New insights into the Southern Ocean's role in climate: An update from SOCCOM

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University of Washington

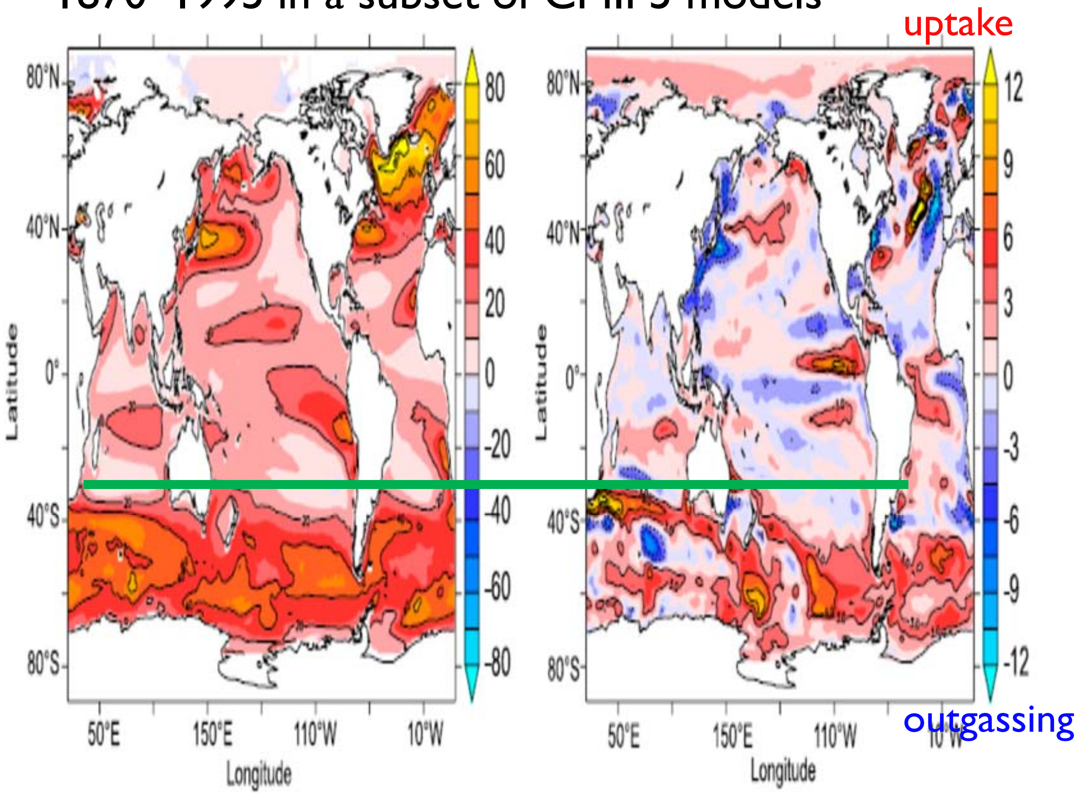
US CLIVAR Summit
August 9, 2017

Southern Ocean role in global carbon cycle

~30% of global surface ocean area

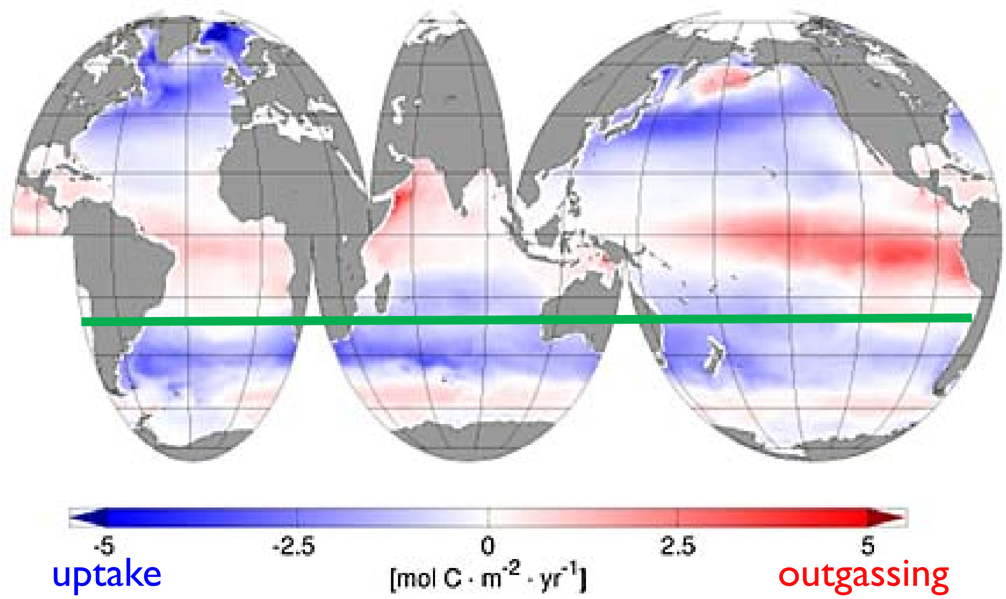
~50% of global oceanic uptake of anthropogenic CO_2

Cumulative anthropogenic CO_2 uptake (mol m^{-2}) 1870–1995 in a subset of CMIP5 models



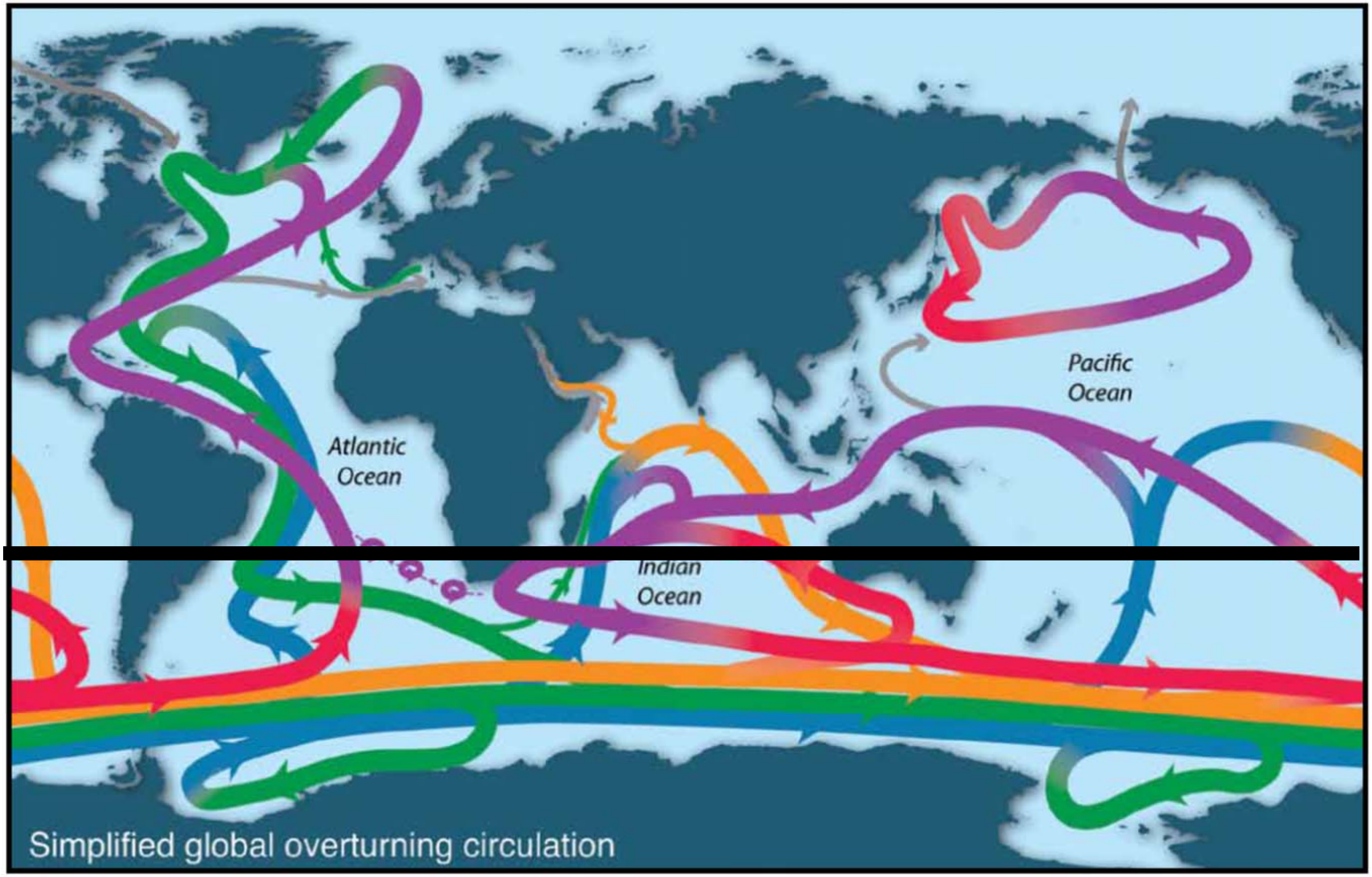
Frölicher et al. 2015

Mean 1982-2011 air-sea CO_2 flux (mol m^{-2} y^{-1}) based on observations



Landschützer et al. 2014

Southern Ocean role in global overturning circulation



Upper ocean and thermocline
Denser thermocline and intermediate
Indo-Pacific Deep Water
North Atlantic Deep Water
Antarctic Bottom Water

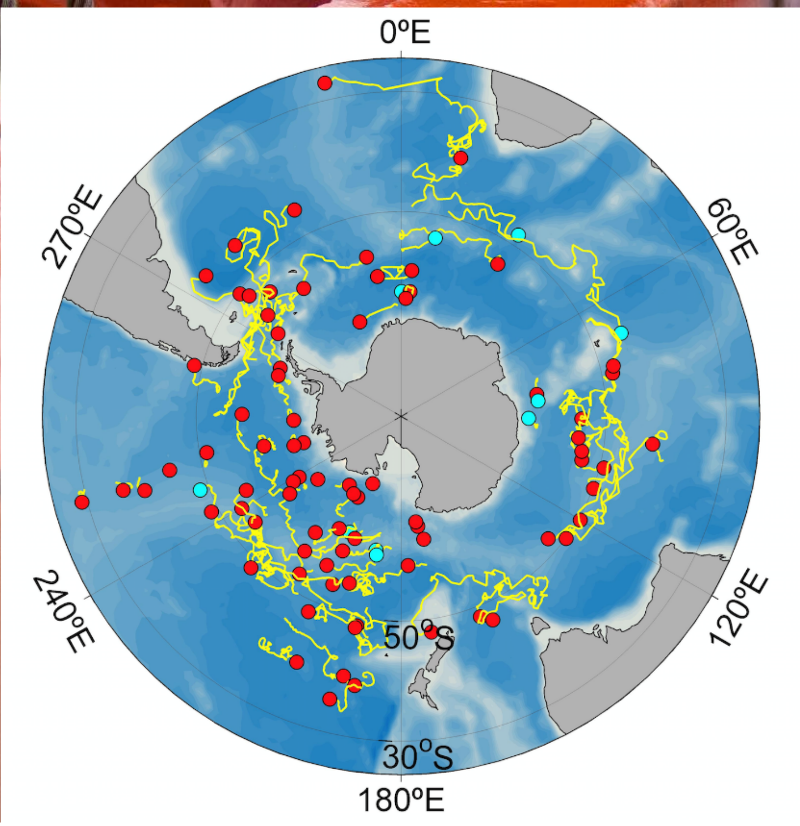
Talley 2013

PEI
PRINCETON ENVIRONMENTAL INSTITUTE

SOCCOM

Southern Ocean Carbon and Climate Observations and Modeling

- Six year, $21 million project to transform our understanding of the Southern Ocean, a major sink of carbon and heat
- Headquartered at Princeton; involves over 80 participants at 13 partner institutions
- Deploying ~200 floats that measure pH, nitrate, oxygen, chlorophyll, particles
- High-resolution modeling and state estimate programs
- Outreach partnership with Climate Central

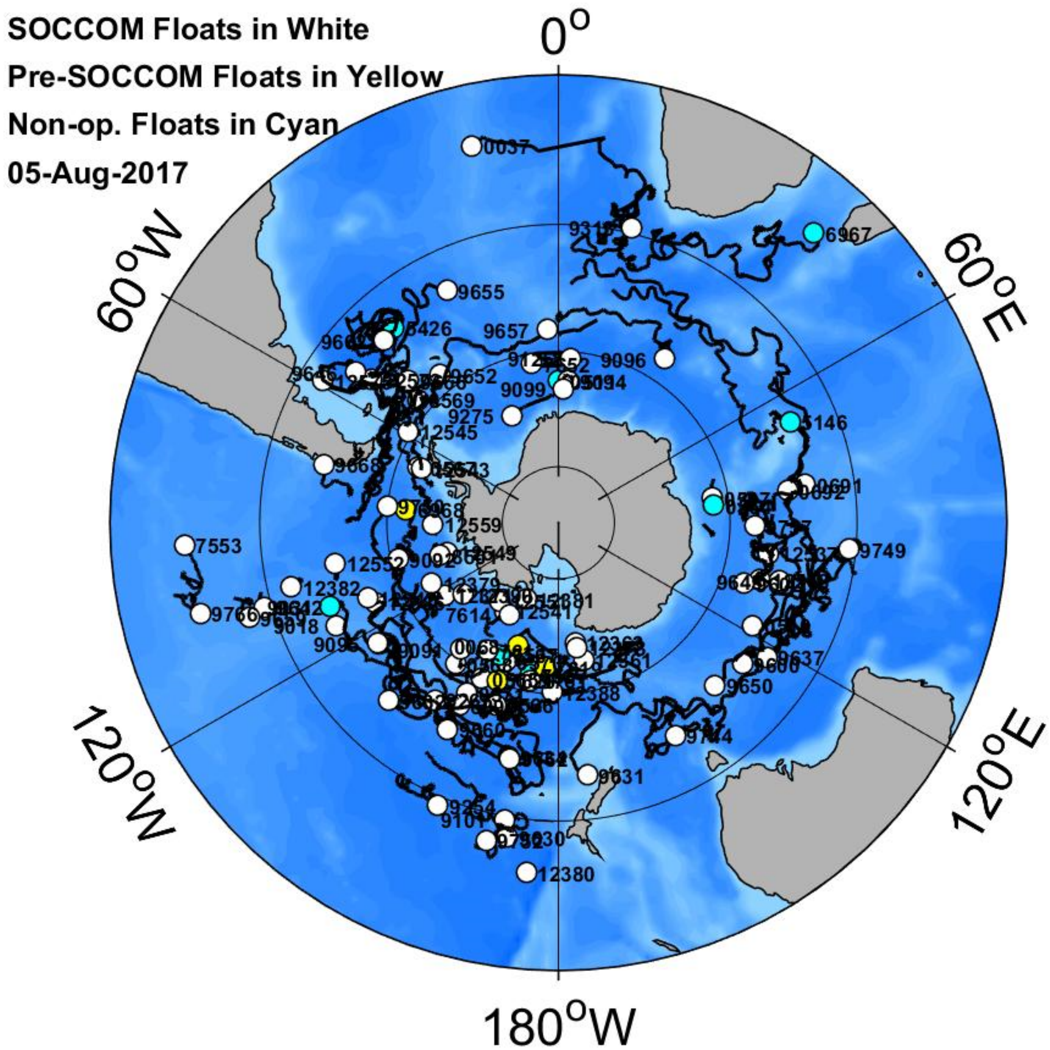


www.soccom.princeton.edu

J. Sarmiento, Princeton
K. Johnson, MBARI

OBSERVATIONS

L. Talley, SIO
S. Riser, UW

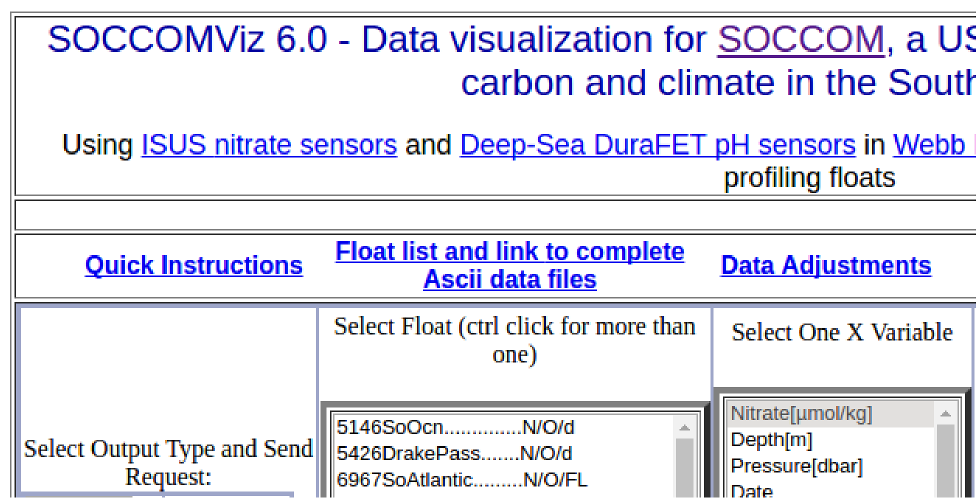


SOCCOM
Southern Ocean Carbon and Climate Observations and Modeling

Floats measure pH, NO_3, O_2, backscatter, fluorescence

91 floats deployed
81 floats operational

Near real-time data available



SOCCOMViz 6.0 - Data visualization for SOCCOM, a US
carbon and climate in the South

Using ISUS nitrate sensors and Deep-Sea DuraFET pH sensors in Webb
profiling floats

Quick Instructions	Float list and link to complete Ascii data files	Data Adjustments

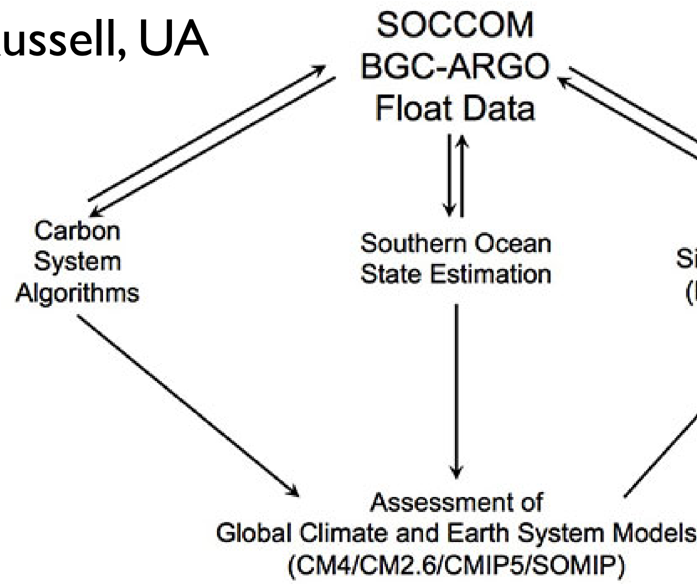
Select Output Type and Send Request:	Select Float (ctrl click for more than one)	Select One X Variable
	5146SoOcn..............N/O/d 5426DrakePass.......N/O/d 6967SoAtlantic.........N/O/FL	Nitrate[µmol/kg] Depth[m] Pressure[dbar] Date

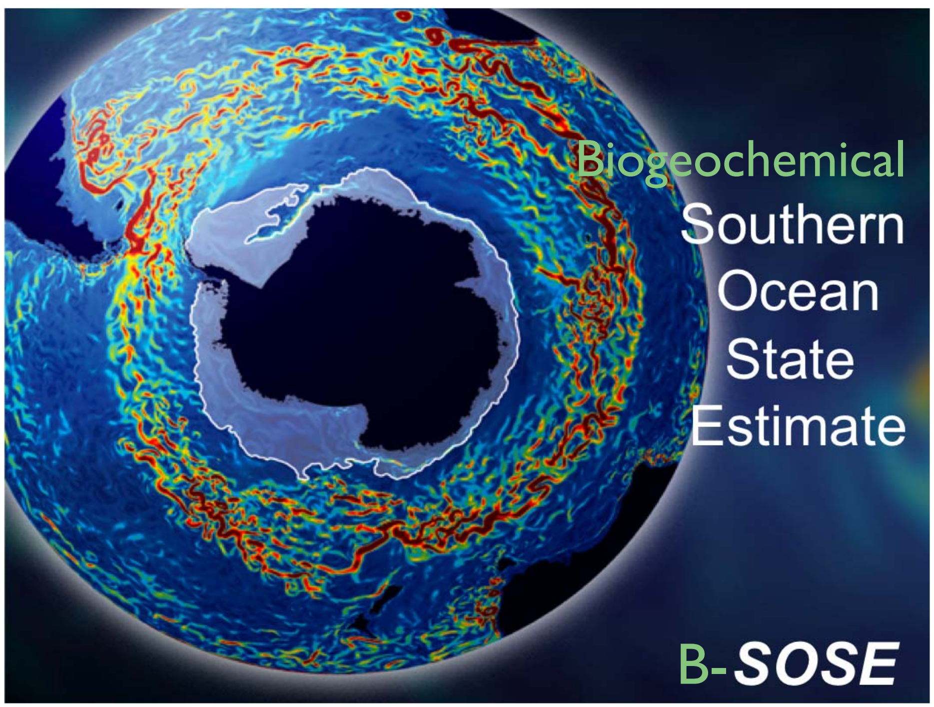
Modeling

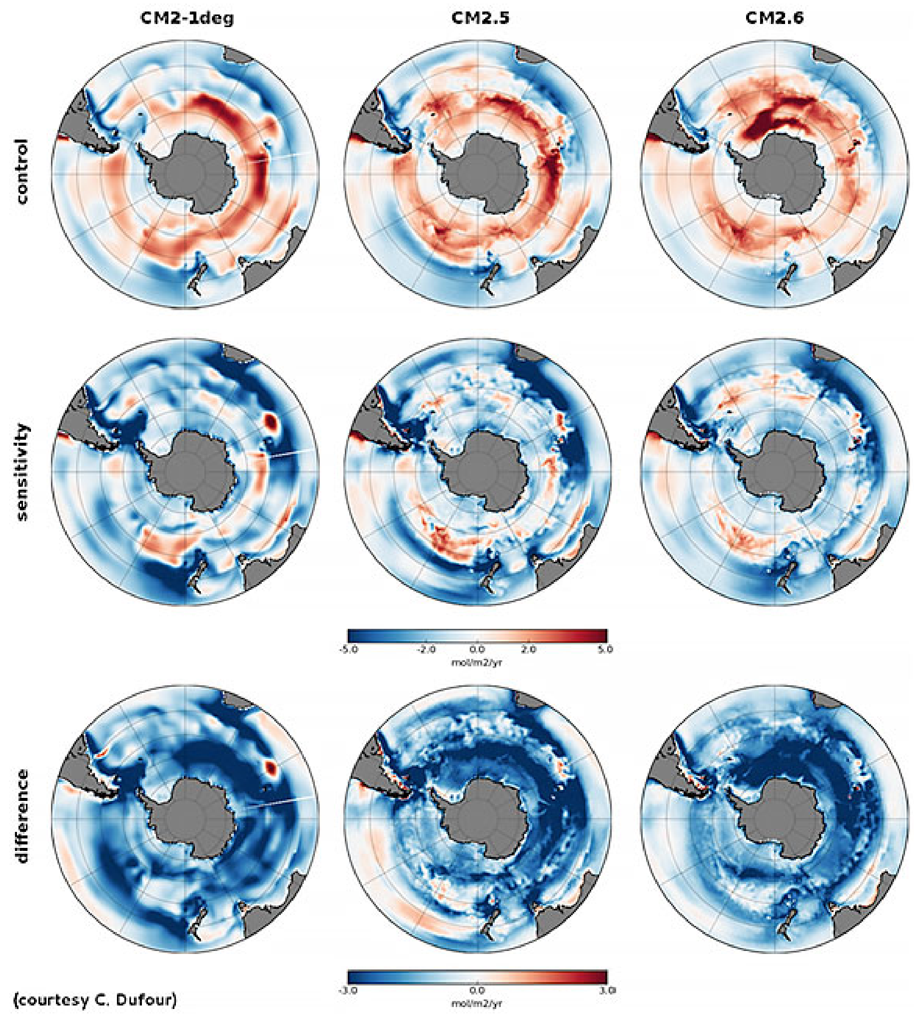
J. Russell, UA

SOCCOM

Southern Ocean Carbon and Climate Observations and Modeling







(courtesy C. Dufour)

Broader Impacts

H. Cullen, Climate Central

SOCCOM

Southern Ocean Carbon and Climate Observations and Modeling

CLIMATE CENTRAL

Education and public outreach

Technology transfer

JOURNAL OF GEOPHYSICAL RESEARCH

Oceans

AN AGU JOURNAL

Special Issue coming soon

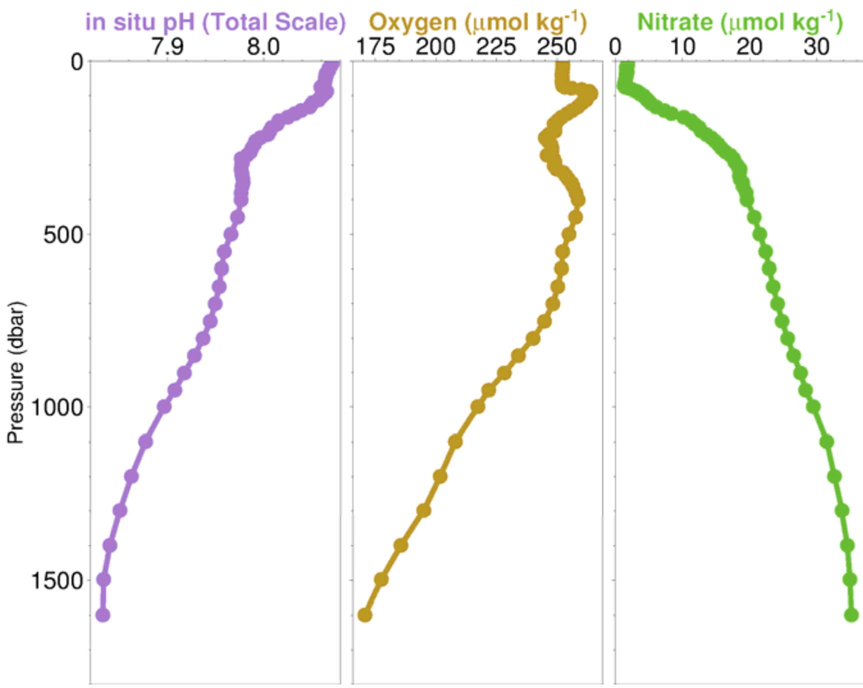
BIOGEOCHEMICAL PROFILING FLOATS

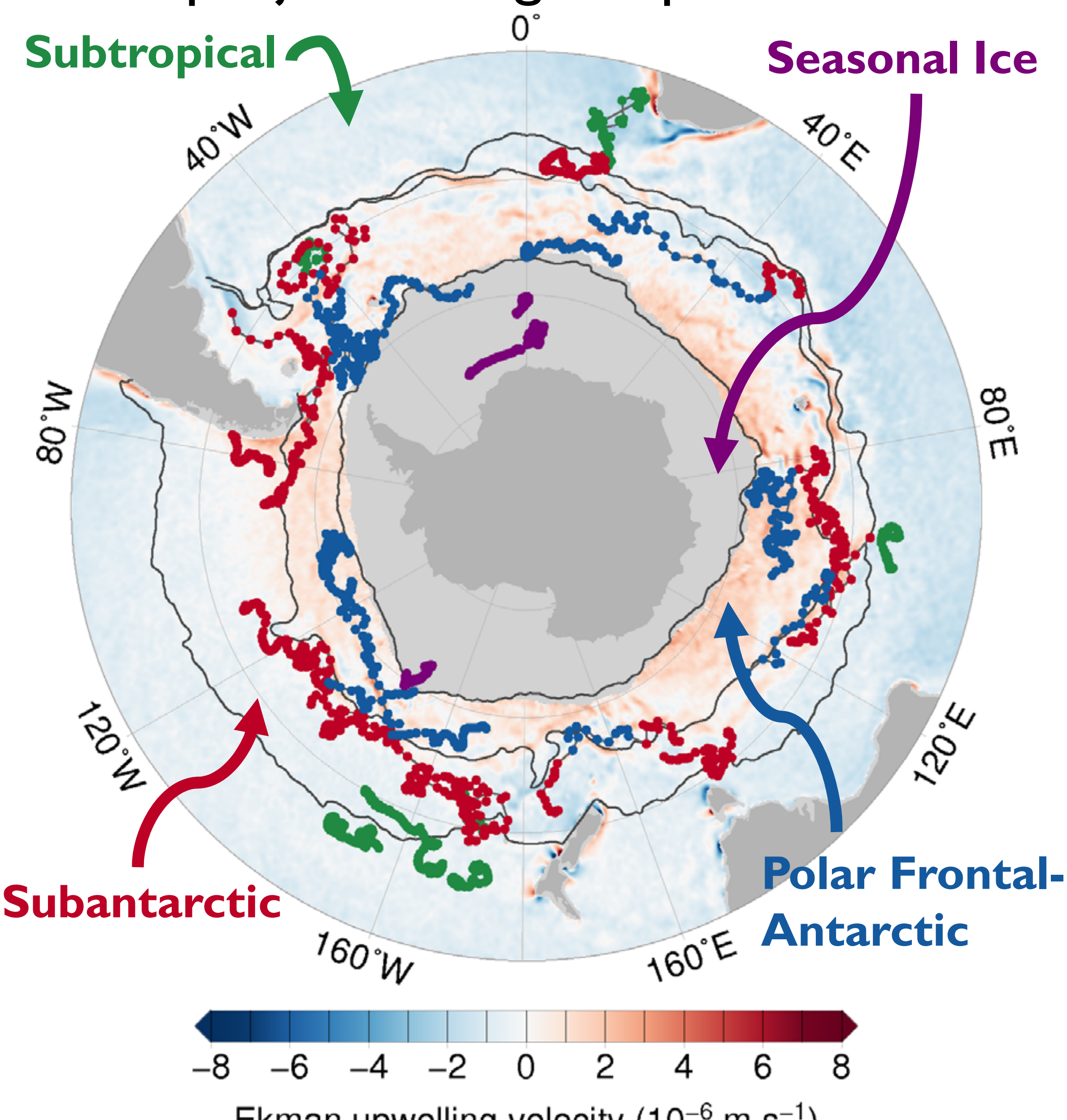
36 floats deployed by SOCCOM project with good pH data, through Apr 2017

pH Martz et al. 2010, Johnson et al. 2016

O_2 Tengberg et al. 2006, Johnson et al. 2015

NO_3 Johnson et al. 2010, 2013





Based on QuikScat wind stress Risien and Chelton, 2008

ANNUAL NET AIR-SEA CO_2 FLUX

+ Outgassing
– Uptake

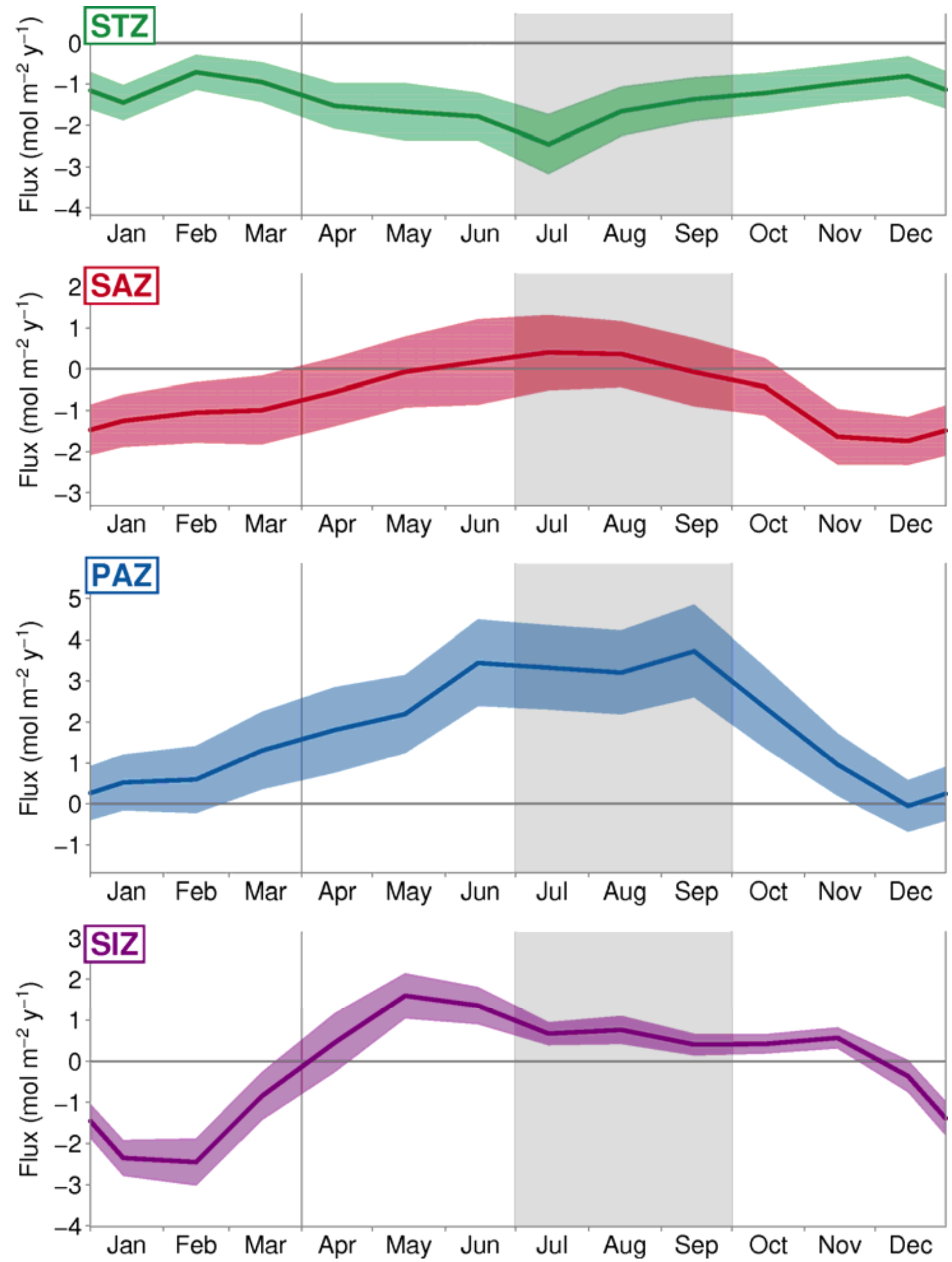
Mean (mol m^{-2} y^{-1})

STZ: -1.4 ± 0.5

SAZ: -0.6 ± 0.8

PAZ: 2.0 ± 0.9

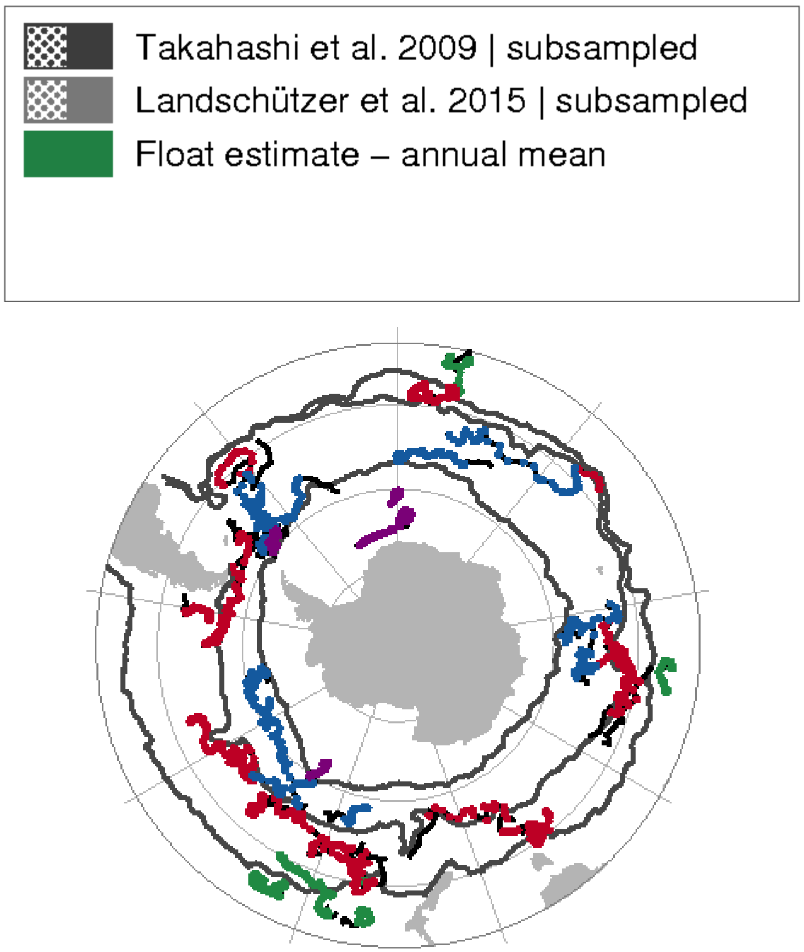
SIZ: 0.03 ± 0.4

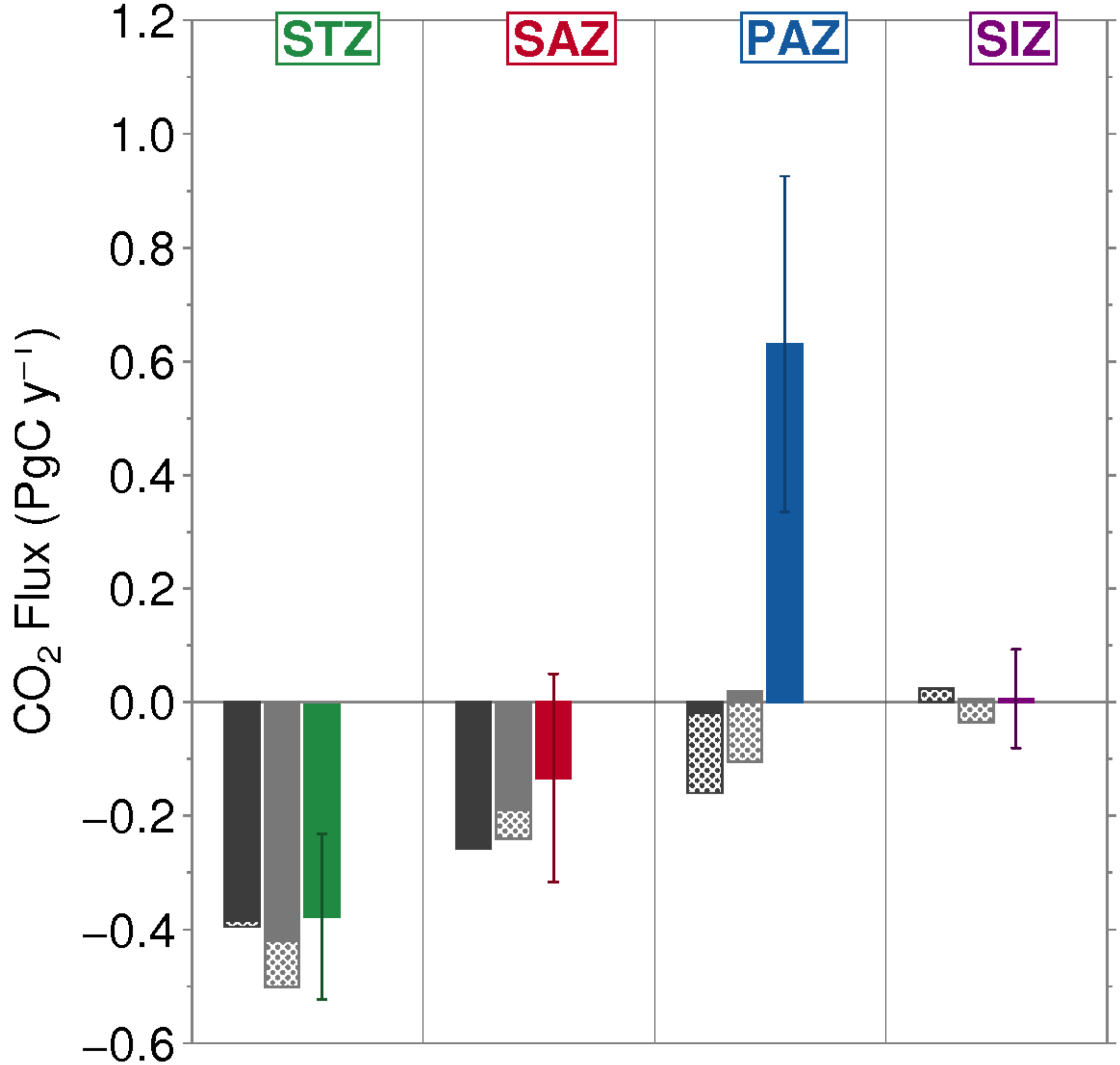


Average global anthropogenic CO_2 uptake = -0.46 ± 0.14 mol m^{-2} y^{-1}

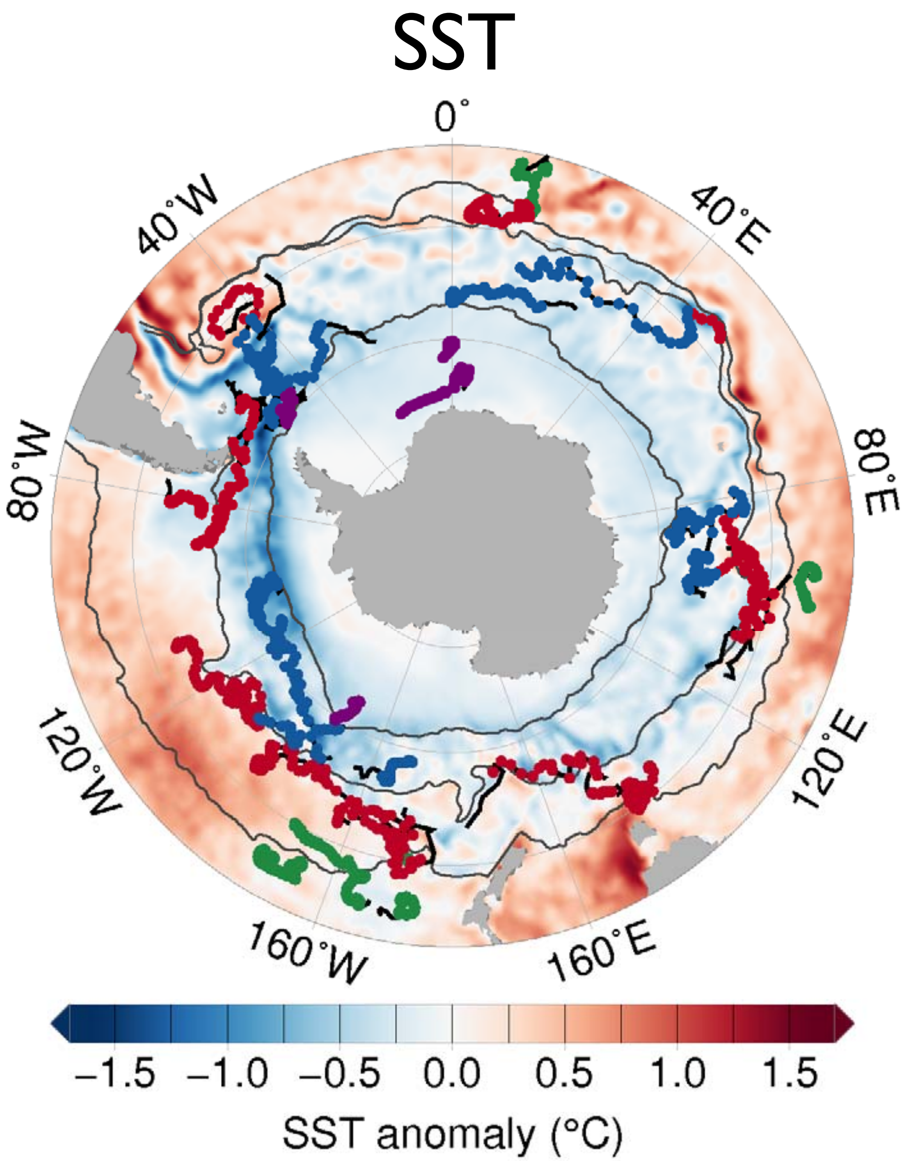
ANNUAL NET OCEANIC CO_2 UPTAKE

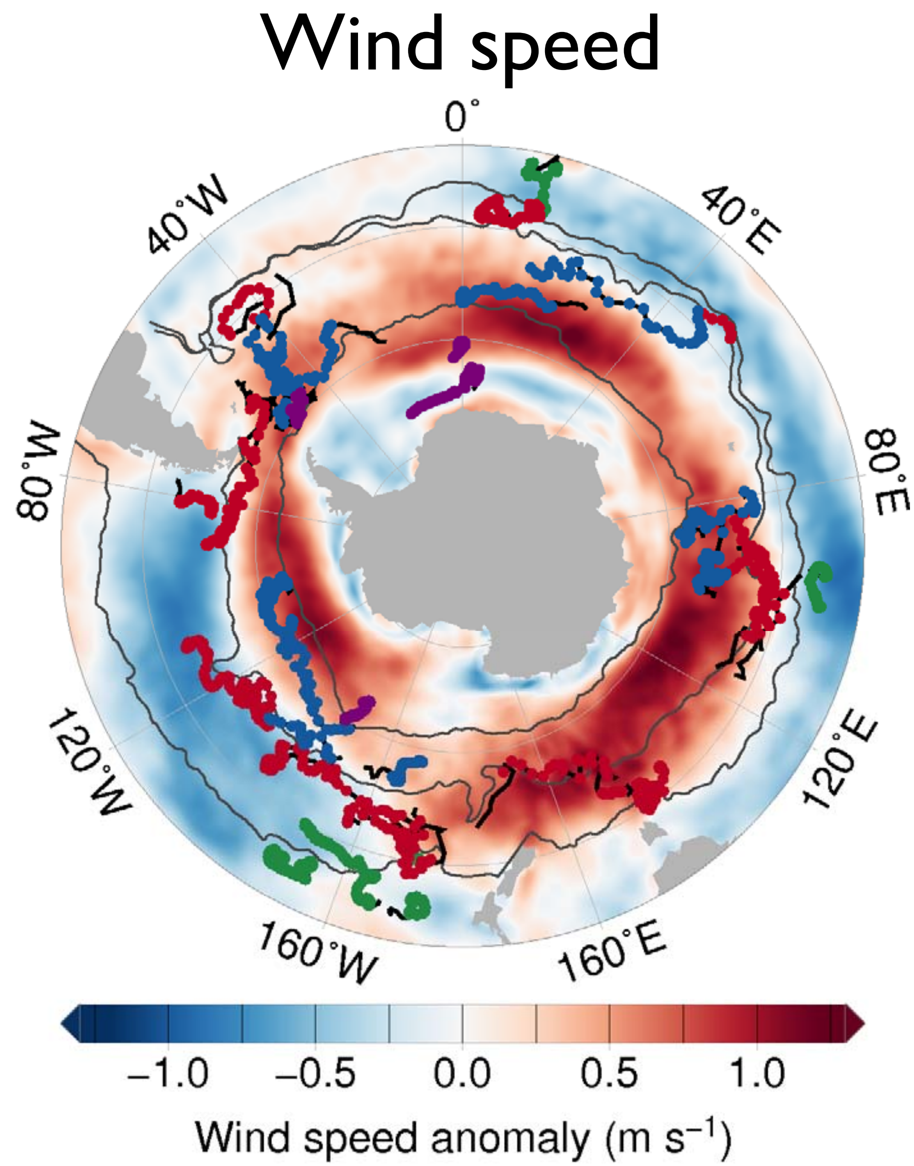
Sample previous estimates at location of floats





ROLE OF INTERANNUAL VARIABILITY

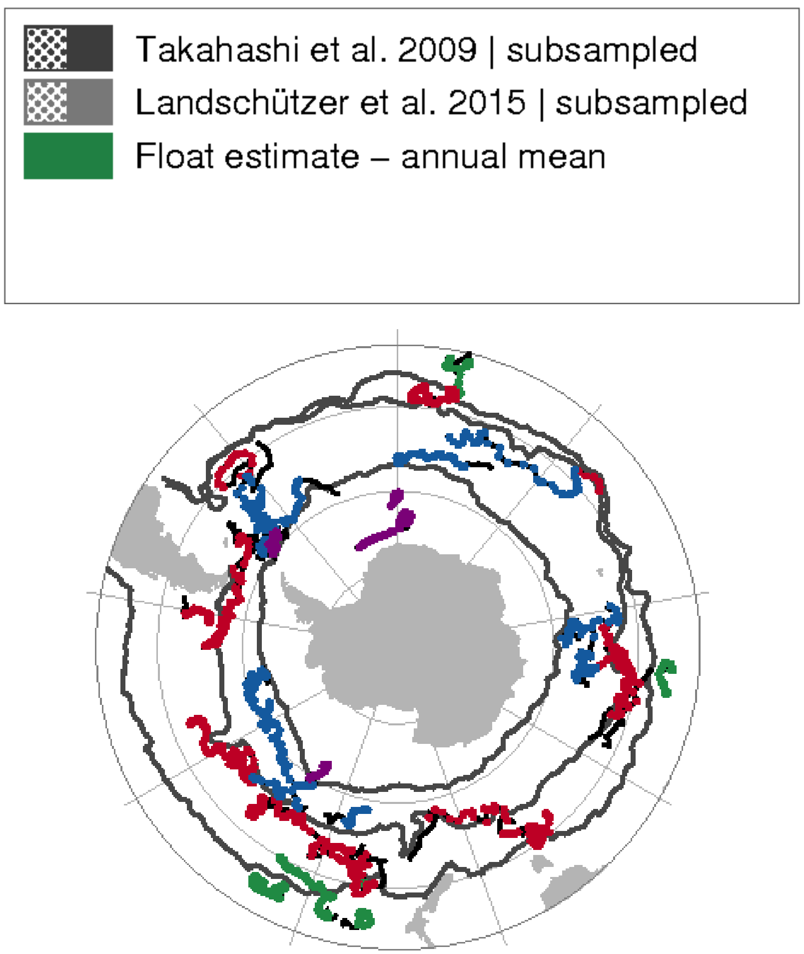


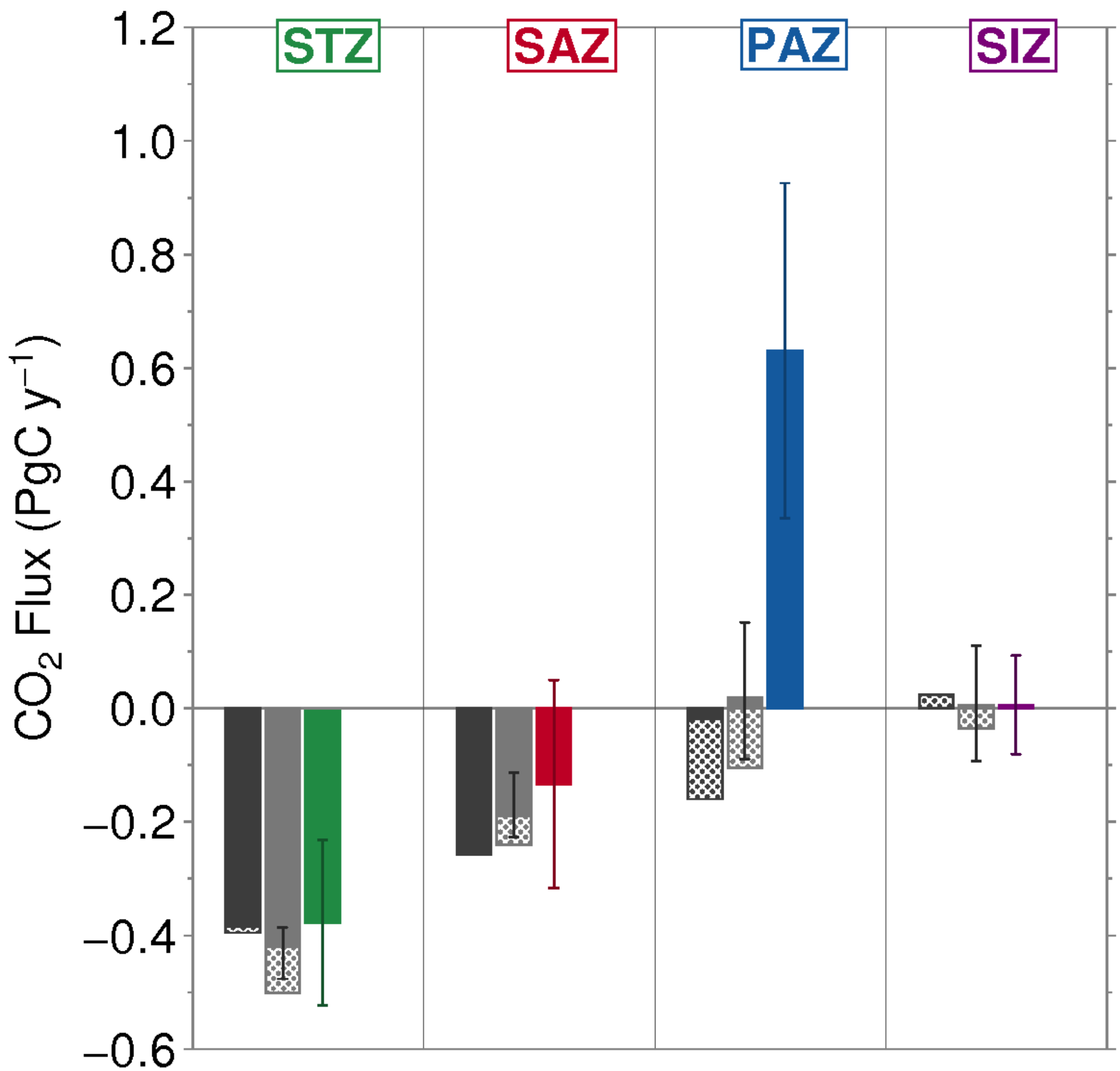


2014-2016 anomalies from mean 1979-2016 ERA-Interim fields

Role of interannual variability

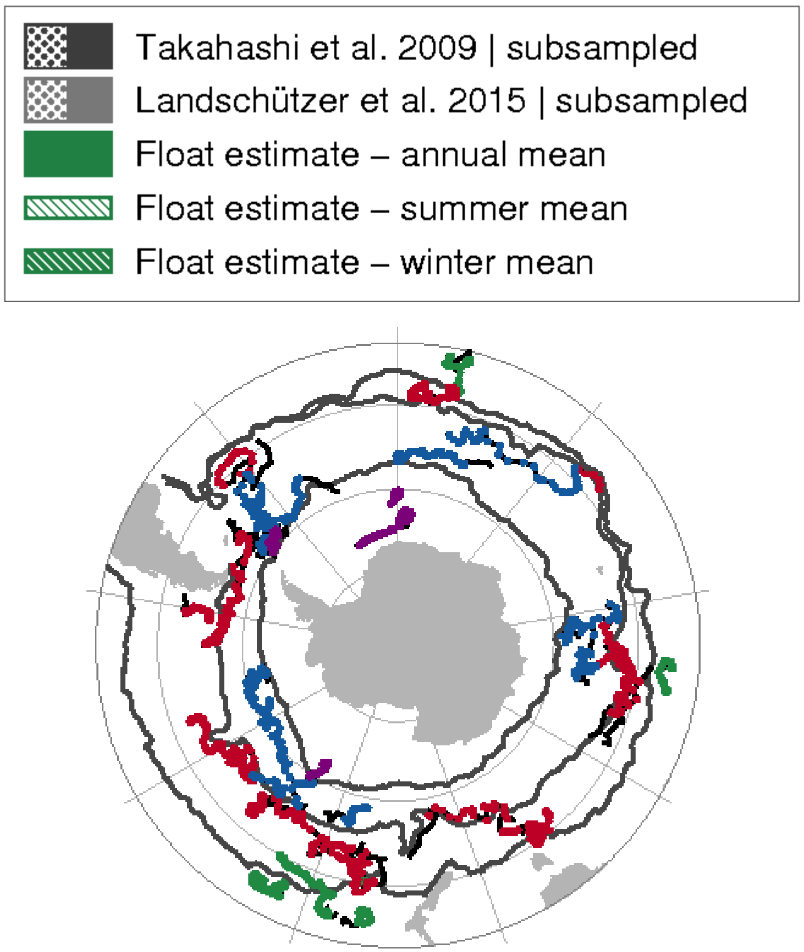
30-year variability from Landschützer estimate

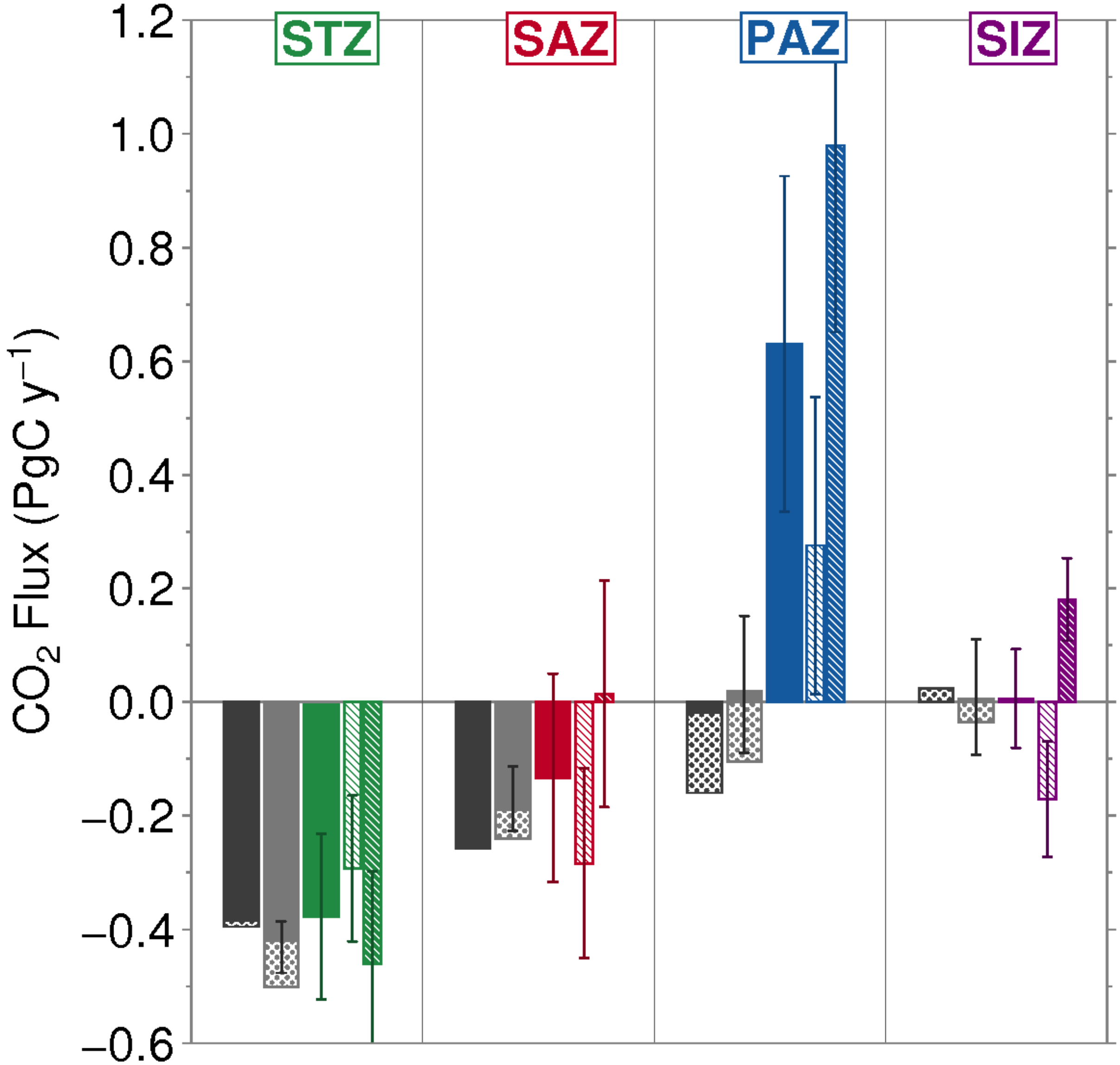




PREVIOUS ESTIMATES UNDERESTIMATE OUTGASSING

Outgassing driven by wintertime fluxes, primarily in PAZ





SEASONAL CYCLE OF CO_2 FLUX

Landschützer and Takahashi estimates miss fall and winter outgassing in PAZ

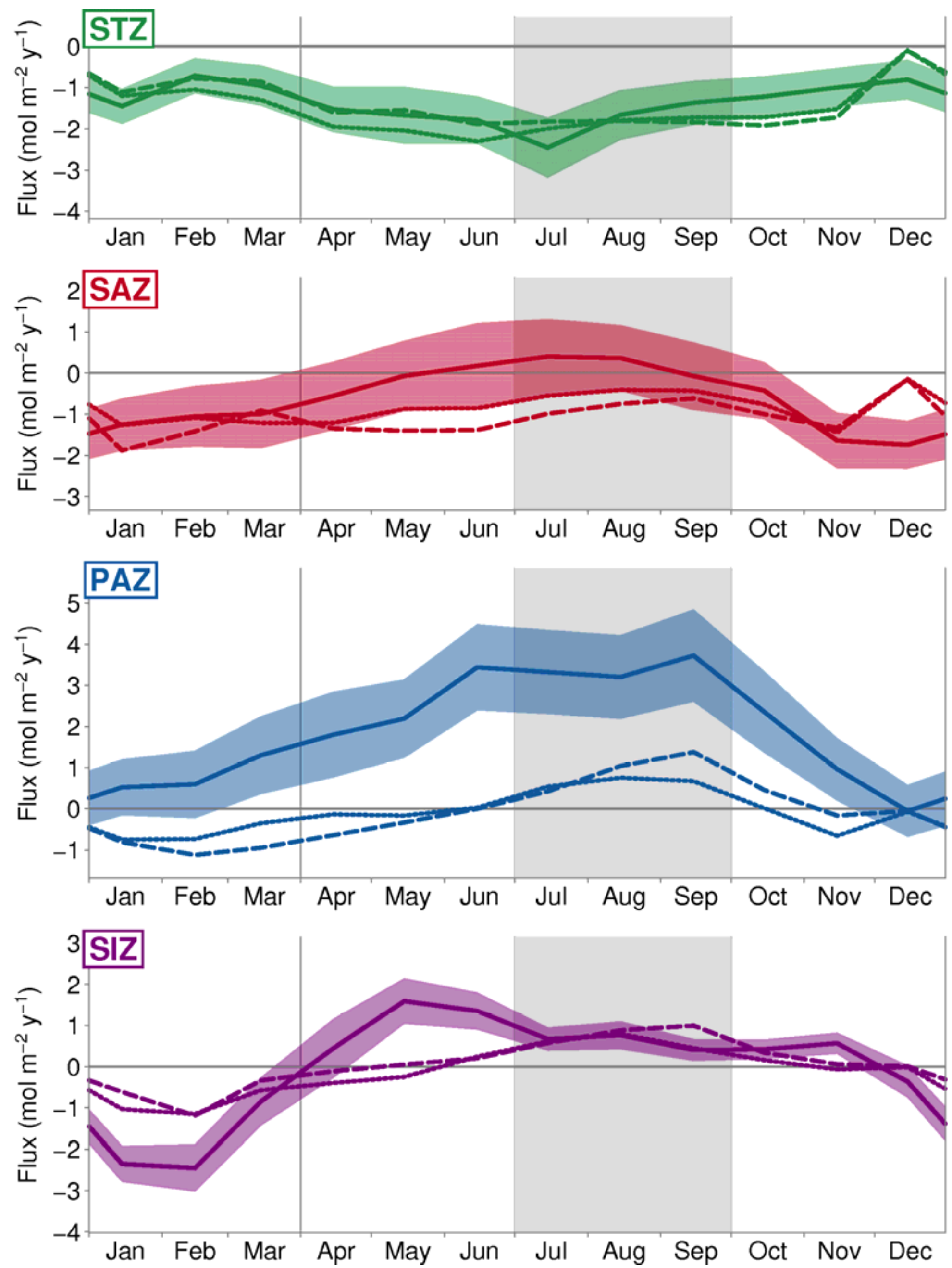
This estimate

Takahashi et al. 2009

Landschützer et al. 2014 2002-2011 mean

+ Outgassing

– Uptake



Conclusions

Float-based estimates show a Southern Ocean CO_2 source to atmosphere of 0.1 ± 0.7 PgC y^{-1}, larger than previous estimates of a sink of ~0.8 PgC y^{-1}, driven by wintertime upwelling of carbon-rich deep water.

Explanations include interannual variability and undersampling during fall and winter in previous estimates.

Thank you

Collaborators:
Jorge Sarmiento, Ken Johnson, Seth Bushinsky, Stephen Riser, Joellen Russell, Lynne Talley, Rik Wanninkhof, Nancy Williams, Carolina DuFour, Henri Drake

Funding:
NOAA Climate and Global Change Postdoctoral Fellowship

Extra Slides

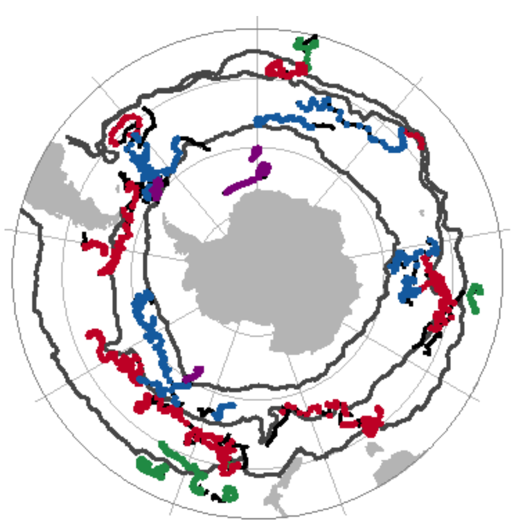
FLOAT-BASED pCO_2

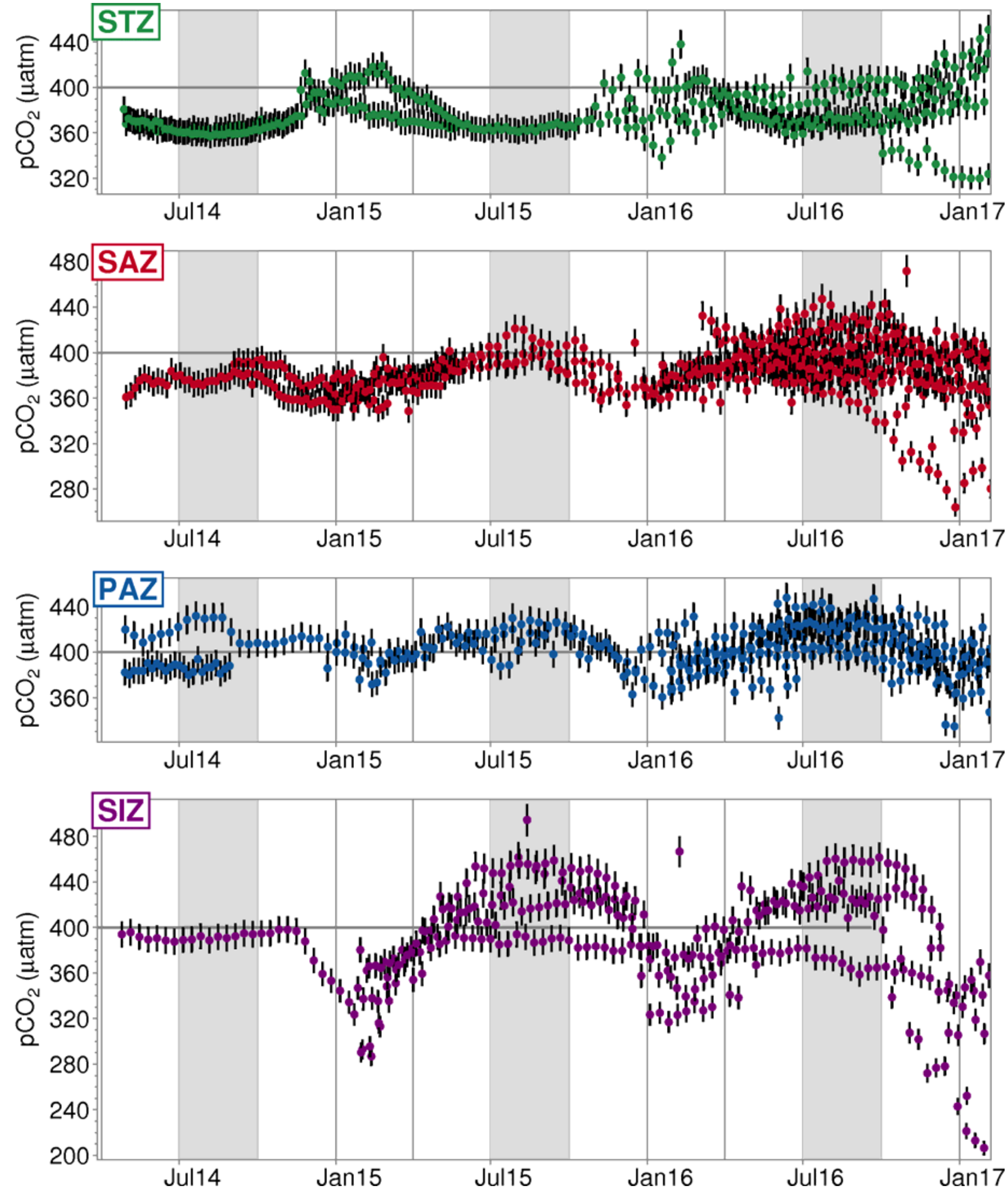
$$pCO_2 = f(\mathrm{pH}, T, S, A_T)$$

pH, *T*, and *S* measured by floats

Alkalinity estimated using multiple linear regression
Carter et al. 2016

Uncertainty after bias-correction estimated at 2.7% (median 10.5 µatm)
Williams et al. 2017





FLOAT-BASED AIR-SEA CO_2 FLUX

+ Outgassing
– Uptake

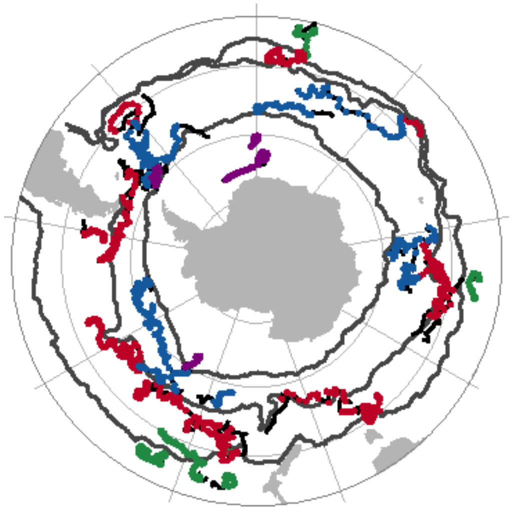
$$F = k \, K_0 \, \Delta pCO_2$$

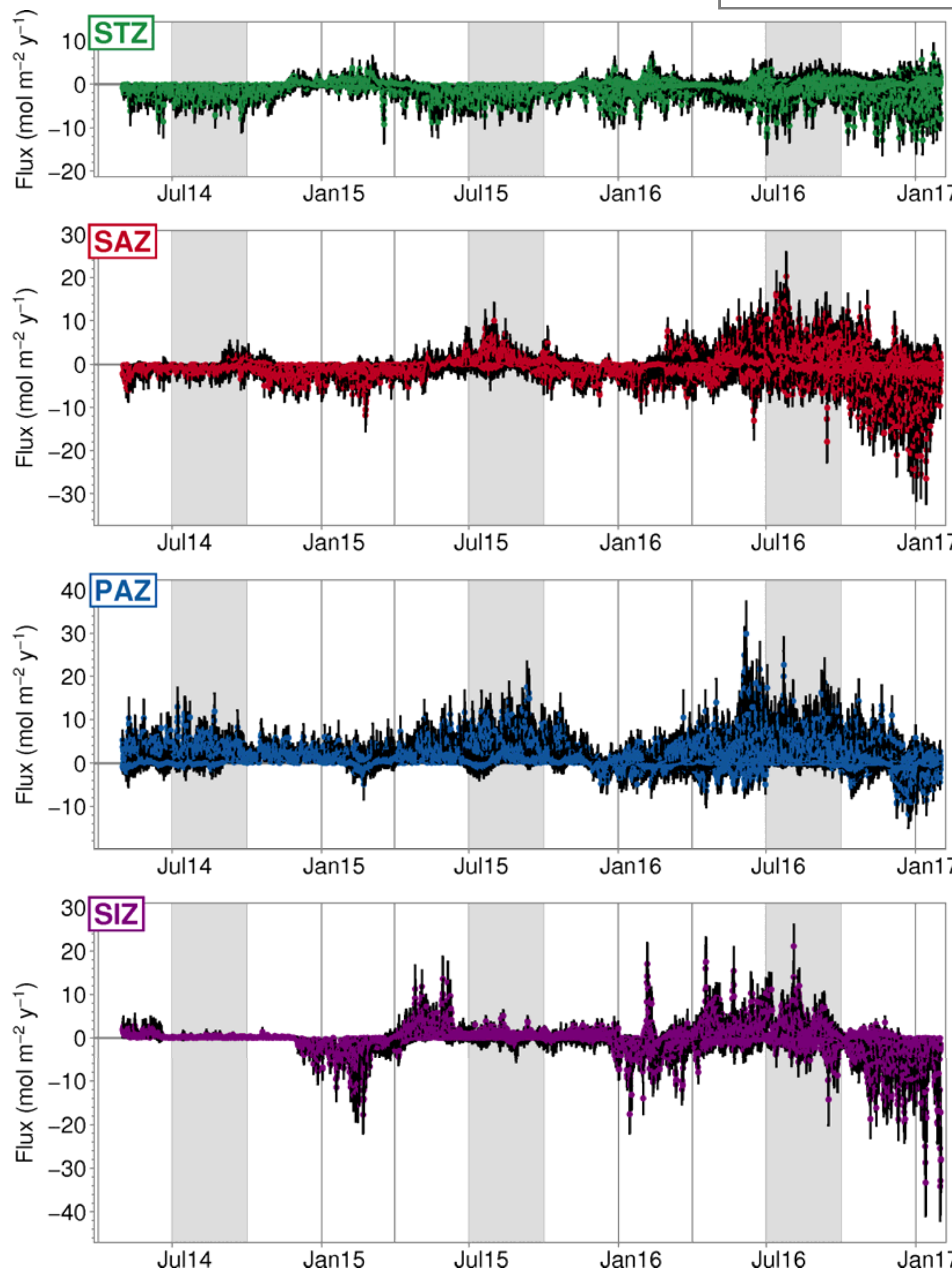
$\Delta pCO_2 = pCO_2^{ocn} - pCO_2^{atm}$

pCO_2^{atm} from Cape Grim observations

k Gas transfer velocity, $\propto$ wind speed squared
Wanninkhof 2014
6-hourly ERA-Interim winds

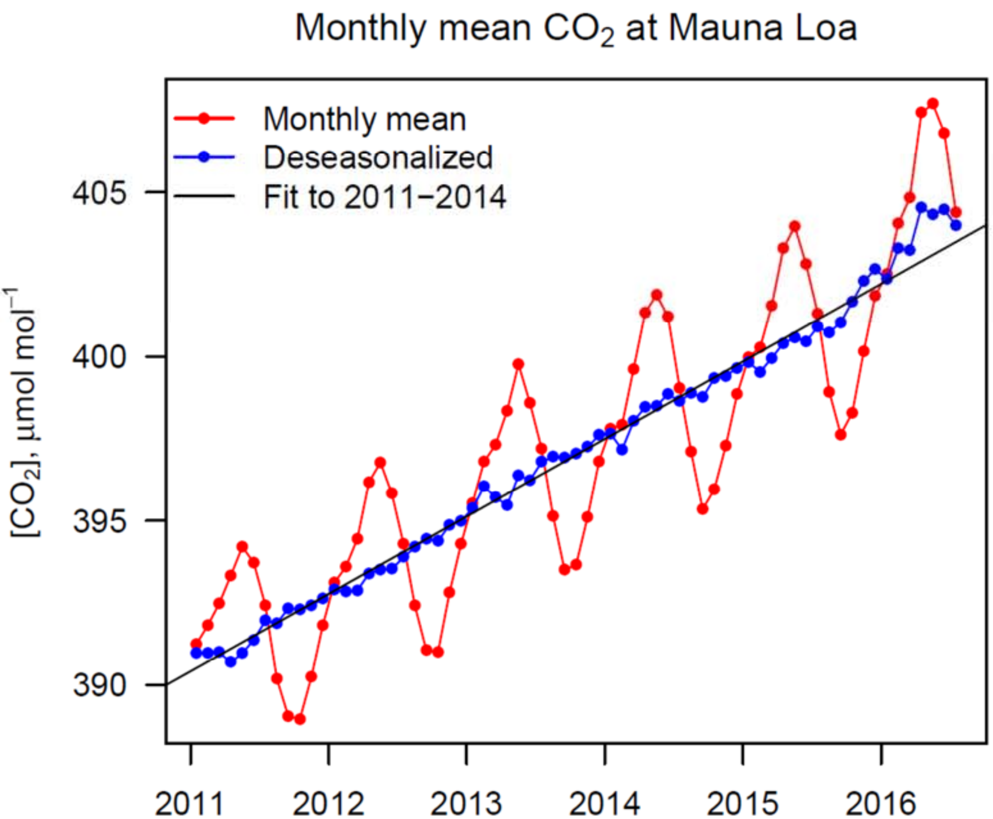
K_0 solubility constant

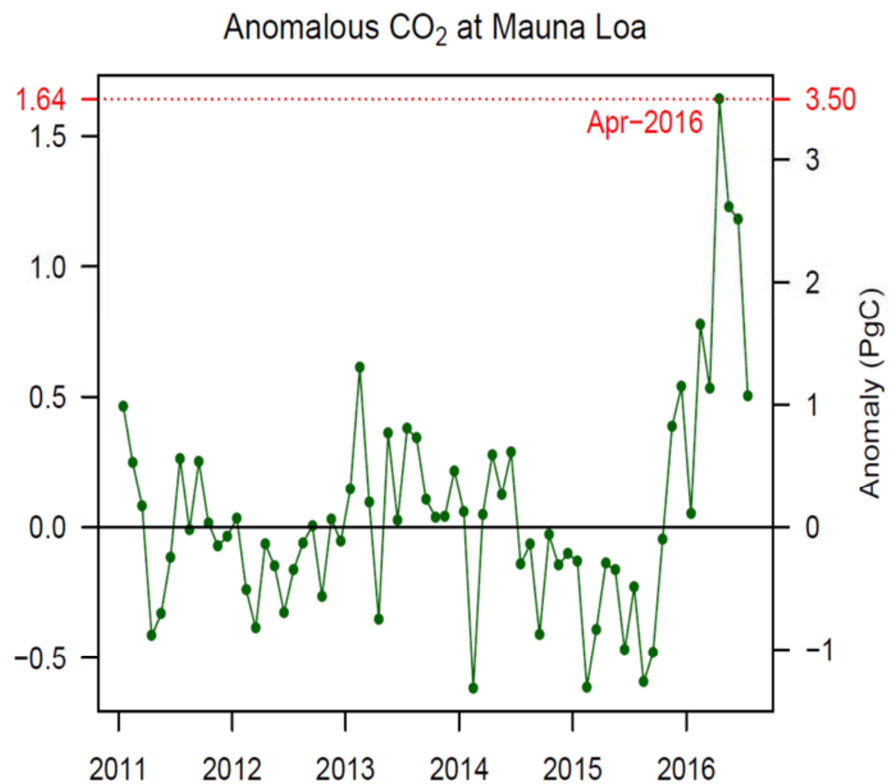




Role of interannual variability

Anomalous CO_2^{atm} associated with 2015-2016 ENSO



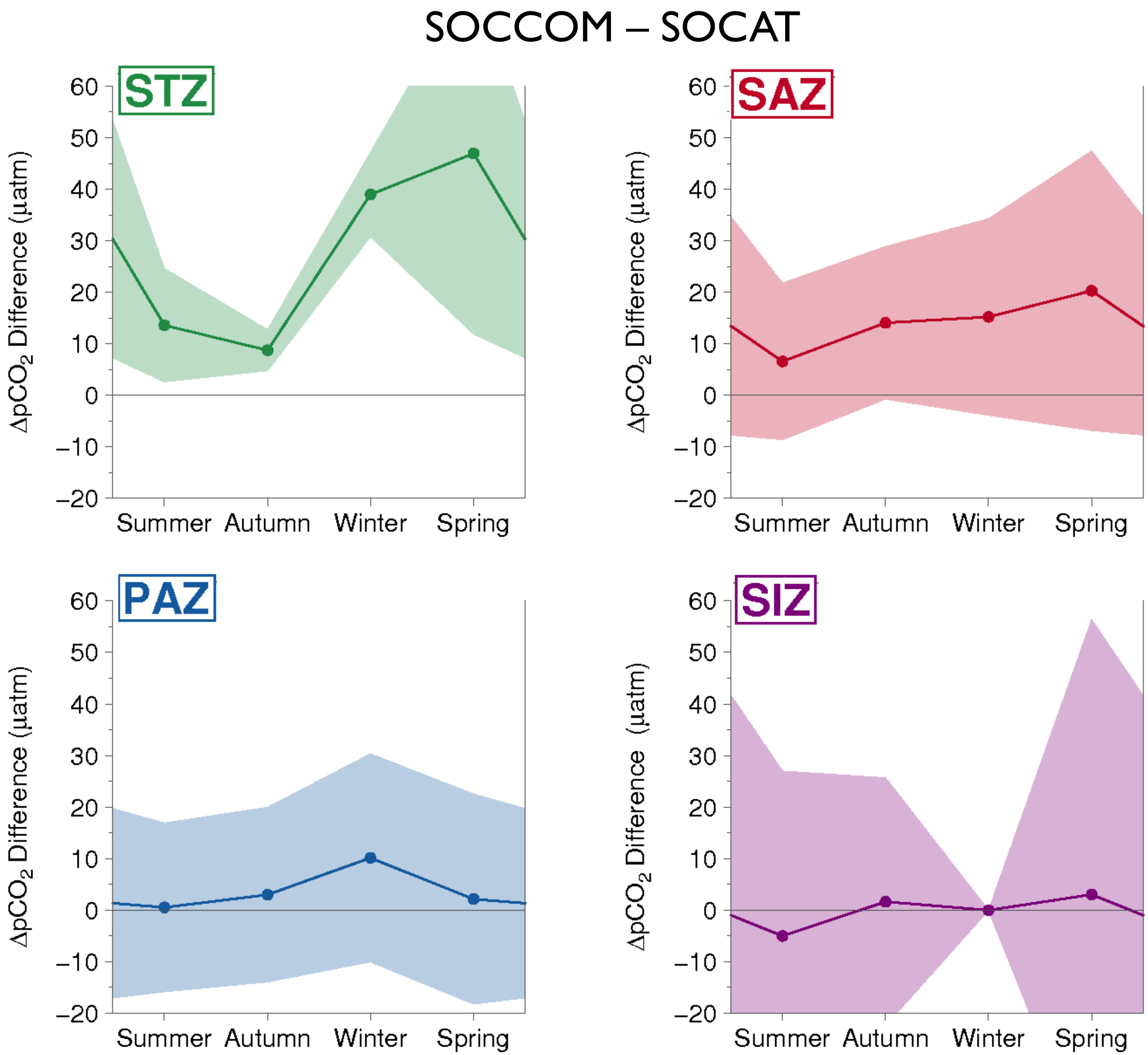


A. Jacobson, personal communication

COMPARISON TO SHIPBOARD ΔpCO_2

Shipboard data from SOCAT v4, within 100 km and 10 days of float profile

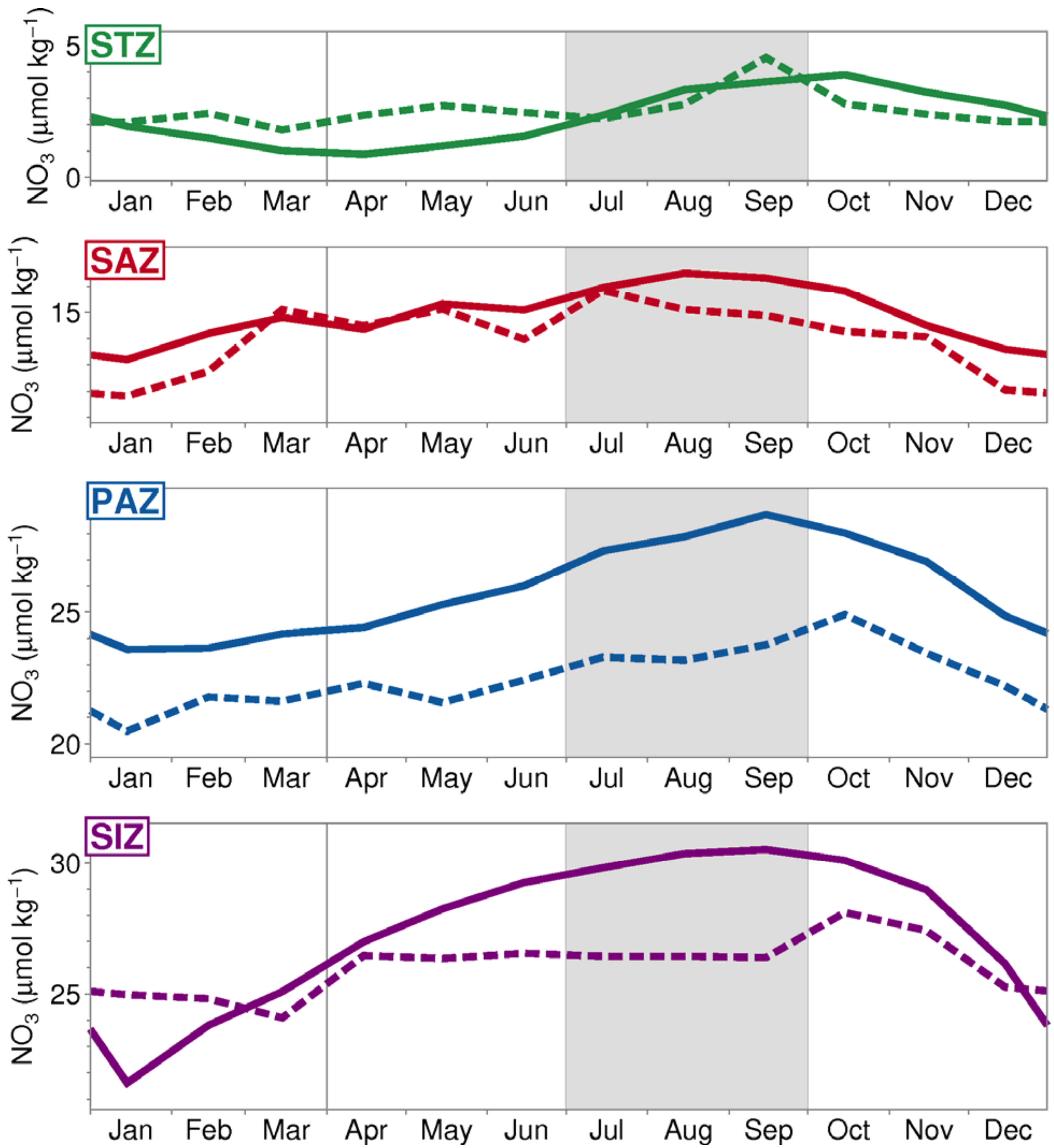
Float-based estimates compare well to SOCAT, except in STZ where temperature differences are large



Seasonal cycle of nitrate in upper 20 m

Floats measure higher nitrate in PAZ compared to World Ocean Atlas

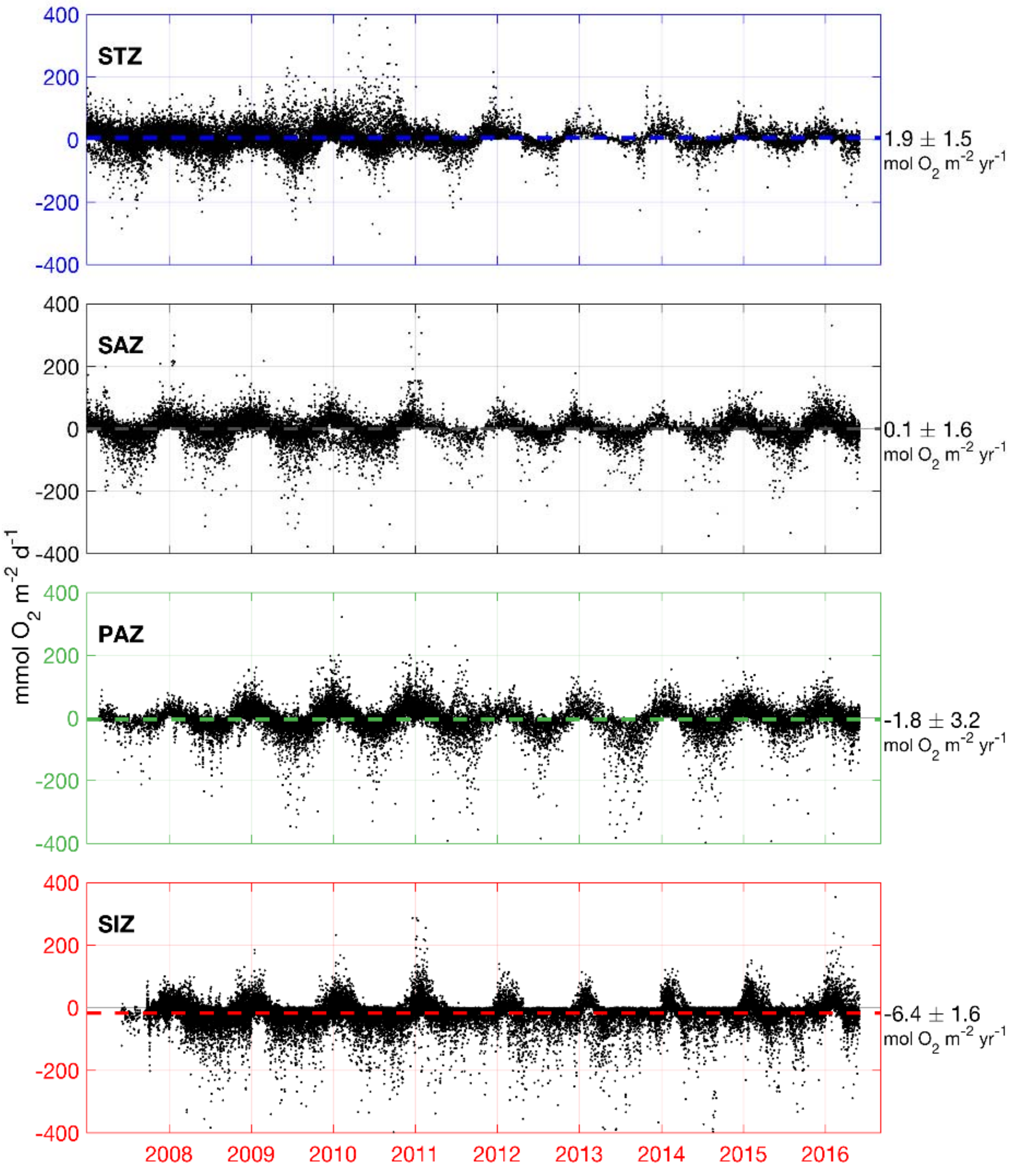
——	This estimate
- -	WOA 13



Southern Ocean oxygen fluxes

+ Outgassing
– Uptake

Bushinsky et al., JGR, in revision



Zone	Flux (mol m^{-2} y^{-1})	
	O_2	CO_2
STZ	1.9 ± 1.5	-0.9 ± 0.5
SAZ	0.1 ± 1.6	-0.3 ± 0.5
PAZ	-1.8 ± 3.2	1.6 ± 0.7
SIZ	-6.4 ± 1.6	-0.4 ± 0.4

Ratio O_2/CO_2 = -0.7 (R^2=0.93)
= -106/150 Redfield ratio

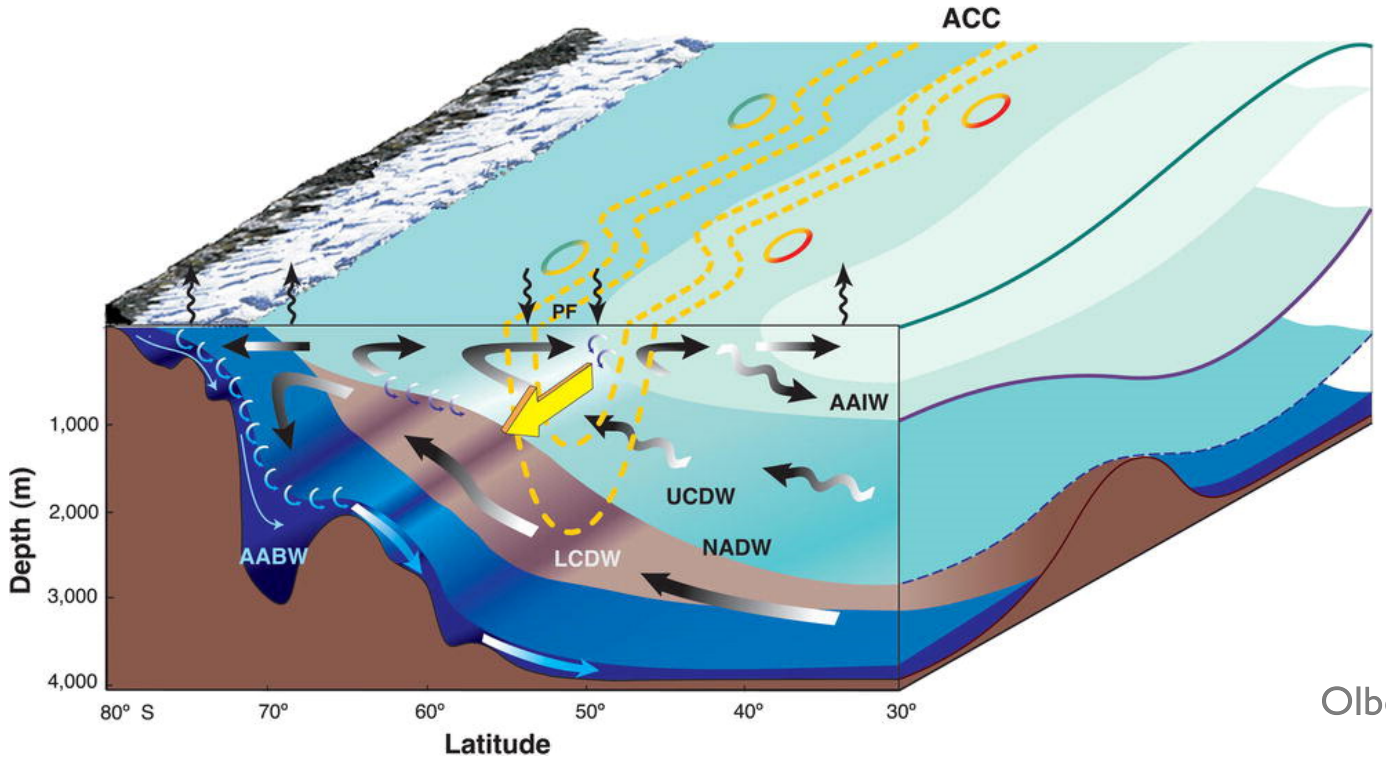
Consistent with upwelling of Circumpolar Deep Water

High in NO_3 and DIC
Low in O_2

Southern Ocean circulation

Zonal flow – Antarctic Circumpolar Current (ACC)

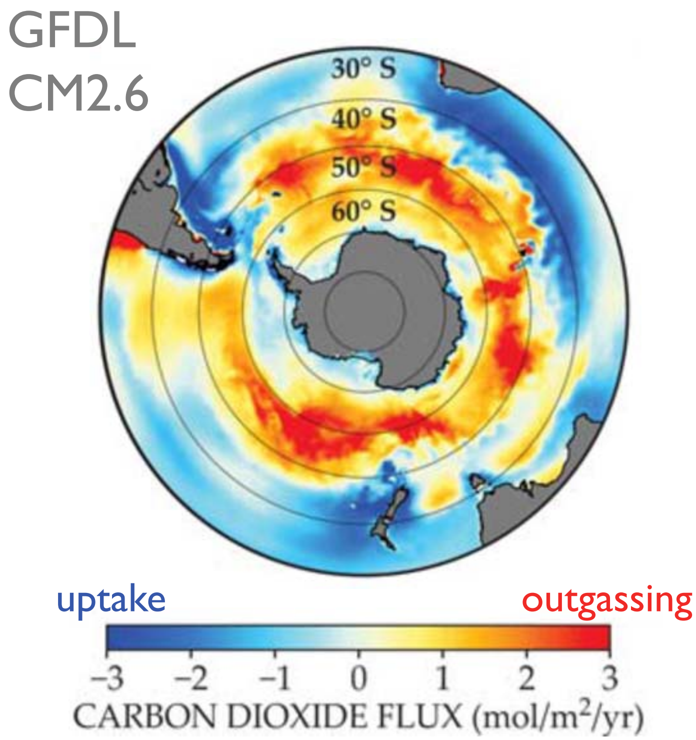
Meridional flow – two overturning cells linked by upwelling of Circumpolar Deep Water

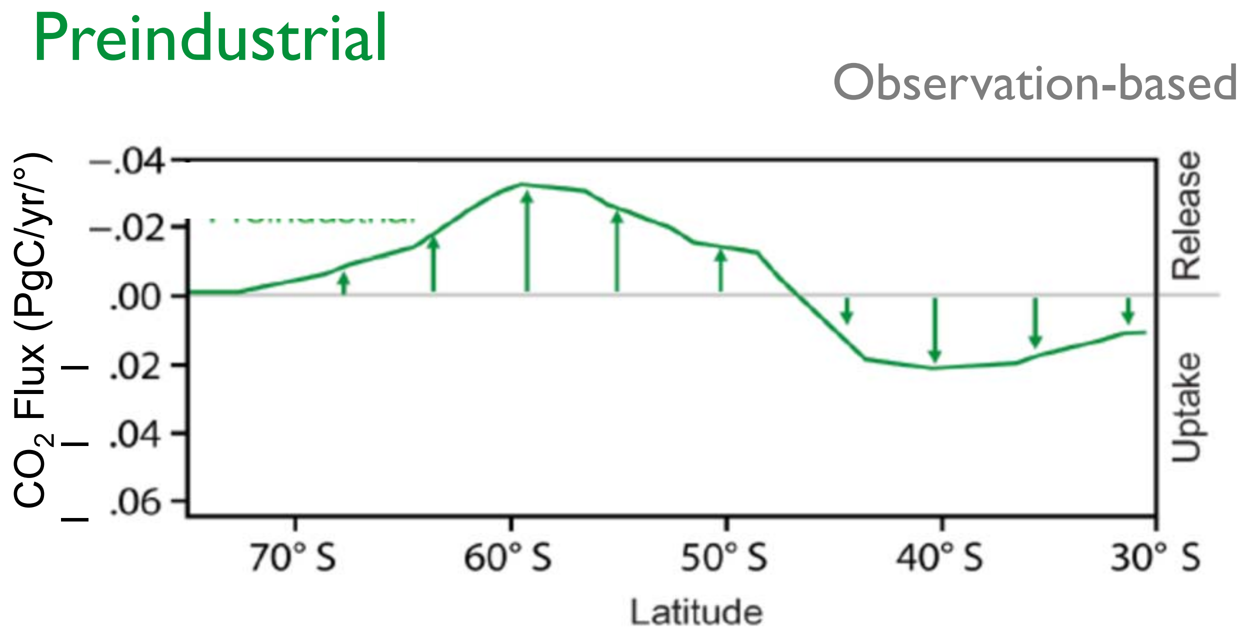


Olbers and Visbeck 2005

PF – Polar Front
AAIW – Antarctic Intermediate Water
UCDW – Upper Circumpolar Deep Water
LCDW – Lower Circumpolar Deep Water
NADW – North Atlantic Deep Water
AABW – Antarctic Bottom Water

CURRENT VIEW OF OCEANIC CARBON UPTAKE

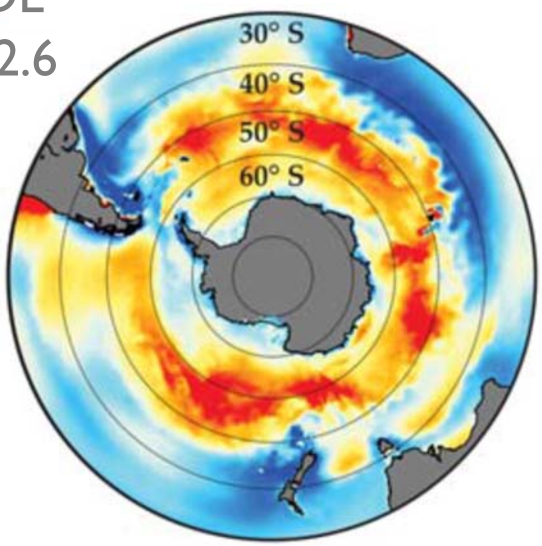




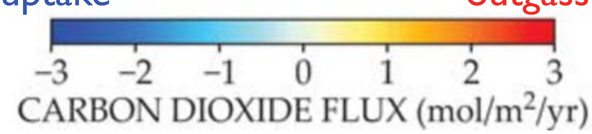
Adapted from Morrison et al. 2015

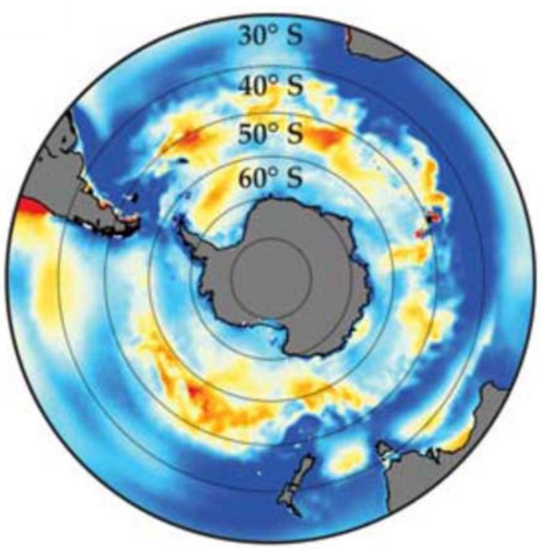
Current view of oceanic carbon uptake

GFDL CM2.6



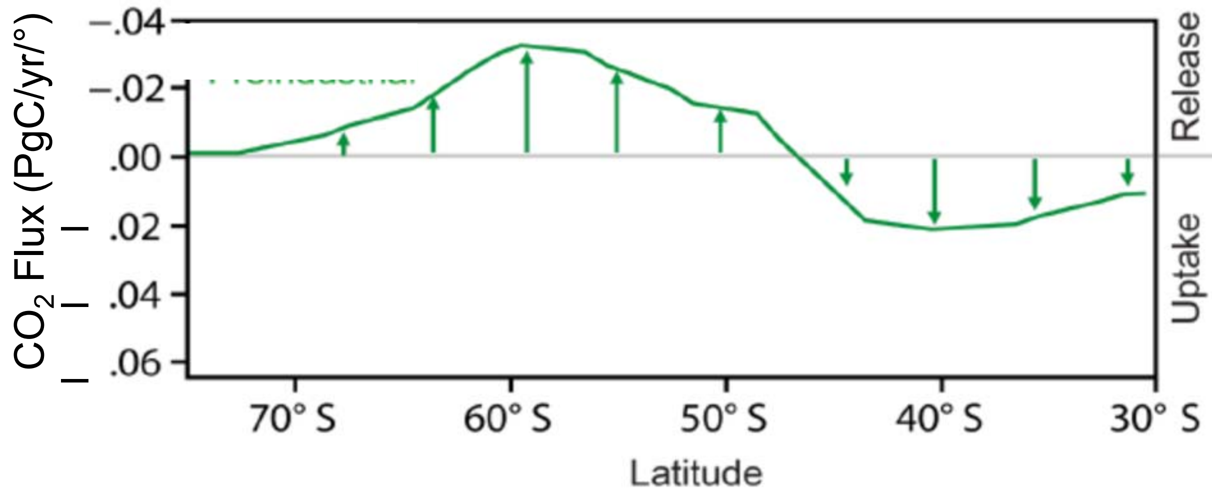
uptake outgassing





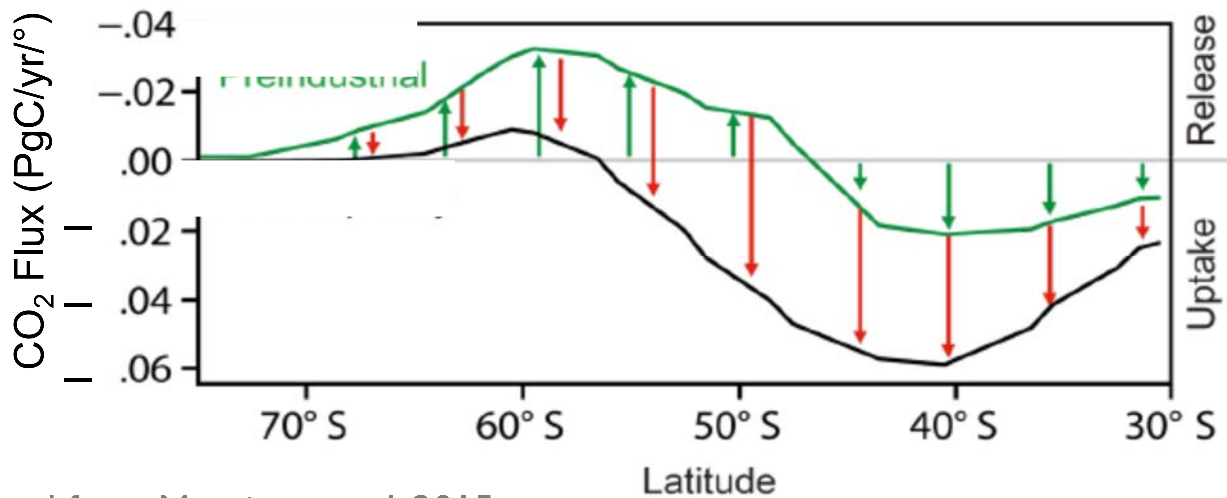
Preindustrial

Observation-based



Contemporary

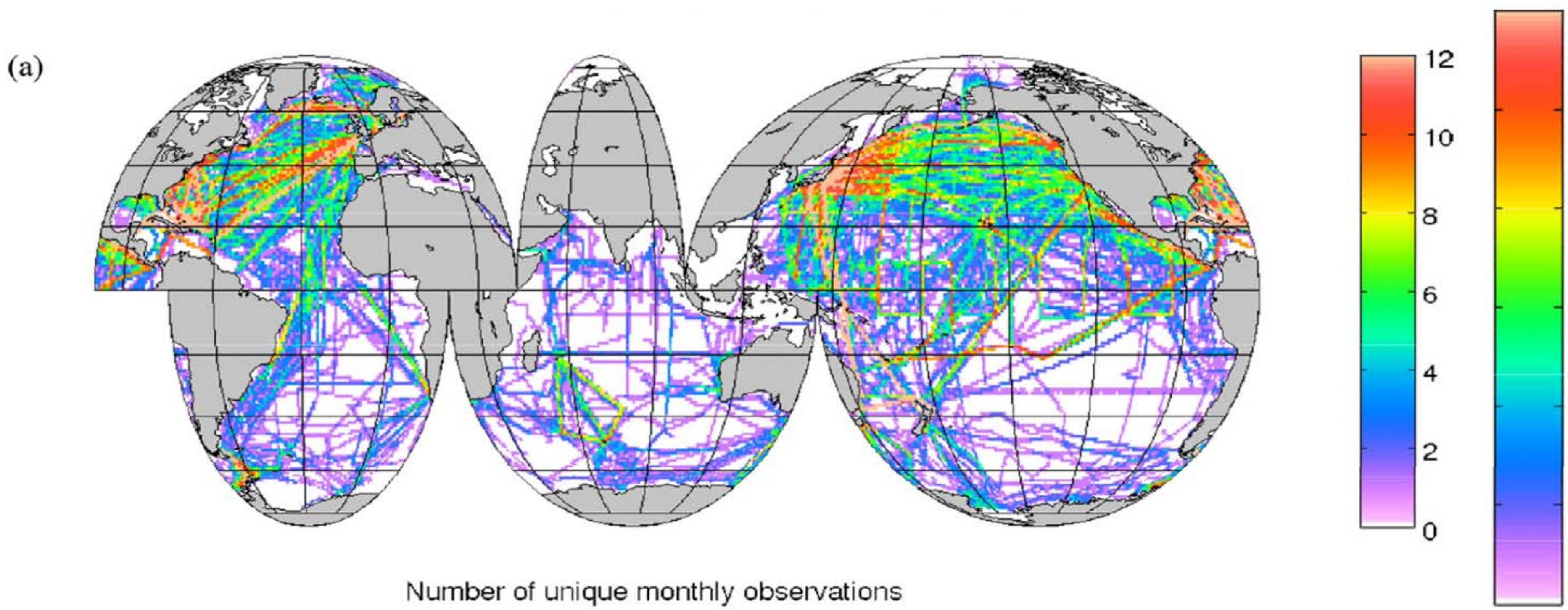
= Preindustrial + Anthropogenic



Adapted from Morrison et al. 2015

OBSERVATIONS OF THE SOUTHERN OCEAN

Historical:
Surface Ocean CO_2 Atlas (SOCAT v2), 1970-2011



Bakker et al. 2014

Months of year
with measurements

Surface partial pressure of CO_2 (pCO_2)

Sources of uncertainty in air-sea flux

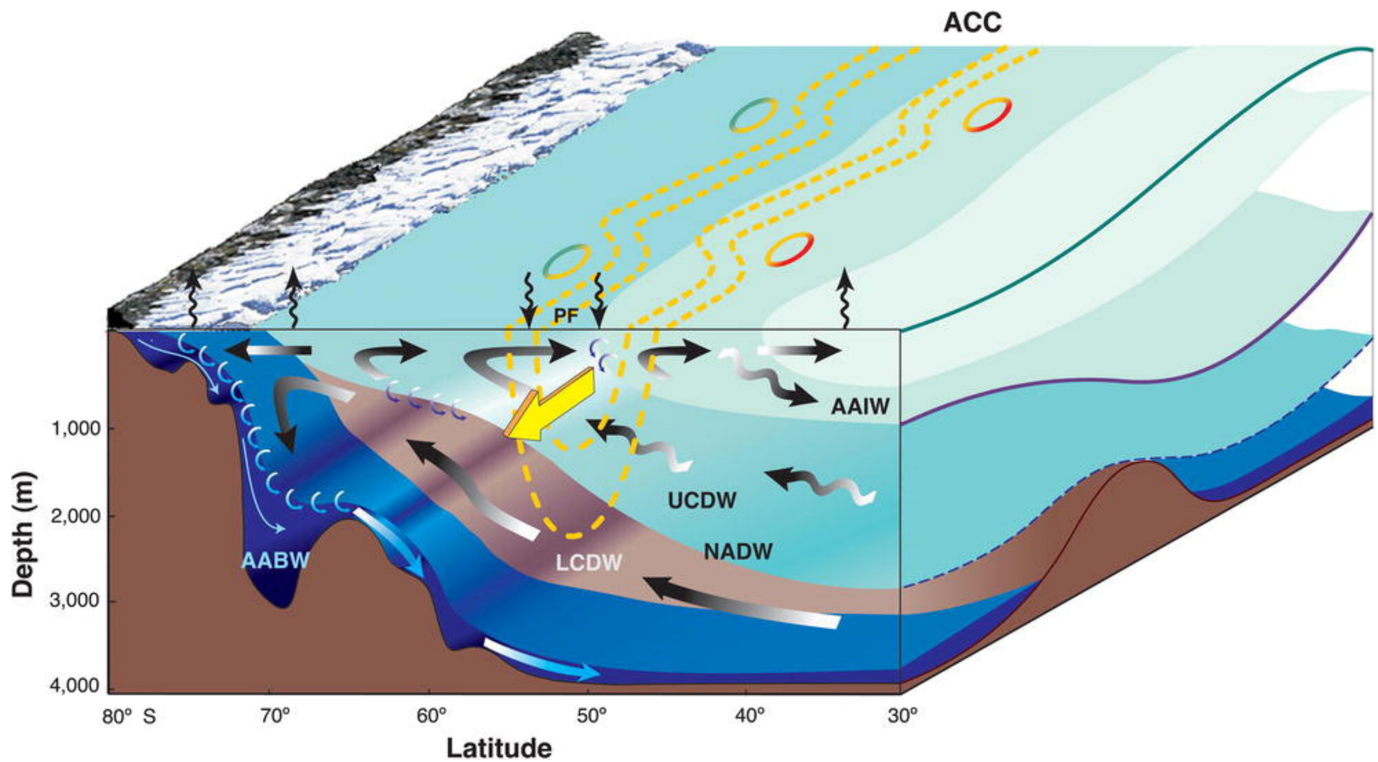
Source of uncertainty	Value
Measured T, random	0.002 C
Measured S, random	0.01 PSU
Gas transfer parameterization, random	12.5% + 10% for low winds, *Wanninkhof 2014*
Wind speed, random	1.5 m s^{-1}, *Chadhuri et al. 2013*
Estimated pCO_2	2.72%, *Williams et al. 2017*
Systematic for all floats	2.04%
Systematic per float	0.04%
Random	1.75%
pCO_2^{atm}, systematic	Given with measurements
P_{atm}, systematic	10 atm, *Salstein et al. 2008*

Southern Ocean circulation

Zonal flow – Antarctic Circumpolar Current (ACC)

Two meridional overturning cells

- Upwelling of deep water
- Northward return in bottom and intermediate layers



Olbers and Visbeck 2005

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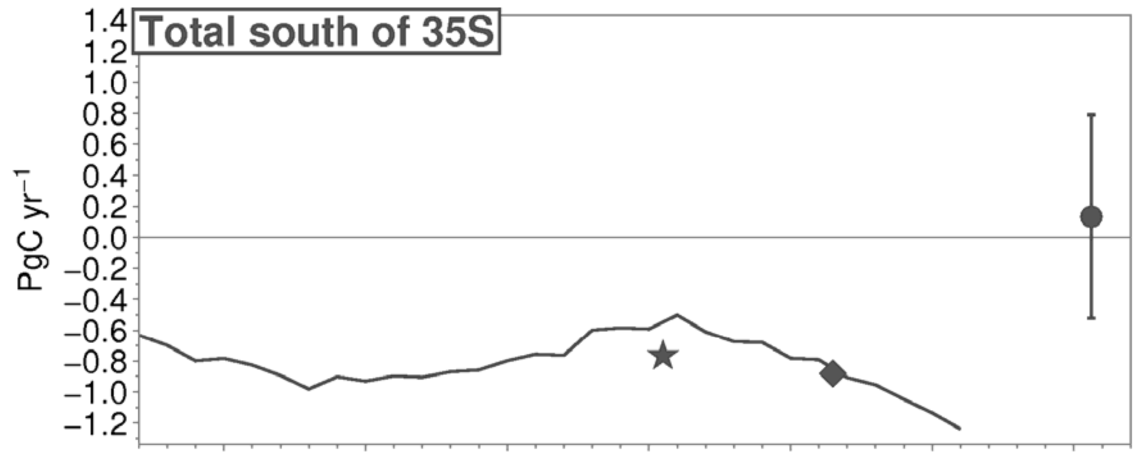
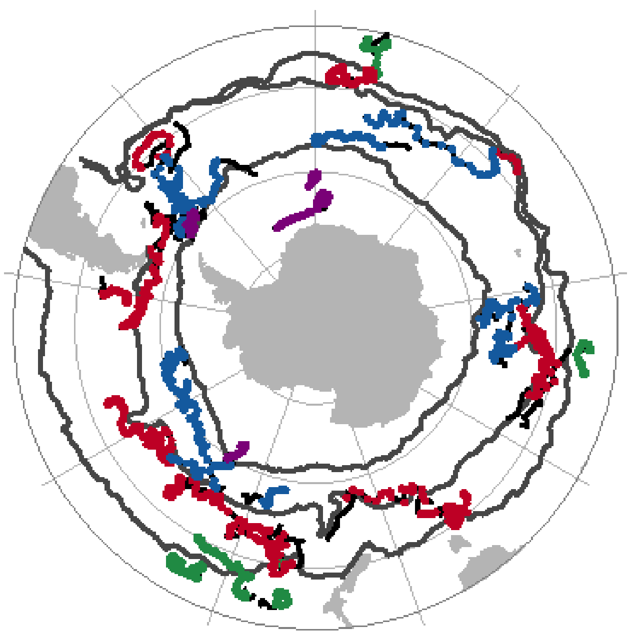
ANNUAL NET OCEANIC CO_2 UPTAKE

- ● This estimate
- ★ Takahashi et al. 2009
- Landschützer et al. 2014
- ◆ 2002-2011 mean
- — 30-yr estimate





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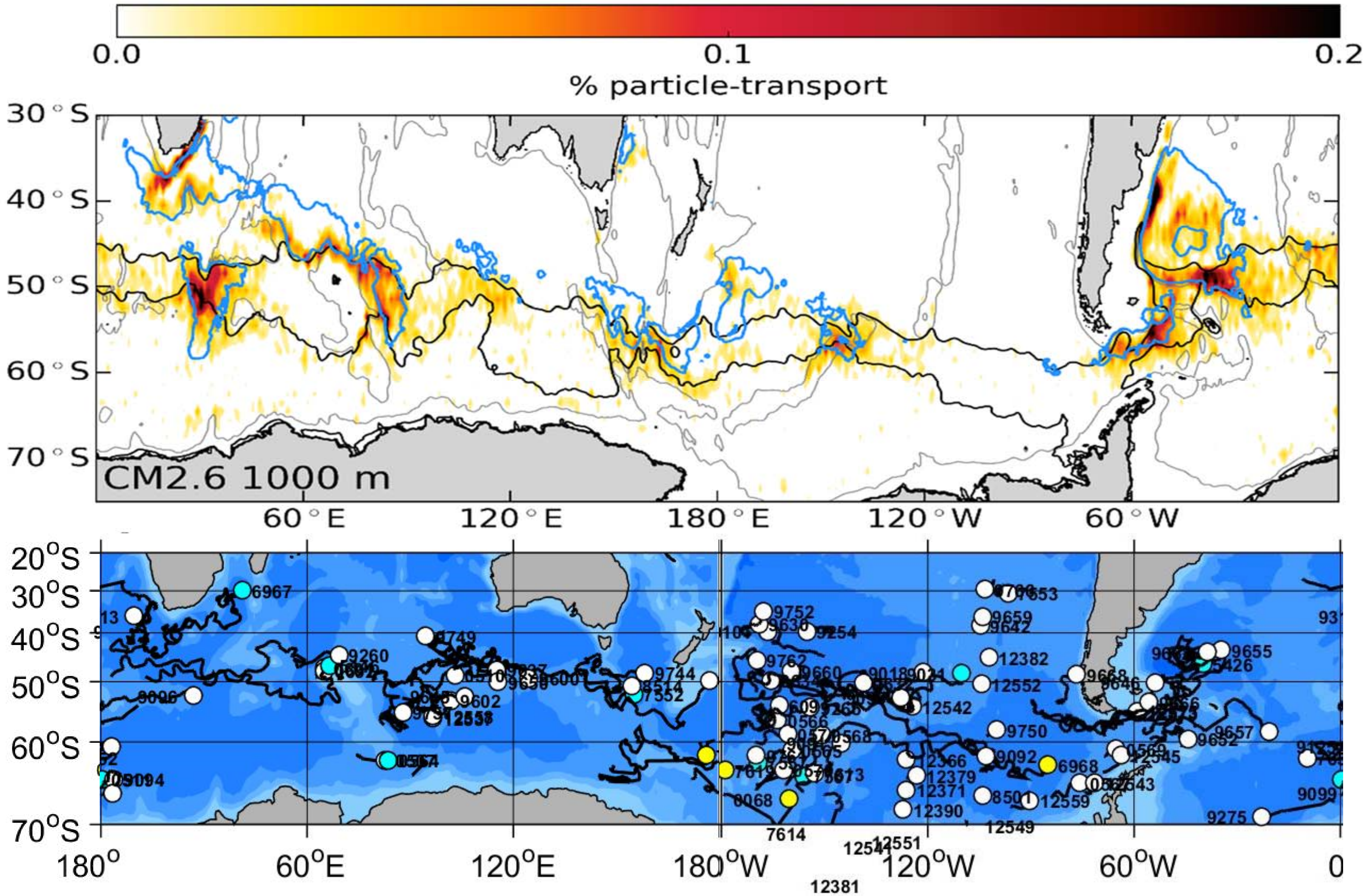
Random	1.75%
pCO_2^{atm}, systematic	Given with measurements
P_{atm}, systematic	10 atm, *Salstein et al. 2008*

Sampling bias

Floats sampling downstream of upwelling hotspots

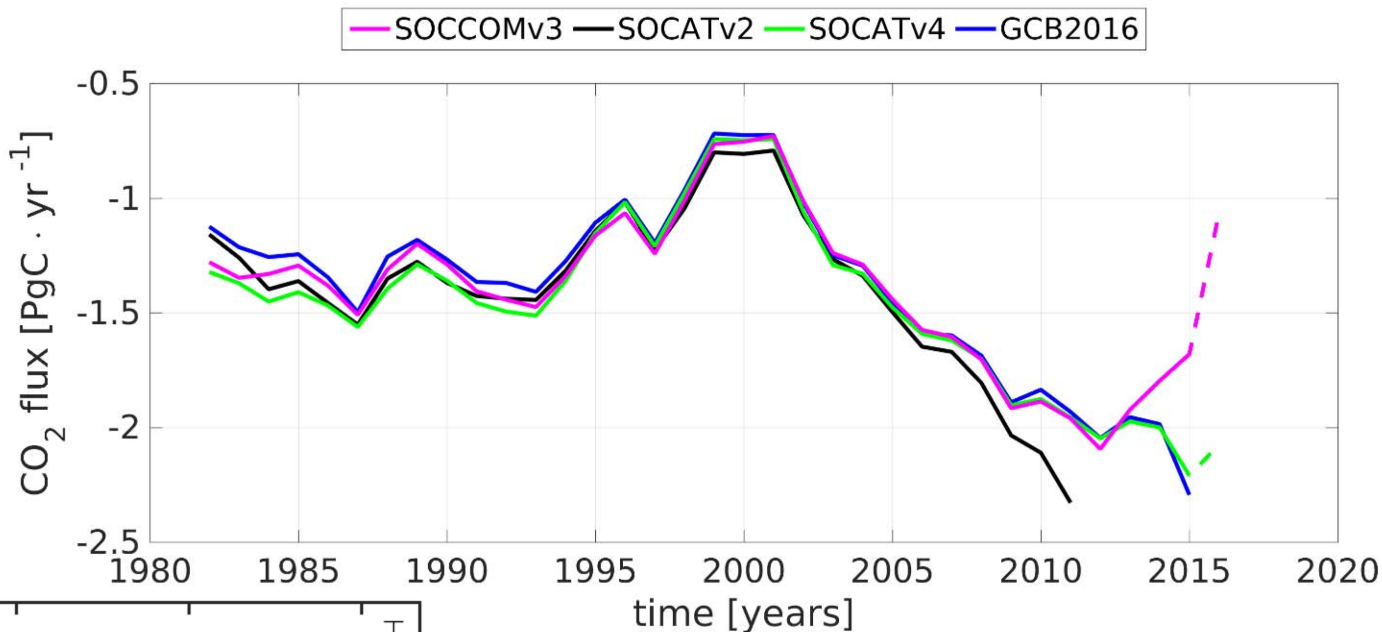
Tamsitt et al., in revision

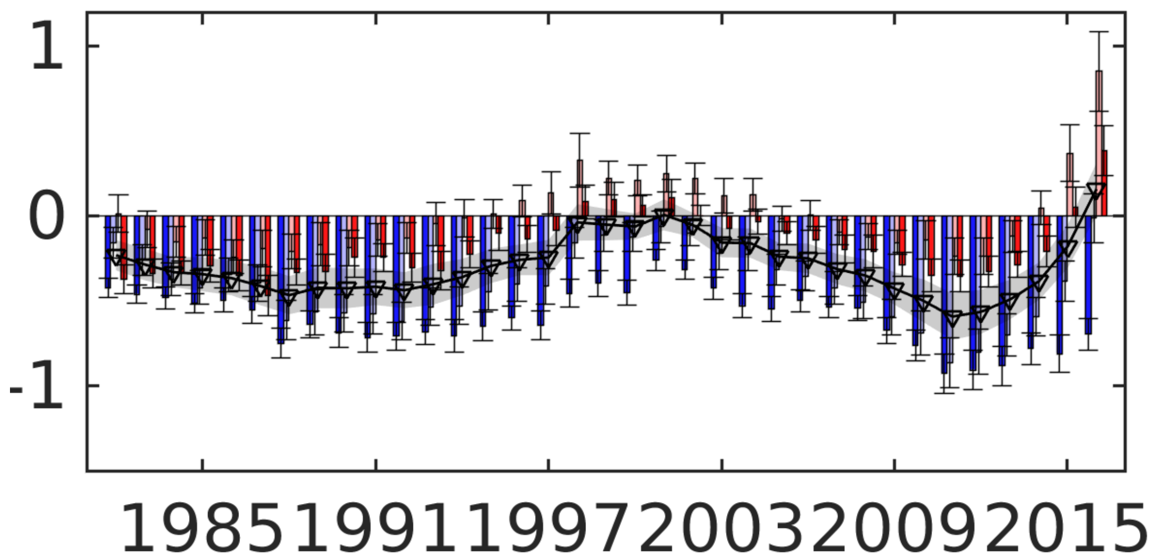


Role of interannual variability

Using SOCCOM data in neural network mapping of global CO_2 flux reduces uptake in 2014-2016

Global oceanic uptake





Southern Ocean south of 44°S

Winter

Summer

P. Landschützer, personal communication

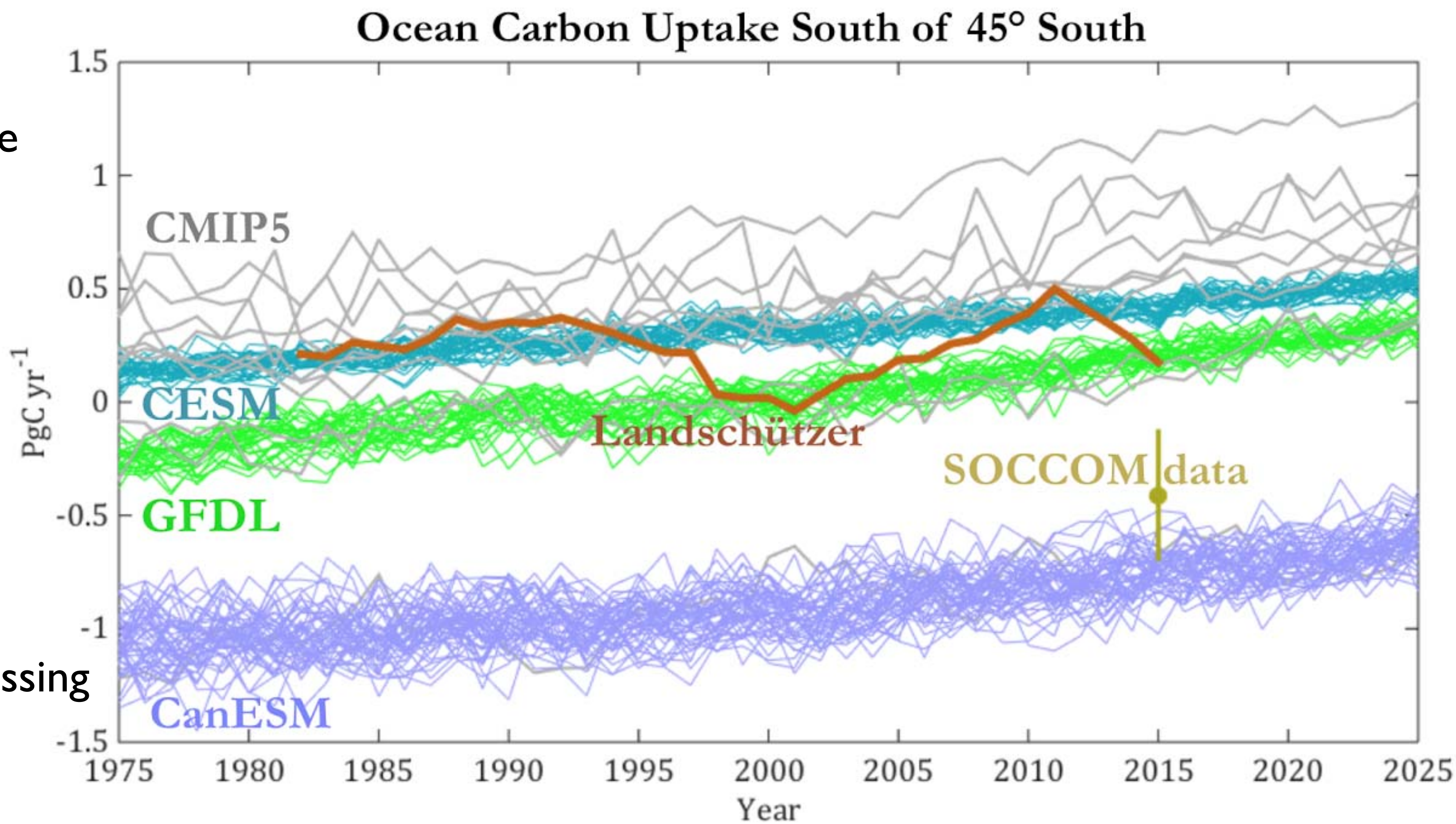
IMPLICATIONS FOR MODELING CARBON CYCLE

Most CMIP models follow previous observational estimates

CanESM has large CO_2 outgassing, high nitrate, strong winds

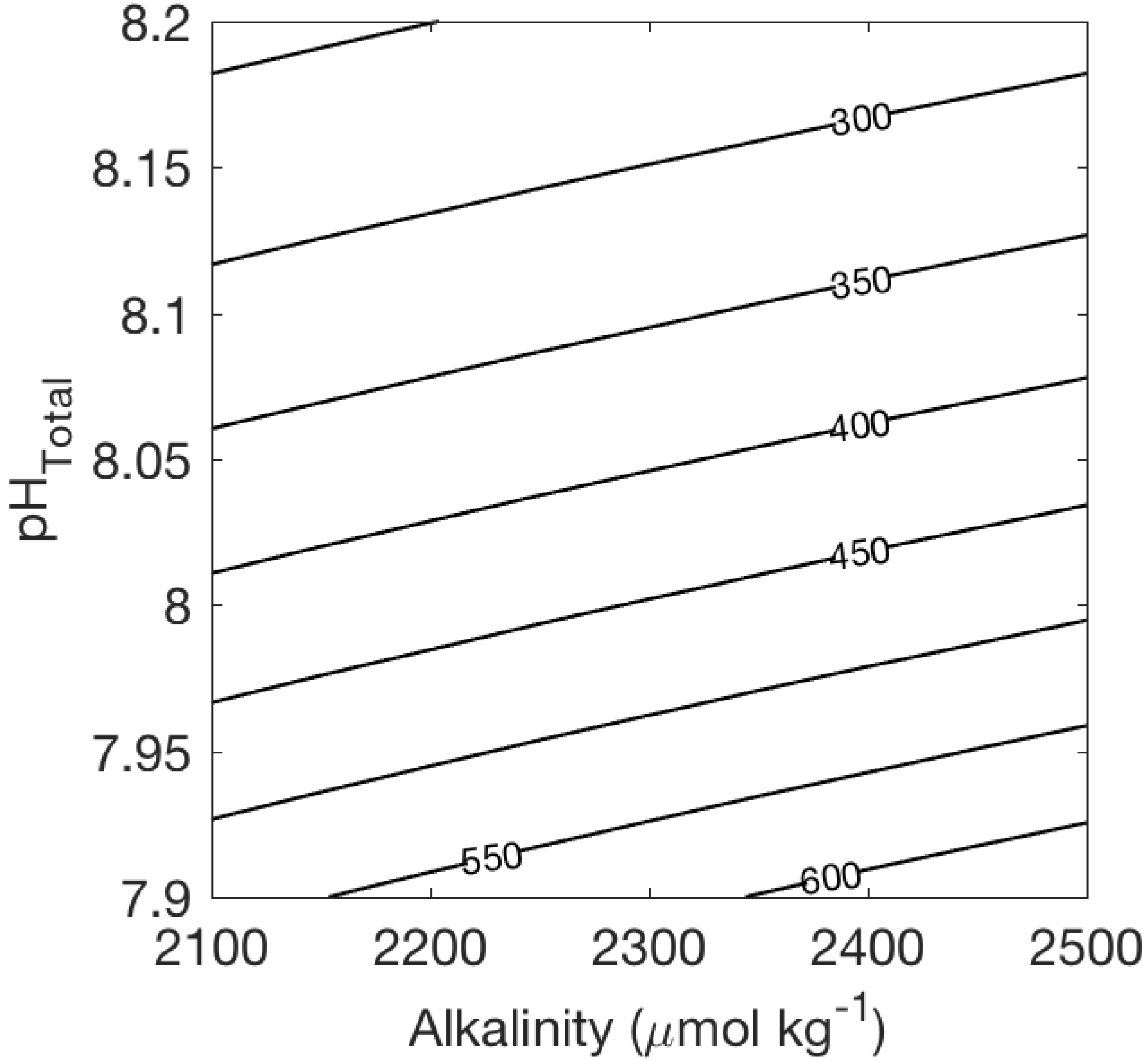
Uptake

Outgassing



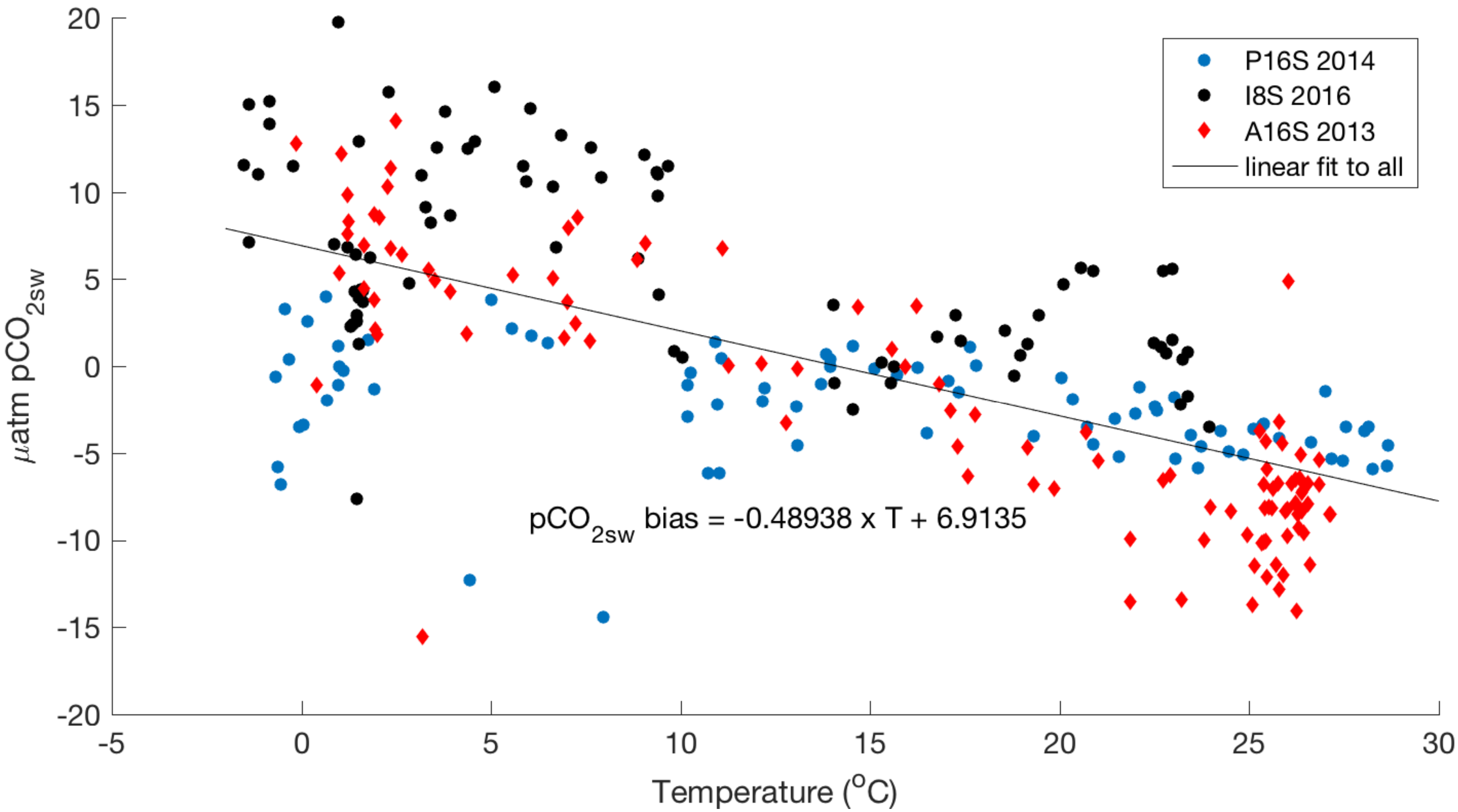
S. Schlunegger, personal communication

pCO_{2SW} CALCULATED AT A RANGE OF REALISTIC OPEN OCEAN SURFACE OCEAN PH AND TA VALUES USING T = 15 °C, S = 35, AND P = 5 DB.



Williams et al, in prep

The difference between pCO_{2sw} calculated from in situ bottle-measured pH and bottle TA and underway-measured pCO_{2sw} at the same temperature plotted as a function of temperature for three GO-SHIP/SOCCOM deployment cruises. Positive values indicate that calculated pCO_{2sw} (pH, TA) is higher than underway-measured pCO_{2sw}.



Williams et al, in prep

MODEL COMPARISON

C. Dufour
McGill University

CMIP5 models

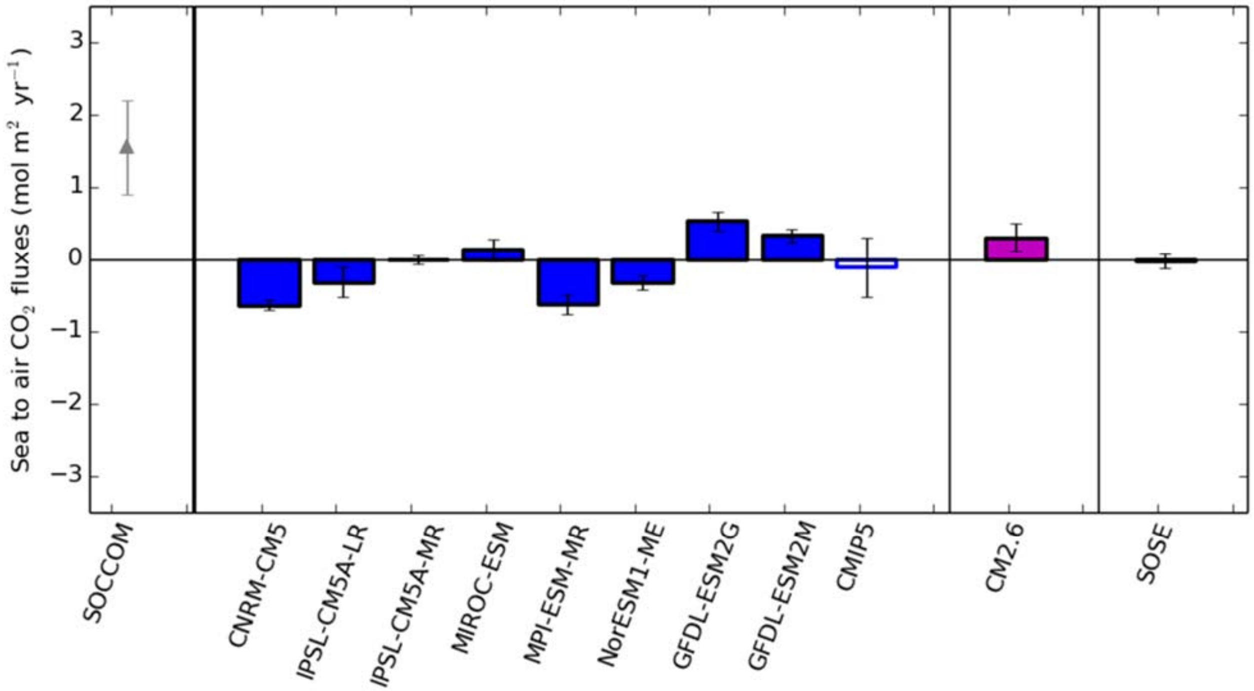
center	name	vertical coordinate	ocean resolution	scenario (time period)
CERFACS	CNRM-CM5	z	0.4° to 2°	historical (1996-2005)
NOAA-GFDL	GFDL-ESM2G	isopycnal		
NOAA-GFDL	GFDL-ESM2M	z		
IPSL	IPSL-CM5A-LR	z		
IPSL	IPSL-CM5A-MR	z		
MIROC	MIROC-ESM	isopycnal		
MPI-M	MPI-ESM-MR	z		
NCC	NorESM1-ME	z		
NOAA-GFDL	CM2.6	z	0.1°	idealized 1%/yr (years 21-30)
Scripps	SOSE*	z	1/6°	historical (2008-2012)

All models are climate models except SOSE which is an ocean-sea ice data assimilating model forced by atmospheric reanalyses (NCEP)

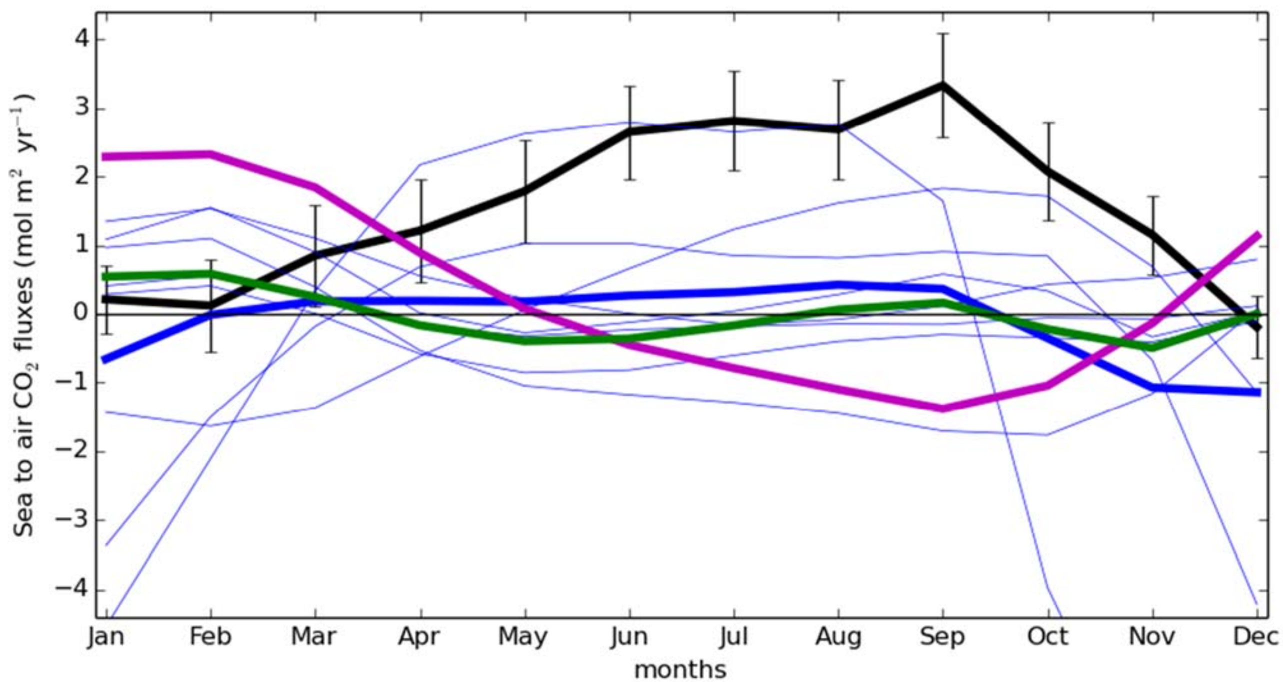
MODEL COMPARISON IN PAZ

C. Dufour
McGill University

Poor agreement in PAZ for annual mean and seasonal cycle



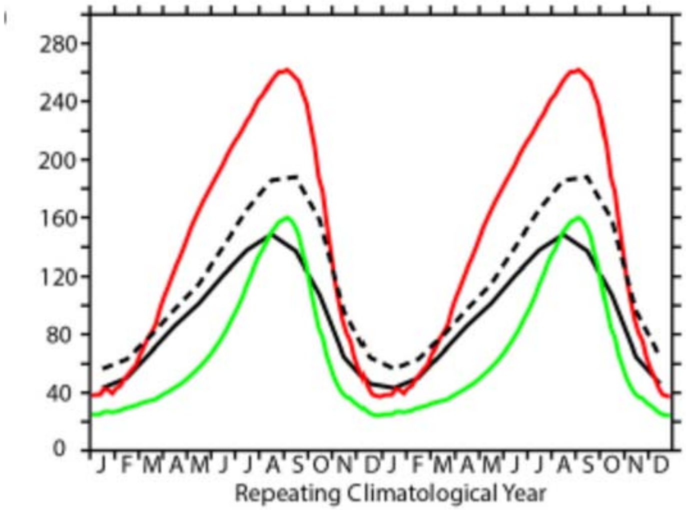
CMIP5 models
GFDL CM2.6
SOSE
Float estimate



WHY ARE THE MODELS DIFFERENT (WRONG)?

Dependence on wind stirring and mixed layer depth seasonality

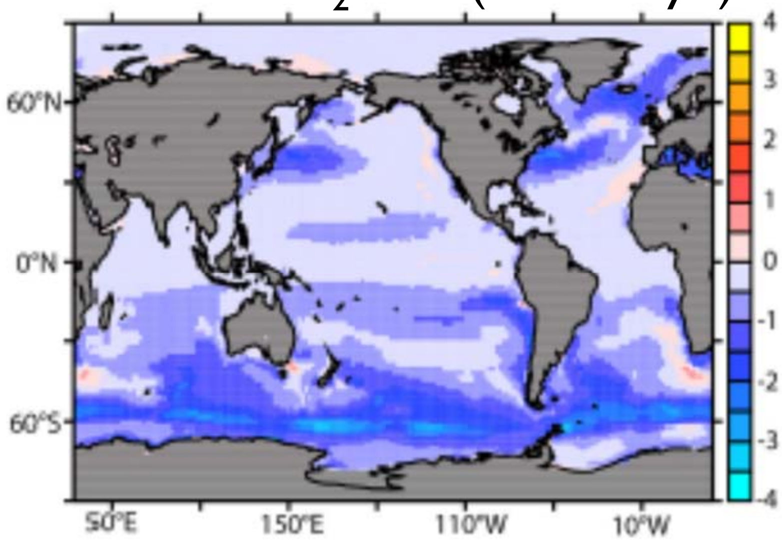
Rodgers et al., 2014



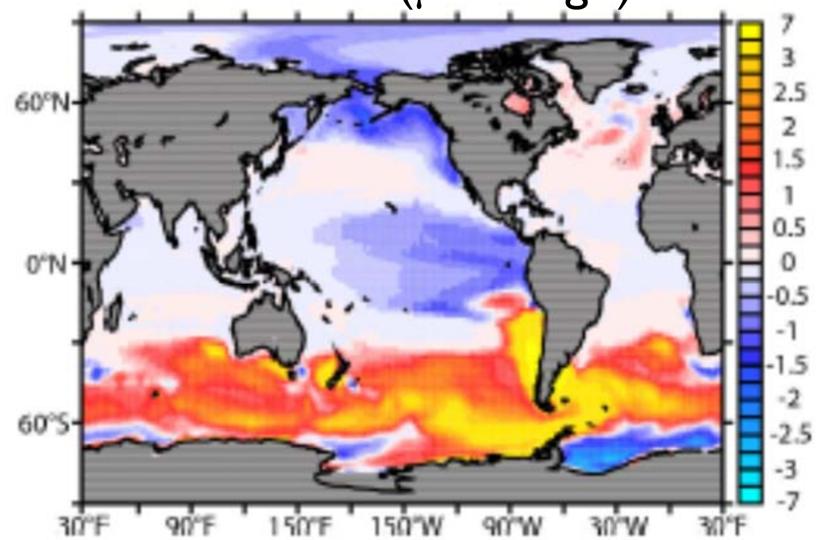
Mean MLD 50-60°S
Observations
Control
Increased wind stirring

Changes (Wind Stir – Control)

Air-sea CO_2 Flux (mol m^{-2} y^{-1})

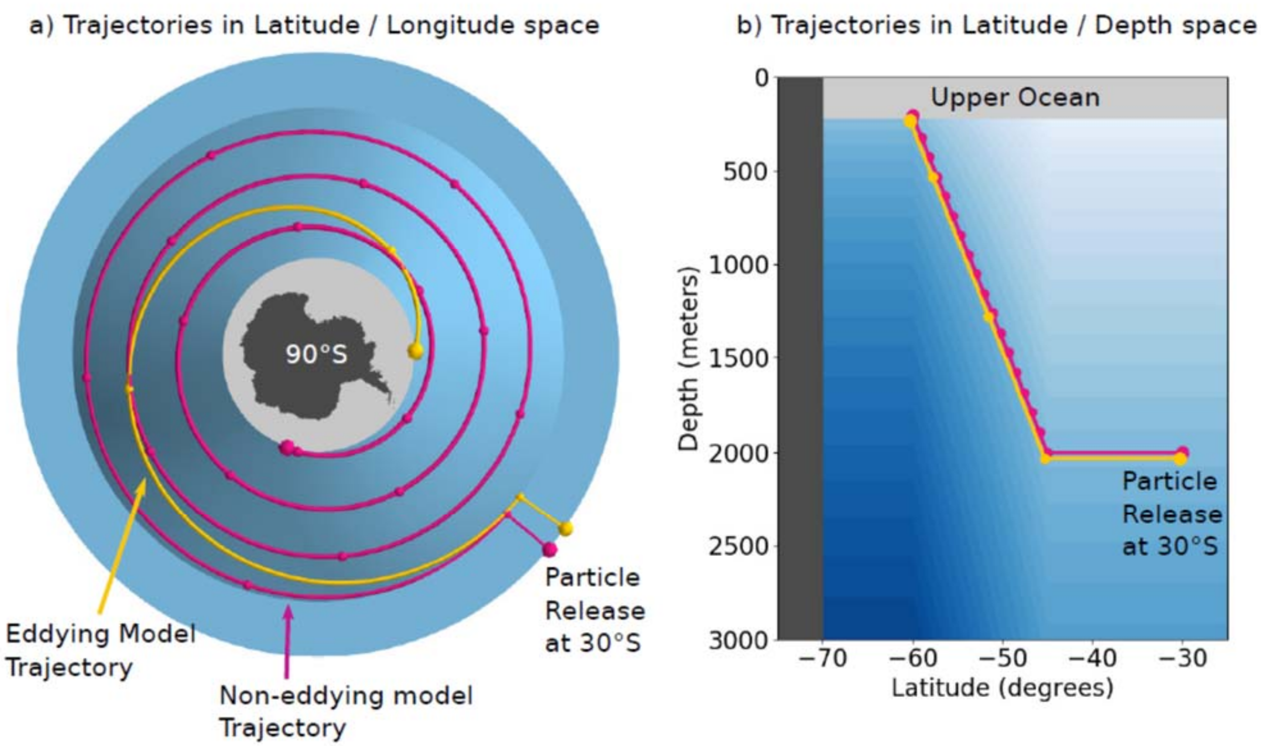


Nitrate (μmol kg^{-1})

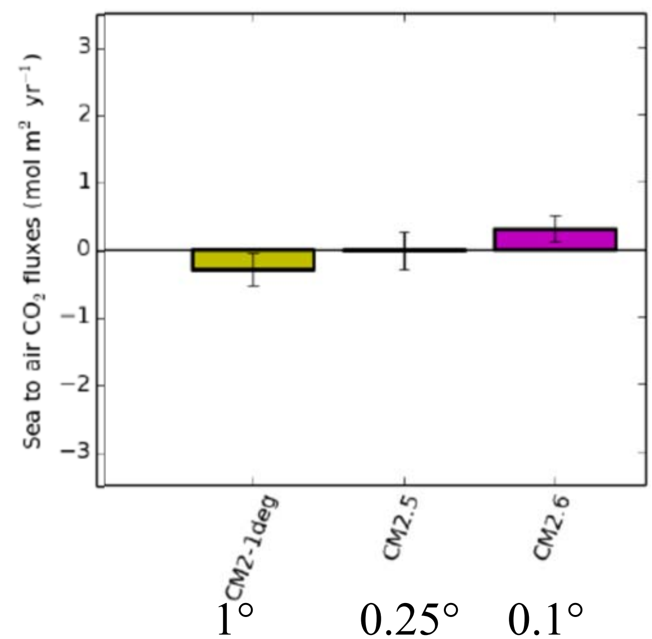


WHY ARE THE MODELS DIFFERENT (WRONG)?

Dependence on mesoscale eddies and timescale of upwelling



CO$_2$ flux in PAZ



	Experiment	Mode of upwelling TTD (years)	Mean number of circumpolar loops
1°	CM2-1deg-5day	87	3.2
0.25°	CM2.5-5day	31	1.7
0.1°	CM2.6-5day	17	0.9
	CM2.6-monthly	26	0.9

Drake et al., in prep