Closure of the global overturning circulation (GOC) through the Southern, Indian and Pacific Oceans

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1. Intertwined AABW and NADW overturning circulations
2. Routes through the Southern, Indian and Pacific Oceans
3. Quantify volume and heat transports
4. Relate to diapycnal diffusivity
(5. small speculation on future of the GOC in a warmer world

Talley (Oceanography, 2013)
Global overturning circulation schematics

Essential elements of overturning circulation

Talley (2013), edited from Talley et al. 2011 (Chapter 14, Fig. 14.11; Descriptive Physical Oceanography, 6th ed.)
Basis of GOC schematics: water masses

(Talley et al., 2011 DPO 6th edition)
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Where do the deep and bottom waters come from?

Nordic Seas Overflow waters, contributing to NADW

Antarctic Bottom Water in Weddell, Ross Seas and Adelie Coast

Talley (1997)
Basis of GOC schematics: Fraction of NADW vs. AABW

At about 2500-3000 m

At the bottom

NADW

AABW

Invasion of CFC-11 marks deep ventilation pathways. Enhancement of upper ocean CFC-11 marks subtropical circulation.
Basis of GOC schematics: Meridional mass transports

Use hydrographic station data to construct geostrophic velocity analysis, top to bottom, global (Reid, 1994, 1997, 2003)
Compute meridional volume transports in layers, include Ekman transport
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Atlantic Ocean

North Atlantic 24°N

South Atlantic 30°S
Basis of GOC schematics: Meridional mass transports

Use hydrographic station data to construct geostrophic velocity analysis, top to bottom, global (Reid, 1994, 1997, 2003)

Compute meridional volume transports in layers, include Ekman transport

Pacific Ocean

North Pacific
24°N

South Pacific
32°S
Global overturning circulation schematics

Essential elements of overturning circulation

Talley (2013), edited from Talley et al. 2011 (Chapter 14, Fig. 14.11; Descriptive Physical Oceanography, 6th ed.)
Processes for the Global Overturning Circulation

Fig. 16. A three-dimensional schematic of global interbasin flow with typical vertical meridional sections for each ocean and their connections in the Southern Ocean by Gordon (1991).

Processes for the Global Overturning Circulation

Essential elements of overturning circulation

Antarctic MOC (AABW)

Wind-driven upwelling

Diffusive upwelling

N. Atlantic MOC (NADW)

Thermocline water

SAMW  Subantarctic Mode Water
AAIW  Antarctic Intermediate Water
NPIW  North Pacific Intermediate Water
IDW  Indian Deep Water
PDW  Pacific Deep Water
NADW  North Atlantic Deep Water
AABW  Antarctic Bottom Water

Talley (Oceanography, 2013)
Indonesian Throughflow (ITF) pathway

The originally oversimplified concept of global overturn (Broecker, Gordon)
Pacific-Indian “conveyor”: (but) one of the essential elements of the GOC

This is obviously too simple: does not include essential Southern Ocean processes, even for NADW. Does not purport to include AABW

Talley et al. 2011 (DPO 6th ed.);
Talley (2013)
A second, oversimplified zonally-averaged view of global overturn: Two cells (NADW and AABW), with solely Southern Ocean upwelling which is also one of the essential elements of the GOC.

Why is this too simple? Missing the Indian and Pacific upwelling.
IDW/PDW and NADW layering in the Southern Ocean

Return path to NADW: upwelling in Southern Ocean – Pacific, Indian or North Atlantic Deep Water?

High salinity in ACC: North Atlantic Deep Water signal

Low oxygen in ACC: Pacific and Indian Deep Water signal

High salinity indicative of NADW rises up below and reaches sea surface south of the low oxygen IDW and PDW.
IDW/PDW and NADW layering in the Southern Ocean

Salinity

Atlantic

NADW salinity maximum in the ACC (light blue)

Indian

Salinity: orange is high

Isoneutral surfaces

\( \gamma_N = 27.8 \) closely represents oxygen minimum in the ACC in all oceans (IDW/PDW)

\( \gamma_N = 28.04 \) closely represents salinity maximum in ACC in all oceans (NADW)

Pacific
IDW/PDW and NADW layering in the Southern Ocean

Same juxtaposition of low oxygen IDW/PDW above high salinity NADW all around Antarctica.

Therefore we can argue that upwelled IDW/PDW feed the northward surface Ekman transports and Subantarctic Mode Water and also join NADW to form AABW (although they do mix, so not so black & white)
Essential elements of overturning circulation

(a) Southern Ocean and low latitude Indian/Pacific upwelling

(b) Low latitude Indian/Pacific upwelling (missing Southern Ocean)

(c) Southern Ocean upwelling & diffusion

Must include both the Pacific-Indian upwelling and the Southern Ocean upwelling.

Route:
NADW upwells in S.O., becomes denser and sinks as AABW. AABW spreads northward into each ocean. Upwells into PDW, IDW and NADW.

All Deep Waters return to S.O. Part of the less dense IDW and PDW upwell to the sea surface and move northward into the gyre (Antarctic Intermediate Water and Subantarctic Mode Water). These eventually become lighter thermocline water and feed NADW.
Overturning transports and heat transports

(a) Mass transports (Sv) for the Global Overturning Circulation

Talley and Lumpkin (in preparation)
Heat budget for the global overturning circulation

Overturning transports and heat transports

Total gains and losses
-1.00 PW total heat loss
2.81 PW total heat gain
-1.81 PW total heat loss

Gains and losses due to GOC only

-0.26 PW (I/P to AABW)
-0.09 PW (NADW to AABW)
0.03 PW (I/P to A)
0.10 PW (I/P to I/P)
0.60 PW (I/P to I/P)
0.23 PW (IDW/PDW to Thermocline)
-0.29 PW (Therm. to NADW)
0.26 PW (AABW to IDW/PDW)
0.09 PW (NADW to IDW)
0.0 PW (A to I/P)
0.02 PW Atl (AABW to NADW)
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35% of SH heat loss goes into AABW production
48% of NH heat loss goes into NADW production
42% of low latitude heat gain goes into the int./deep Indian and Pacific

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Southern-Ocean centric, but illustrative of the processes that control GOC globally:
- Winds (stress and curl) – upwelling and circulation
- Air-sea heat loss and gain
- Air/ice-sea freshwater fluxes (here due to ice processes)
- Diapycnal mixing
External controls on GOC?

Wind stress and wind stress curl, especially Southern Ocean (due to Drake Passage), driving upwelling there
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Air-sea fluxes: heating/cooling

Air-sea fluxes: freshwater (saltier Atlantic and fresher Pacific)
Low latitude vertical velocities and diffusivities diagnosed from this overturning:
Order $10^{-4}$ m$^2$/sec (Munk values) (Talley, Reid, Robbins, J. Clim. 2003)

<table>
<thead>
<tr>
<th></th>
<th>$w$ (cm/sec)</th>
<th>$\kappa$ (m$^2$/sec)</th>
<th>$w$ (cm/sec)</th>
<th>$\kappa$ (m$^2$/sec)</th>
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</thead>
<tbody>
<tr>
<td>Indian</td>
<td>$7 \times 10^{-5}$</td>
<td>$1.7 \times 10^{-4}$</td>
<td>$31 \times 10^{-5}$</td>
<td>$6.8 \times 10^{-4}$</td>
</tr>
<tr>
<td>Pacific</td>
<td>$4 \times 10^{-5}$</td>
<td>$0.8 \times 10^{-4}$</td>
<td>$16 \times 10^{-5}$</td>
<td>$3.5 \times 10^{-4}$</td>
</tr>
<tr>
<td>Atlantic</td>
<td>$7 \times 10^{-5}$</td>
<td>$1.5 \times 10^{-4}$</td>
<td>$25 \times 10^{-5}$</td>
<td>$5.5 \times 10^{-4}$</td>
</tr>
</tbody>
</table>
Implications for globally averaged diffusivity

From Lumpkin and Speer (2007). Conclusions from Talley et al (2003) were very similar – need $10^{-4}$ m$^2$/sec
Diapycnal diffusivity at 30S in the Indian Ocean estimates, based on CTD strain and LADCP shear to parameterize assuming internal wave mixing (Kunze et al., 2006): Values of up to $10^{-4}$ m$^2$/sec in abyssal ocean, over topo., but not really high enough.

Same quantity from Argo profiles, using Kunze-Polzinz method, based on CTD strain, assuming mixing due to internal waves (Whalen, Talley, MacKinnon, in prep.). Equatorial enhancement, but overall values about one order of magnitude smaller than transport diagnosed values $3 \times 10^{-5}$ m$^2$/sec.
Observed diapycnal diffusivity

Upper ocean diapycnal diffusivity from Argo profiling floats
Whalen, Talley, MacKinnon (GRL, 2012)

Waterhouse et al. (JPO submitted): NO missing deep mixing based on direct observations and turbulence parameterizations. Average deep diffusivity is 1 “Munk”
Waterhouse et al. (JPO submitted): sufficient diapycnal mixing to result in global mean deep diffusivity of $1 \text{ Munk} = 1 \times 10^{-4} \text{ m}^2\text{s}^{-1}$
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Waterhouse et al. (JPO submitted): Sources of diapycnal mixing from internal tides and near-inertial waves
Speculation about future of the GOC in a warming world: Ocean salinity and overturning circulation

The Atlantic and Indian Oceans are salty from top to bottom compared with the fresher Pacific

Dense deep and bottom waters are formed where salinity is highest (North Atlantic) and where salt is produced bountifully as part of the formation process (Antarctic)

Deep/bottom waters are NOT formed in the fresher N. Pacific

Talley (2008) using Levitus
Speculation about future of the GOC in a warming world: Changing atmospheric water content and P-E

Decadal trend of total precipitable water (from satellite measurements) (1988-2010)

Precipitation minus evaporation has a trend (satellite observations) (1978-2004)

Wentz et al., 2007
How is Earth’s precipitation projected to change?

Dry areas become drier.
Wet areas become wetter.
Summer high latitudes become wetter.

IPCC AR4 (2007)
Speculations about a warmer, wetter world?

All oceans will become warmer and more stratified.

Pacific will get even fresher than now, and even less likely to overturn.

Antarctic will get warmer with less ice formation and less brine rejection, possibly less very dense Bottom Water production.

Atlantic will get even saltier, and more likely to overturn after a lag – it will still “win”.

MANY OTHER FACTORS!!!!!
Conclusions

Global overturning circulation includes surface formation of NADW and AABW plus internal, diffusive formation of IDW and PDW (these are well known)

Upwelling of all deep waters to the sea surface in the Southern Ocean: IDW and PDW are less dense and farther to the north than NADW, and feed the northward flow into the thermocline

Upwelled NADW and a portion of the upwelled IDW/PDW feed the large production of very dense AABW

Upwelling into and through the IDW and PDW is an important part of the global energy budget, and requires diapycnal diffusion deep within the ocean: 42% or so of low latitude heat works its way down to the deep ocean

Required average diapycnal diffusion is about 1 “Munk” or $10^{-4} \text{ m}^2/\text{sec}$, and is now accounted for from direct observations of dissipation
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