Taking the “Circumpolar” out of the

Antarctic Circumpolar Current:

The ACC and the OC

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Let’s not completely forget the circumpolar part ...
Key components:

• Westerly winds create regions of convergent and divergent Ekman transport.
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- Tilted isopycnals support the growth of baroclinic mesoscale eddies.
- Mesoscale eddies stir along density surface and transport mass poleward.
- Density surfaces may outcrop at the surface and be subject to buoyancy forcing.
The gospel according to Marshall and Radko (2003)

The "residual" overturning arises from a near-cancellation of wind (mean) and eddy overturning circulations.

The Southern Ocean is adiabatic outside of the surface mixed layer where buoyancy forcing sets the residual overturning.
Water mass modification and the overturning circulation

In steady state, the S. Ocean surface buoyancy forcing constrains the geometry of the overturning circulation.

The buoyancy flux separatrix north of the Antarctic continent is roughly co-located with the 70% quantile of annual mean sea ice coverage.
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The ACC in the global overturning circulation
M('n’z)OC: The meridional (and zonal) overturning circulation

It is a truth universally acknowledged ...

Adiabatic cell associated with NADW and eddy-driven upwelling in the Southern Ocean.

Diabatic cell associated with AABW and diffusive upwelling.

Our modern figure-eight overturning

The modern global overturning circulation consists of a single “figure-eight” cell.

This structure is distinct from the traditional two-cell paradigm composed of adiabatic (surface-forced) and diabatic (diffusive) cells.
A non-zero overturning circulation requires a transformation of water to different density classes.
Water mass modification and the overturning circulation

Modification processes

1. Interior (diapycnal) mixing (internal wave breaking);
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2. High latitude formation processes (sea ice formation; ocean-ice shelf interactions; buoyancy forcing in polynyas)

3. Buoyancy forcing at the surface of the Antarctic Circumpolar Current.
solid white line in Fig. 3 confirms that the transition between Antarctica arises under permanent sea ice, where the heat fluxes buoyancy flux changes sign in the SO. The meridional surface flow in a steady state must be divergent. Thus, the surface meridional flow in a steady state must be divergent. This argument is, however, useful only if we find a paleoproxy for the rest of our argument. Ferrari et al. (2014) gives an excellent review of our current understanding of the large-scale 3D circulation.

Our modern three-dimensional overturning circulation

Modern

The ragged gray line is the crest of the main bathymetric features of the Ocean. The dashed black line represents the southern extent of the quasi-permanent sea ice line, here defined as the area of negative buoyancy flux scales with the extent of the quasi-permanent sea ice line has shifted equatorward compared with modern

Our modern three-dimensional overturning circulation

Upper

Modern

$\ell_1$

0km

2km

4km

Our modern three-dimensional overturning circulation

$\ell_1$

0km

2km

4km

Our modern three-dimensional overturning circulation

$\ell_1$

0km

2km

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Our modern three-dimensional overturning circulation

$\ell_1$
A three-dimensional residual-mean overturning

Two-dimensional model:

$$\left. \frac{\partial \psi}{\partial y} \right|_b = 0$$

(adiabatic interior)
A three-dimensional residual-mean overturning

Two-dimensional model:
\[ \left. \frac{\partial \psi}{\partial y} \right|_b = 0 \]  
(adiabatic interior)

Three-dimensional model:
\[ \left. \frac{\partial \psi^{(y)}}{\partial y} \right|_b + \left. \frac{\partial \psi^{(x)}}{\partial x} \right|_b = 0 \]

Transport streamfunctions:
\[ \psi^{(x)}_i = \Psi_i = -Uz_i \]  
Zonal (barotropic)  
ACC transport

\[ \psi^{(y)}_i = \overline{\psi} + \psi^* = -\frac{\tau}{\rho f} + K \left. \frac{\partial z_i}{\partial y} \right|_b \]  
(i = A, P)  
Wind  
Eddies
A three-dimensional residual-mean overturning

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\psi_i^{(y)} = \overline{\psi} + \psi^* = -\frac{\tau}{\rho f} + K \frac{\partial z_i}{\partial y}
\]  
\(i = A, P\)

Wind
Eddies

Average across a sector of the ACC:

Atlantic

\[
\psi_A^{(y)}
\]

Pacific

\[
\psi_P^{(y)}
\]
Two-layer example

In all experiments the ocean depth was 3000 m. Transport definitions are provided in section 3. The dashed line in panels (d) and (e) correspond to panels (b) and (c).

Jones and Cessi (2016), Thompson et al. (2016)
Fig. 3. Zonal-mean isopycnal depths in the Atlantic and Pacific, as predicted by (a) our analytical solution and (b) the 27.9 kg m$^{-3}$ neutral density surface in the global ocean climatology of Gouretski and Koltermann (2004). Our solution predicts that isopycnals should lie shallower in the Atlantic sector than in the Pacific in order to support zonal convergence/divergence of mass between basins and thus complete the "figure-of-eight" global OC. The balance between this zonal convergence/divergence and the corresponding meridional divergence/convergence of mass within isopycnal layers by eddy thickness fluxes implies that the isopycnal depth difference should be concentrated close to the northern edge of the ACC. Note the latitude set in panel (b) in order to approximately align the ACC cores in the Atlantic and Pacific basins.

Model-observation comparison

Key points:

- Difference in isopycnal depth is concentrated to the north of the ACC.
- Isopycnals are deeper in the Pacific to support a transport from the Atlantic to the Pacific in deeper density classes and from the Pacific to the Atlantic in shallower density classes.

\[ K = 1500 \text{ m}^2 \text{s}^{-1}, \tau = 0.12 \text{ N m}^{-2}, T = 10 \text{ Sv} \text{ and } U = 10 \text{ cm s}^{-1} \]

Thompson et al. (2016)
Flow-topography interactions & ACC hotspots