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!
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 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)


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

Gnanadesikan, 1999

Nikurashin and Vallis, 2012
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
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.

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 compiled, 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.
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 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

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

But we want a constraint on the residual circulation, $\Psi$. 
Coupling of volume and buoyancy: Water Mass Transformation

Density increases downward

The transport of volume across density classes - "Water Mass Transformation" - requires sources and sinks of buoyancy (e.g. Walin, 1982, Speer and Tziperman, 1992).
A residual circulation must transport buoyancy! This constrains its integrated state.

Density increases downward

Buoyancy source

Buoyancy sink

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

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

Newsom and Thompson, submitted
Linking surface buoyancy flux and the GOC

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

\( \Psi \) must be structured to somehow move buoyancy southward out of Indo-Pacific Basin & northward into the Atlantic.

Northward buoyancy transport

\[ B_{tot}(y) = \int_{y_0}^{y_{	ext{min}}} \int_{X_E}^{X_W} f_{surf}(x, y) dx dy \]

Total surface buoyancy flux

\[ B_{tot}(y) = \int_{y_0}^{y_{	ext{min}}} \int_{\sigma_{\text{min}}(y)}^{\sigma_{\text{max}}(y)} \frac{g}{\rho_0} \Psi(y, \sigma) d\sigma \]

Residual overturning across the full depth

\[ g \]

\[ \rho_0 \]

\[ \sigma_{\text{min}}(y) \]

\[ \sigma_{\text{max}}(y) \]
Circulation and Interior Buoyancy Transport

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

Newson 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)
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?
Northward buoyancy transport

But … mass is also imported into the Pacific!!!!

Northward heat transport PW

latitude
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

Surface Density Flux: Freshwater

Surface Density Flux: Heat

TOTAL
SOUTHERN OCEAN
ATLANTIC
INDO-PACIFIC
Let's focus on the Northern Hemisphere processes, since in this region the basins are least coupled, and their relative differences are maximized.

This is making a prediction that we need to address the water and the heat.
Marshall and Speer, 2012

Talley, 2013
• This can be used to infer rates of NADW, and also rates of modification in the SO.

• 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.