The Southern Ocean and the Global Carbon Cycle

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Southern Ocean circulation

Wind-forced Antarctic Circumpolar Current (ACC)
Meridional overturning circulation: Upper and lower cells

L. Talley
Anthropogenic CO$_2$ uptake is mediated by circulation

Ocean $C_{\text{ant}}$ inventory (1990s)

Natural carbon distributions

Gruber et al., 2009
The Southern Ocean leak in the biological pump

Sigman et al., 2010
Southern Ocean air-sea fluxes: model uncertainty

CMIP5 modeled air-to-sea CO$_2$ fluxes

Anav et al. 2013
CO$_2$ flux is a small residual of opposing terms; O$_2$ flux is not

Sea-to-air fluxes
Net community production

GPP: Gross primary productivity
NPP: Net primary productivity
NCP: Net community production

after Sigman & Hain 2012
Sluggish versus energetic oceans

Kinetic energy
Global eddy-resolving integration: Model configuration

Forcing
CORE ‘Normal Year’ (adjusted to climatology, i.e. repeating annual cycle)

Initialization
Physics ($U$, $V$, $T$, $S$): prior physics-only integration ($\sim 15$ yrs)
Long-lived pools ($DIC$, $Alk$, nutrients): GLODAP/WOA climatologies, MLR gap-fill
Phytoplankton, Fe, etc.: interpolated from prior $1^\circ$ solution

Configuration details

<table>
<thead>
<tr>
<th></th>
<th>Low resolution</th>
<th>High resolution</th>
</tr>
</thead>
<tbody>
<tr>
<td>Grid</td>
<td>$1^\circ$ (60L), displaced pole</td>
<td>$0.1^\circ$ tripole (62L)</td>
</tr>
<tr>
<td>Tracer Horiz. Closure</td>
<td>GM, diagnostic $\kappa$</td>
<td>Biharmonic</td>
</tr>
<tr>
<td>Momentum Closure</td>
<td>Anisotropic harmonic viscosity</td>
<td>Biharmonic</td>
</tr>
<tr>
<td>Advection</td>
<td>Upwind-3</td>
<td>Centered (T&amp;S), Upwind-3 (BGC)</td>
</tr>
<tr>
<td>Topography</td>
<td>Full-cell ETOPO2</td>
<td>Partial-cell ETOPO2</td>
</tr>
<tr>
<td>Coupling interval</td>
<td>Daily</td>
<td>6 hr</td>
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:: Seasonal gas exchange ::
Tracer transport: resolved versus parameterized eddies

Tracer equations

\[
\frac{\partial \varphi}{\partial t} + \nabla \cdot \mathbf{u} \varphi + \nabla \cdot \mathbf{u}' \varphi' - \frac{\partial}{\partial z} \left( \kappa_v \frac{\partial \varphi}{\partial z} \right) = J_\varphi(x) + \nabla^2_H \left( \kappa_H \nabla^2_H \varphi \right)
\]

Tendency + Mean advection + Eddy advection - Vertical mixing = Source/sink

\[
\frac{\partial \varphi}{\partial t} + \nabla \cdot \mathbf{u} \varphi + \nabla \cdot \mathbf{u}' \varphi' + \nabla \cdot \mathbf{u}_{GM} \varphi - \nabla \cdot K_{iso} \nabla \varphi - \frac{\partial}{\partial z} \left( \kappa_v \frac{\partial \varphi}{\partial z} \right) = J_\varphi(x)
\]

:: Seasonal gas exchange ::
Surface ocean nitrate budget: vertical advection

Low resolution (1°)

High resolution (0.1°)
Surface ocean nitrate budget: vertical advection

Low resolution (1°)

High resolution (0.1°)

:: Seasonal gas exchange ::
Surface ocean nitrate budget: regional comparison

Low resolution (1°)

High resolution (0.1°)
Southern Ocean seasonal gas exchange

![Graphs showing seasonal gas exchange in the Southern Ocean](image)

- DIC Surface Gas Flux
- Dissolved Oxygen Surface Flux
- NPP
Atmospheric $O_2$ and $CO_2$ observations in Drake Passage

courtesy of B. Stephens

courtesy of B. Stephens
O$_2$/N$_2$ Ratio and CO$_2$ Airborne Southern Ocean Study (ORCAS)

Meridional section: O$_2$ in Austral Summer

courtesy of B. Stephens
Core measurement objectives

- Large-scale O$_2$ and CO$_2$ distributions: 50°S–70°S, 0–14km;
- Vertical O$_2$:CO$_2$ ratios across boundary-layer top and through mid-troposphere;
- O$_2$ and CO$_2$ fluxes inferred from Lagrangian particle dispersion back-trajectories: (1) regional scale, using upwind/downwind flights 30-hr apart, (2) whole campaign.

GV Scientific Payload

<table>
<thead>
<tr>
<th>Instrument</th>
<th>Measurement</th>
<th>Institution</th>
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</thead>
<tbody>
<tr>
<td>Airborne Oxygen Instrument (AO2)</td>
<td>$\delta$(O$_2$/N$_2$), CO$_2$</td>
<td>NCAR EOL</td>
</tr>
<tr>
<td>Quantum Cascade Laser Spectrometer (QCLS)</td>
<td>CO$_2$, CH$_4$, N$_2$O, CO</td>
<td>Harvard/Aerodyne/NCAR</td>
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<tr>
<td>Picarro</td>
<td>CO$_2$, CH$_4$, H$_2$O</td>
<td>NOAA/CU</td>
</tr>
<tr>
<td>Medusa Flask Sampler</td>
<td>$\delta$(O$_2$/N$_2$), CO$_2$, $\delta$(Ar/N$_2$), $\delta^{13}$C, $\delta^{18}$O, and $\Delta^{18}$C of CO$_2$</td>
<td>NCAR/Scripps</td>
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<tr>
<td>Portable Remote Imaging Spectrometer (PRISM)</td>
<td>Hyperspectral water-leaving radiance</td>
<td>JPL</td>
</tr>
<tr>
<td>Advanced Whole Air Sampler (AWAS)</td>
<td>Over 80 trace gases, including DMS, OCS, halocarbons, MeONO$_2$, isoprene</td>
<td>NCAR/U. Miami</td>
</tr>
<tr>
<td>HIAPER Trace Organic Gas Analyzer (TOGA)</td>
<td>Over 60 VOCs, including nitrate species, DMS, and VSL halocarbons</td>
<td>NCAR</td>
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The Southern Ocean plays a pivotal role in the global carbon cycle:
- Overturning circulation mediates uptake of atmospheric transient;
- Biological production mitigates outgassing of natural carbon.

CMIP5 models struggle to simulate the seasonal cycle of gas exchange, largely indicative of disparate representations of biological production.

Parameterized eddy mixing appears to produce reasonable annual mean fluxes of macronutrients (NO$_3^-$); discrepancies in seasonal production between low and high resolution simulations may be attributable to differences in iron cycling.

Atmospheric observations may provide a means of constraining the magnitude of Southern Ocean air-sea fluxes on seasonal to interannual timescales.