The Southern Ocean and the Global Carbon Cycle

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Southern Ocean Cross Working Group Session

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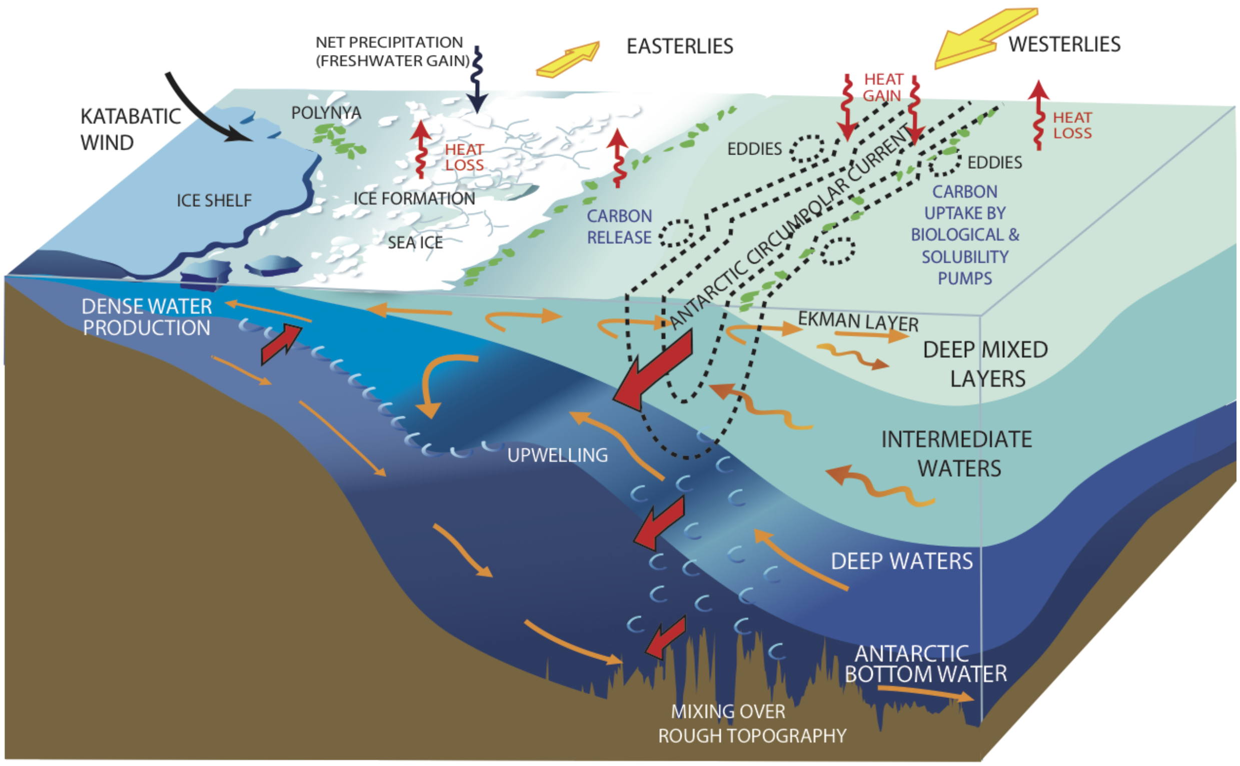
Southern Ocean circulation

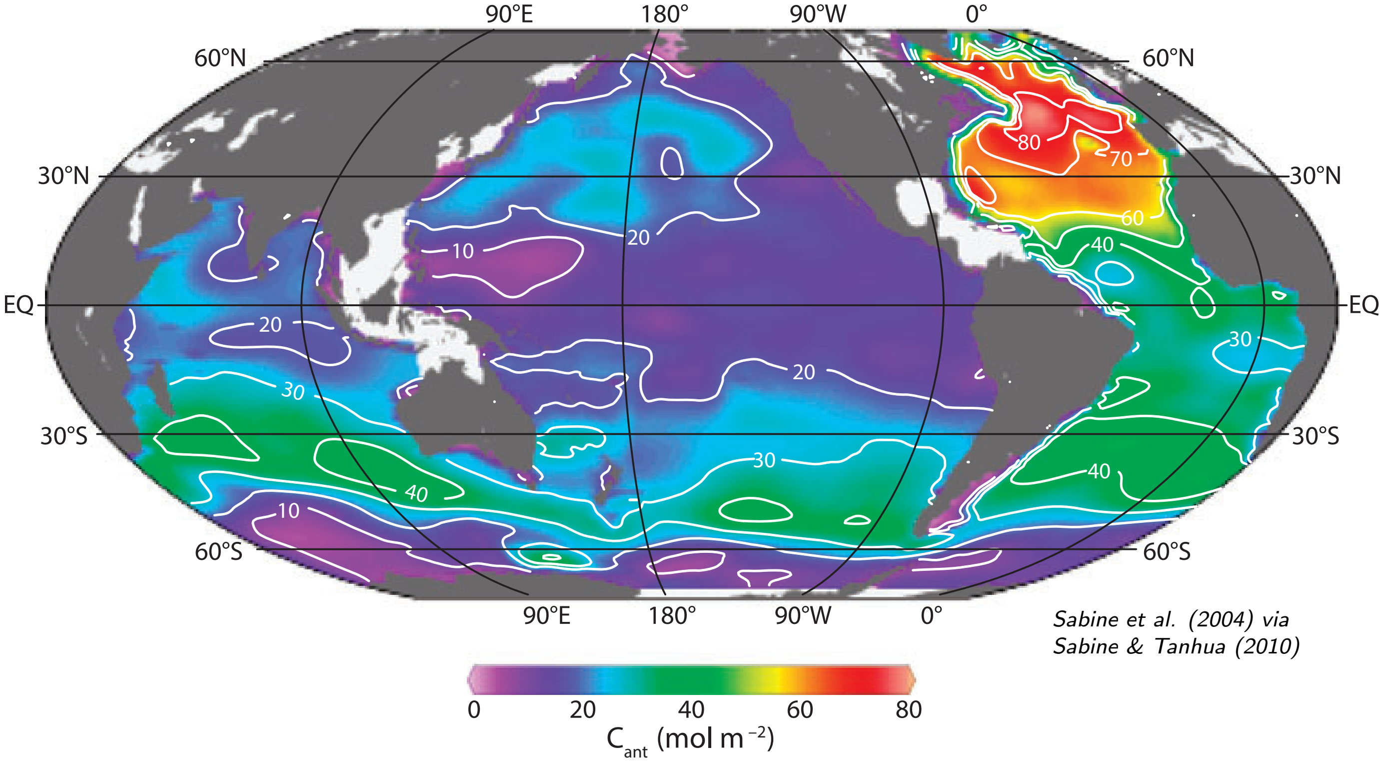


Wind-forced Antarctic Circumpolar Current (ACC)
Meridional overturning circulation: Upper and lower cells

L. Talley

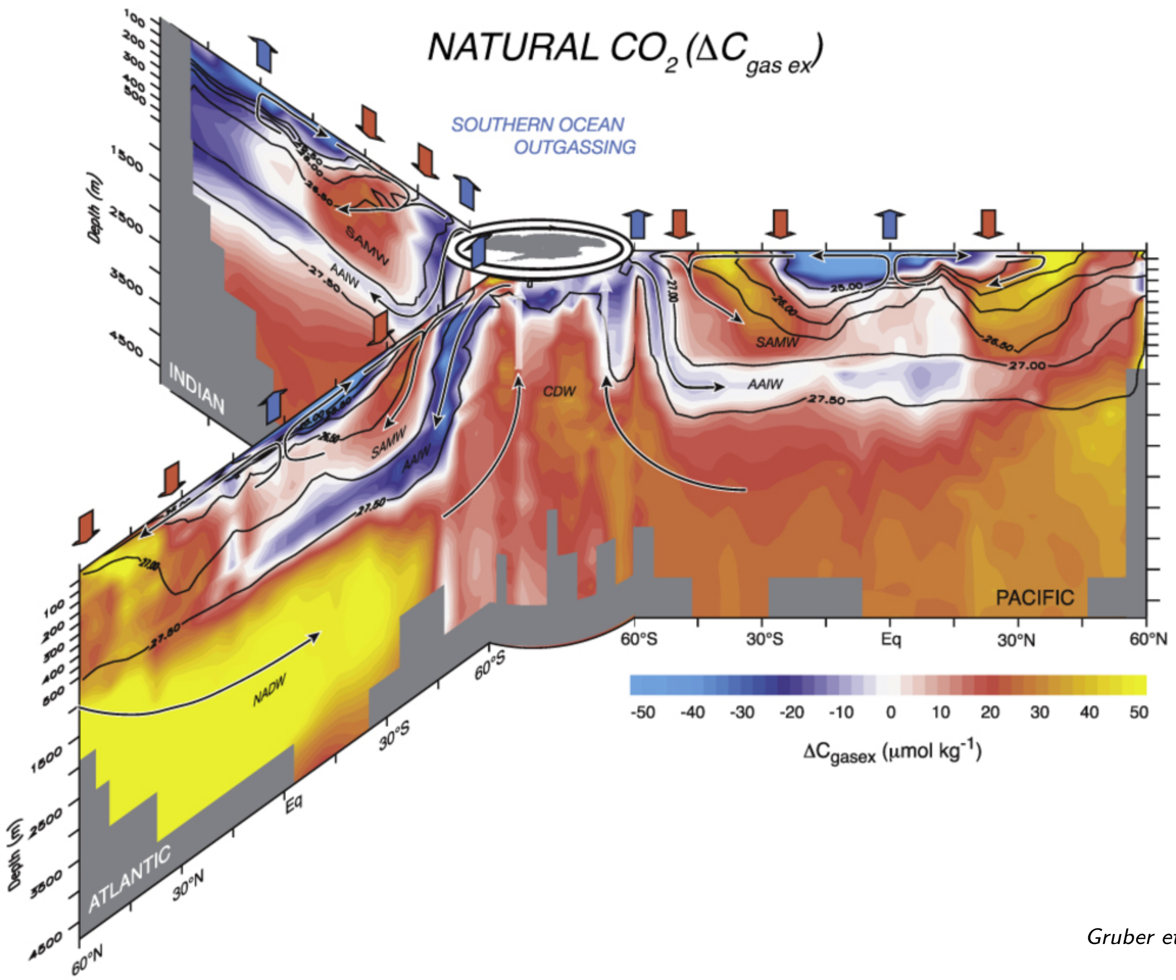
Anthropogenic CO_2 uptake is mediated by circulation

Ocean C_{ant} inventory (1990s)



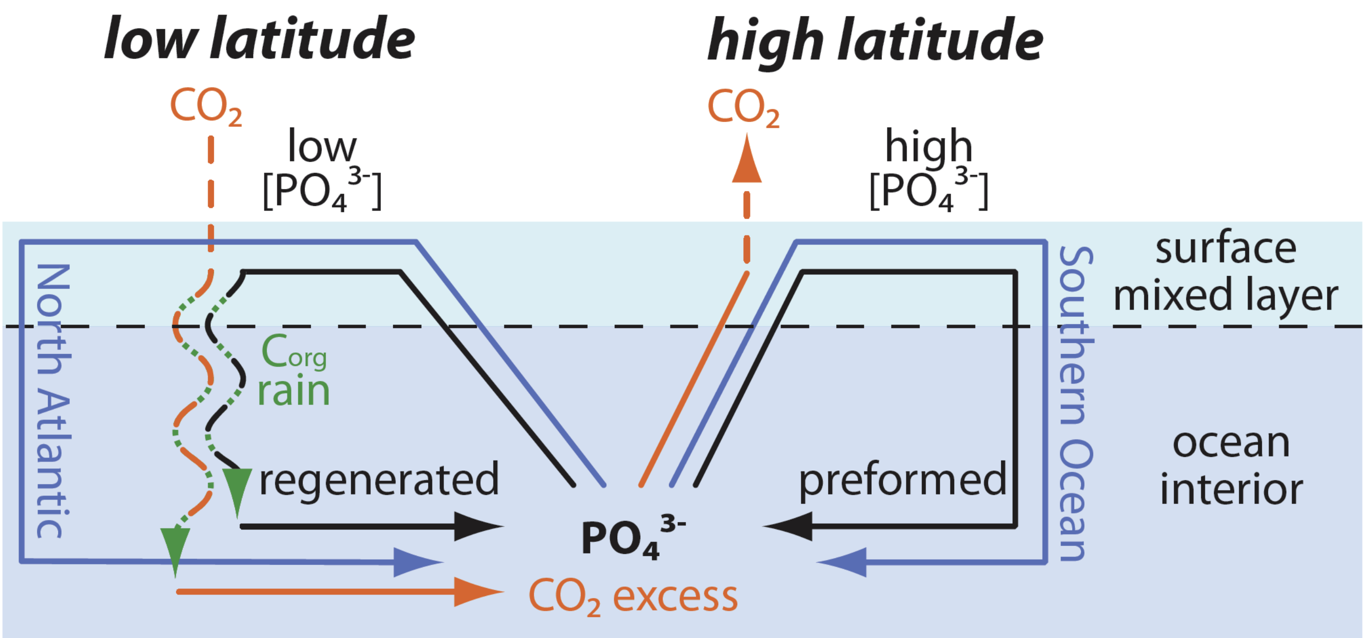
Sabine et al. (2004) via
Sabine & Tanhua (2010)

Natural carbon distributions



Gruber et al., 2009

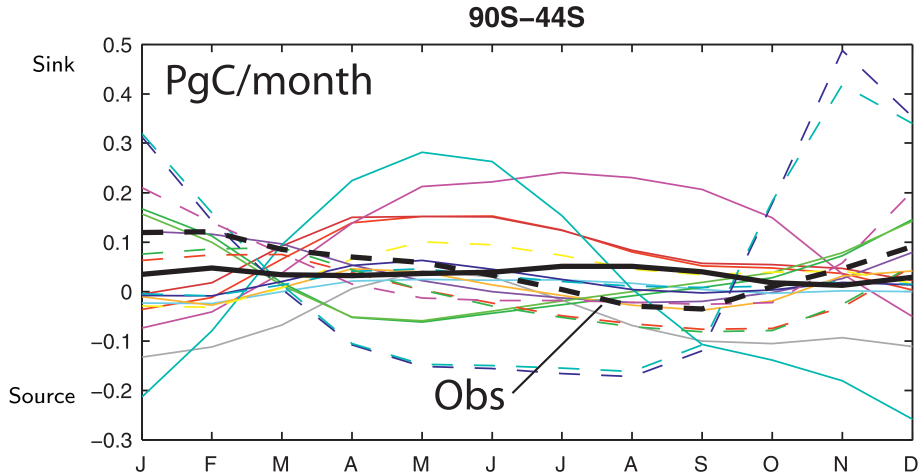
The Southern Ocean leak in the biological pump



Sigman et al., 2010

Southern Ocean air-sea fluxes: model uncertainty

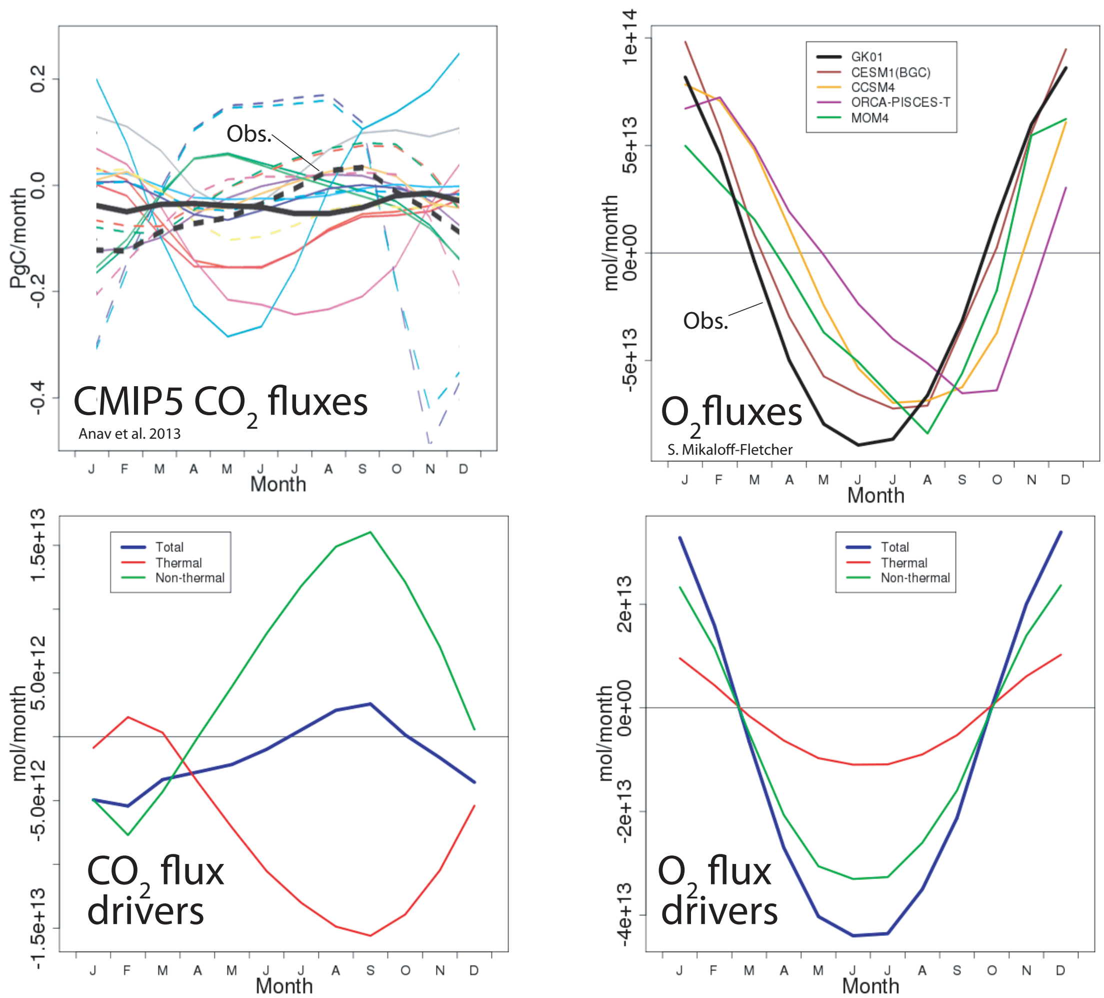
CMIP5 modeled air-to-sea CO_2 fluxes



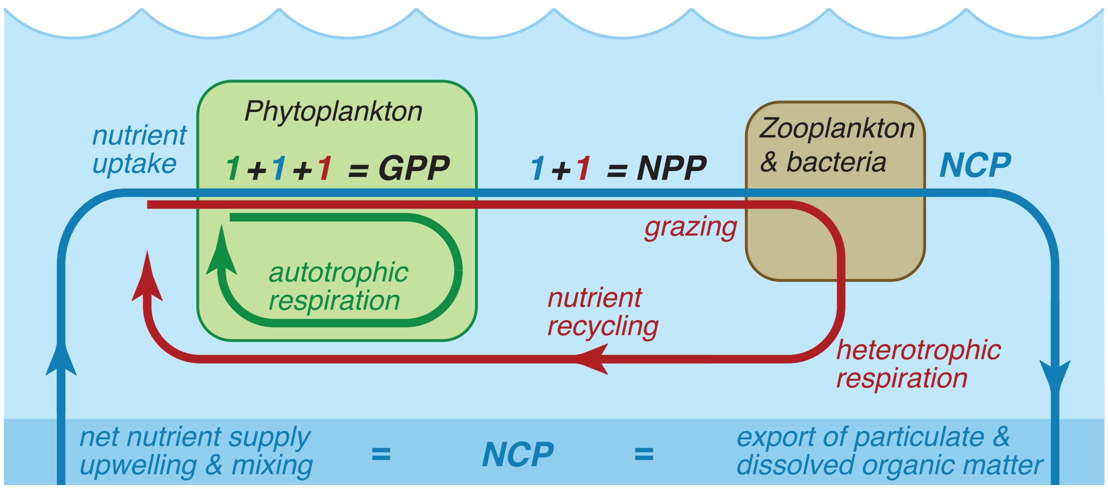
Anav et al. 2013

CO_2 flux is a small residual of opposing terms; O_2 flux is not

Sea-to-air fluxes



Net community production



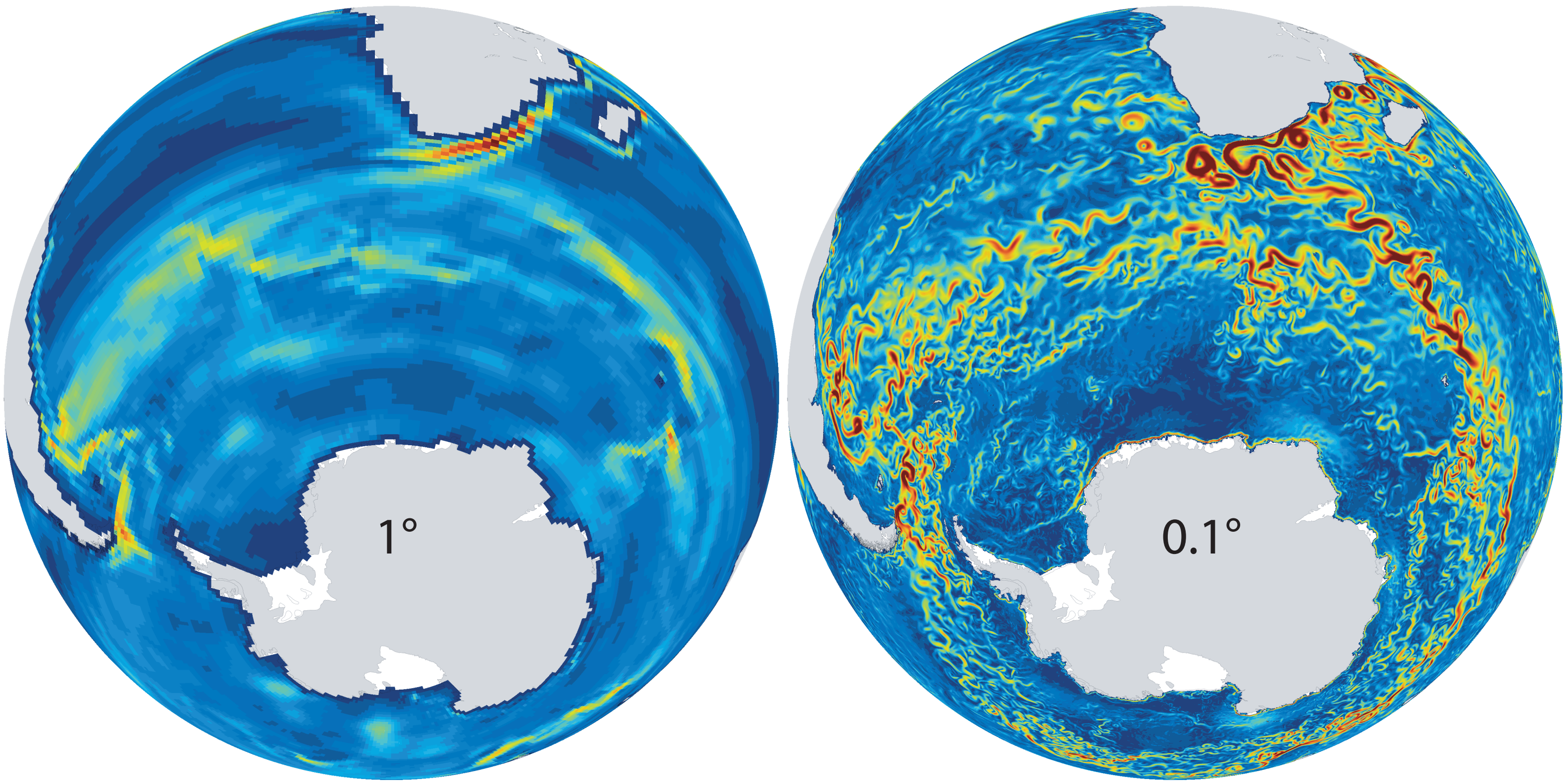
GPP: Gross primary productivity
NPP: Net primary productivity

NCP: Net community production

after Sigman & Hain 2012

Sluggish versus energetic oceans

Kinetic energy



Global eddy-resolving integration: Model configuration

Forcing

CORE 'Normal Year' (adjusted to climatology, i.e. repeating annual cycle)

Initialization

Physics (U, V, T, S): prior physics-only integration ($\sim$ 15 yrs)

Long-lived pools (DIC, Alk, nutrients): GLODAP/WOA climatologies, MLR gap-fill

Phytoplankton, Fe, etc.: interpolated from prior 1° solution

Configuration details

	Low resolution	**High resolution**
Grid	1° (60L), displaced pole	0.1°tripole (62L)
Tracer Horiz. Closure	GM, diagnostic κ	Biharmonic
Momentum Closure	Anisotropic harmonic viscosity	Biharmonic
Advection	Upwind-3	Centered (T&S), Upwind-3 (BGC)
Topography	Full-cell ETOPO2	Partial-cell ETOPO2
Coupling interval	Daily	6 hr

Tracer transport: resolved versus parameterized eddies

Tracer equations

Hi-res

$$\frac{\partial \varphi}{\partial t} + \nabla \cdot \overline{\mathbf{u}}\,\overline{\varphi} + \nabla \cdot \overline{\mathbf{u}'\,\varphi'} - \frac{\partial}{\partial z}\left(\kappa_v \frac{\partial \varphi}{\partial z}\right) = J_{\varphi}(\mathbf{x}) + \underbrace{\nabla_H^2\left(\kappa_H \nabla_H^2 \varphi\right)}_{\text{biharmonic lateral diffusion}}$$

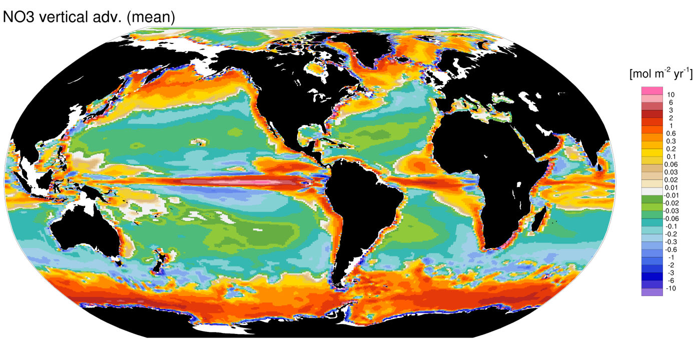
Tendency + Mean advection + Eddy advection − Vertical mixing = Source/sink

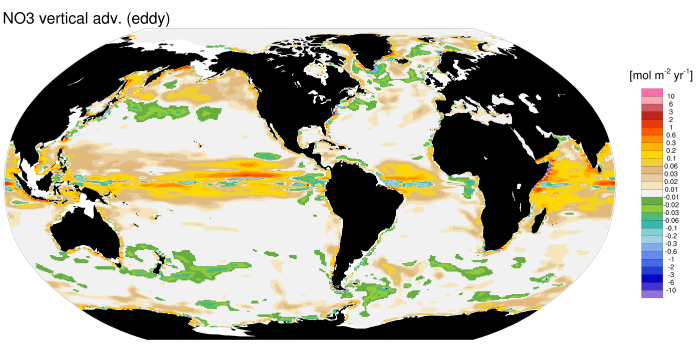
Lo-res

$$\frac{\partial \varphi}{\partial t} + \nabla \cdot \overline{u}\,\overline{\varphi} + \nabla \cdot \overline{\mathbf{u}'\,\varphi'} + \underbrace{\nabla \cdot \overline{\mathbf{u}_{GM}\,\varphi}}_{\text{eddy-induced advection}} - \underbrace{\nabla \cdot K_{iso} \nabla \varphi}_{\text{isopycnal mixing}} - \frac{\partial}{\partial z}\left(\kappa_v \frac{\partial \varphi}{\partial z}\right) = J_{\varphi}(\mathbf{x})$$

Surface ocean nitrate budget: vertical advection

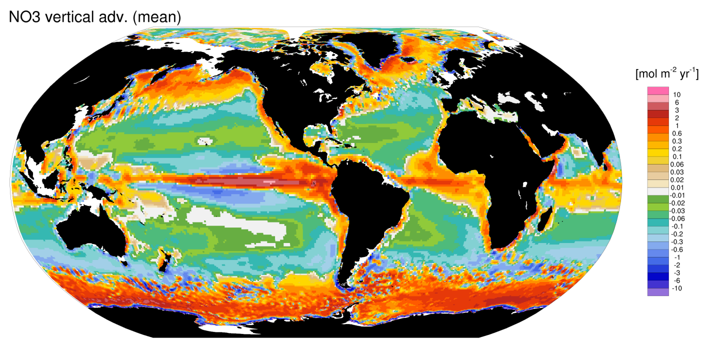
Low resolution (1°)

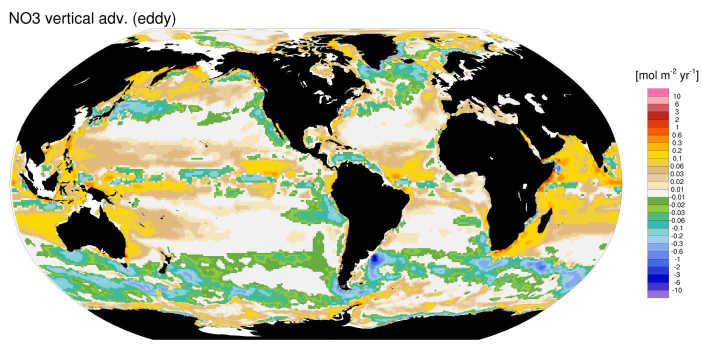




resolved eddies

High resolution (0.1°)

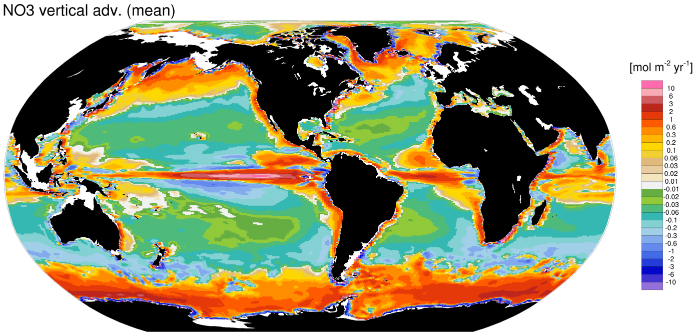




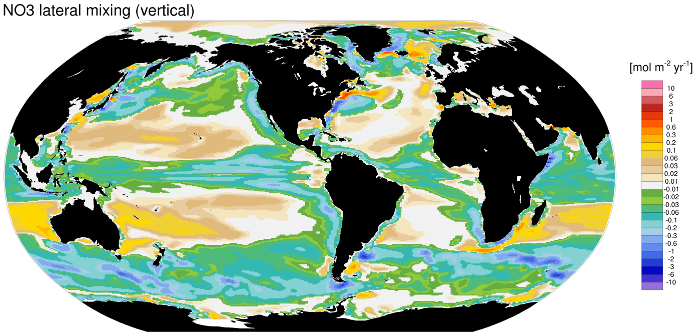
Surface ocean nitrate budget: vertical advection

Low resolution (1°)

NO3 vertical adv. (mean)



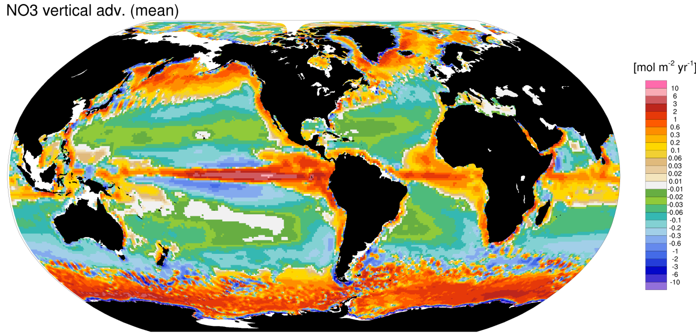
NO3 lateral mixing (vertical)



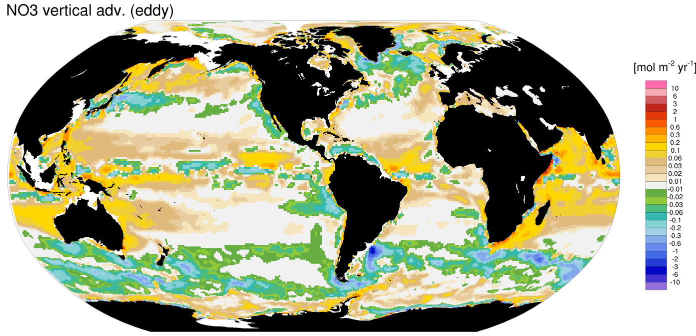
parameterized eddies

High resolution (0.1°)

NO3 vertical adv. (mean)



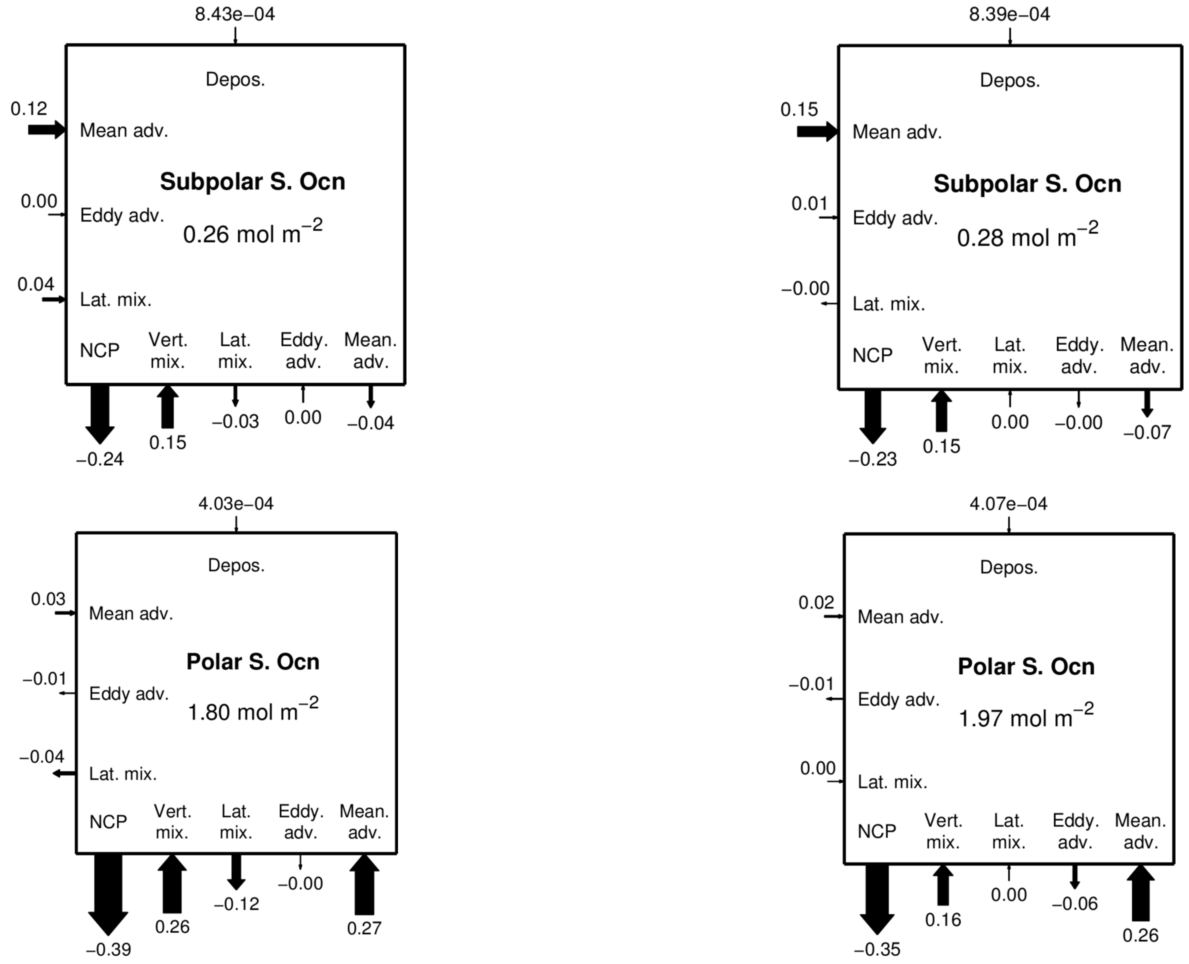
NO3 vertical adv. (eddy)



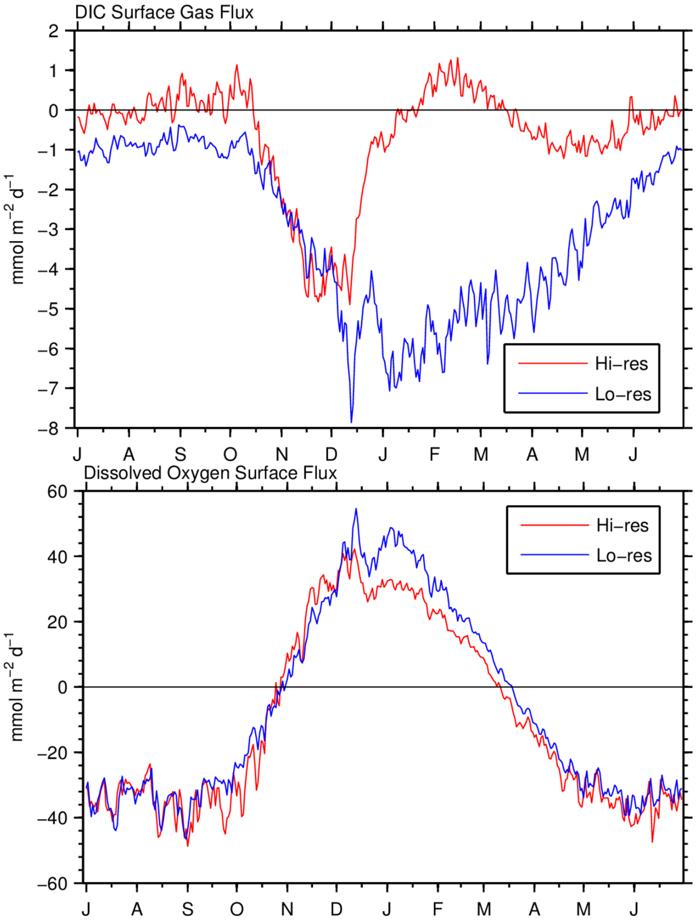
Surface ocean nitrate budget: regional comparison

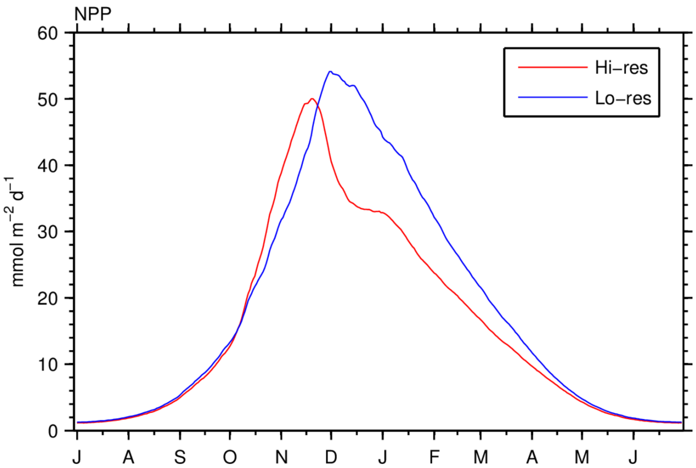
Low resolution (1°)

High resolution (0.1°)

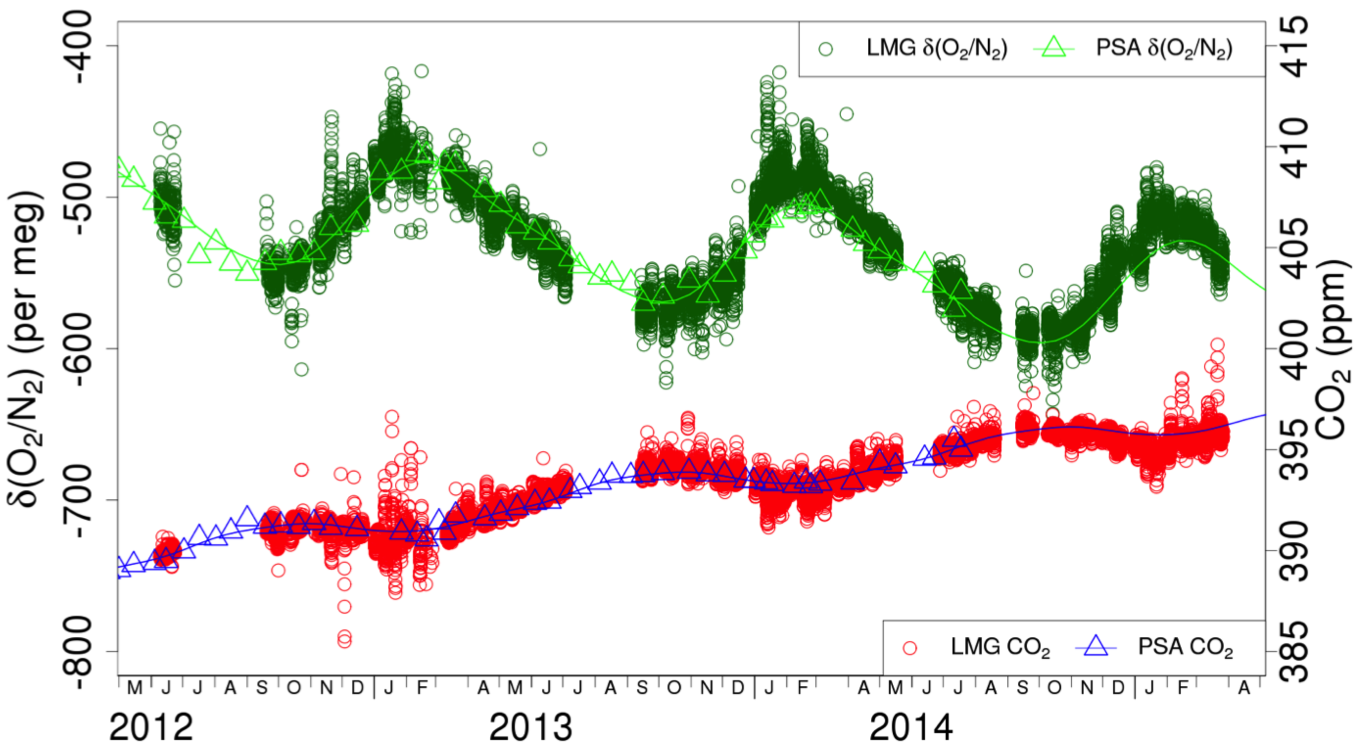


Southern Ocean seasonal gas exchange





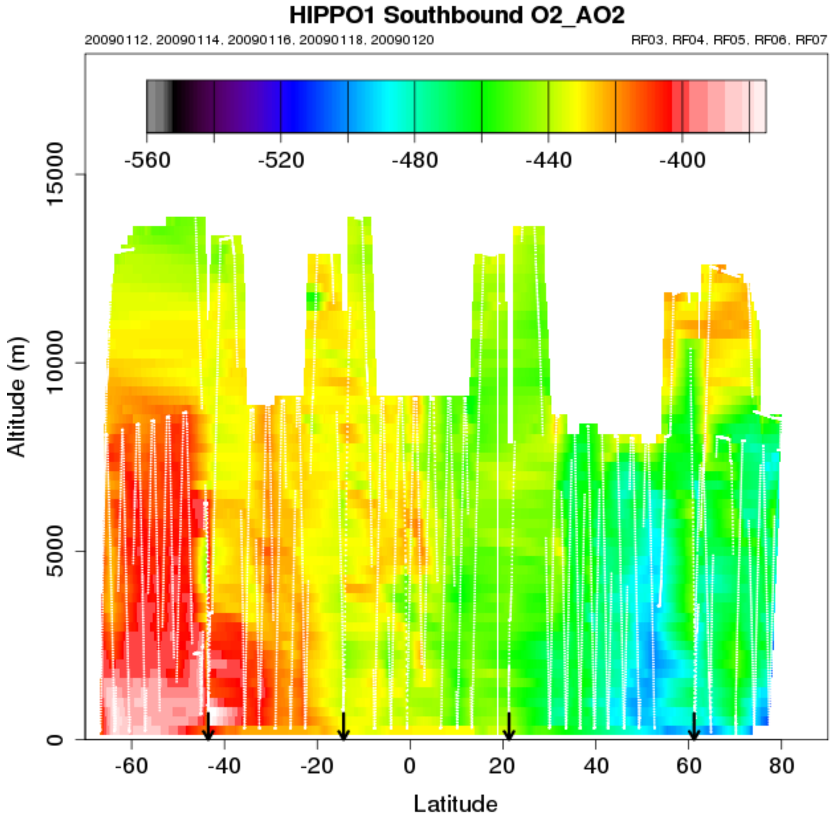
Atmospheric O_2 and CO_2 observations in Drake Passage



courtesy of B. Stephens

O_2/N_2 Ratio and CO_2 Airborne Southern Ocean Study (ORCAS)

Meridional section: O_2 in Austral Summer



courtesy of B. Stephens

PIs: Britt Stephens and Matt Long (NCAR), Ralph Keeling (Scripps), Colm Sweeney (U. Colorado), Eric Kort (U. Michigan)

Jan-Feb 2016
Punta Arenas, Chile

Core measurement objectives

- Large-scale O_2 and CO_2 distributions: 50°S–70°S, 0–14km;
- Vertical O_2:CO_2 ratios across boundary-layer top and through mid-troposphere;
- O_2 and CO_2 fluxes inferred from Lagrangian particle dispersion back-trajectories: (1) regional scale, using upwind/downwind flights 30-hr apart, (2) whole campaign.

GV Scientific Payload

Instrument	**Measurement**	**Institution**
Airborne Oxygen Instrument (AO2)	$\delta(O_2/N_2)$, CO_2	NCAR EOL
Quantum Cascade Laser Spectrometer(QCLS)	CO_2, CH_4, N_2O, CO	Harvard/Aerodyne/NCAR
Picarro	CO_2, CH_4, H_2O	NOAA/CU
Medusa Flask Sampler	$\delta(O_2/N_2)$, CO_2, $\delta(Ar/N_2)$, $\delta^{13}C$, $\delta^{18}O$, and $\Delta^{14}C$ of CO_2	NCAR/Scripps
Portable Remote Imaging Spectrometer (PRISM)	Hyperspectral water-leaving radiance	JPL
Advanced Whole Air Sampler (AWAS)	Over 80 trace gases, including DMS, OCS, halocarbons, $MeONO_2$, isoprene	NCAR/U. Miami
HIAPER Trace Organic Gas Analyzer (TOGA)	Over 60 VOCs, including nitrate species, DMS, and VSL halocarbons	NCAR

Summary

The Southern Ocean plays a pivotal role in the global carbon cycle:

- Overturning circulation mediates uptake of atmospheric transient;
- Biological production mitigates outgassing of natural carbon.

CMIP5 models struggle to simulate the seasonal cycle of gas exchange, largely indicative of disparate representations of biological production.

Parameterized eddy mixing appears to produce reasonable annual mean fluxes of macronutrients (NO_3^-); discrepancies in seasonal production between low and high resolution simulations may be attributable to differences in iron cycling.

Atmospheric observations may provide a means of constraining the magnitude of Southern Ocean air-sea fluxes on seasonal to interannual timescales.