The Once and Future Battles of Thor and the Midgard Serpent

Or

The Southern Hemisphere Westerlies and the Antarctic Circumpolar Current

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Mean Sea Surface Height from Geosat altimetry (Gille 1994)
The circulation of the Southern Ocean is one of the primary sources of error in projecting climate change.

A. 85% of the anthropogenic carbon currently entering the atmosphere will dissolve in the ocean - the rate is limited by the rate at which deep waters are exposed to the surface.

B. The Southern Ocean accounts for about 40% of the total oceanic uptake and controls the air-sea gas fluxes associated with the biological pump.

C. Source of crucial water mass formation - SAMW, AAIW, and AABW.

D. There is significant disagreement between models about the rate at which water masses are transformed within the Southern Ocean.
Position of Major Fronts (from S. Rintoul)
What the Conveyor Belt Missed

- Reasonable model of the thermohaline deep water formation in the North Atlantic

BUT

- Requires high diffusion to return deep water to surface
- No divergence-driven upwelling
- No Southern Ocean Ventilation of Deep Water

The Southern Ocean Divergence

Elements of the overturning circulation in the Southern Ocean

Salinity along 30° W in the Atlantic
WOCE Section A16
Trends in the Southern Annular Mode

Fig. 3. December-May trends (left) and the contribution of the SAM to the trends (right). Top, 22-year (1979–2000) linear trends in 500-hPa geopotential height. Bottom, 32-year (1969–2000) linear trends in surface temperature and 22-year (1979–2000) linear trends in 925-hPa winds. Shading is drawn at 10 m per 30 years for 500-hPa height and at increments of 0.5 K per 30 years for surface temperature. The longest vector corresponds to ~4 m/s.

Thompson & Solomon (2002)
John Austin: The animation shows the evolution of northern and southern hemisphere ozone as simulated in the GFDL coupled chemistry-climate model.
Figure 10.17. (a) Multi-model mean of the regression of the leading EOF of ensemble mean Northern Hemisphere sea level pressure (NH SLP thin red line). The time series of regression coefficients has zero mean between year 1900 and 1970. The thick red line is a 10-year low-pass filtered version of the mean. The grey shading represents the inter-model spread at the 95% confidence level and is filtered. A filtered version of the observed SLP from the Hadley Centre (HadSLP1) is shown in black. The regression coefficient for the winter following a major tropical eruption is marked by red, blue and black triangles for the multi-model mean, the individual model mean and observations, respectively. (b) As in (a) for Southern Hemisphere SLP for models with (red) and without (blue) ozone forcing. Adapted from Miller et al. (2006).
Column inventory of anthropogenic CO₂ in the oceans (after Sabine et al. 2002). High inventories are associated with deep water formation in the North Atlantic and intermediate and mode water formation between 30°S and 50°S (Feely and Sabine, http://www.pmel.noaa.gov/co2/PressConference.html)
Fig 3. Temperature trends computed from ALACE hydrography differences bin-averaged in 1° by 1° squares. For this analysis, ALACE/hydrography pairs were used if the hydrographic measurements were collected after 1930, and they were separated from the ALACE observations by at least 10 years in time and by less than 220 km in space.
Figure 1. Schematic depiction of the high-latitude ice-atmosphere response to +SAM.

The base image is from T. Mitchell (http://www.jisao.washington.edu/sam) and shows the regression of SLP anomalies onto a SAM-derived index (see transcom.colostate.edu for details).

The arrows schematically depict wind anomalies during a +SAM scenario.
The Southern Ocean in the AR4 Climate Models 1860 control
Uncertainty in modeled CO$_2$ fluxes
due to physical processes

Orr et al. (2002)
Climate system models

Atmosphere
(momentum, temperature, mass, humidity)

Atmospheric chemistry

Terrestrial biology

Land surface

Ocean biology

Sea ice

Ocean chemistry

Ocean
(momentum, temperature, salinity, mass)
Comparison of AR4 Coupled Climate Models

Maximum westerly wind stress vs ACC strength

Russell et al., 2006a
Barotropic Streamfunction (Sv) &
Sea Surface Height (m)

Russell et al., 2006a
Zonally-averaged wind stress (N/m²).
Observed (black), GFDL-CM2.1 (blue, circle), GFDL-CM2.0 (blue, triangle)
Impact of Current Position on Temperature Error (0:200m)
The Subtropical Front is defined as a Salinity of 34.9-35.0 at 100m. The southern boundary of the ACC is defined as $\sigma_0$ of 1027.6 at 200m. (After Orsi, 1999)
Locations of the Polar and Subtropical Fronts
(as defined by Orsi et al., 1995)
for 8 of the models submitted for the IPCC AR4 Assessment
Types of Circulation Errors

1. About Right (ACC strength and position, Westerly Winds, Freshwater and heat fluxes, NADW heat and salt transport the Southern Ocean) - GFDL CM2.1, MIROC3.2(hires)

2. Wind stress errors that lead to incorrect ACC transports
   a) Too high wind stress over ACC (CSIRO-Mk3.0, MIROC(medres), UKMO-HadGEM1
   b) Too weak wind stress produce weak ACC (CNRM and IAP)
   c) Equatorward displacement of strong winds (GFDL CM2.0, BCCR-BCM2.0, MRI-CGM2.3.2a, both CCMA models)
   d) Equatorward displacement of weak winds (GISS-AOM, GISS-ER)

3. Incorrect formation of NADW
   a) NADW too warm, fresh or weak (INM-CM3.0, IPSL-CM4)
   b) NADW too large (UKMO-HadCM3)
The Southern Ocean
1980-2008
Subtropical Front (salinity between 34.9 and 35.0 at 100m)
Subantarctic Front (temperature between 4°C and 5°C at 400m)
Polar Front (temperature minimum in the upper 200 meters between 1°C and 2°C)
Southern Boundary of the ACC (sigma-0 between 27.55 and 27.65)
All definitions are after Orsi et al. (1995).
RMS Error for the Models

[Graph showing monthly RMS error for various models, with different markers and lines representing each model's performance over the months.]
Change in Winds and Sea Ice Coverage Between 2003-7 and 1982-6
The Southern Ocean in a Warming World
ΔpCO₂ (350 - ocean) at 30°S
The Westerlies drive CO₂ out of the deep ocean through the divergence around Antarctica.
ΔpCO₂ (450 - ocean) at 30°S
ΔpCO₂ (550 - ocean) at 30°S
$\Delta pCO_2$ (720 - ocean) at 30°S
Historical evolution of CO₂ exchange

Atmospheric CO₂ (ppmv)

Southern Ocean Sea-Air CO₂ exchange

outgassing

uptake
Model Response to SRESA1B Scenario

(CO$_2$ increases to 700+ppm @ year 2100, steady to 2300)

...as CO$_2$ increases (~doubles), the S. Hemisphere’s westerly winds strengthen (max zonal wind stress + ~10%)

Russell et al., 2006b

Red=CM2.0, Black=CM2.1
As one might expect in a warming world, the area over which potential densities exceed 27.1 \((\sigma_\theta)\) at 100m depth (shown in yellow) is reduced as surface waters warm, and the depths at which the \(\sigma_\theta\) 27.1 surface lie become deeper.
The outcrop area decreases as the surface waters warm.

...decreases by $\approx 8 \times 10^6 \text{ km}^2$ (~33%) in CM2.1

... decreases by $\approx 7 \times 10^6 \text{ km}^2$ (~50%) in CM2.0
Yet the amount of water that has been in contact with the surface less than 50 years prior grows because of more Southern Ocean ventilation. (due to more surface divergence)

...increases by ~6% in CM2.1...

...less so in CM2.0

Red = CM2.0, Black = CM2.1
Are these trends observable?
observed $\Delta^{14}C$ in Drake Passage

mean $\Delta^{14}C$

changes in $\Delta^{14}C$ (‰)

1973
2006

Courtesy C. Sweeney
Northward transport of light water ($\sigma_\theta \leq 27.5$) at 40°S plotted against the ACC transport at Drake Passage for each of the models considered in this study. The blue circle is GFDL-CM2.1, the red circle is GFDL-CM2.0, the green circle is MIROC-3.2(hires), and the purple circle is MRI-CGCM2.3.2. The northward transport is a rough measure of the dense-to-light water transformation occurring in the Southern Ocean; b) time series of the northward transport of light water at 40°S (the conversion rate) for the GFDL-CM2.1 (blue), GFDL-CM2.0 (red) and MRI-CGCM2.3.2 (purple) coupled climate models. These time series are of the annual mean conversion rate, smoothed with a centered-mean 9-year running smoother.
Heat and solubility-related carbon inventory grows over time

More so in CM2.1 (solid) than CM2.0 (dash) as time goes on & effects of deep ventilation differences become more apparent.
Heat and “Carbon” Storage Difference in 2300

CM2.1 - CM2.0 (2300-2000)

(A) Heat Storage Difference (10^9 J/m^2)
CM2.1 - CM2.0

(B) "Carbon" Storage Difference (mol/m^2)
CM2.1 - CM2.0

Heat Storage Difference (10^9 J/m^2)
Carbon Storage Difference (mol/m^2)
Caveats!

- We assume a constant pH distribution, ignoring the effect of buffering.

- We assume a constant biological pump, i.e. no change in surface to deep DIC distribution.

  - These are clearly important effects that need to be addressed - but the appropriate tracers weren’t included in the AR4 models.
Time series of volume averaged ocean temperature difference (°K), the various integrations minus the control.

From Stouffer, Russell & Spelman, 2006
Surface air temperature difference, perturbation integration minus the 1860 control integration (°K).

Stouffer, Russell & Spelman (2006)
Poleward-Intensification of the Southern Hemisphere Westerlies: Ecosystem Impacts (with D. Ainley, C. Tynan & A. Drain)
Paleo-Westerlies during Glacial-Interglacial transitions
Mechanisms to increase nutrient utilization efficiency

1) Increase nutrient utilization (e.g., John Martin’s “Iron Hypothesis”)
2) Reduce nutrient supply (e.g., glacial stratification hypothesis)
Upwelling is tied to efficiency of the ocean’s “biological pump”

Surface nitrate illustrates high efficiency of the biological pump over most of the ocean. Principal exception is the Southern Ocean.

From: iridl.ldeo.columbia.edu/SOURCES/LEVITUS94
Iron fertilization was not pervasive in the glacial Southern Ocean

Reconstructed change in export production (Glacial - Holocene):
Blue = lower during glacial; Red = higher during glacial

Kohfeld et al., Science, 2005
Increased wind stress at 60°S drives upwelling in the So. Ocean

Maximum wind stress at the latitude of the Drake Passage favors upwelling of deep CO₂-rich water masses.
Upwelling occurs South of the Zero in Wind Stress Curl
The Westerlies drive CO$_2$ out of the deep ocean through the divergence around Antarctica.

**Diagram:****
- DP/ACC
- Thermocline
- Unproductive Southern Ocean circuit
- Biologically productive North Atlantic circuit
Feedback during tropospheric warming

- Increased Atmospheric CO₂
- Stronger ACC, Stronger Upwelling
- Poleward Shifted Westerlies
- Tropospheric Warming
The tests that any simulation of the glacial/interglacial transition must pass:

- Are the changes in Antarctic air temperature and CO$_2$ coincident? (Petit et al 1999)?

- Do Antarctic temperatures rise several hundred years ahead of atmospheric CO$_2$ at each termination? (Fischer et al., 1999; Caillon et al., 2003)

- Are the deepest Atlantic waters significantly more depleted in $\delta^{13}C$ during the glacial? (Broecker, 1982; Duplessy et al 1988; Herguera et al, 1992; Sarnthein et al 1994;
Idealized Model Domain

Fresh water flux shown (mm/day)
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Idealized Model
Antarctic Air Temperature and Atmospheric CO₂
Change in $\delta^{13}C$ between the modern and glacial Atlantic due to the buildup of respired CO$_2$ at depth. The figure was constructed by subtracting the $\delta^{13}C$ of the water overlying 56 sediment cores in the eastern Atlantic from the $\delta^{13}C$ of benthic foraminifera of glacial age (after Duplessey et al., 1988, Kroopnick, 1985, and Boyle, 1992, with additional data from Curry et al., 1988, Flower et al., 2000, Hodell et al., 2003, and Mackensen et al., 2001). A value of 0.3 per mil was added to the difference to remove the effect of isotopically light terrestrial carbon that invaded the ocean at the time of the LGM.
Maximum Southern Ocean upwelling coincided with deglacial rise in CO$_2$

**SUMMARY OF EVIDENCE:**

Peak upwelling (opal flux) coincided with:
- warming in Antarctica,
- deglacial rise in CO$_2$
- deglacial drop in atm. $\Delta^{14}$C

Including pause during ACR

Anderson et al, 2009
The Southern Hemisphere Westerlies determine the partition of carbon between deep ocean and atmosphere by controlling the rate of global deep ocean ventilation.

Poleward intensification of the SH Westerlies decreases stratification in the Southern Ocean allowing the deep ocean to equilibrate with the atmosphere.

*** To see this effect in a model requires a good simulation of S.H. westerlies & NADW.***