Annual CO$_2$ and O$_2$ dynamics in the Ross Sea, Antarctica

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Importance of the Southern Ocean

Anthropogenic CO₂

Column inventory (mol m⁻²) and Cumulative flux up to 2008 (mol m⁻²)
based on tracer time distributions

Khatiwala et al. 2009
Southern Ocean

Marinov et al. 2006
Antarctic continental shelves
Ross Sea

Antarctic continental shelves
Deepwater formation

Padman et al. 2009
CO₂ sink

Arrigo et al. 2008
Key questions

1. What are the mechanics of the Ross Sea CO$_2$ sink?
2. What are the sensitivities of the system?
3. How do key variables scale relatively?
Upper ocean mass balance
Upper ocean mass balance

\[ h \frac{\partial C}{\partial t} = J_{xy} + J_z + J_{\text{gas}} + J_{\text{bio}} \]

- mixed layer depth
- lateral mixing
- entrainment/diffusion
- gas exchange
- net community production
Net community production
Net community production

\[ h \frac{\partial C}{\partial t} = J_{phy} + J_{gas} + J_{ncp} \]
High latitude, weakly buffered

Sarmiento & Gruber 2006
Extreme drawdown

[Map and graphs showing ice free time and carbon dioxide concentration changes over time with marked seasonal RFs: ~18 for Spring and 15 for Summer.]
Seasonality

SeaWiFS-derived primary productivity along $180^\circ$ E, Arrigo algorithm
Gas exchange

\[
pCO_{2\text{atm}} \quad ? \quad J_{\text{gas}}
\]

\[
\begin{align*}
\frac{\partial C}{\partial t} = J_{\text{phy}} + J_{\text{gas}} + J_{\text{ncp}}
\end{align*}
\]
Gas exchange

\[ J_{\text{gas}, \text{O}_2} = k^{o_2} (O_{2, \text{sat}} - O_{2}^{\text{sw}}) \]

\[ J_{\text{gas}, \text{CO}_2} = k^{co_2} \gamma (p\text{CO}_2^{\text{atm}} - p\text{CO}_2^{\text{sw}}) \]
Gas exchange

\[ p_{\text{CO}_2^{\text{atm}}} \]

\[ \text{Ice} \]

\[ p_{\text{CO}_2^{\text{sw}}} \]

\[ J_{\text{gas}} \]

\[ J_{\text{gas, O}_2} = (1 - A) k^{O_2} \Delta O_2 \]

\[ J_{\text{gas, CO}_2} = (1 - A) k^{CO_2} \gamma \Delta p_{\text{CO}_2} \]

where \( A \) is the fractional ice coverage.
Differing O₂ and CO₂ dynamics

- Air-sea exchange is more sluggish for CO₂ than for O₂.

\[ p_{CO_2} \text{ continues to decline after } O_2 \text{ concentrations have stabilized.} \]

\[
\Delta O_2/Ar = \frac{(O_2/Ar)_{sw}}{(O_2/Ar)_{sat}}
\]

\[ \Rightarrow \text{ biological oxygen saturation} \]

(bubble and state change components removed)

Lines show 1-box model simulation with constant NCP (39.5 mmol C m⁻² d⁻¹) and constant wind (4.2 m s⁻¹).
Excess O$_2$?

\[ \text{PO}_4^* = [\text{PO}_4^{3-}] + \frac{[\text{O}_2]}{170} - 1.95 \mu \text{mol kg}^{-1} \]

- O$_2$:P conservative with respect to biology.
- Gas exchange leads to O$_2$ deficit in summer.
Stratification

\[ h \frac{\partial C}{\partial t} = J_{phy} + J_{gas} + J_{ncp} \]
Stratification

Box model: NCP = constant, stochastic wind.

Analytical expression:

\[ O_2(t) = O_{2, \text{sat}} \left( 1 + \Delta O_2,i \right) e^{-kt} - \frac{\text{NCP}/h - kO_{2, \text{sat}}}{k} \left( 1 - e^{-kt} \right) \]
Dynamical stratification in early Spring

NBP06-08, spring cruise
Dynamical stratification in early Spring

predominately southerly wind

Spring water column observations
Dynamical stratification in early Spring

Fronts

\[ b = -\frac{g \rho}{\rho_o} \]
Dynamical stratification in early Spring

Buoyancy generation

\[ \int_0^{100} b \, dz \times 10^{-3} \]

ROMS simulation results

2D w/ lateral buoyancy gradient

1D only surface buoyancy fluxes
Dynamical stratification in early Spring

Enhanced winter-spring transition at fronts

Spring water column observations
Annual sink dynamics

Forcing

Mechanics :: annual dynamics
Annual sink dynamics
Upper ocean properties

Mechanics :: annual dynamics
Annual sink dynamics

Net sink for both O₂ and CO₂

\[
\int J_{gas,O_2} \, dt = 110 \text{ mol m}^{-2}
\]

\[
\int J_{gas,CO_2} \, dt = 1.4 \text{ mol m}^{-2}
\]
Annual sink dynamics
Interannual variability (sign convention reversed)

Arrigo & Van Dijken 2007
Influence on the atmosphere

Atmospheric potential oxygen

\[ J_{\text{APO}} = -J_{\text{gas, O}_2} - 1.1J_{\text{gas, CO}_2} \]

APO is mostly conservative with respect to the terrestrial biosphere and fossil fuel emissions. 

Battle et al. 2008
Representing heterogeneity

Model biases

Anthropogenic CO$_2$ ($\mu$mol l$^{-1}$)  

CFC-11 ($\mu$mol l$^{-1}$)

* Thorsten et al. 2009
Representing heterogeneity

Lachkar et al. 2007
Questions?