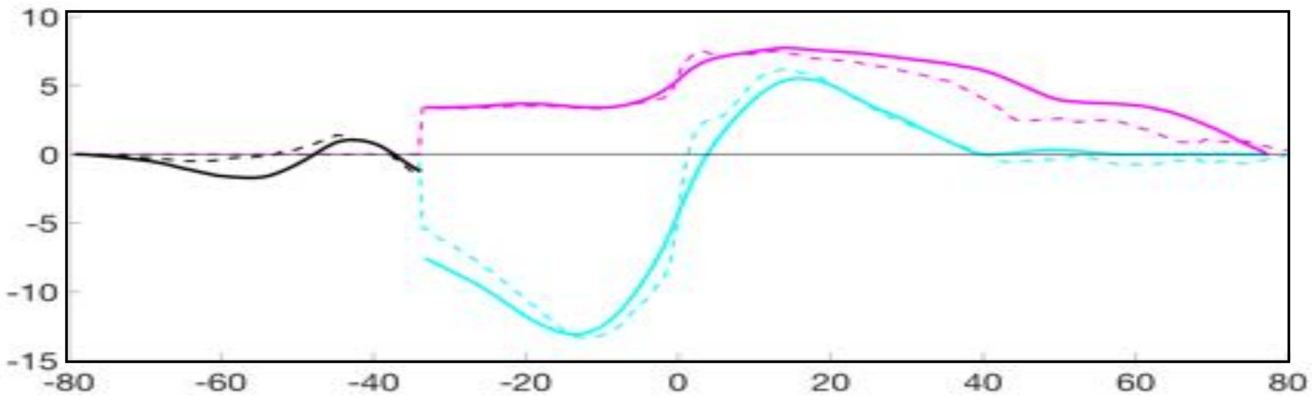



The **net** GOC can be inferred from surface buoyancy fluxes alone.

Northward Buoyancy Transport

$B_{tot}$

$10^8\ m^4 s^{-3}$




**Ψ** must be structured to somehow move buoyancy southward out of Indo-Pacific Basin & northward into the Atlantic.

Northward buoyancy transport

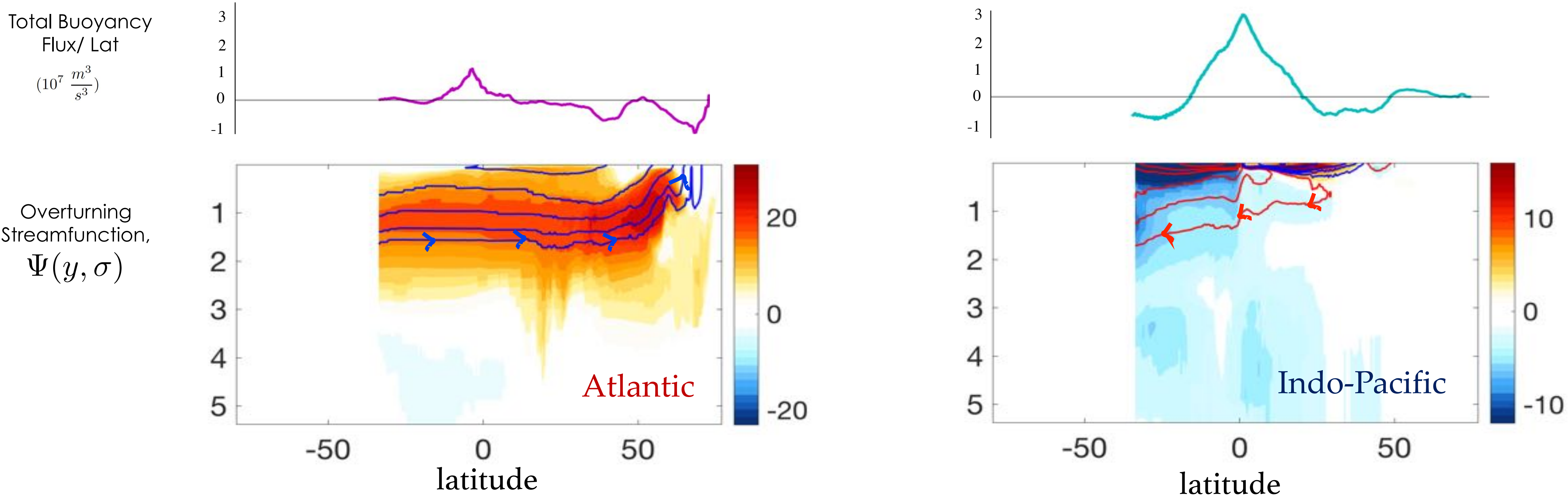
Total surface buoyancy flux

Residual overturning across the full depth

$$B_{tot}(y) = -\int_{90}^{y}\int_{X_E}^{X_W} f_{surf}(x,y)dxdy = \frac{g}{\rho_0}\int_{\sigma_{max}(y)}^{\sigma_{min}(y)} \Psi(y,\sigma)d\sigma$$

Newsom and Thompson, submitted

# Circulation and Interior Buoyancy Transport




Buoyancy Transport Function, $B(y,\sigma) = -\frac{g}{\rho_0}\int_{\sigma_{max}(y)}^{\sigma} \Psi(y,\sigma)d\sigma$

These streamlines map the spatial distribution of how buoyancy "pushes" and "pulls" the residual circulation.

Newsom and Thompson, submitted

# Part Two Summary (or, where does this get us?)

We cannot understand how the AMOC is closed without thinking of the thermodynamic "demands" of the other basins. .

The Indo-Pacific places equal "demands" on the overturning circulation

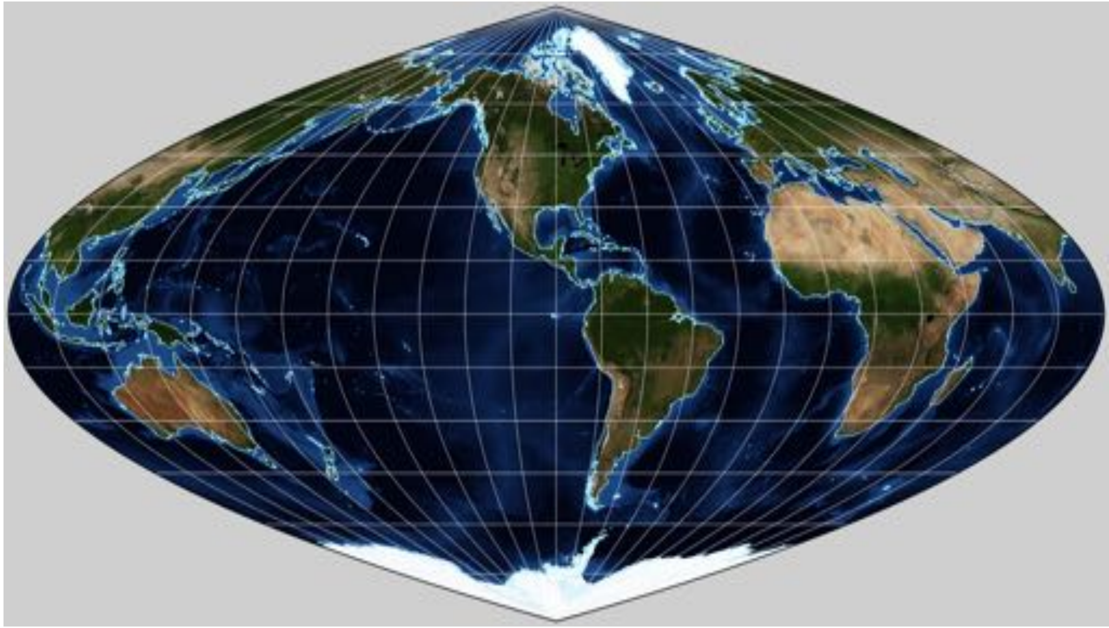
It must import sufficient dense waters to act as a buoyancy sink for buoyant surface waters.

This limits how much can be closed by the Southern Ocean.

Does it's geometry seed a tendency towards an inter-basin "warm route?

1) surface area distribution
2) need to form counterclockwise circulation across strong stratification.

This possibility is consistent with some dynamic arguments (e.g. Cessi and Jones, 2017)



NASA, http://www.giss.nasa.gov/tools/gprojector/help/projections.html

The Global Overturning Circulation must balance the formation of NADW, AABW and "IPLW" (Indo-Pacific Light Water).

# Conclusions (and into the 4th dimension)

The AMOC and the Global Overturning Circulation are influenced by many dynamic processes.

Conditions in the North Atlantic and Southern Ocean are established mediators of the ocean and climate state. Climatic shifts in the past and future are often conceptualized with a “bipolar seesaw” model in mind.

Thermodynamics emphasize key role of the Indo-Pacific…which could act as another “lever” on the circulation.

The influence of Indo-Pacific thermocline dynamics and zonal “warm route” dynamics on AMOC and GOC dynamics are relatively unexplored in theoretical, process-based frameworks.

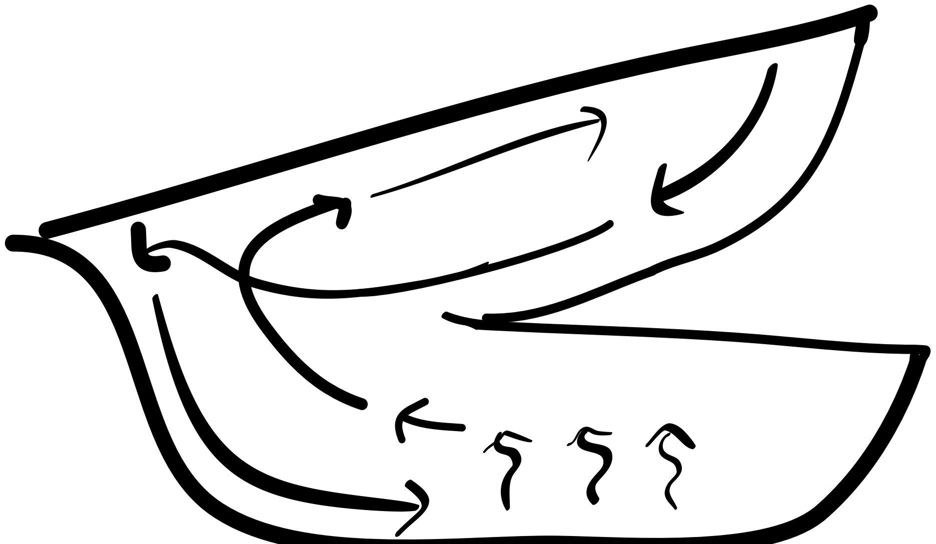
Overturning variability: ENSO? Monsoons? MJO?

Overturning evolution: low latitude mediation of high latitude shifts? Low latitude influence on GOC stability?

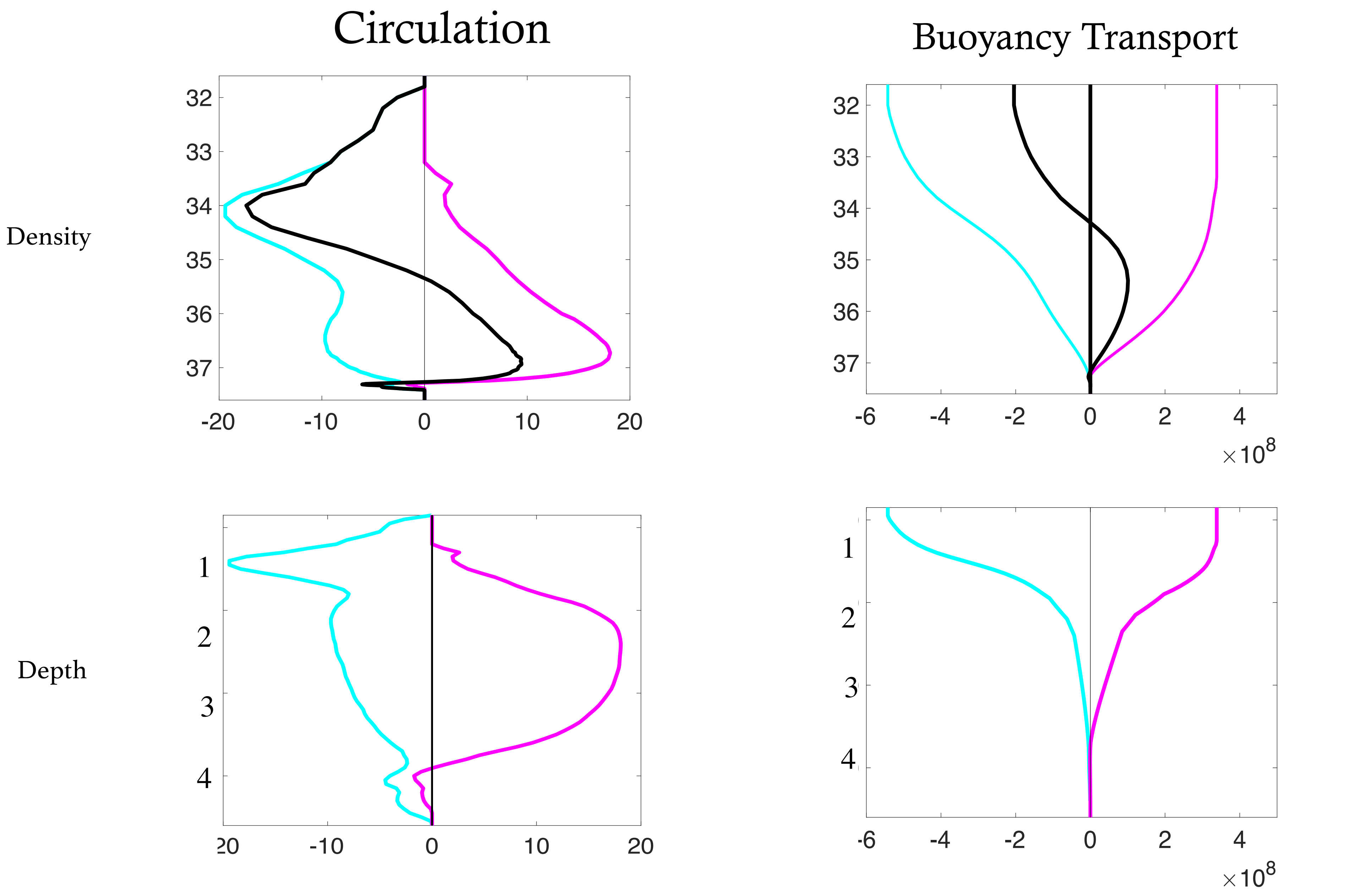
Thank you!

Questions?

3-D “cold route”



3-D “warm route”



Circulation
Buoyancy Transport
Density
Depth
32
33
34
35
36
37
-20
-10
0
10
20
-6
-4
-2
0
2
4
$\times 10^8$
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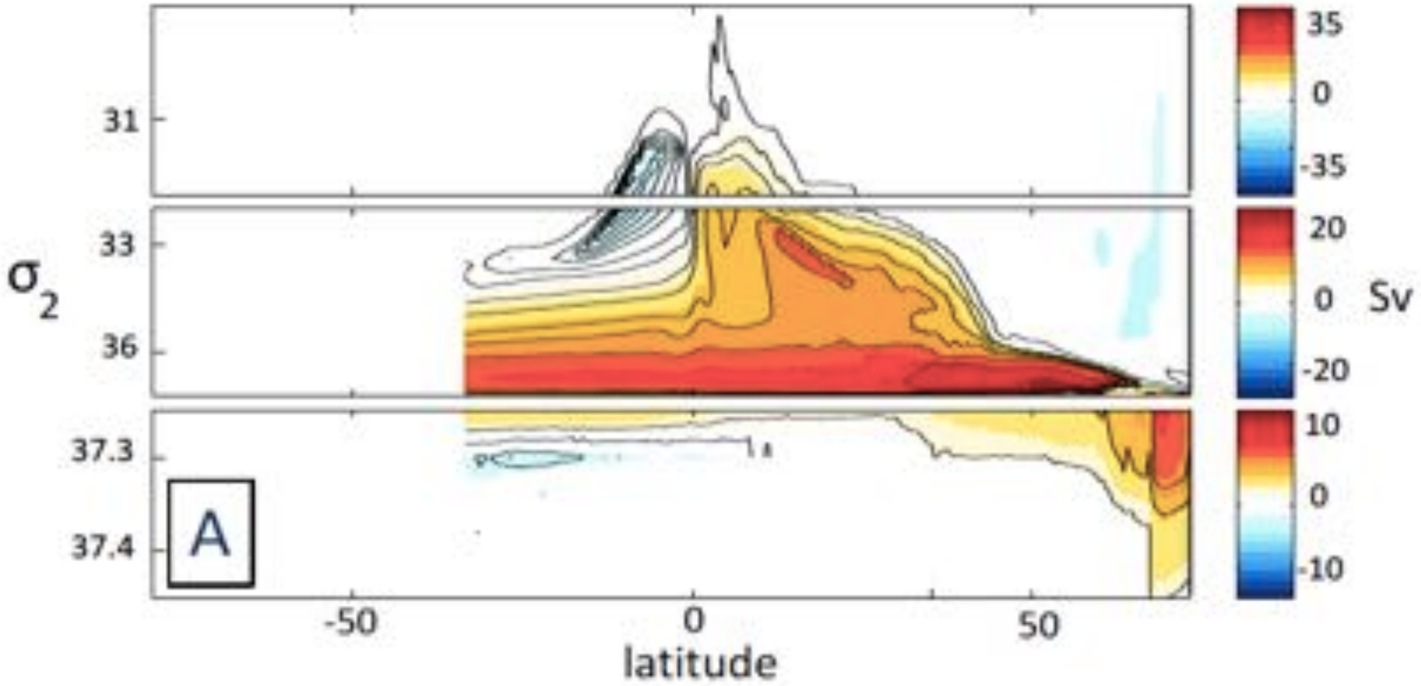
0
2
4
$\times 10^8$


31
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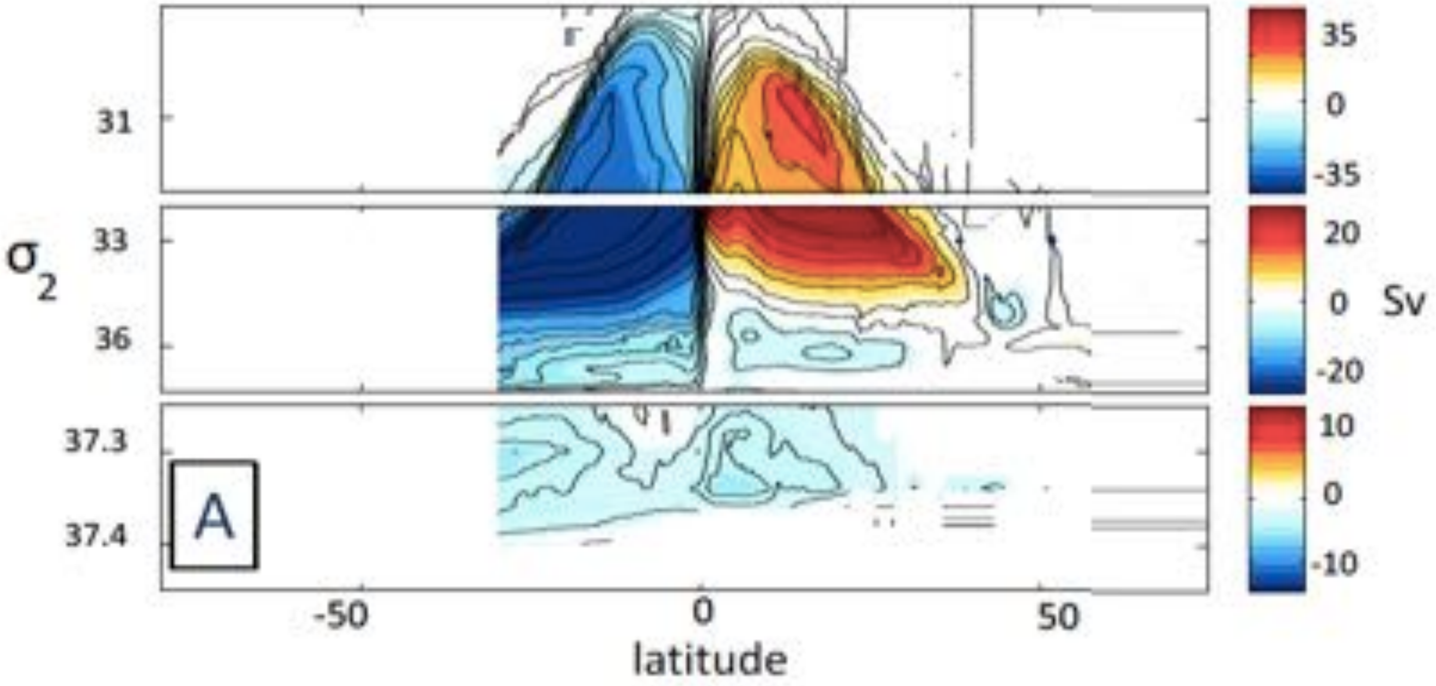
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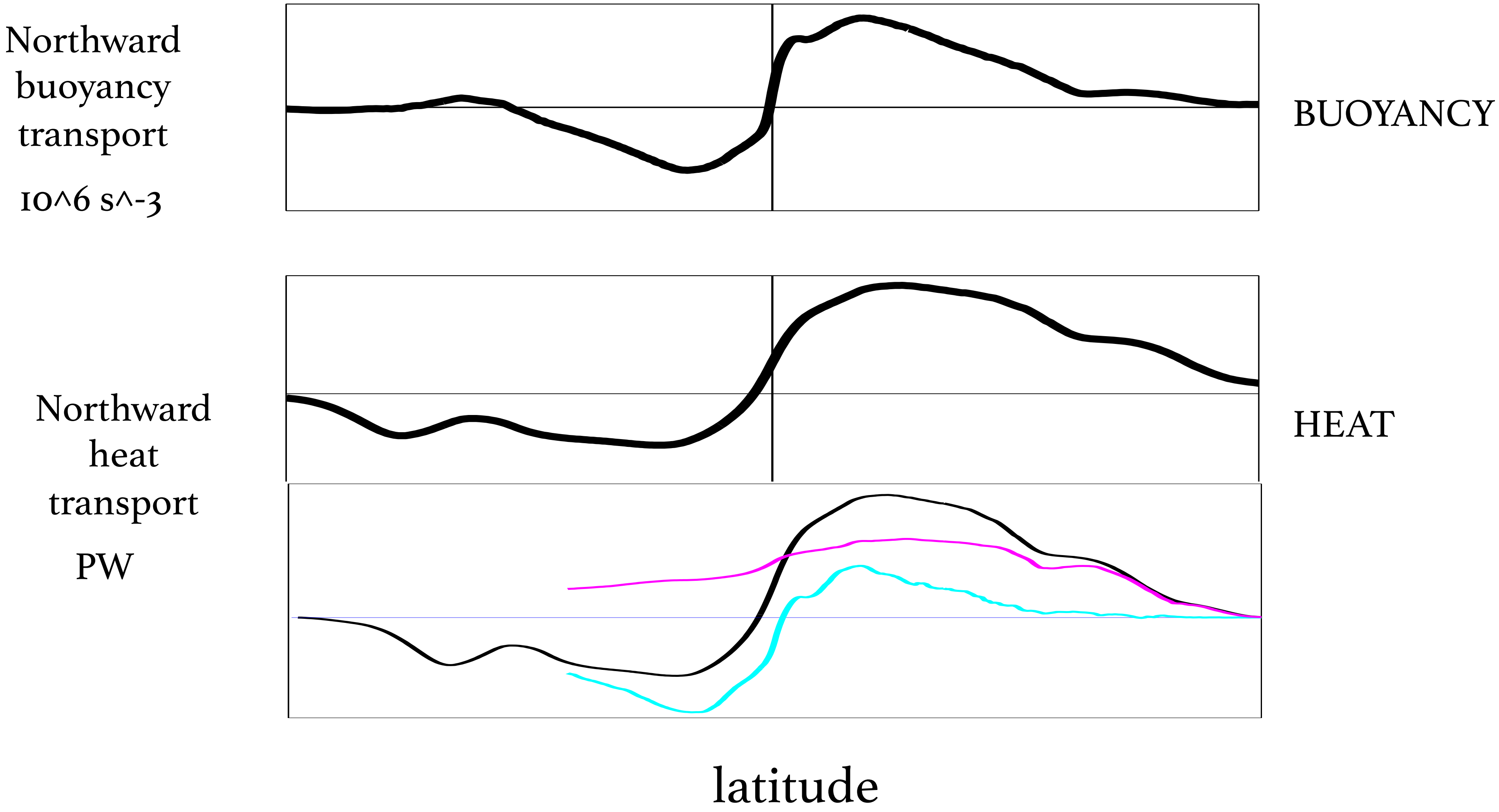
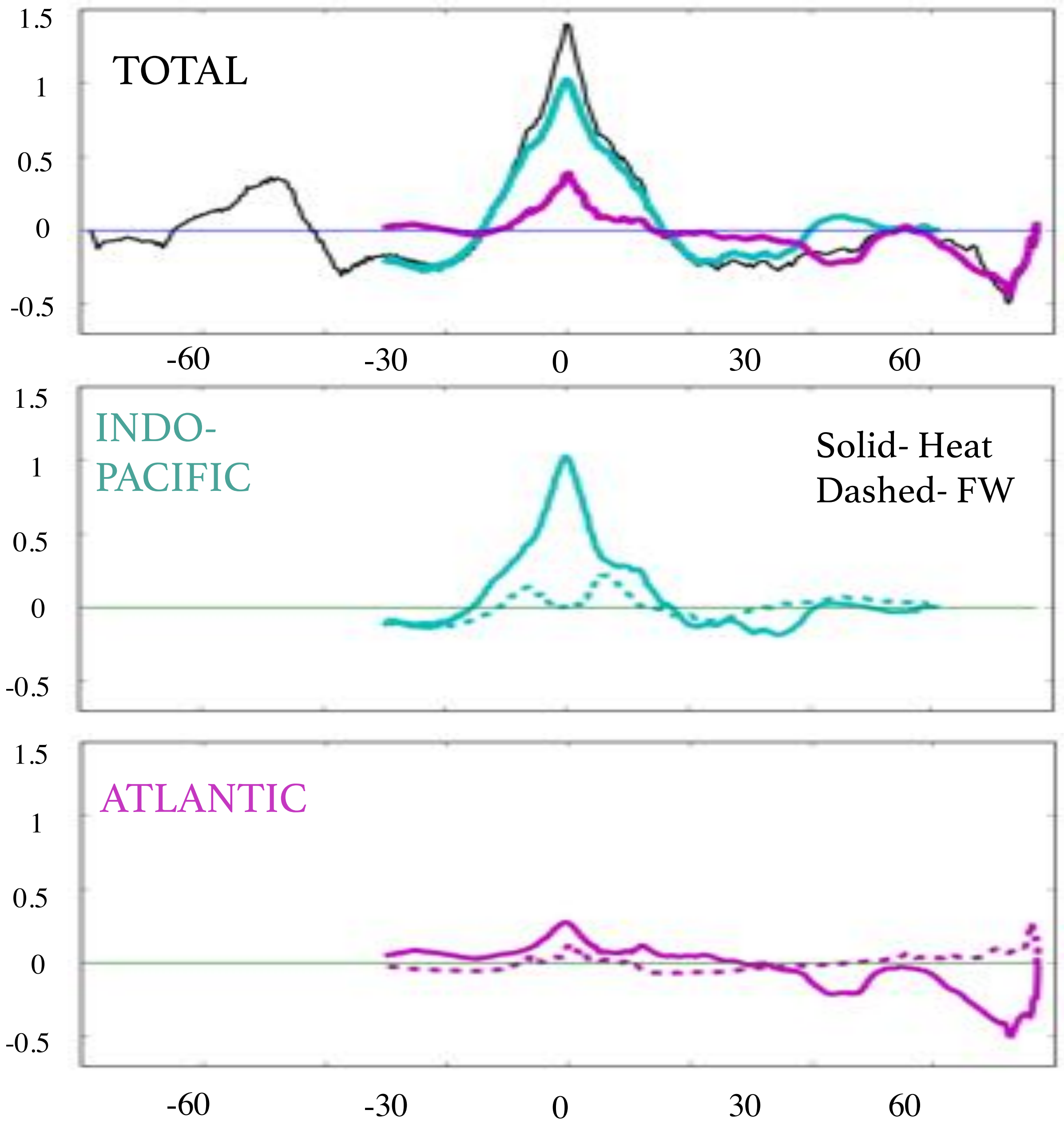
# *Buoyancy, Heat, and Freshwater Transport*

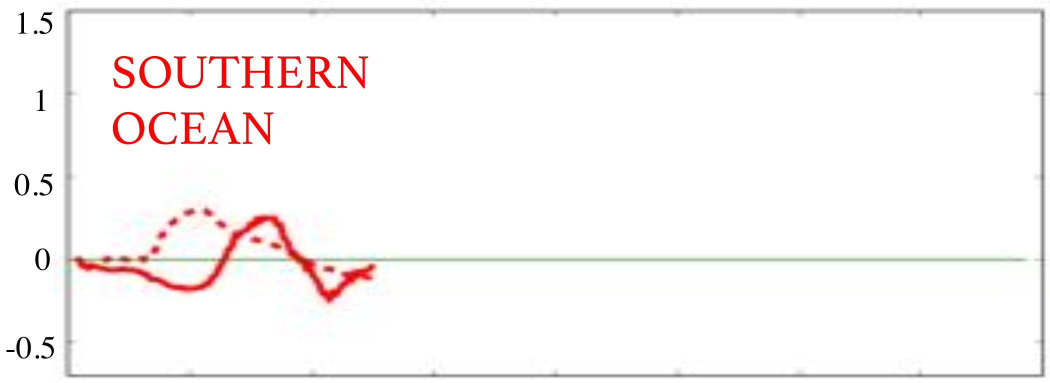


# *Basin-Scale Buoyancy Flux*

Total buoyancy gain
per latitude

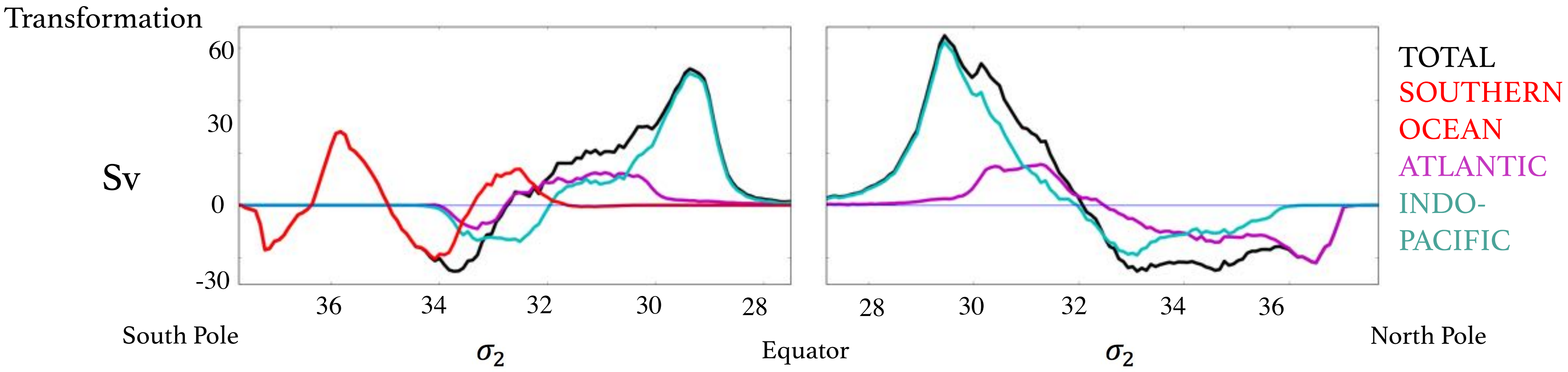
10 m^3 s^-3

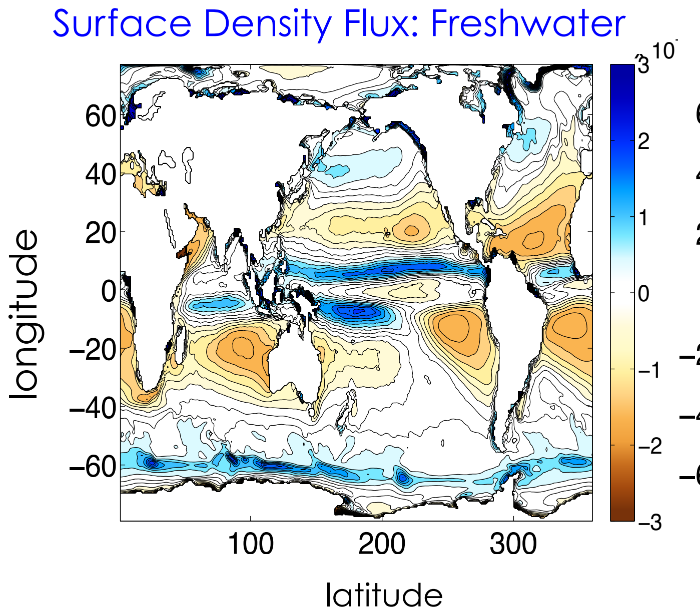


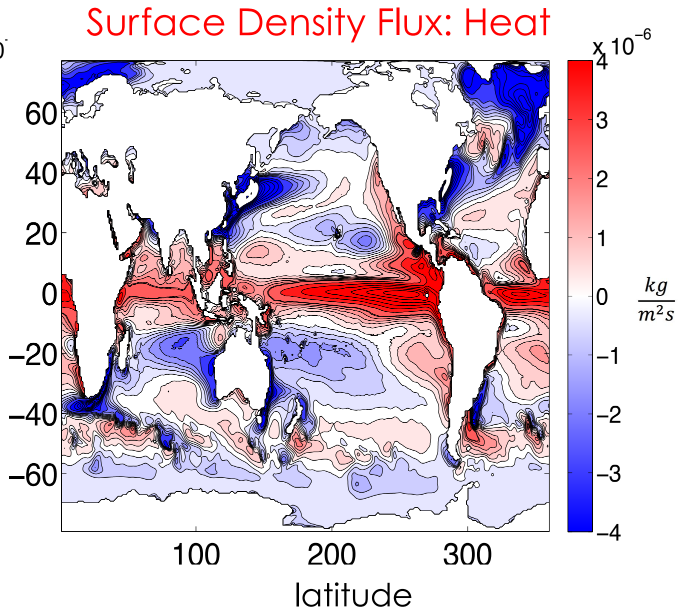




There must be buoyancy transport out of the Indo-Pacific, into the Atlantic without any buoyancy convergence in the Southern Ocean.

# *Basin-Scale Surface Transformation*



the Northern Hemsisphere
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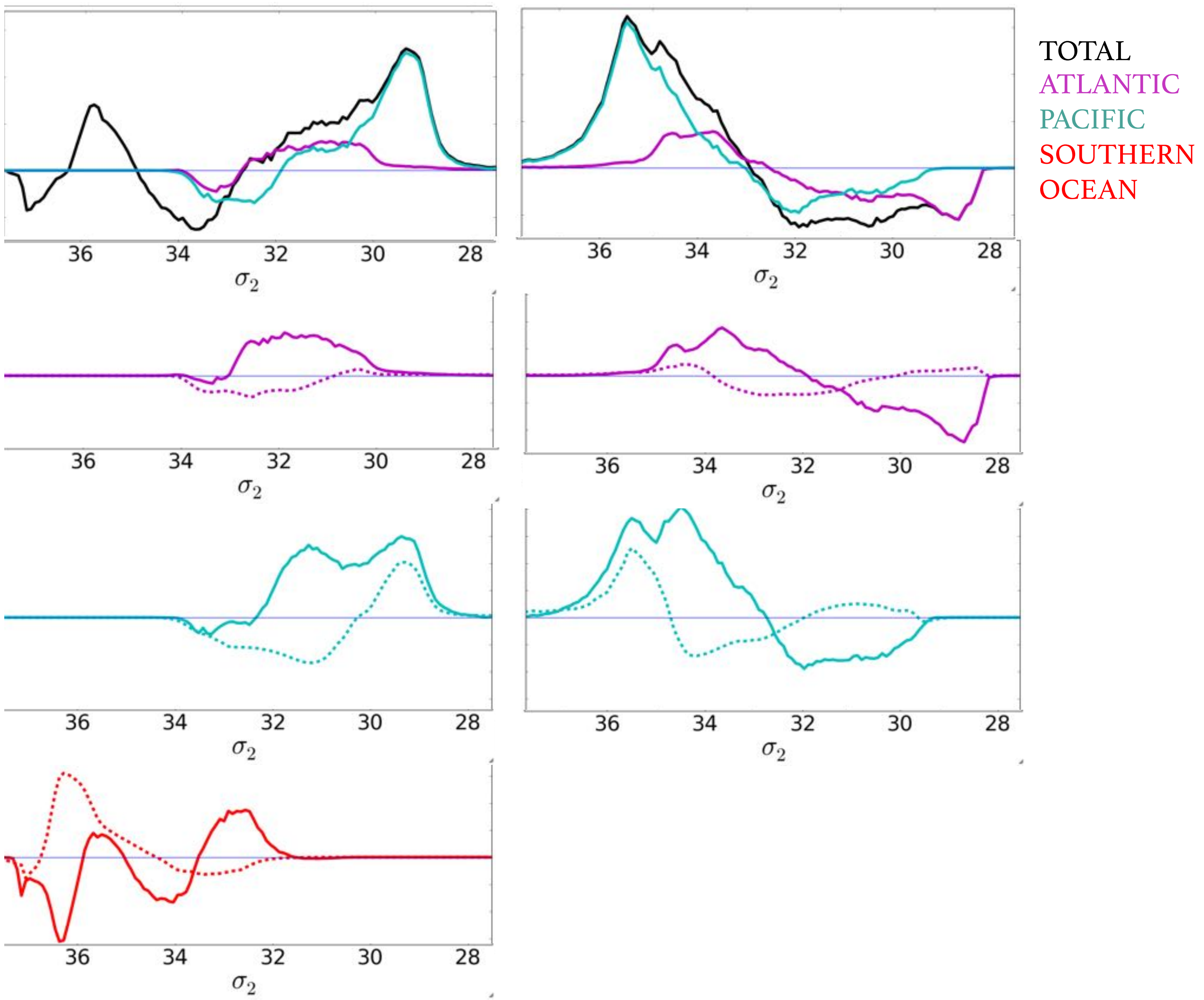
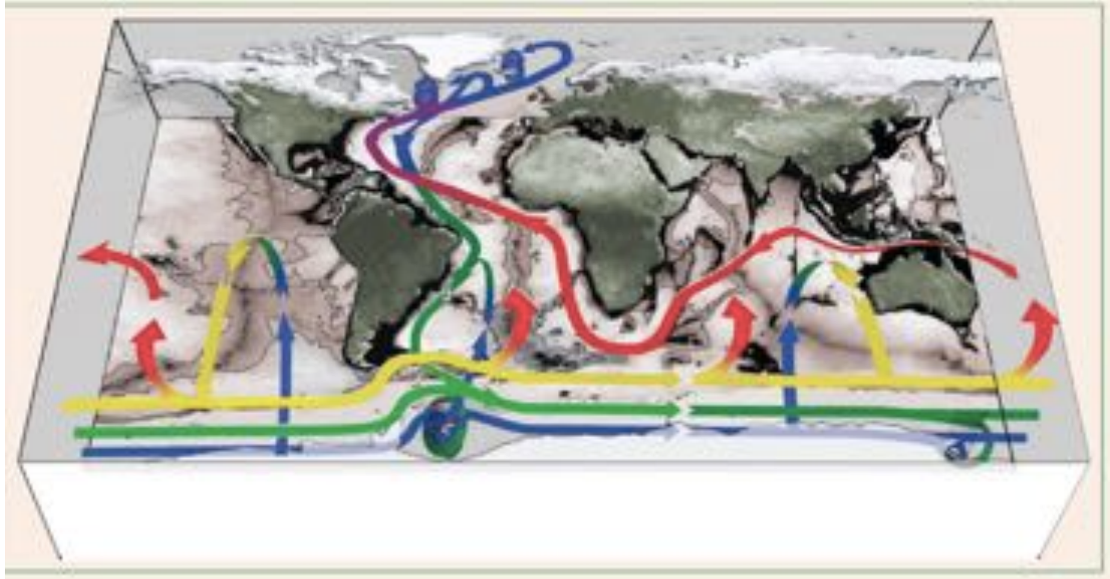
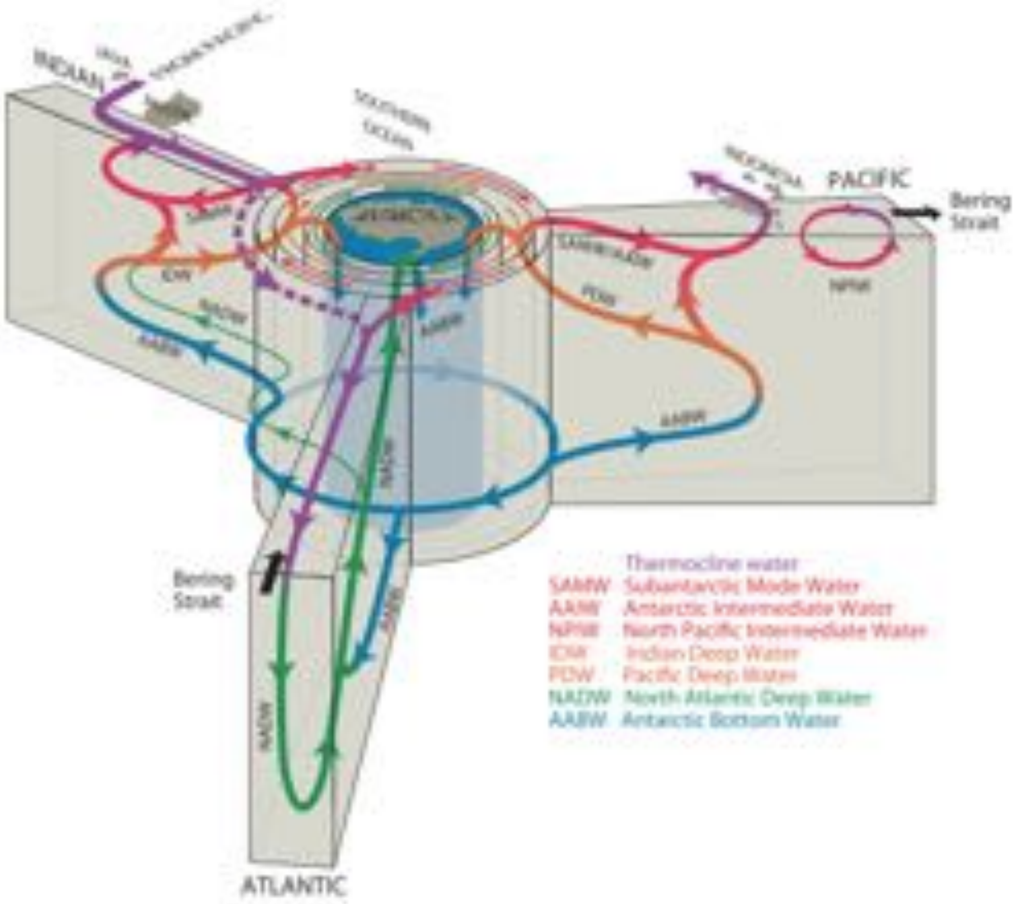
# *Basin-Scale Surface Transformation*



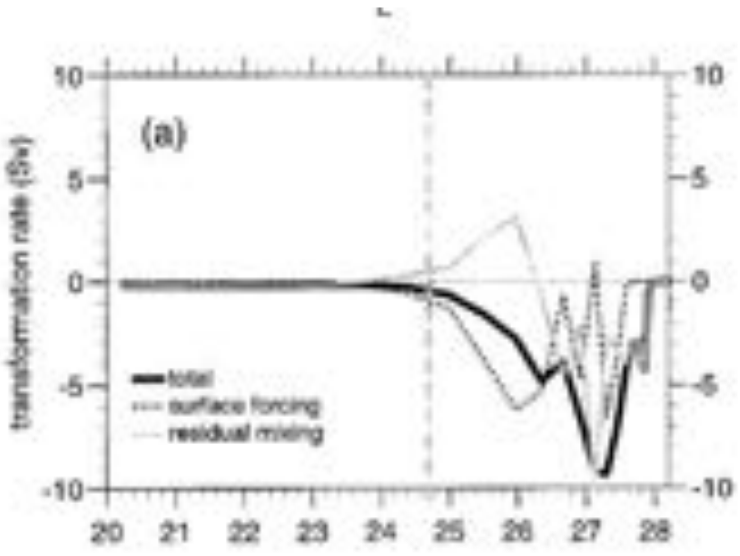


Marshall and Speer, 2012

Talley, 2013



- This can be used to infer rates of NADW, and also rates of modification in the SO.



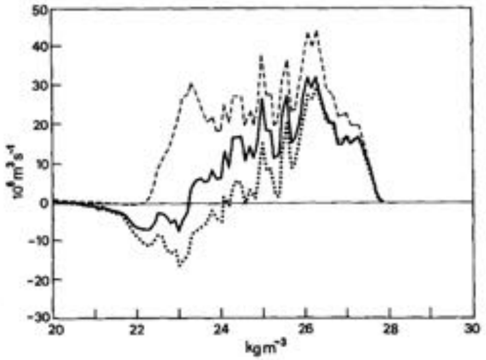



FIG. 1. Cross-isopycnal mass flux or transformation as a function of sea surface density for three climatological datasets: Budyko (dashed), Isemer and Hasse (solid), and Bunker (dotted).

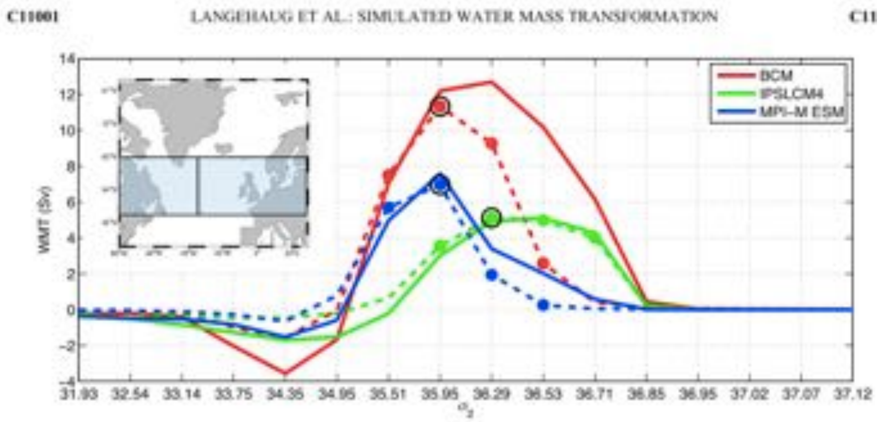


Figure 3. Annual mean surface forced water mass transformation (WMT) as a function of density, integrated over the entire subpolar region (48°N–62°N as indicated in the inset; solid lines) and over the eastern subpolar region (east of 35°W; dashed lines). The WMT has been estimated for each month, and the annual mean is then averaged over 500 years. Filled circles indicate the density range that corresponds to the WMT shown in Figures 5–7, whereas the black circle indicates the maximum WMT in the eastern subpolar region.

- Radko and Kamenkovich, Han, estimated this N-S component, implicit in the frameworks of Wolfe and Cessi, Nikurusin and Vallis, etc- shared range of isopycnals, that need to experience opposing surface buoyancy flux.
- Found 2/3 of the circ closed by push-pull mode; didn’t actually look at transformation beyond mid-latitudes, and didn’t make much AABW.