Carbon as Velcro: Connecting physical climate variability and biogeochemical dynamics in the Southern Ocean

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Part 1: The Mean State
Observed sea-air CO$_2$ flux

Takahashi et al. (2009)
Ocean circulation and CO$_2$

Modified from Speer et al. (2000)
Integrated (<44°S) sea-air CO₂ flux

data from Gruber et al. (2009)
Why the model spread?

Getting the physics “right”

Orr et al. (2002)
Small-scale variability

Anthropogenic CO₂ uptake and storage

Ito et al. (2010)
Ecologists aren’t off the hook!

Integrated (<44°S) sea-air CO$_2$ flux

data from T. Ito (unpublished)
Modeling the ecosystem

The MAREMIP project: Phase I results

SeaWiFS  CCSM-BEC  NEMURO  PISCES  Green

surface chlorophyll concentration
\([\ln(\text{mg m}^{-3})]\)

data provided by M. Vogt
Part 2: Variability
Historical evolution of CO$_2$ exchange

Atmospheric CO$_2$ (ppmv)

Southern Ocean Sea-Air CO$_2$ exchange

outgassing

uptake
Historical evolution of $\text{CO}_2$ exchange

![Graph showing the historical evolution of atmospheric CO$_2$ exchange from 1775 to 2000.](image)

- **Atmospheric CO$_2$ (ppmv)**
  - Y-axis values: 280 to 380

- **Time Period**
  - X-axis: 1775 to 2000

- **Southern Ocean Sea-Air CO$_2$ Exchange**
  - Outgassing
  - Uptake

The graph illustrates the increase in atmospheric CO$_2$ levels from 1775 to 2000, with a notable increase starting around 1950.
Variability and trends in CO$_2$

Lovenduski et al. (2008)
Modes of climate variability

Southern Annular Mode (SAM)

El Niño – Southern Oscillation (ENSO)
SAM drives CO$_2$ flux variability

spatially-integrated (<35°S), de-trended CO$_2$ fluxes

de-trended SAM index

Lovenduski et al. (2007)
SAM drives CO$_2$ flux trend

pre-industrial CO$_2$
flux trend
trend congruent
with SAM

Lovenduski et al. (2008)
Causes of variability

Lovenduski et al. (2008)

zonal-mean dissolved inorganic carbon

\( \mu \text{mol kg}^{-1} \)

increased meridional overturning

stronger wind stress

Lovenduski et al. (2008)
The great eddy debate

Can coarse-resolution ocean models simulate an appropriate response to increasing Southern Hemisphere winds?

a few references …

Hallberg and Gnadadesikan (2006)
Boning et al. (2008)
Hogg et al. (2008)
Screen et al. (2009)
Farneti et al. (2010)
Spence et al. (2010)
Farneti and Gent (2011)
Gent and Danabasoglu (in press)
SAM drives ecosystem variability

Mixed Layer Depth anomaly (+ SAM)

Surface chlorophyll anomaly vs. mixed layer depth anomaly

Statistically significant

Sallée et al. (2010)
Part 3: Future Changes
Stratification

a. $\Delta$ SST ($^\circ$C)
b. $\Delta$ Stratification (kg/m$^3$)
c. $\Delta$ Ice fraction

Marinov et al. (2010)
Wind-driven circulation

\[ \Delta \text{Meridional Overturning} \]

- GHG simulation
- Ozone Recovery simulation

\[ \Delta \text{Meridional Overturning} \]

- SAM index

\[ hPa \]

- Year

Sigmond et al. (2011)
Acidification

surface $\Delta CO_3^{2-}$ in 2100

$\Delta CO_3^{2-} = [CO_3^{2-}] - [CO_3^{2-}]_{sat}$

Orr et al. (2005)
The issues that plague us...

The Mean State

1. How large is the Southern Ocean CO$_2$ sink?
2. Can we accurately model CO$_2$ uptake?
   a) Accurately representing physics
   b) Accurately representing ecology
3. What is the role of eddies in CO$_2$ uptake and transport?
The issues that plague us...

Variability

1. How do eddies respond to increasing wind stress?

2. Can we observe variability and trends?
   1. physical circulation
   2. CO$_2$ fluxes, storage
   3. ecology
The issues that plague us...

Future Changes

1. Stratification of the Southern Ocean
   1. Impacts on carbon storage
   2. Impacts on ecology

2. Wind-driven circulation changes
   1. Will the wind stress continue to increase?
   2. How will this impact carbon and ecology?

3. How quickly will Southern Ocean acidification proceed?
The End!