
Annual CO₂ and O₂ dynamics in the Ross Sea, Antarctica

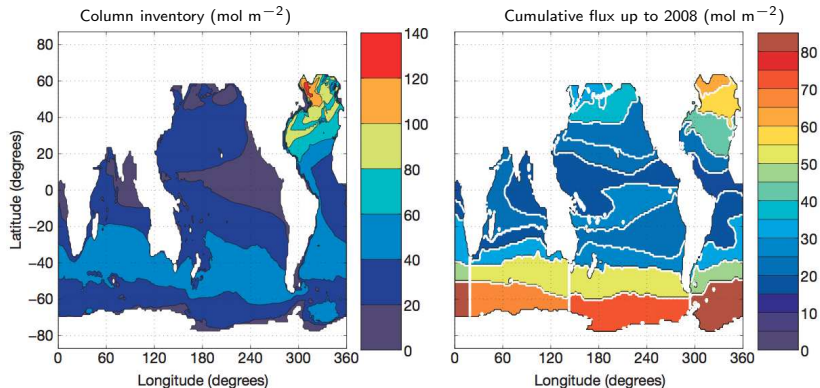
Matthew Long

Environmental Earth System Science
Stanford University

16 February 2010

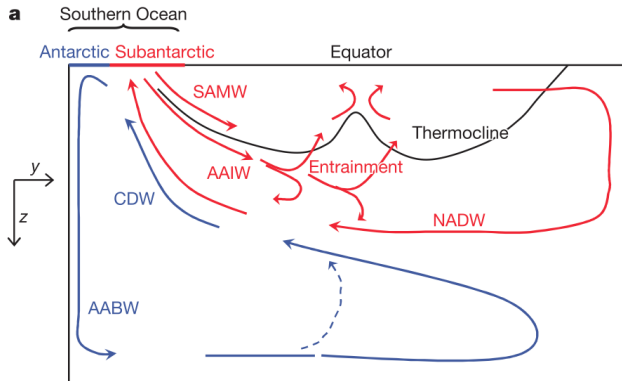
Importance of the Southern Ocean

Anthropogenic CO₂



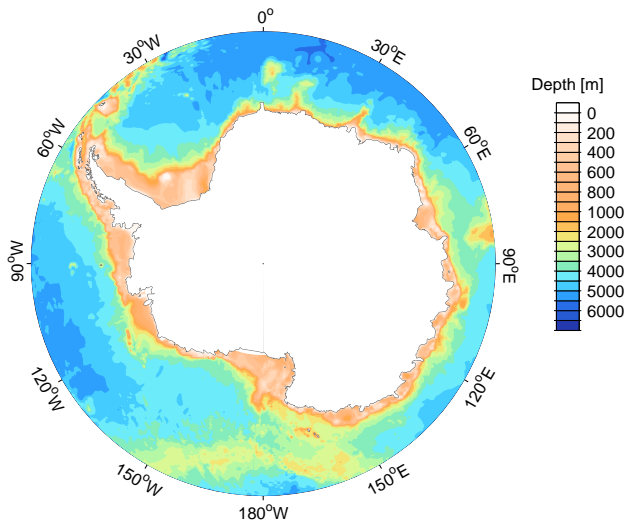
based on tracer time distributions
Khatiwala et al. 2009

Southern Ocean

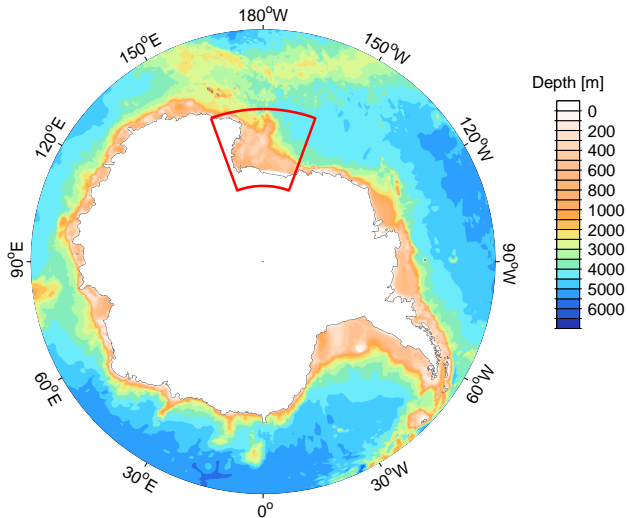


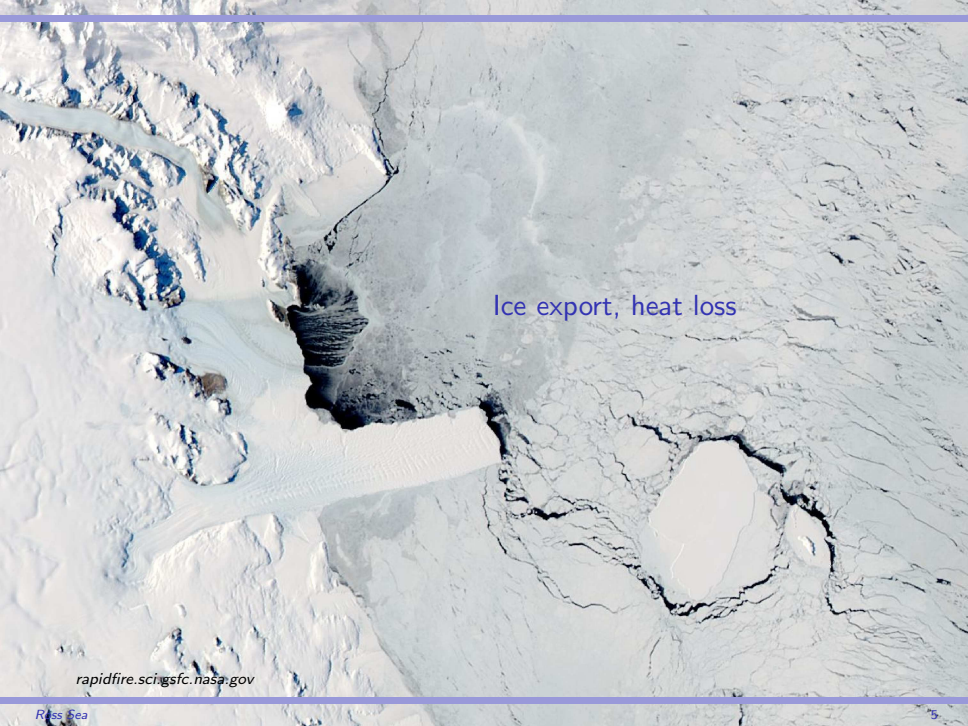
Marinov et al. 2006

Antarctic continental shelves



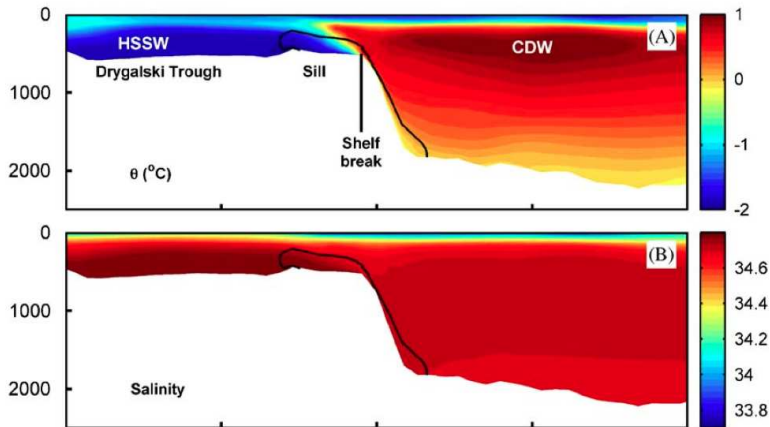
Ross Sea



A satellite image of an ice shelf, likely in the Ross Sea. A prominent rift runs vertically through the center of the image, with a large, dark, irregularly shaped lead (open water) at its base. The ice surface is heavily textured with numerous small, interconnected leads and cracks, creating a complex, maze-like pattern. The overall color palette is dominated by various shades of white and light blue, with some darker blue areas indicating deeper water or thinner ice.

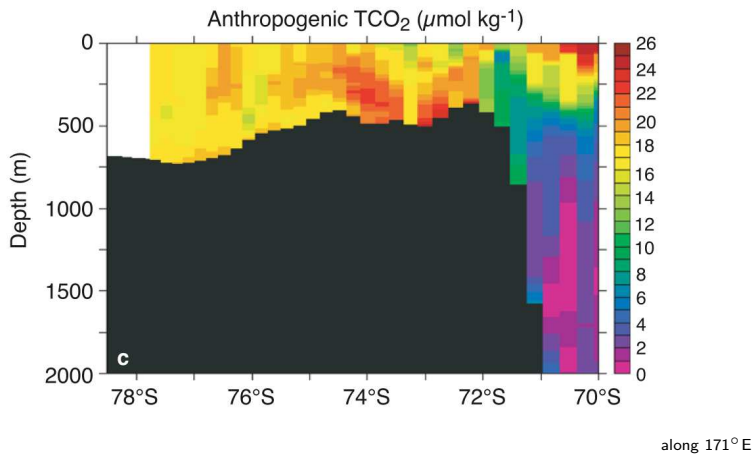
Ice export, heat loss

Deepwater formation



Padman et al. 2009

CO₂ sink

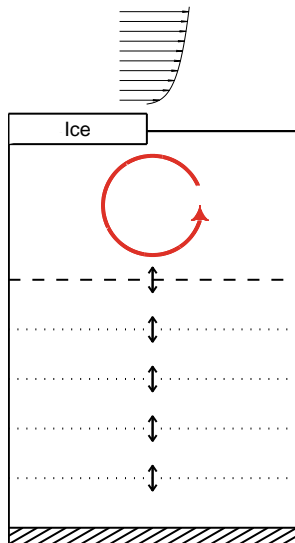


Arrigo et al. 2008

Key questions

1. What are the mechanics of the Ross Sea CO₂ sink?
2. What are the sensitivities of the system?
3. How do key variables scale relatively?

Upper ocean mass balance



Upper ocean mass balance

$$h \frac{\partial C}{\partial t} = J_{xy} + J_z + J_{gas} + J_{bio}$$

mixed layer depth

lateral mixing

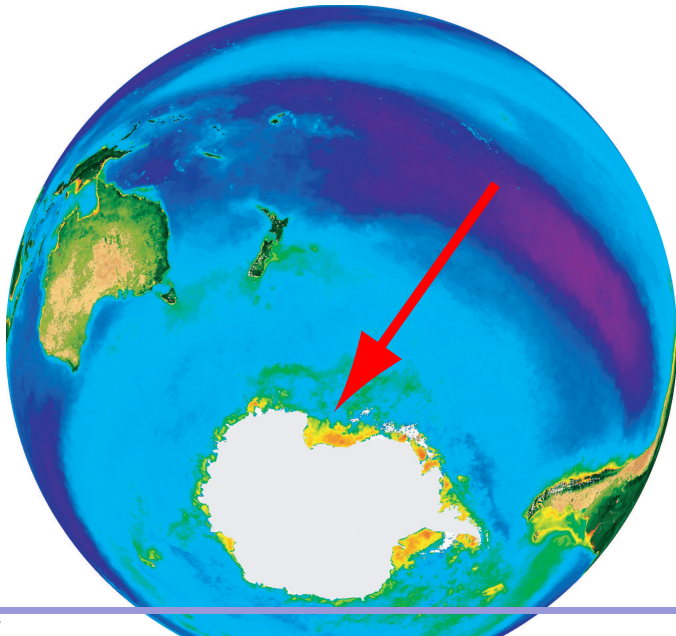
entrainment/diffusion

gas exchange

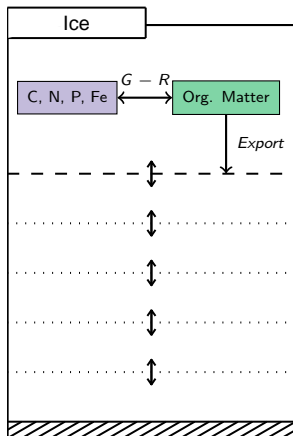
net community production

The diagram shows the equation $h \frac{\partial C}{\partial t} = J_{xy} + J_z + J_{gas} + J_{bio}$. The term $h \frac{\partial C}{\partial t}$ is linked to 'mixed layer depth'. The term J_{xy} is linked to 'lateral mixing'. The term J_z is linked to 'entrainment/diffusion'. The term J_{gas} is linked to 'gas exchange'. The term J_{bio} is linked to 'net community production'. Each term is enclosed in a colored box: J_{xy} and J_z are red, J_{gas} is purple, and J_{bio} is green. Arrows point from the text labels to their respective terms in the equation.

Net community production

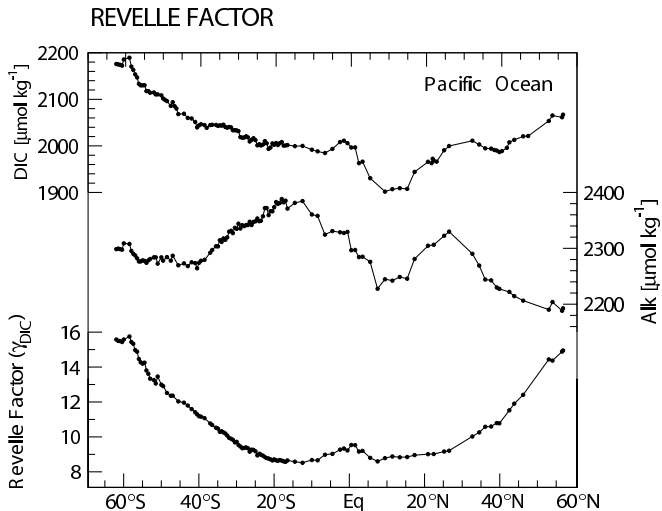


Net community production



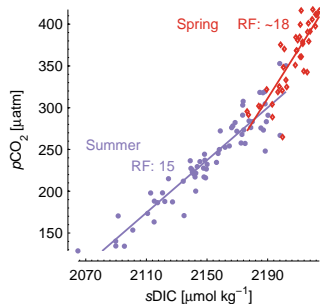
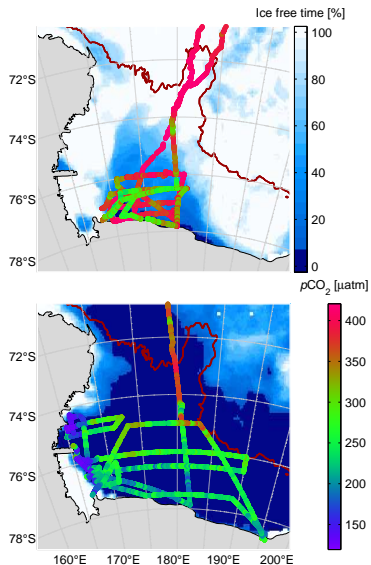
$$h \frac{\partial C}{\partial t} = J_{phy} + J_{gas} + J_{ncp}$$

High latitude, weakly buffered

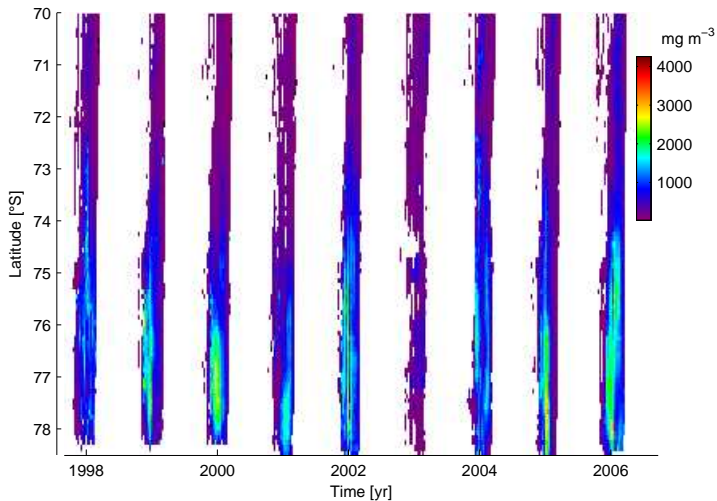


Sarmiento & Gruber 2006

Extreme drawdown

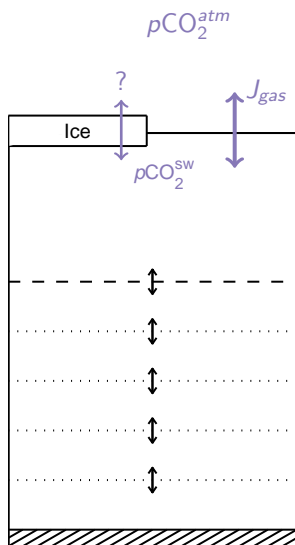


Seasonality



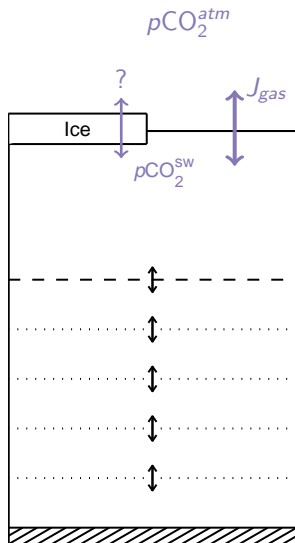
SeaWiFS-derived primary productivity along 180° E, Arrigo algorithm

Gas exchange



$$h \frac{\partial C}{\partial t} = J_{\text{phy}} + J_{\text{gas}} + J_{\text{nep}}$$

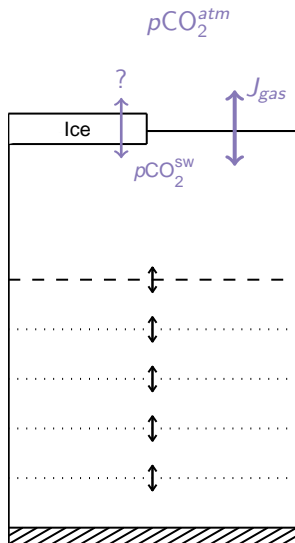
Gas exchange



$$J_{\text{gas},\text{O}_2} = k^{\text{O}_2} (\text{O}_{2,\text{sat}} - \text{O}_2^{\text{sw}})$$

$$J_{\text{gas},\text{CO}_2} = k^{\text{CO}_2} \gamma (p\text{CO}_2^{\text{atm}} - p\text{CO}_2^{\text{sw}})$$

Gas exchange

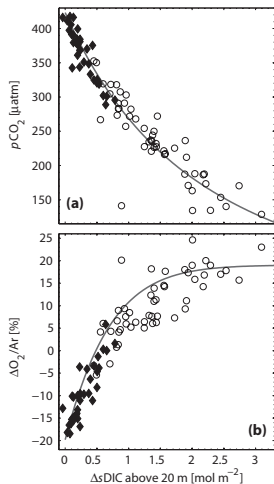


$$J_{gas,O_2} = (1 - A) k^{O_2} \Delta O_2$$

$$J_{gas,CO_2} = (1 - A) k^{CO_2} \gamma \Delta pCO_2$$

where A is the fractional ice coverage.

Differing O₂ and CO₂ dynamics



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).

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

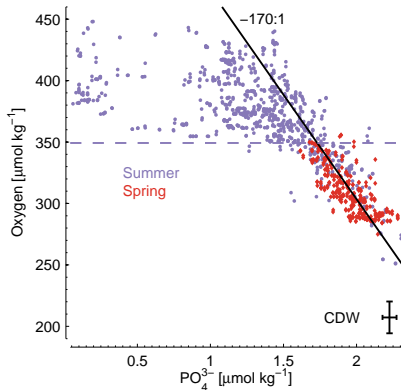
$p\text{CO}_2$ continues to decline after O₂ concentrations have stabilized.

$$\Delta\text{O}_2/\text{Ar} = \frac{(\text{O}_2/\text{Ar})_{sw}}{(\text{O}_2/\text{Ar})_{sat}}$$

⇒ biological oxygen saturation (bubble and state change components removed)

Excess O₂?

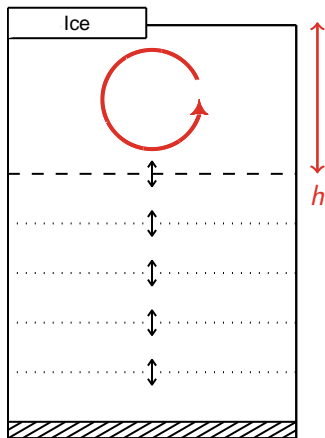
$$PO_4^* = [PO_4^{3-}] + \frac{[O_2]}{170} - 1.95 \mu\text{mol kg}^{-1}$$



- ▶ O₂:P conservative with respect to biology.

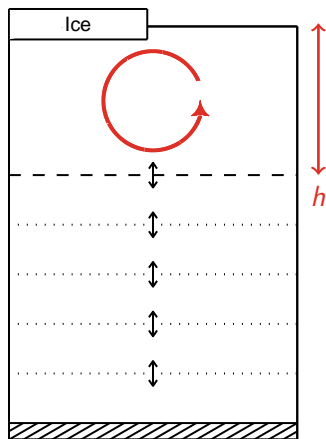
Gas exchange leads to O₂ deficit in summer.

Stratification

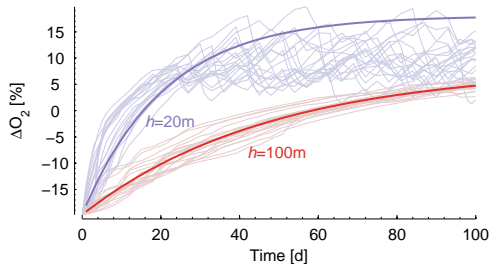


$$h \frac{\partial C}{\partial t} = J_{phy} + J_{gas} + J_{ncp}$$

Stratification



$$k = \frac{\text{piston velocity}}{h}$$

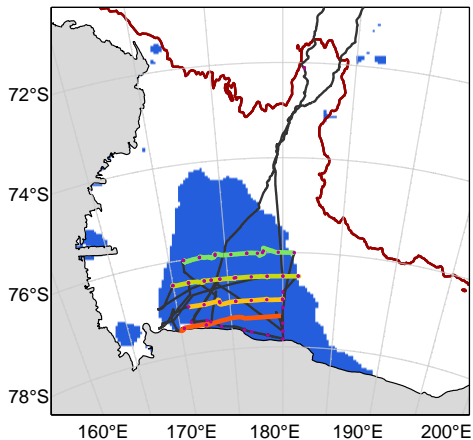


Box model: $NCP = \text{constant}$, stochastic wind.

Analytical expression:

$$O_2(t) = O_{2,sat} (1 + \Delta O_{2,i}) e^{-kt} - \frac{NCP/h - kO_{2,sat}}{k} (1 - e^{-kt})$$

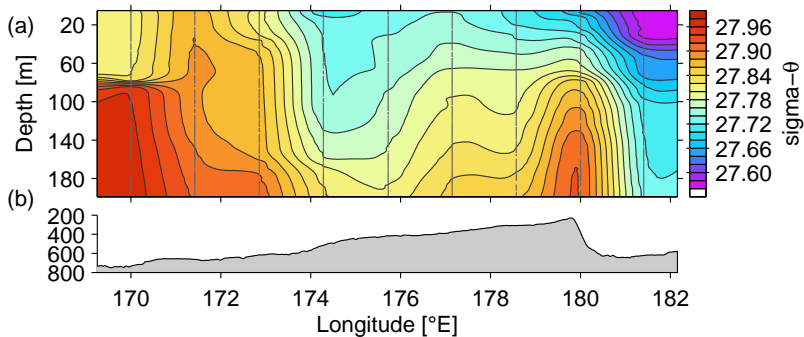
Dynamical stratification in early Spring



NBP06-08, spring cruise

Dynamical stratification in early Spring

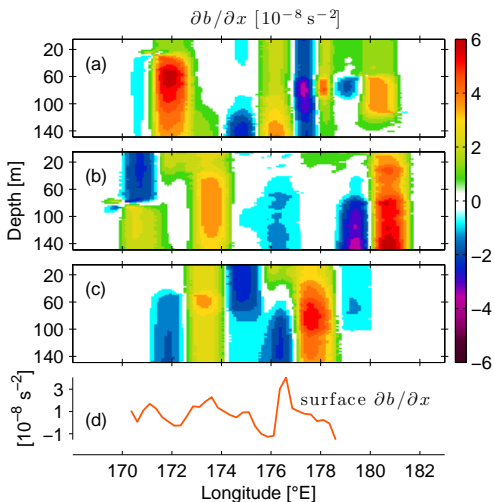
⊕ predominately southerly wind



Spring water column observations

Dynamical stratification in early Spring

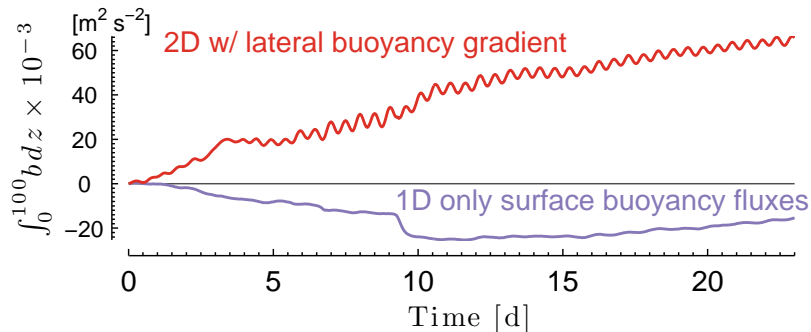
Fronts



$$b = -g\rho/\rho_o$$

Dynamical stratification in early Spring

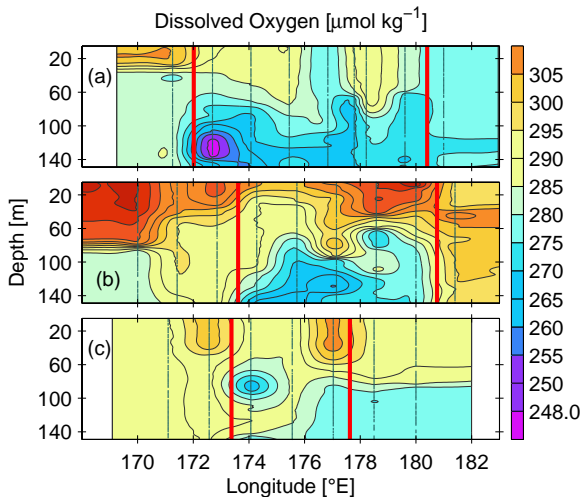
Buoyancy generation



ROMS simulation results

Dynamical stratification in early Spring

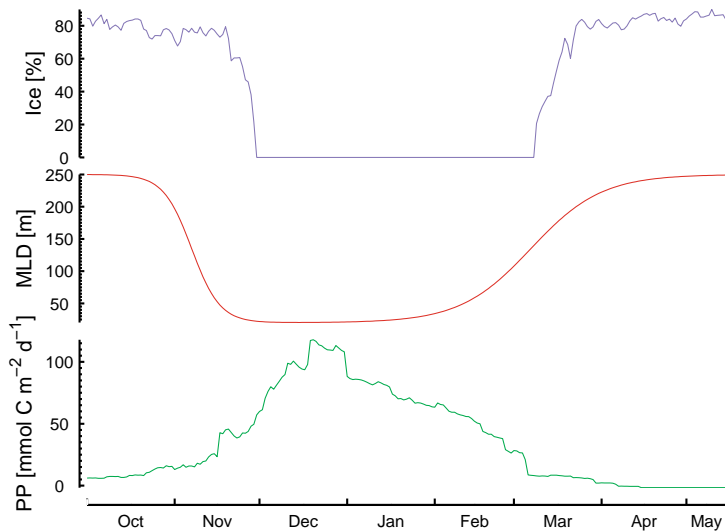
Enhanced winter-spring transition at **fronts**



Spring water column observations

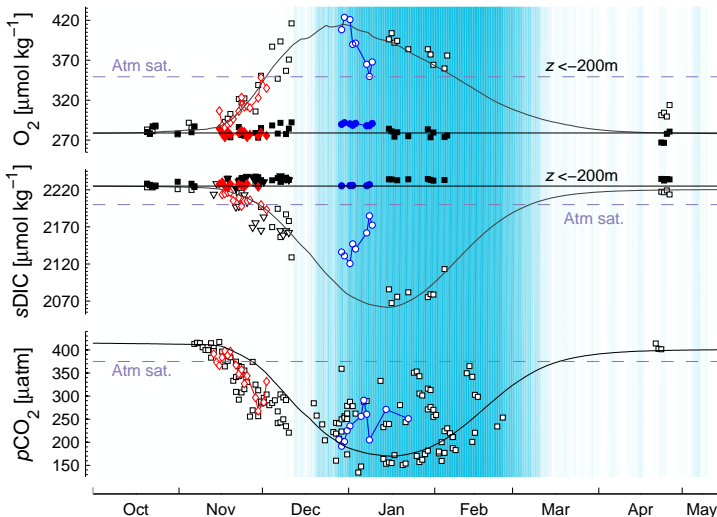
Annual sink dynamics

Forcing



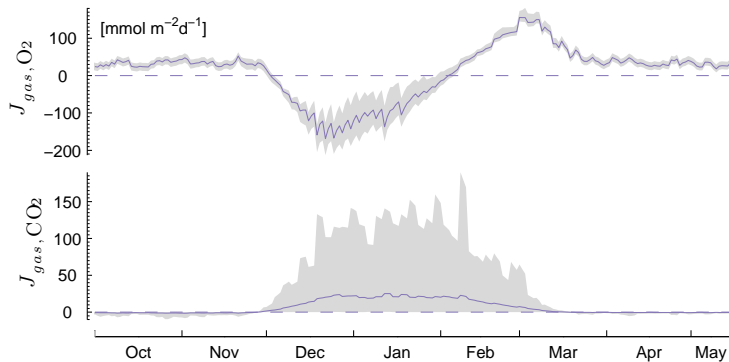
Annual sink dynamics

Upper ocean properties



Annual sink dynamics

Fluxes



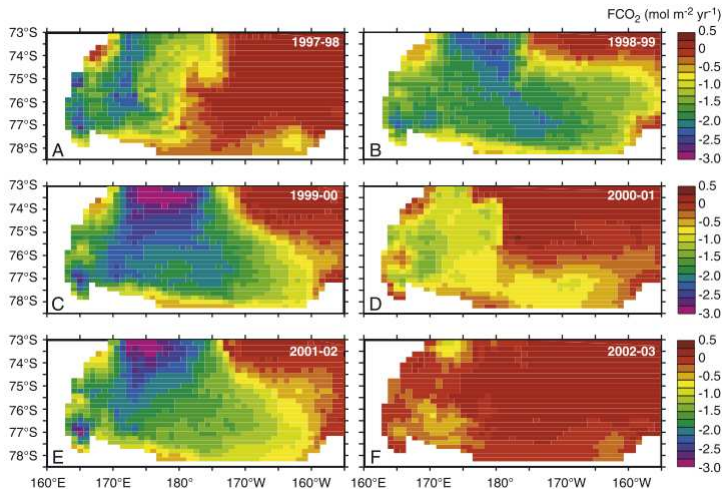
Net sink for both O_2 and CO_2

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

$$\int J_{gas,CO_2} dt = 1.4\ mol\ m^{-2}$$

Annual sink dynamics

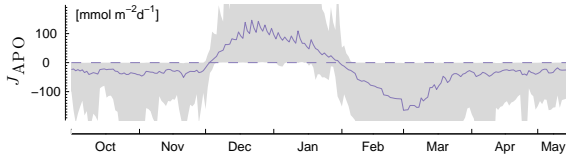
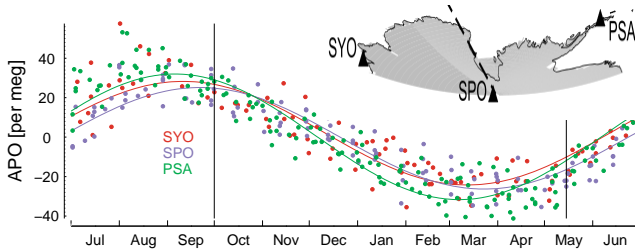
Interannual variability (sign convention reversed)



Arrigo & Van Dijken 2007

Influence on the atmosphere

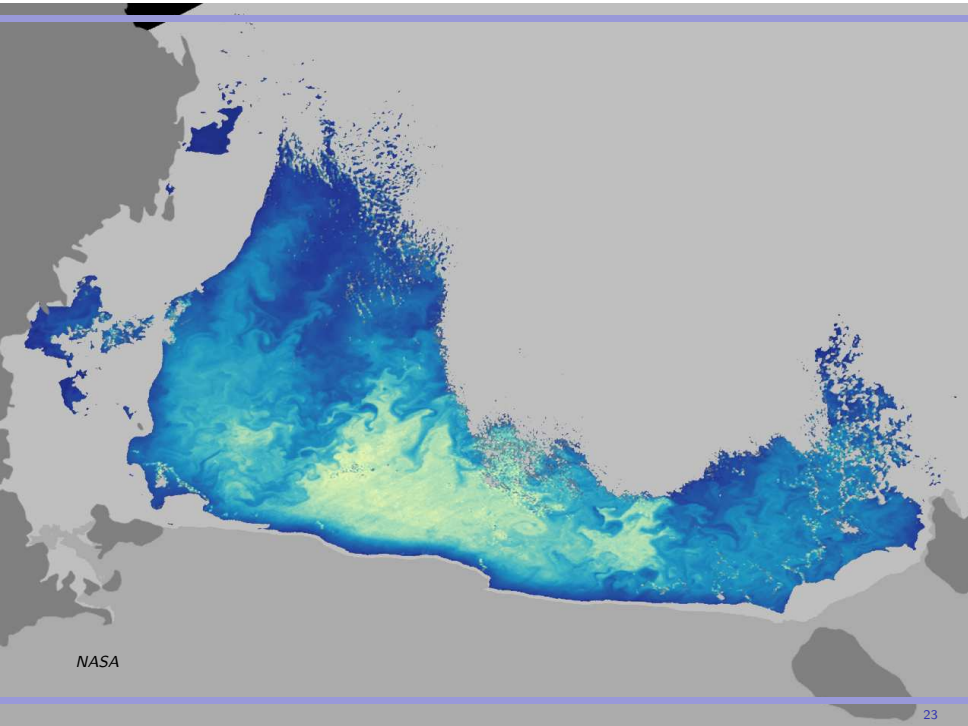
Atmospheric potential oxygen



$$J_{APO} = -J_{gas, O_2} - 1.1J_{gas, CO_2}$$

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

Battle et al. 2008

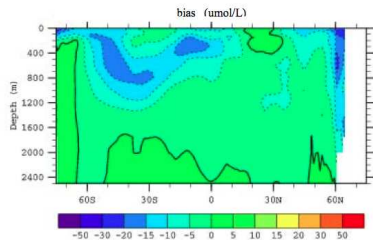


NASA

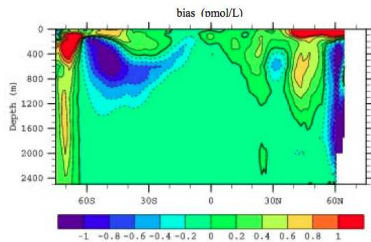
Representing heterogeneity

Model biases

Anthropogenic CO₂ ($\mu\text{mol l}^{-1}$)

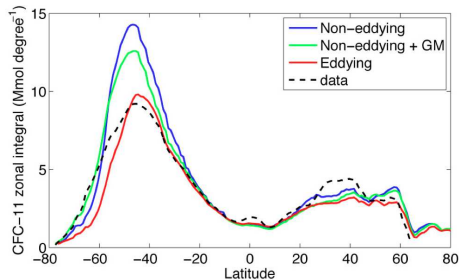


CFC-11 ($\mu\text{mol l}^{-1}$)

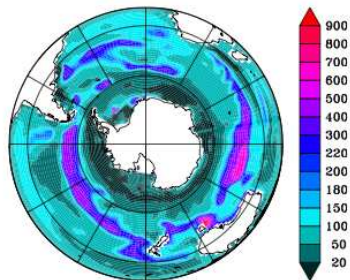


Thorten et al. 2009

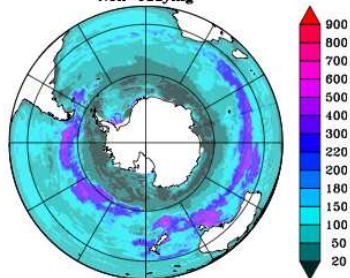
Representing heterogeneity



Lachkar et al. 2007



Non-eddying



Eddying

Questions?

