The Southern Ocean in a high-CO$_2$ world: Changes in inorganic and organic carbon fluxes

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The Ocean in a High CO$_2$-World
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THE SOUTHERN OCEAN

THE PREINDUSTRIAL CARBON CYCLE

Hoppema et al., 2004
THE SOUTHERN OCEAN
THE PREINDUSTRIAL CARBON CYCLE

Hoppema et al., 2004
The Southern Ocean
The contemporary carbon cycle
SOUTHERN ANNULAR MODE (SAM)

- SAM Index:
  - Sea level pressure anomalies between the subpolar low and the subtropical high-pressure systems
**SOUTHERN ANNULAR MODE (SAM)**

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**SOUTHERN ANNULAR MODE (SAM)**

The Southern Annular Mode (SAM) is a mode of variability in the Southern Hemisphere's climate. It is characterized by a band of increased westerlies over the Southern Ocean, which influences weather patterns in the Southern Hemisphere. This band moves south or north depending on the phase of the SAM, affecting the climate over Antarctica and the surrounding oceans.

- **Antarctica**: The continent at the bottom of the Southern Hemisphere, covered in ice and surrounded by the Southern Ocean.
- **Polar Front**: A boundary between the polar and subtropical climates.
- **Surface Ocean**: The upper layer of the ocean where most of the Earth's surface is covered.
- **Deep Ocean**: The lower layers of the ocean, beneath the surface ocean.
SOUTHERN ANNULAR MODE (SAM)

Increased westerlies

Polar Front

atmosphere

surface ocean

Counter-acting transport by eddies?

Antarctica

Increased westerlies

Deep ocean

Antarctic shelf

Surface ocean

Deep ocean
ECOSYSTEM MODEL REcoM-2

Geider et al., 1998; Schartau et al., 2007; Hohn et al., 2009; Hauck et al., GBC, under review
MODEL RUNS

Atm CO₂

Climatological forcing (CORE)
Climatological dust

Inter-annual varying forcing (NCEP-R1)
Monthly dust (1979-2010)
MODEL RUNS

Atm CO₂

- Climatological forcing (CORE)
- Climatological dust
- Inter-annual varying forcing (NCEP-R1)
- Monthly dust (1979-2010)

Changes due to atm CO₂ increase AND perturbed atmospheric forcing

Only changes due to perturbed atmospheric forcing
MEAN MODEL STATE

MOST LIMITING FACTORS FOR PHYTOPLANKTON GROWTH

Nanophytoplankton

Diatoms

Feb

Feb

Si-limitation

N-limitation

Fe-limitation
**Response to SAM**

Satellite-derived SST (°C) response per unit increase SAM Index

Modelled SST (°C) response per unit increase SAM Index

Lovenduski and Gruber 2005
Response to SAM

Modelled total chlorophyll response
(mg m^{-3} per unit increase SAM)
Modelled total chlorophyll response  
(mg m$^{-3}$ per unit increase SAM)
Modelled total chlorophyll response
(mg m\(^{-3}\) per unit increase SAM)

Polar Front

- iron limitation
  - iron addition
  - deepening MLD
  \[ \text{chlorophyll increase} \]

- limitation by macro-nutrients
  - iron addition
  - deepening MLD
  \[ \text{chlorophyll decrease} \]
Carbon Budget

Response of upward DIC advection
(mm mol m⁻² y⁻¹ per unit increase SAM at 100 m)
CARBON BUDGET

Response of upward DIC advection
(mmol m$^{-2}$ y$^{-1}$ per unit increase SAM at 100 m)
CARBON BUDGET
CARBON BUDGET

Delta DIC \(_{100m}\) (Pg C yr\(^{-1}\))

Latitude

-0.01
0
0.01

Biology
Gas exchange

80S 70S 60S 50S 40S 30S
CARBON FLUX ANOMALIES AT POSITIVE SAM

Sources and sinks for perturbed surface DIC budget at positive SAM (Pg C yr\(^{-1}\))

Hauck et al., GBC, under review
**SAM-related carbon budget summary**

- Upwelling of DIC south of Polar Front ≈ balanced by northward Ekman transport and downwelling north of Polar Front
- Changes in gas exchange and biological carbon export are of similar magnitude, but much smaller than advective changes
- SAM related sea-air CO$_2$ flux in SO is $0.09 \pm 0.03$ PgC yr$^{-1}$, similar to a recent eddy-resolving study (Dufour, 2011)
The Southern Ocean in a High-CO$_2$ World

- CO$_2$ uptake rate might grow slower than atm. CO$_2$ concentrations due to circulation changes as response to the positive SAM (Le Quéré et al., 2007)
- Anthropogenic ocean acidification will proceed, might even be amplified by upwelling of carbon-rich deep water (Lenton et al., 2009)