Observations of the Meridional Overturning Circulation in the Southern Ocean

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Zonal Circulation - Antarctic Circumpolar Current

- Circumpolar (but not strictly zonal)
- Transport range: 95 - 184 Sv
- Comprises multiple deep-reaching fronts
- Barrier to meridional flow
- Energetic mesoscale field acts as “blender”

Mean positions of major ACC fronts (black) on mean dynamic topography (color) of the Southern Ocean. (Orsi et al., 1995; Maximenko and Niiler, 2005)
The ACC Meridional Overturning Circulation

$\psi_{residual} = \overline{\psi} + \psi^*$

- MOC is a residual between 2 opposing circulations, Eulerian mean (wind+buoyancy driven) & eddy-mean.

Marshall and Radko, 2003
The ACC Meridional Overturning Circulation

\[ \psi_{\text{residual}} = \overline{\psi} + \psi^* \]

• MOC is a residual between 2 opposing circulations, Eulerian mean (wind+buoyancy driven) & eddy-mean.

• Observed tracer distribution results from the residual circulation.

• Earliest evidence of MOC comes from tracer distributions, e.g. Merz (1925), Sverdrup (1933) and Deacon (1937)

Fig. 8. Schematic two-cell meridional overturning circulation in the Southern Ocean. An upper cell is primarily formed by northward Ekman transport and southward eddy transport in the UCDW layer. A lower cell is primarily driven by dense water formation near the Antarctic continent.
Southern Ocean MOC from observed tracers, air-sea fluxes and currents

(Lumpkin & Speer, 2007)
Southern Ocean MOC from observed tracers, air-sea fluxes and currents

AABW formation (cooling & brine rejection)  

SAMW, AAIW  

UCDW  

LCDW  

Antarctica  

Subtropical/tropical upper ocean waters  

Southern Ocean wind-driven (adiabatic) upwelling & surface buoyancy flux  

NADW formation (convection)  

Surface warming  

2D schematic of the globally averaged streamfunction

(10, 0)  

(10, 10)
Deep Water Layers from Salinity/O² Tracers

Atlantic 20°W
\( \gamma^N = 28.04 \, \text{kg m}^{-3} \) is core of NADW, salinity maximum layer

Indian 90°E
\( \gamma^N = 27.8 \, \text{kg m}^{-3} \) is core of IDW, oxygen minimum layer

Pacific 165°W
\( \gamma^N = 27.8 \, \text{kg m}^{-3} \) is core of PDW, oxygen minimum layer

(Talley, 2013)
Southern Ocean MOC from observed tracers, air-sea fluxes and currents

2D schematic accounting for differences in Deep Water formation/pathways

2D schematic of the globally averaged streamfunction
Is the Southern Ocean MOC changing?

\[ s = \frac{\tau}{\rho f \kappa} \]

- Southern Ocean winds are increasing
- Southern Ocean is warming and freshening
- Isopycnal slope, \( s \), is relatively constant
- For zero overturning, zonal mean theory predicts:
  - Isopycnal slope is directly proportional to wind stress
  - Inversely proportional to eddy stirring

(Böning et al., 2008)

(Swart & Fyfe, 2012)
The wind-driven ACC - eddy saturation

- Southern Ocean winds are increasing
- EKE is increasing, less in Atlantic
- ACC transport relatively unchanged

Eddy saturation: increased eddy intensity and a saturation of ACC transport

(Hogg et al., 2015)
The wind-driven MOC - eddy saturation vs. eddy compensation

- Southern Ocean westerlies are increasing
- Northward Ekman transport is increasing
- Eddy energy is increasing - does eddy transport compensate for Ekman transport?

Topic of current debate, but scaling arguments (Meredith et al. 2012) suggest that eddies do NOT fully compensate
- Depth range of eddy transport likely deeper than the Ekman layer
- Zonal variations in eddy characteristics suggest local dynamics modify the MOC along the ACC
Zonal variation in meridional transport by ACC eddies

High eddy variability along ACC:
- downstream of meanders
- associated with topography

Hotspots of exchange:
- Southwest Indian Ridge (SWI)
- Kerguelen Plateau (KP)
- Campbell Plateau (CP)
- East Pacific Rise (EPR)
- Drake Passage (DP)

Thompson & Sallée, 2012
Poleward eddy heat flux estimates

<table>
<thead>
<tr>
<th>Reference</th>
<th>Location</th>
<th>Local flux (kW/m²)</th>
<th>Integrated transport (10¹⁵W = PW)</th>
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</thead>
<tbody>
<tr>
<td><strong>Current meters</strong></td>
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<tr>
<td>Bryden (1979)a</td>
<td>Drake Passage (2700 m)</td>
<td>−6.7</td>
<td>−0.5</td>
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<tr>
<td>Sciremammano et al. (1980)</td>
<td>Drake Passage (1000–2500 m)</td>
<td>−17</td>
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<tr>
<td>Nowlin et al. (1985)</td>
<td>Drake Passage (500–2700 m)</td>
<td>−3.7b</td>
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<td>Johnson and Bryden (1989)</td>
<td>Drake Passage (580–3560 m)</td>
<td>−12</td>
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<td>Phillips and Rintoul (2000)</td>
<td>51°S, 143°E (400–3300 m)</td>
<td>−11.3b, −40.6c</td>
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<tr>
<td><strong>Hydrography</strong></td>
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<tr>
<td>deSzeoke and Levine (1981)</td>
<td>ACC</td>
<td>−0.45</td>
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<tr>
<td>Macdonald and Wunsch (1996)</td>
<td>30°S</td>
<td>−0.9 ± 0.3</td>
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<td>Sloyan and Rintoul (2000)</td>
<td>30–40°S</td>
<td>−0.36 ± 0.08</td>
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<tr>
<td>Ganachaud and Wunsch (2000)</td>
<td>20–30°S</td>
<td>−0.7 ± 0.3</td>
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<td><strong>Altimetry</strong></td>
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<td>Keffer and Holloway (1988)</td>
<td>ACC (~53°S)</td>
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<td>Stammer (1998)</td>
<td>40°S</td>
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<td>53°S</td>
<td>−0.05</td>
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<td><strong>Global energy balance</strong></td>
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<td>Gordon and Owens (1987)</td>
<td>ACC</td>
<td>−0.31</td>
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<td>Gille (2000)</td>
<td>ACC (900m)</td>
<td>ALACE Floats</td>
<td>−[5-10]</td>
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<td>−[0.3-0.6] ± 0.3</td>
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Gille, 2000

\[ \rho c_p \overline{u'} \overline{T'} = -\kappa \rho c_p \partial \overline{T} \partial y \]
Eddy heat fluxes across the ACC in Drake Passage

- Drake 1979 (ISOS)
- DRAKE 2006-2008, French-Korean IPY
- cDrake 2007-2011, US IPY
Drake 1979 and DRAKE 2006-2008: 1-Year Mean Eddy Heat Fluxes from Moorings

- 11 of 24 EHF estimates are significant
- All are poleward
- Amplitude decreases to the south

Ferrari et al., 2014
cDrake: Vertical structure of 4-Year Mean Cross-Stream DEHF

Watts et al., in prep.
Watts et al., in prep.

**cDrake: Vertical structure of 4-Year Mean Cross-Stream DEHF**

- **median of sites** [2,4,5] yields peak of 0.008 C m/s = 32 kWm$^{-2}$
- **50%** of flux below 800 m
- **values** still large at 1500-3500m, about 20% of peak
  - compare to Bryden (1979) mean EHF of 6.5 kWm$^{-2}$ at 2700 m
- **vertical integral** is ~50 MWm$^{-1}$
  - compare to Phillips & Rintoul (2000) vertically integrated EHF of 40 MWm$^{-1}$, using shear coordinates
cDrake: Eddy heat fluxes at representative sites

\[ v'_{\text{ref}T'} \quad (°C \text{ cm/s}) \]

Intense poleward fluxes in SAF/PF interfrontal zone; (BC instability)

In PF, mean EHF grows in strong poleward pulses, downstream of Shackleton Fracture Zone

Weak heat flux events upstream of SFZ

Mean \(<v'_{\text{ref}T'}>\) stable in 2 years

Watts et al., in prep.
we recommend extreme caution in using with-COARE estimates in net buoyancy flux calculations that use unmodified radiation and freshwater flux fields from NCEP1/ERA. The COARE estimates might however be valid and useful when only the turbulent heat fluxes are of interest.

7. Discussion and conclusions

Air–sea flux estimates are especially poor in the Southern Ocean, largely because of the sparseness of both oceanic and meteorological ocean surface observations (e.g., Josey et al. 1999; Taylor 2000; Kubota et al. 2003).

TABLE 4. The RMS difference of monthly means and its standard deviation (years 2005–07) for net air–sea heat and freshwater heat-equivalent flux estimates over the ocean south of 24.7°S. For the comparison all datasets are interpolated on a 1/83 grid. “No FW” means that there is no independent freshwater flux estimate.

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<tr>
<th></th>
<th>NCEP1 ERA</th>
<th>NCEP1</th>
<th>1°C ERA</th>
<th>SOSE LY09</th>
<th>NCEP1 —</th>
<th>ERA 1°C</th>
<th>No FW</th>
<th>No FW</th>
<th>No FW</th>
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<th>RMS heat flux difference (W m⁻²)</th>
<th>ERA 1°C</th>
<th>NCEP1</th>
<th>1°C No FW</th>
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<td>RMS freshwater (heat-equivalent) flux difference (W m⁻²)</td>
<td>30.3</td>
<td>5.5</td>
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Differences between zonal/time averages for 6 different heat flux estimates indicate large uncertainties.

Differences are largest in ACC and WBC (not shown).
Changing sea-ice and glacial melt patterns

Antarctic ice shelf thickness change 2003-8

Glacial ice mass loss

Pritchard, 2012

Rignot et al., 2008

Warmer ocean appears to be increasing basal melt along Antarctic coastal ice-sheet margins, esp. in the Amundsen and Bellingshausen Seas.

Glacial ice mass loss is strongly associated with locales of increased influx of warm waters.
Summary

• Inversion of tracer fields yields a robust measure of the zonal mean Southern Ocean MOC strength $O(20$ Sv) but not its variability.

• Southern Ocean eddies are increasing and are significantly correlated with increasing winds.

• Eddies provide a mechanism for ACC transport to saturate and as well as partial compensation for the increase in overturning due to increased Ekman transport.

• Zonal variations in mass and tracer fluxes extend vertically throughout the water column and localize cross-ACC transport. These variations are associated with topography and vary with depth and distance across the ACC.

• Observations are critical for determining mechanisms of exchange, calibrating models and testing parameterizations.
Southern ocean is undersampled. Of particular interest to the SO MOC are the following:

- Observations to improve air-sea flux estimates
- Deep observations and observations south of the ACC - on the shelves and under sea-ice
- Time series in key locations in order to determine whether/how the MOC is changing
- Satellite and float observations for global estimates
- Observations to improve models, and models for global estimates
- Southern Ocean State Estimate provides a useful way to combine ocean physics and observations