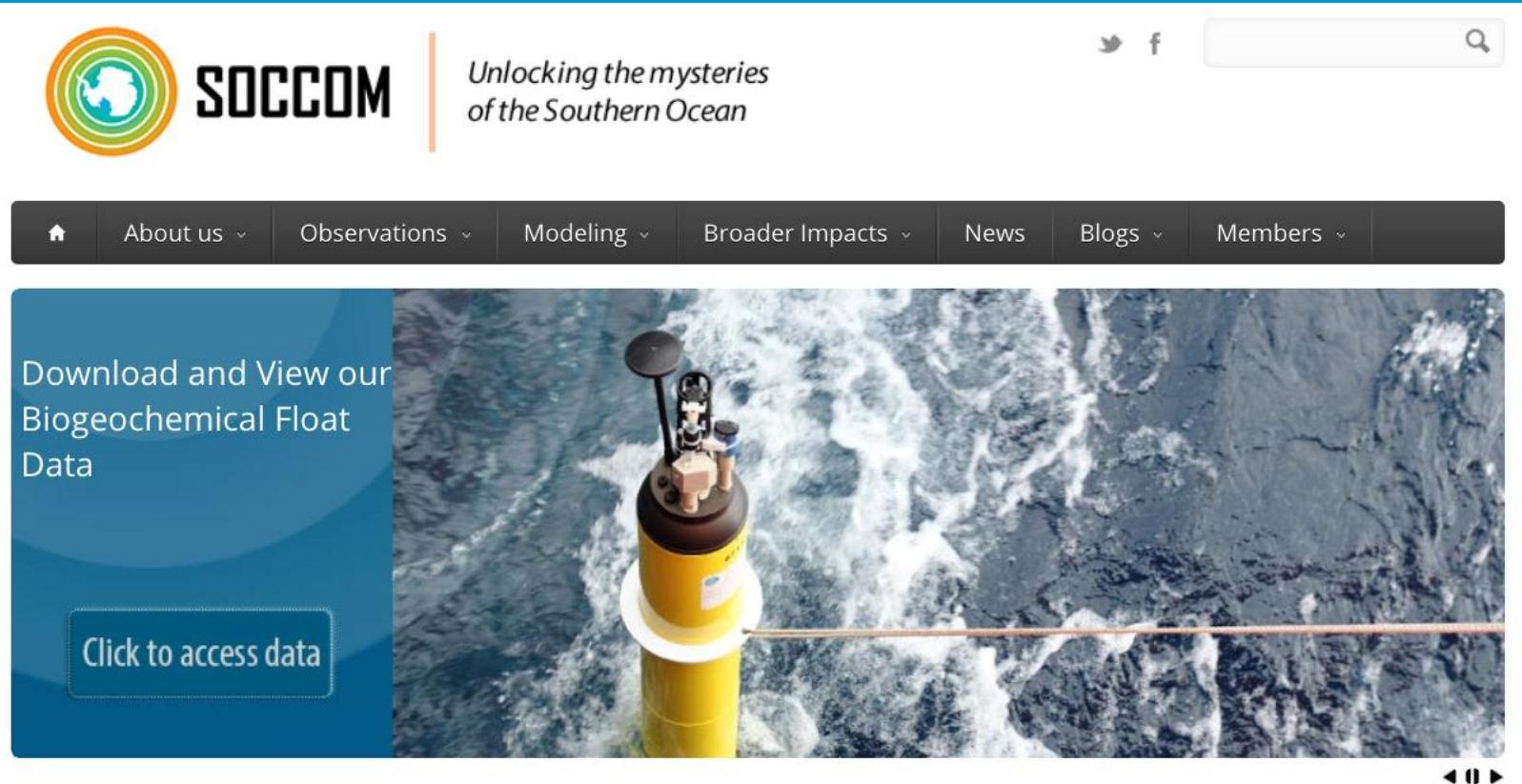


# Biogeochemical, ocean, and sea-ice data assimilation in the Southern Ocean

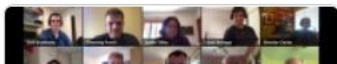
ECMWF/OceanPredict workshop on Advances in Ocean DA

Matt Mazlof & Ariane Verdy, May 2021



The image shows the top section of the SOCCOM website. On the left is the SOCCOM logo, which consists of a stylized globe with concentric orange and green rings, followed by the text "SOCCOM" in bold black letters. To the right of the logo is the tagline "Unlocking the mysteries of the Southern Ocean" in a smaller, italicized font. Further right are social media icons for Twitter and Facebook, and a search bar. Below this is a dark navigation bar with white text links: "Home", "About us", "Observations", "Modeling", "Broader Impacts", "News", "Blogs", and "Members". The main banner features a large photograph of a yellow oceanographic buoy with various sensors on top, floating in the dark blue Southern Ocean. On the left side of the banner, there is a blue overlay with the text "Download and View our Biogeochemical Float Data" and a button that says "Click to access data".

## Latest News

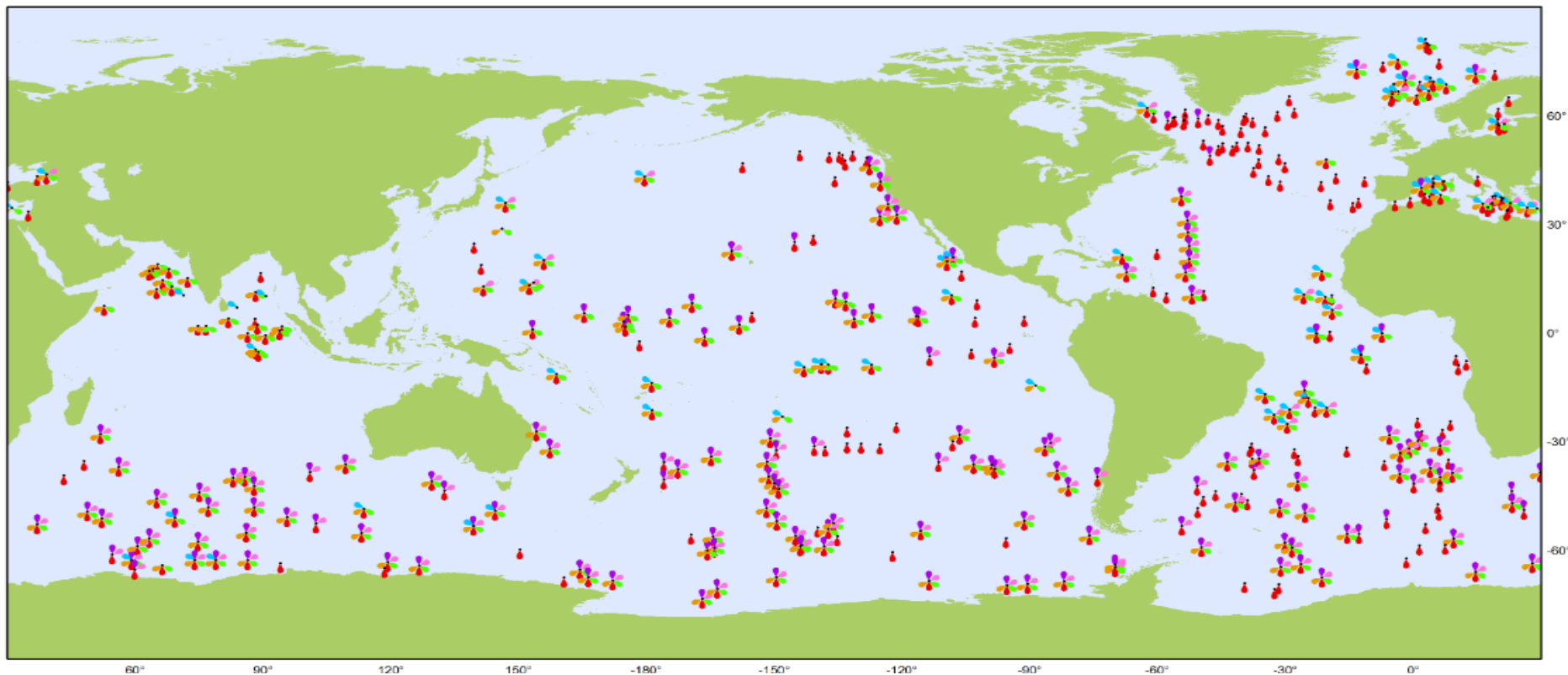


## Southern Ocean Carbon and Climate Observations and Modeling

The Southern Ocean Carbon and Climate Observations and Modeling project (SOCCOM) is a multi-institutional program focused on unlocking the mysteries of the Southern Ocean and determining its



BGC-Argo is rapidly expanding, and beginning to provide sufficient coverage of in situ observations to justify a DA effort



### Sensor Types

April 2021

Latest location of operational floats (data distributed within the last 30 days)

Operational Floats (387)



Suspended particles (211)



Nitrate (152)



Downwelling irradiance (66)



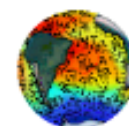
Chlorophyll a (211)



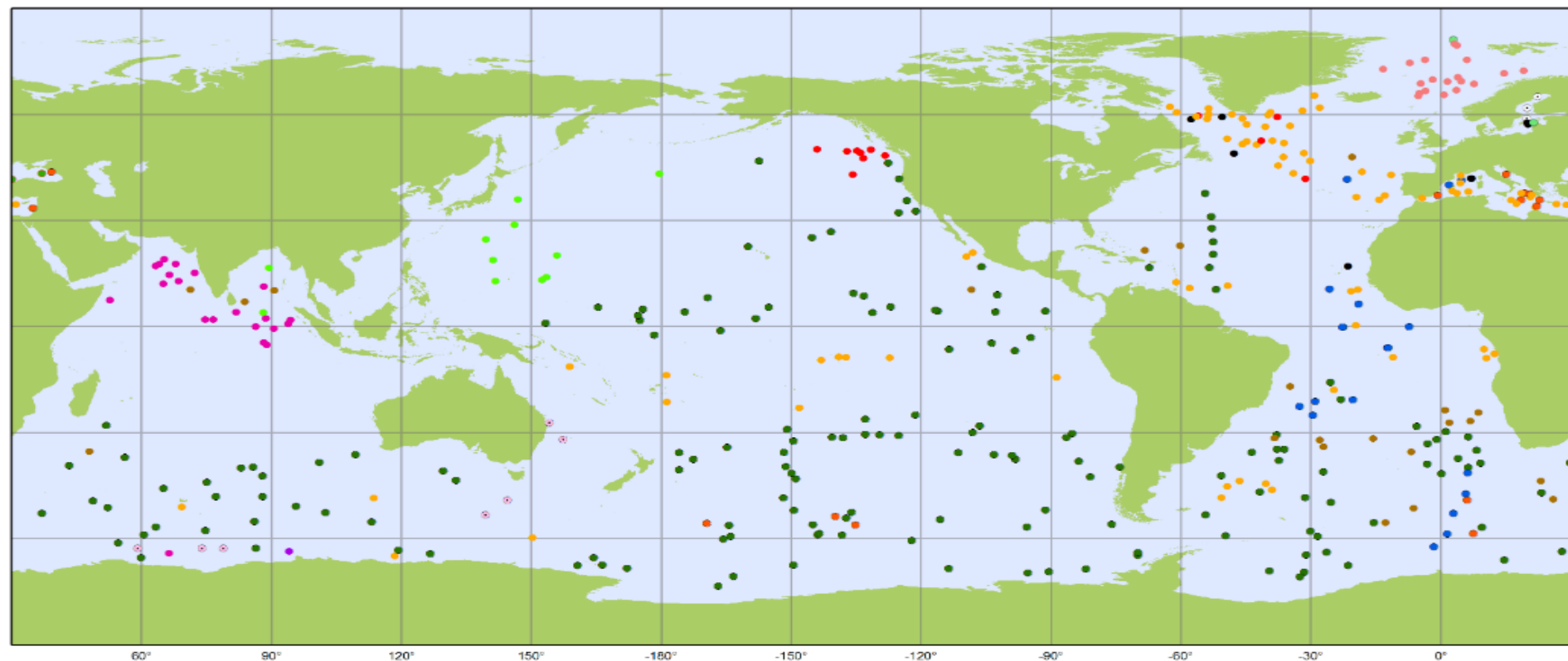
pH (165)



Oxygen (376)



# BGC-Argo is an international effort in terms of both float investments and deployment efforts



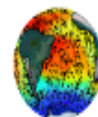
Argo BioGeoChemical

National contributions - 387

April 2021

Latest location of operational floats (data distributed within the last 30 days)

⊗ AUSTRALIA (7)	● CHINA (11)	● FRANCE (78)	● ITALY (14)	● POLAND (2)
● BULGARIA (2)	● EUROPE (19)	● GERMANY (8)	● JAPAN (1)	● UK (22)
● CANADA (12)	⊗ FINLAND (4)	● INDIA (21)	● NORWAY (19)	● USA (167)



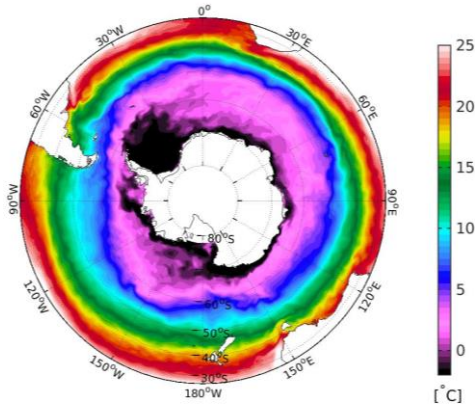
## Number of vertical profiles from ship, Argo, BGC-Argo:

	2011	2012	2013	2014	2015	2016	2017	2018	2019
<b>Ship</b>	26876	31112	35942	35454	31022	30178	28843	22156	9477
<b>Argo TS</b>	29187	34197	34806	35174	36957	36699	31928	29045	20957
<b>BGC-Argo O<sub>2</sub></b>	5845	7378	7780	10185	9093	8948	8919	7552	6780
<b>BGC-Argo NO<sub>3</sub></b>	585	1073	2138	2288	2214	2381	3100	3069	3571
<b>BGC-Argo pH</b>	0	32	72	414	609	1055	1616	1434	1513



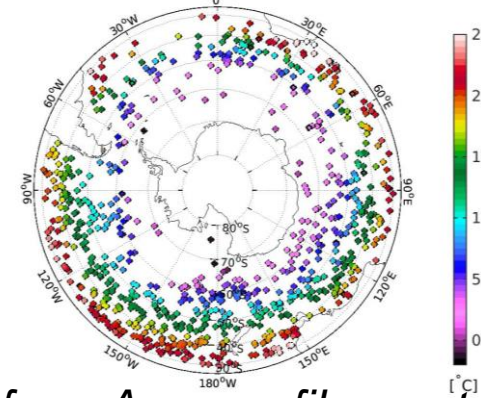
# 4D-Var, “adjoint” method

adjusting initial conditions & atmospheric forcing



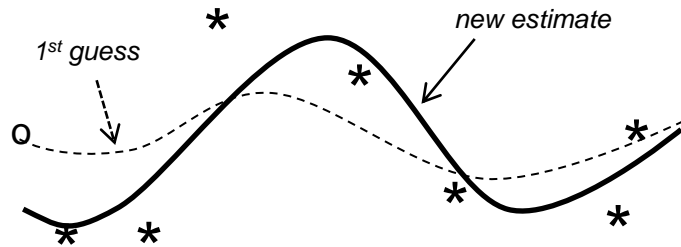
Atmospheric state from ERA5

adjust inputs to bring the model closer to observations of the actual ocean state



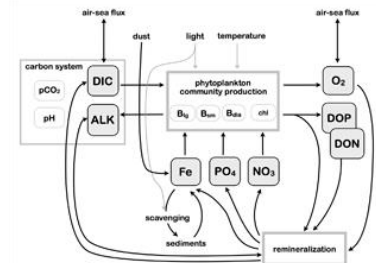
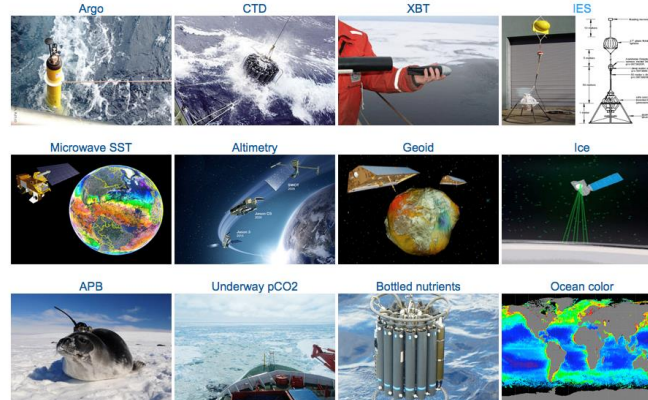
e.g. from Argo profiles, satellites, ...

minimize the “cost function” :



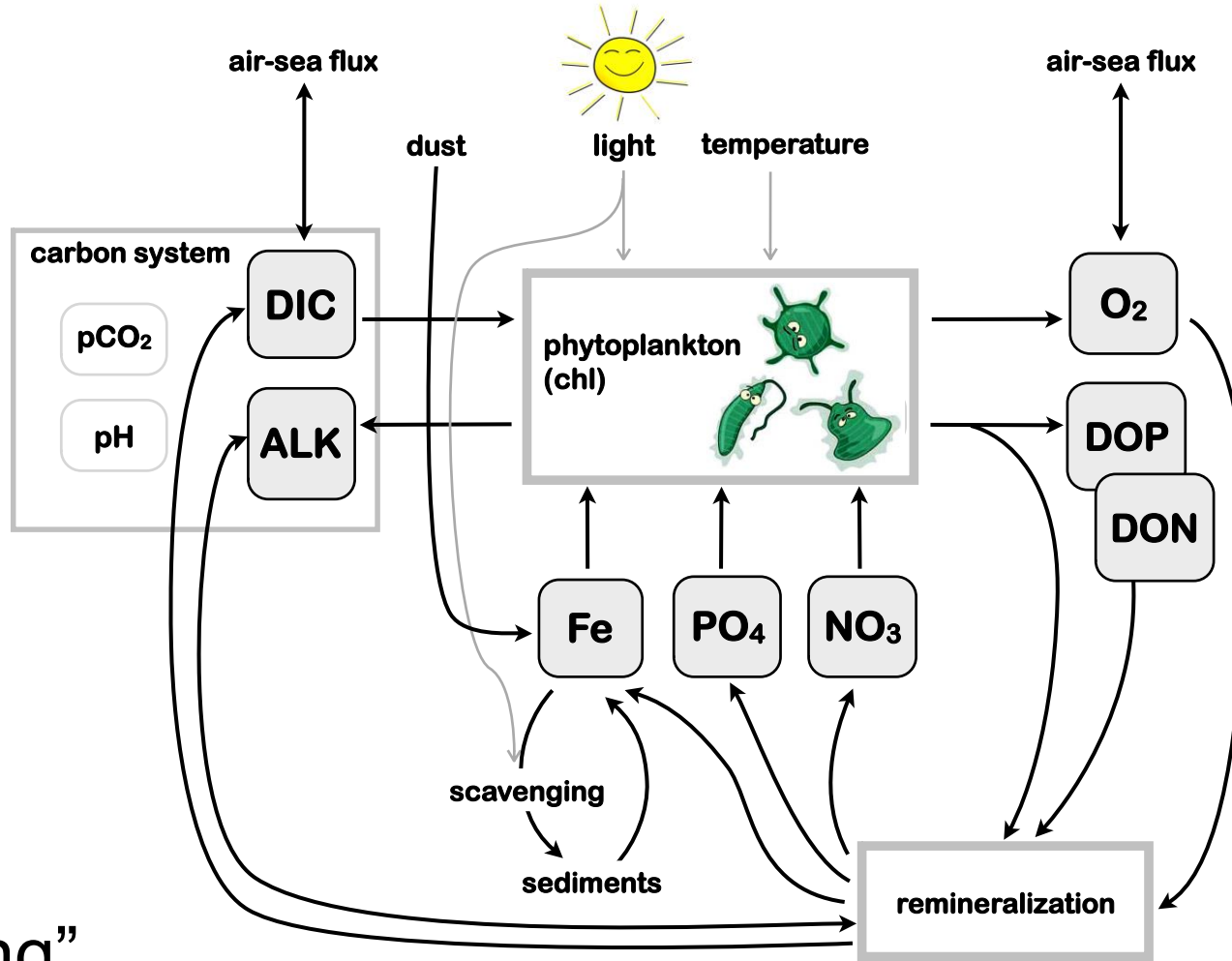
$$\Sigma (\text{weighted model-observations misfit})^2 + \Sigma (\text{weighted adjustment to inputs})^2$$

## B-SOSE: biogeochemical + physical state optimized together



# N-BLING: Biogeochemistry with Light, Iron, Nutrients, and Gases

Evolved from Galbraith et al (2010). Currently using 9 prognostic tracers



“N-bling”

all prognostic and diagnostic variables are estimated; can be compared / constrained to observations

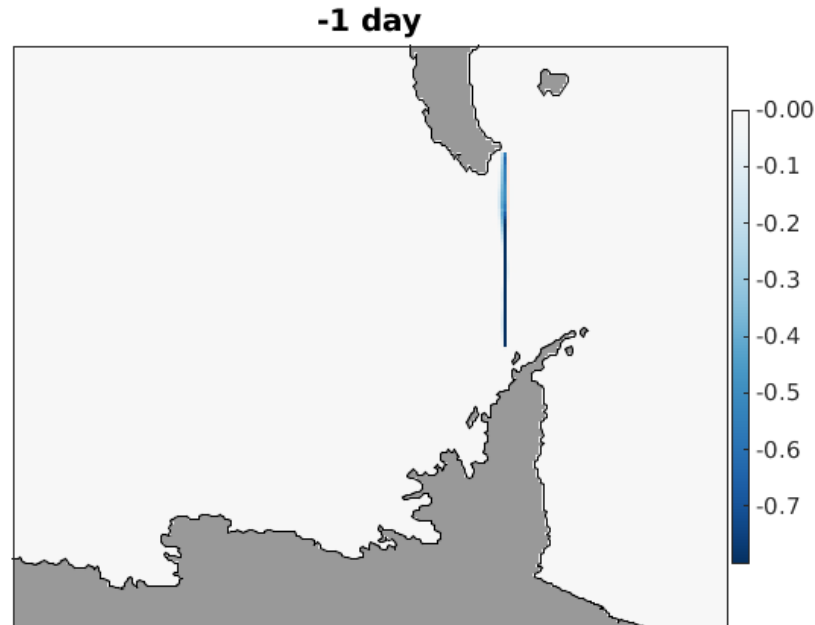
# Percent error occurring in back propagation due to linearization assumption

Information propagates forwards in the nonlinear ocean model.

$$\mathbf{x}(t+1) = \mathbf{M} \mathbf{x}(t)$$

Information propagates backwards in the linear adjoint model.

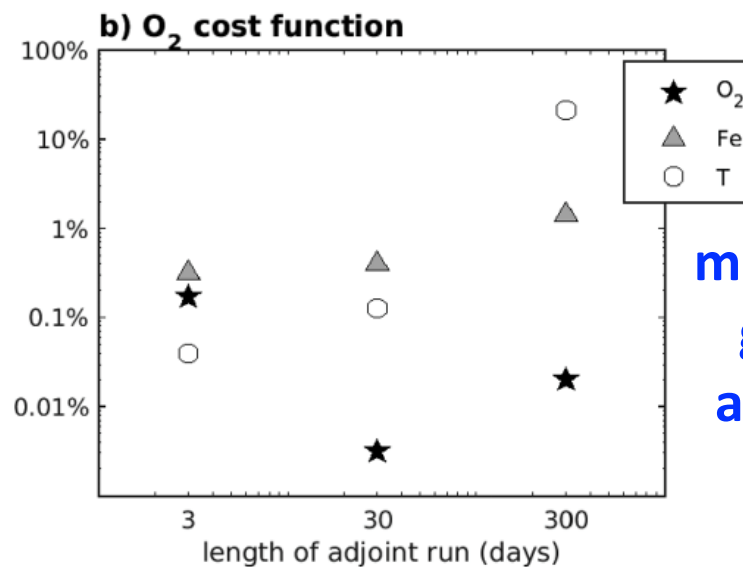
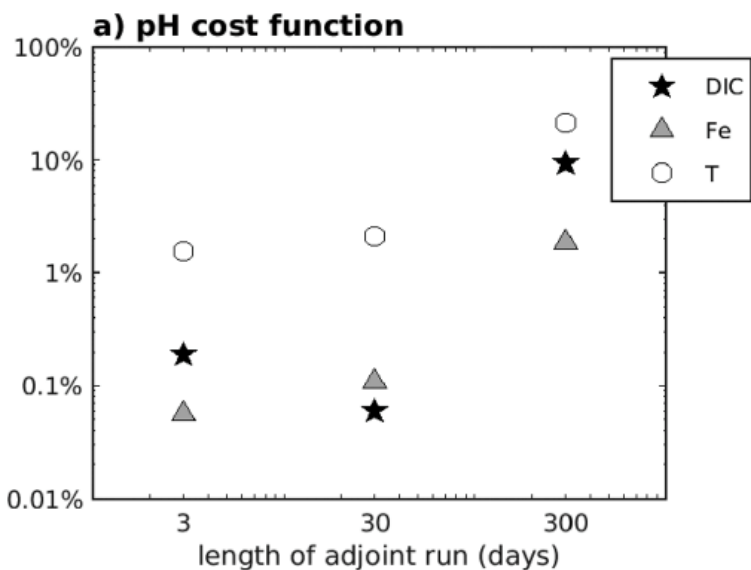
$$\mathbf{x}(t-1) = \mathbf{M}^T \mathbf{x}(t)$$



Cost is square of pH (50–100 m depth) and interior oxygen (200–300 m depth)

$$\mathbf{M} \text{ gradient} = \text{FWD} = ( \text{cost}(+) - \text{cost}(-) ) / ( \Delta \text{DIC}(+) - \Delta \text{DIC}(-) )$$

$$\text{Error} = ( \text{ADJ} - \text{FWD} ) / \text{FWD}$$

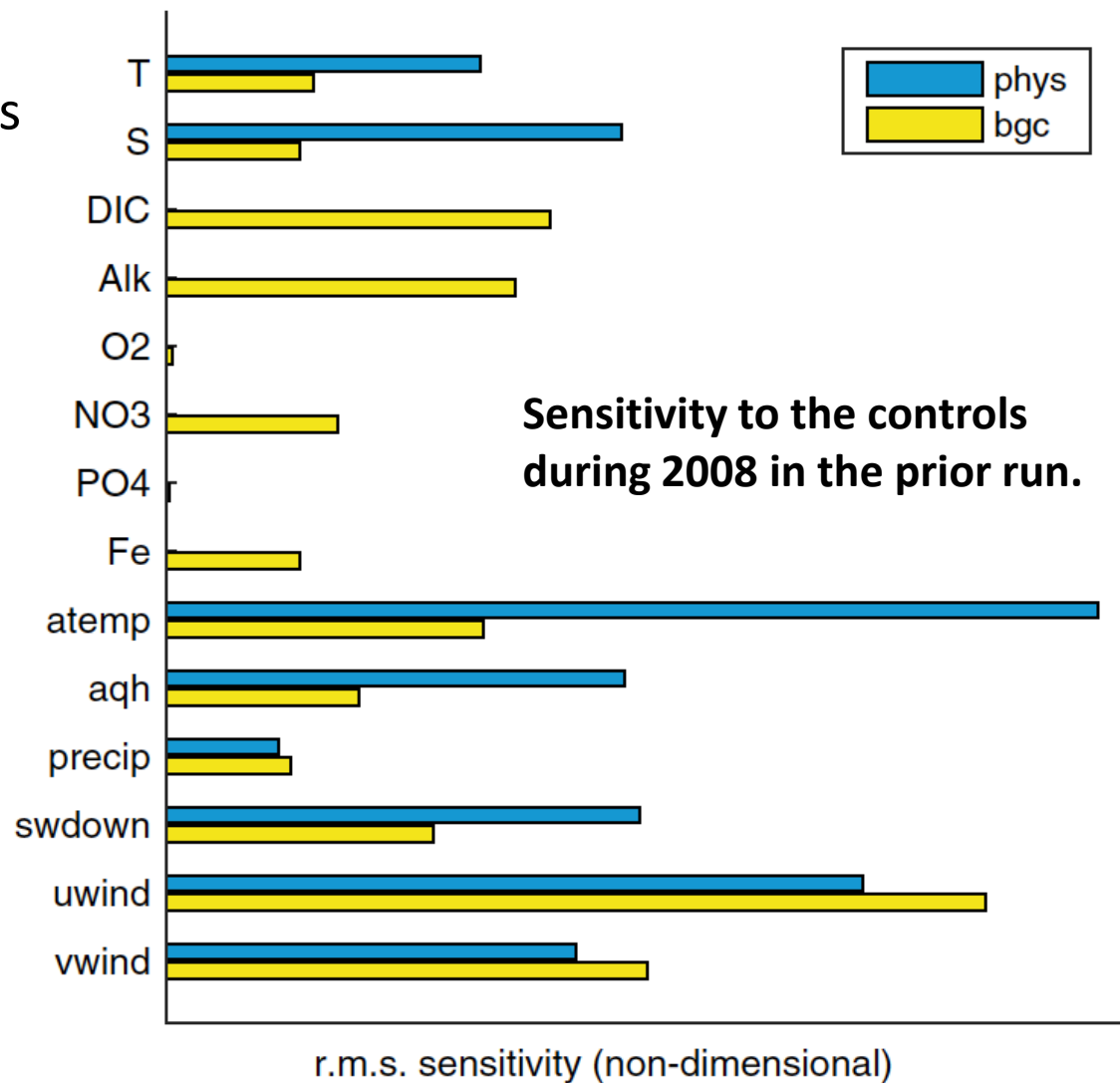


**BGC variables act largely like passive tracers, making the adjoint gradients more accurate than for salinity and temperature**

Examining sensitivity of prior misfits to the controls quantifies the relative influence of each type of constraint

- Blue: the cost function consists of only physical constraints
- Yellow: the cost function consists of only biogeochemical constraints

The larger the sensitivity, the more influence the constraints have on the optimization.



**Temperature, salinity, and sea surface height observations constrain the circulation and solubility, giving them a strong impact on bgc properties. Biogeochemical properties often have strong vertical gradients, allowing them to significantly constrain the circulation and vertical exchanges.**



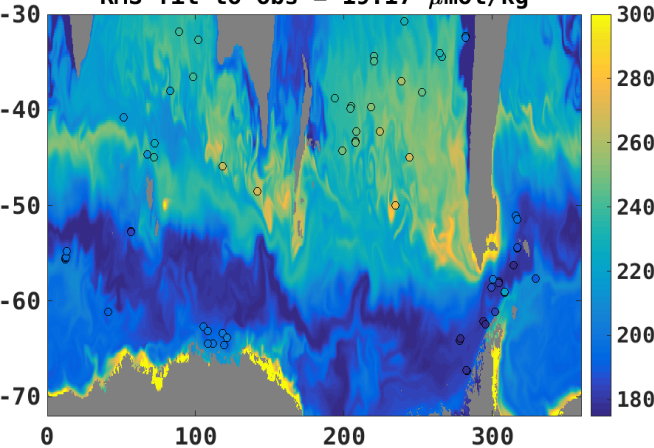


# SOCCOM Status in year 2: 2015 - 2016

- Gathering constraints and building automated validation documentation
- Began optimizing 2008-2009 at 1/3° and it worked well!

December 2008

RMS fit to obs = 19.17  $\mu\text{mol/kg}$



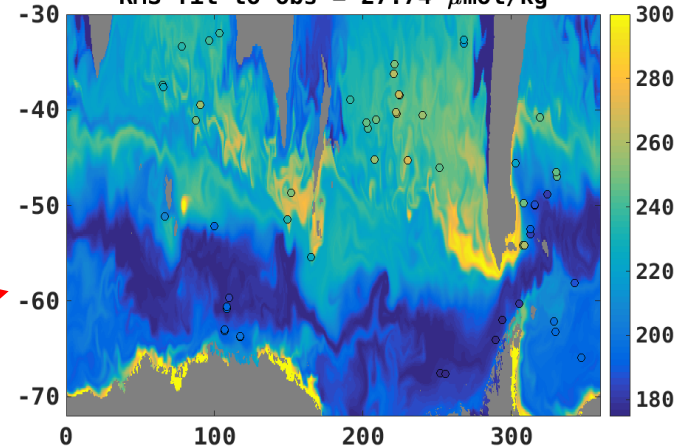
**Oxygen at 500 m.**

**Argo obs shown with  
filled circles.**

← **B-SOSE Iteration 45** →

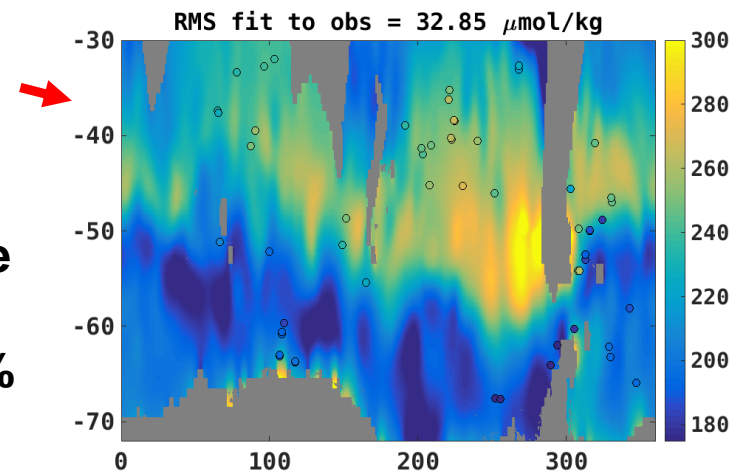
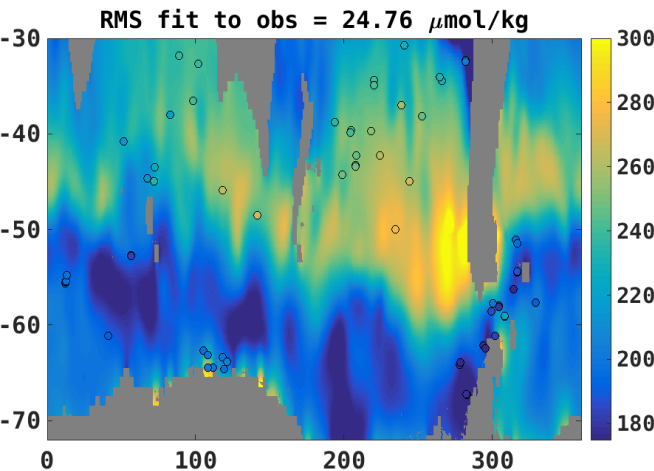
December 2009

RMS fit to obs = 27.74  $\mu\text{mol/kg}$



**WOA 2009  
climatology**

**B-SOSE is 23% more  
consistent with obs.  
In Dec. 2008 and 16%  
more in Dec. 2009.**



# Validation

\* = assimilated

## Comparisons with gridded products

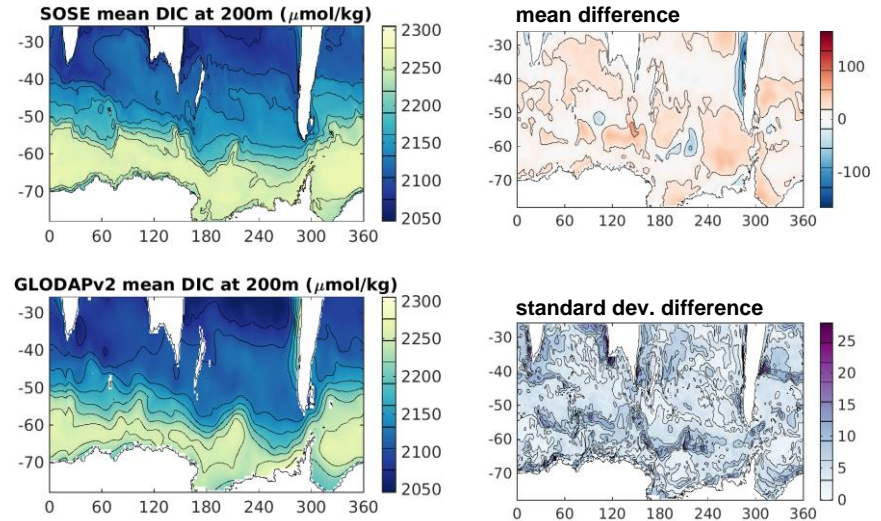
- \* ocean color (chl, POC)
- \* altimetry
- \* microwave SST
- \* sea ice

Argo monthly mapped product

AVISO SSH

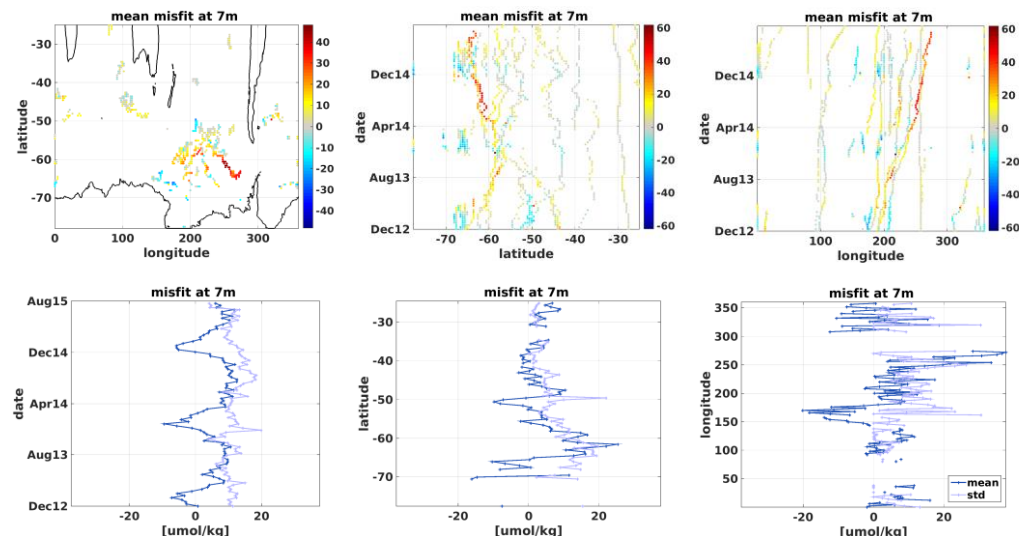
GLODAPv2, WOA13, SOCAT  
climatologies

Landschützer monthly mapped product

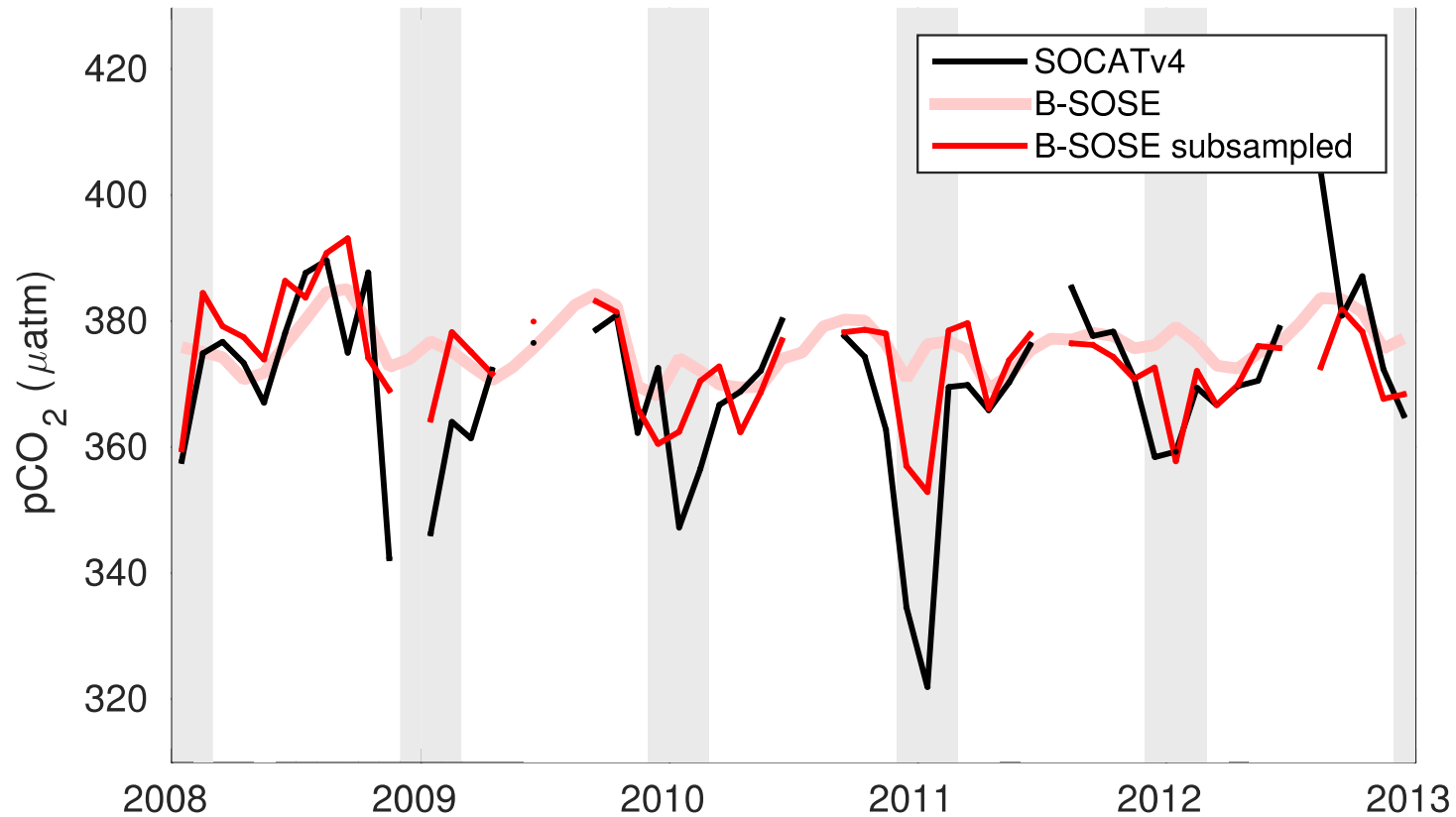


## Comparisons with in situ observations

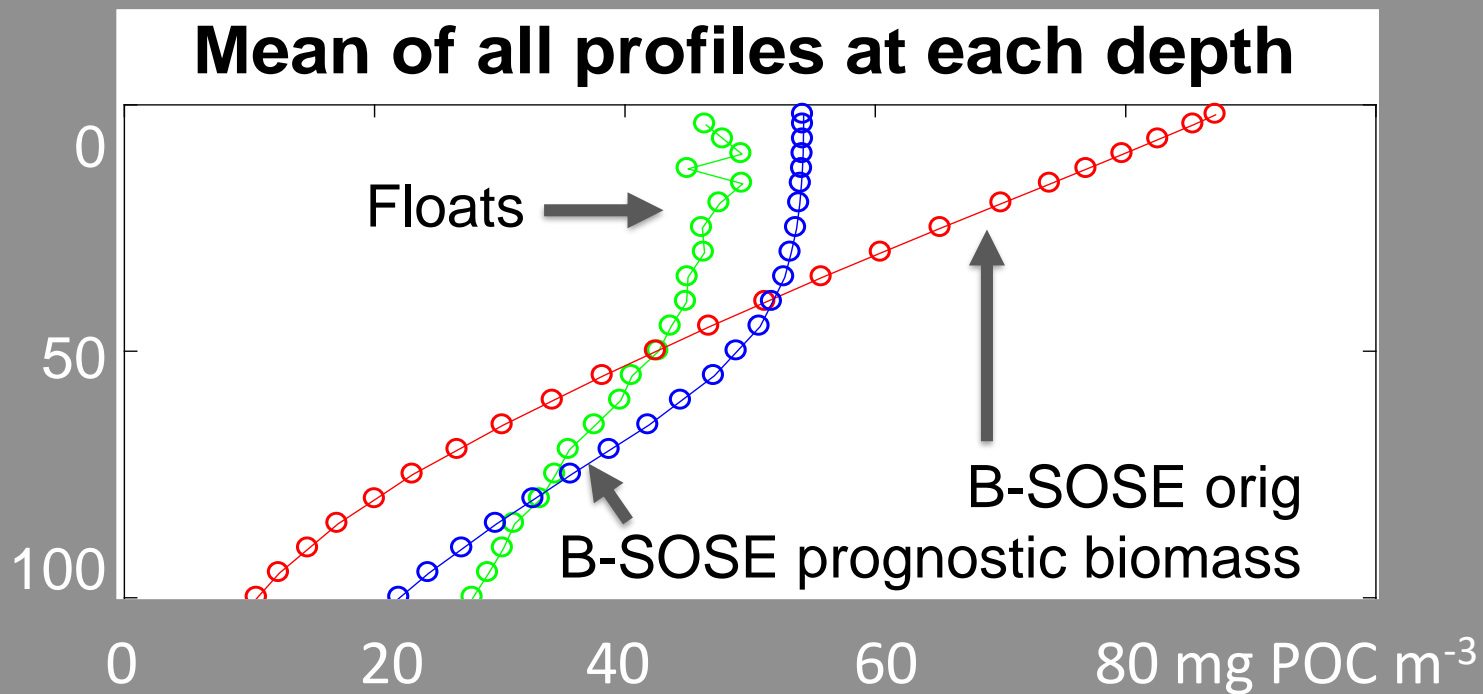
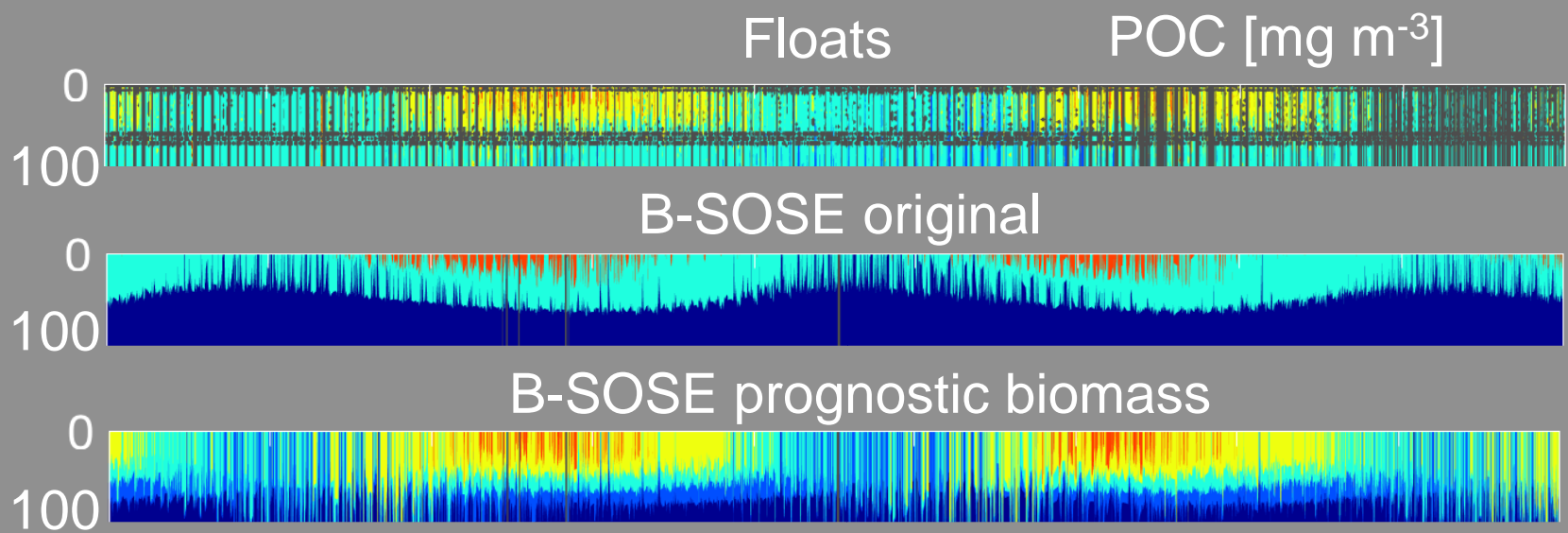
- \* Argo profiles (T,S)
- \* calibrated bgc-Argo (O<sub>2</sub>)
- \* SOCCOM floats
- \* SOCAT (pCO<sub>2</sub>)
- \* GLODAPv2 (carbon, nutrients)
- \* CTD (T, S, O<sub>2</sub>, chl)
- \* XBT, MEOP, PIES
- GEOTRACES



# pCO<sub>2</sub> in Drake Passage



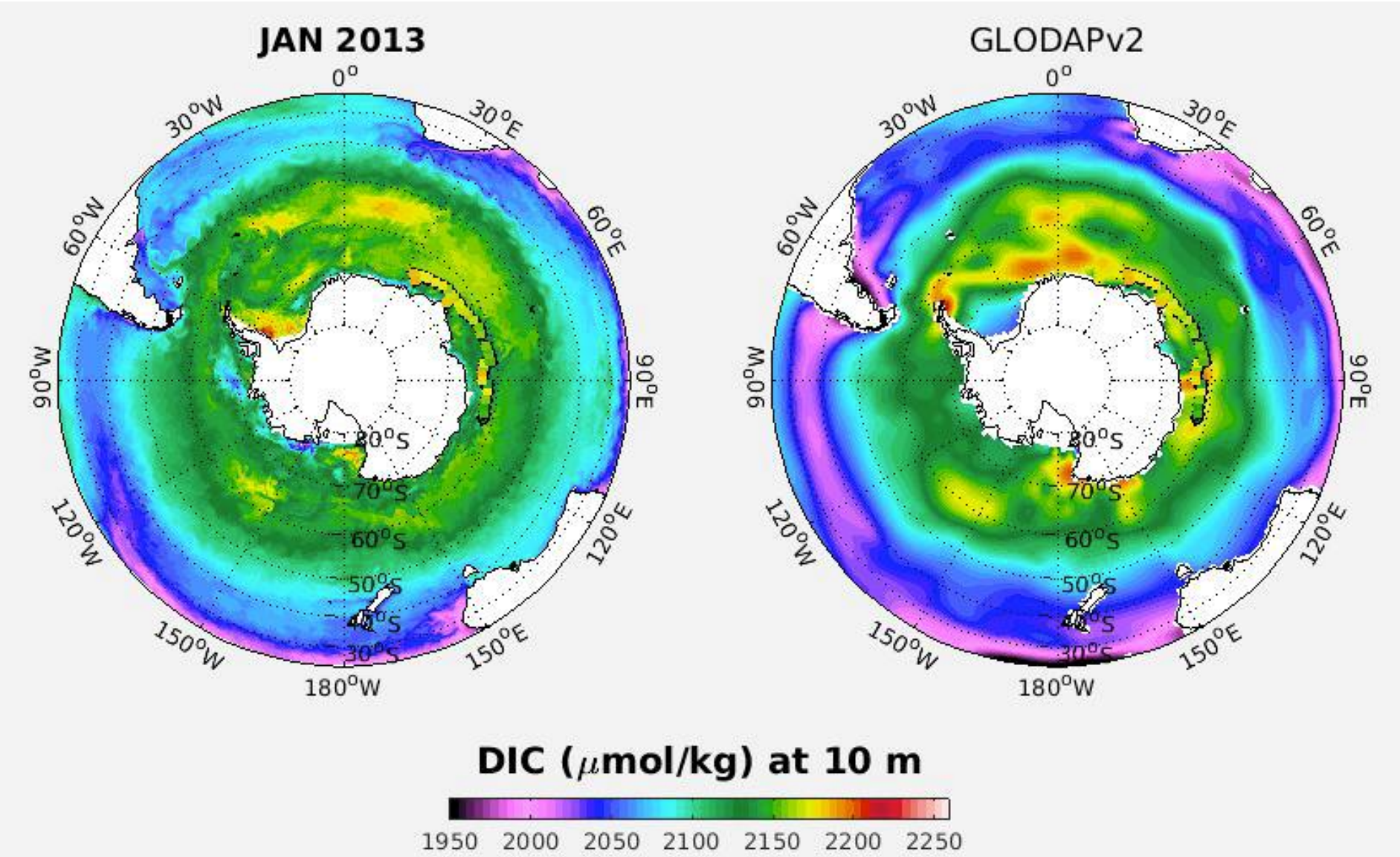
Monthly-averaged pCO<sub>2</sub> in Drake Passage (75°W to 55°W, south of 50°S) from SOCATv4 observations (black) [Bakker et al., 2016; Munro et al., 2015a, 2015b], and from B-SOSE (area average in pink; subsampled at the location of observations in red). Summer months are shaded gray.



**BGC highly sensitive to vertical transport,  
amplifying problems with the physical model**

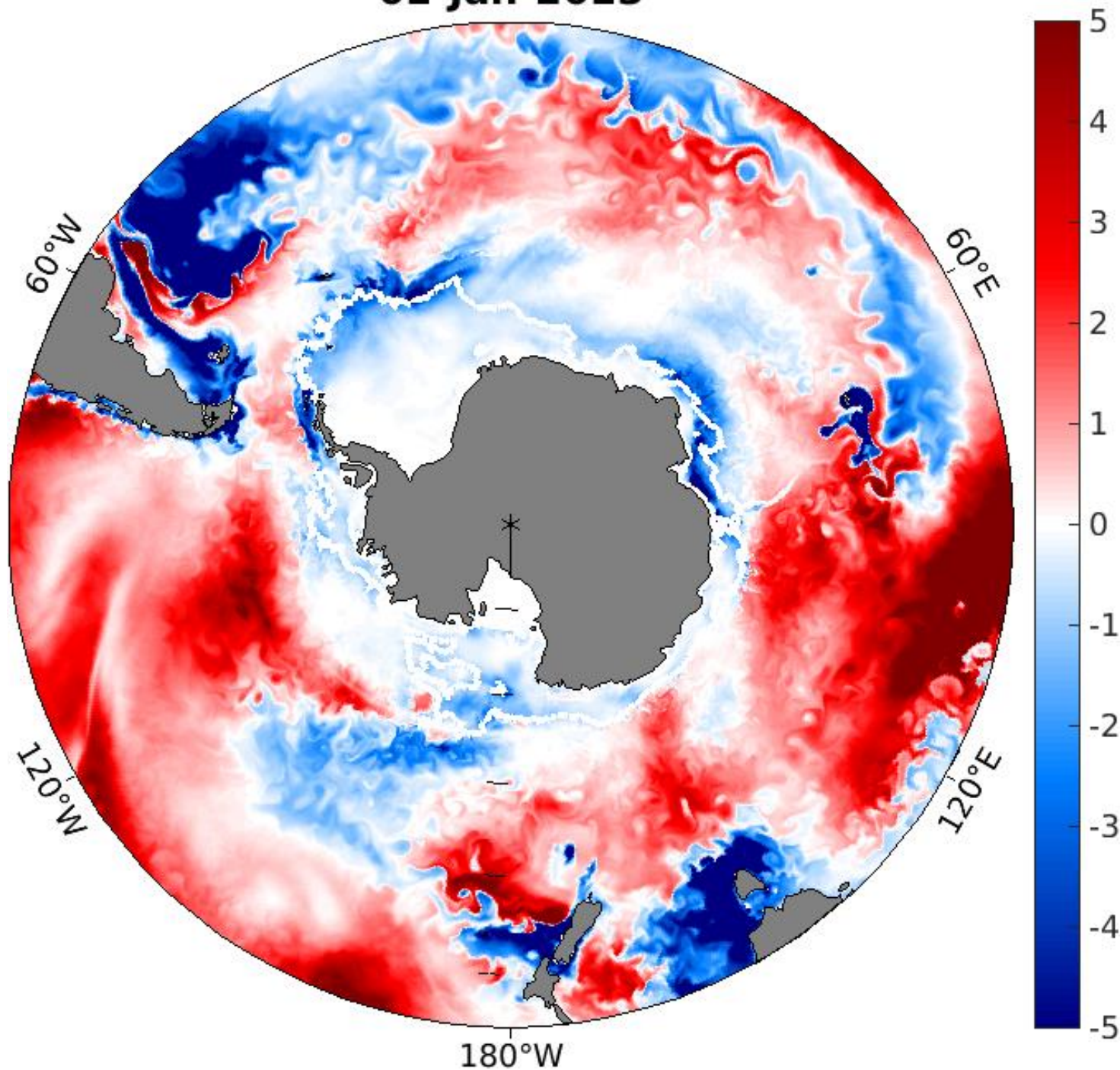


Ocean carbon content is strongly trending  
Cannot assume stationarity





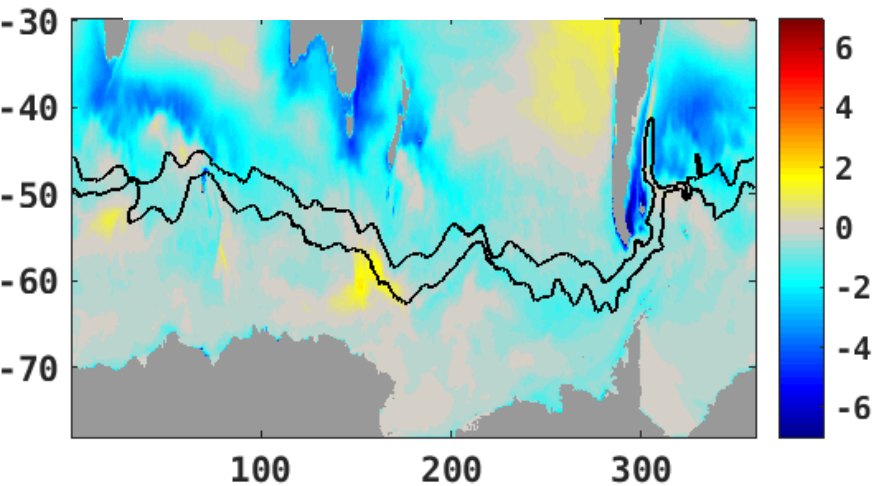
01-Jan-2013



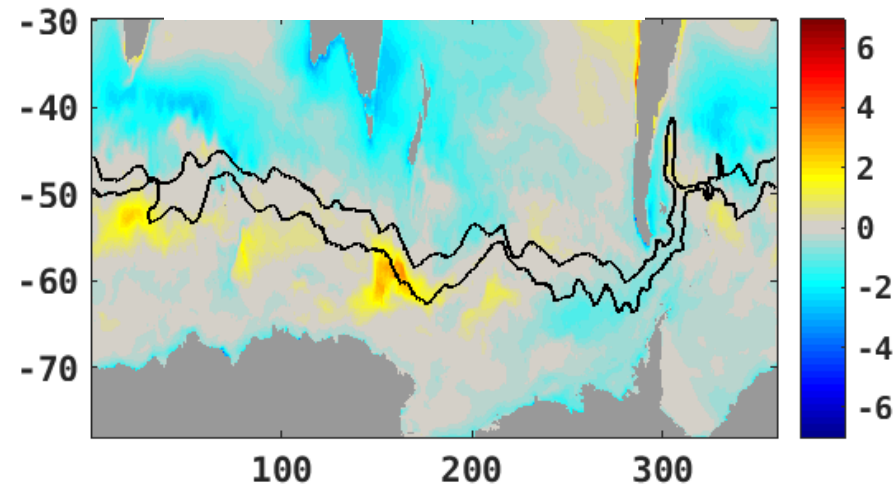
Air-sea CO<sub>2</sub> flux  
[mol m<sup>-2</sup> yr<sup>-1</sup>]  
from B-SOSE  
2013 - 2017  
solution

## Mean air-sea CO<sub>2</sub> flux [mol m<sup>-2</sup> yr<sup>-1</sup>]

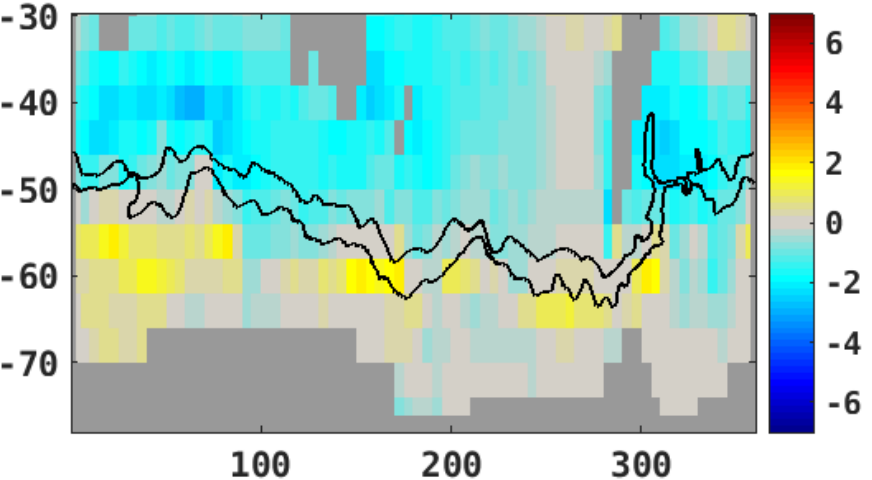
BSOSE iteration 122



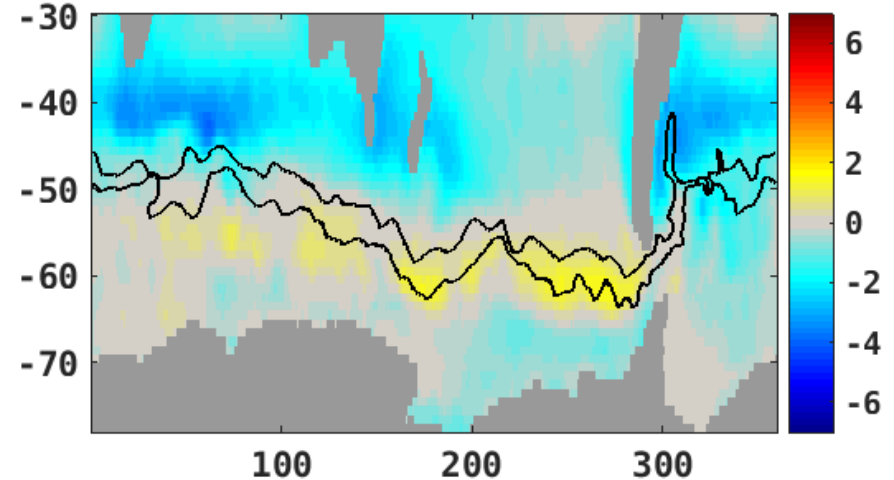
BSOSE iteration 133



Takahashi mean



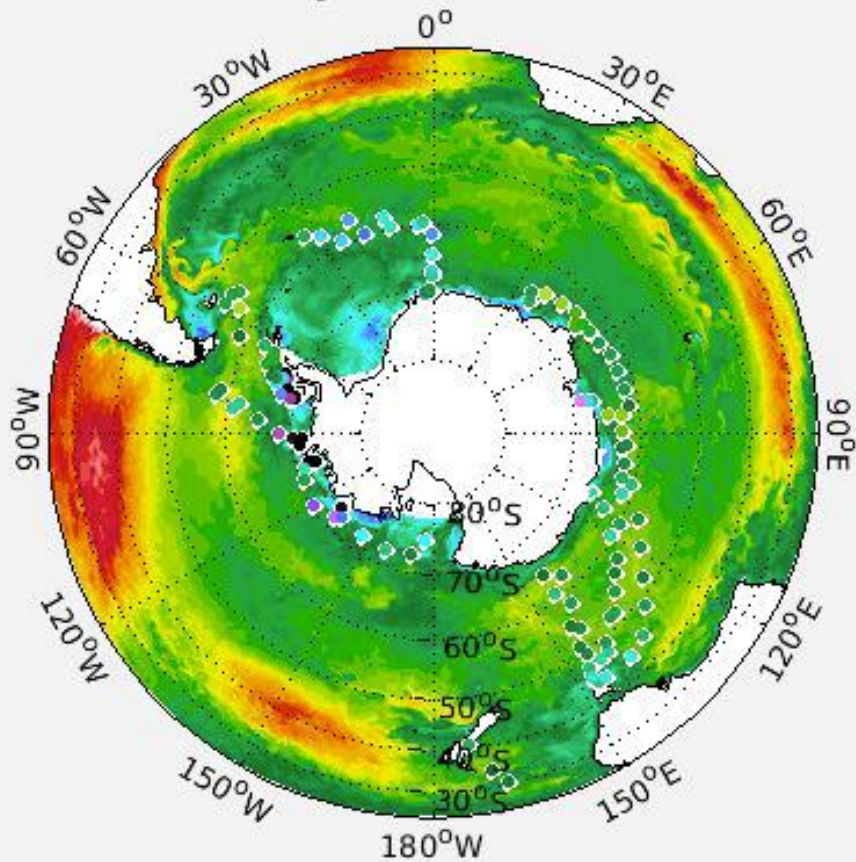
Landschutzer mean 20013-2018



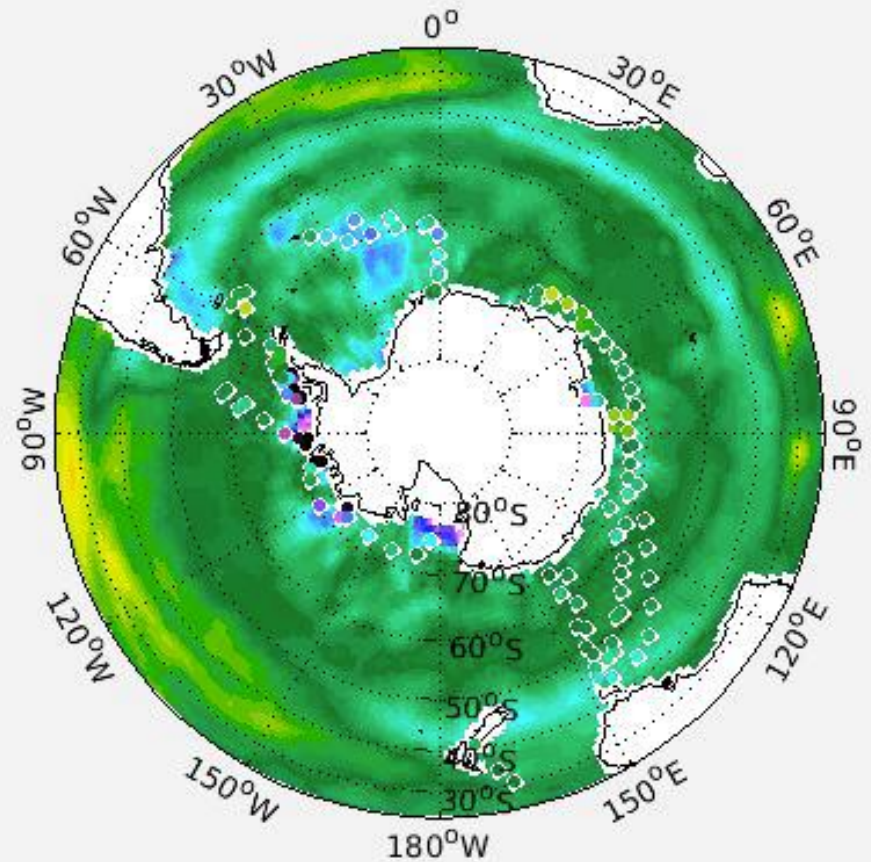
Mean CO<sub>2</sub> flux is highly sensitive to model state and inputs (e.g. mixing parameterizations)



**JAN 2013**



**Landschutzer**

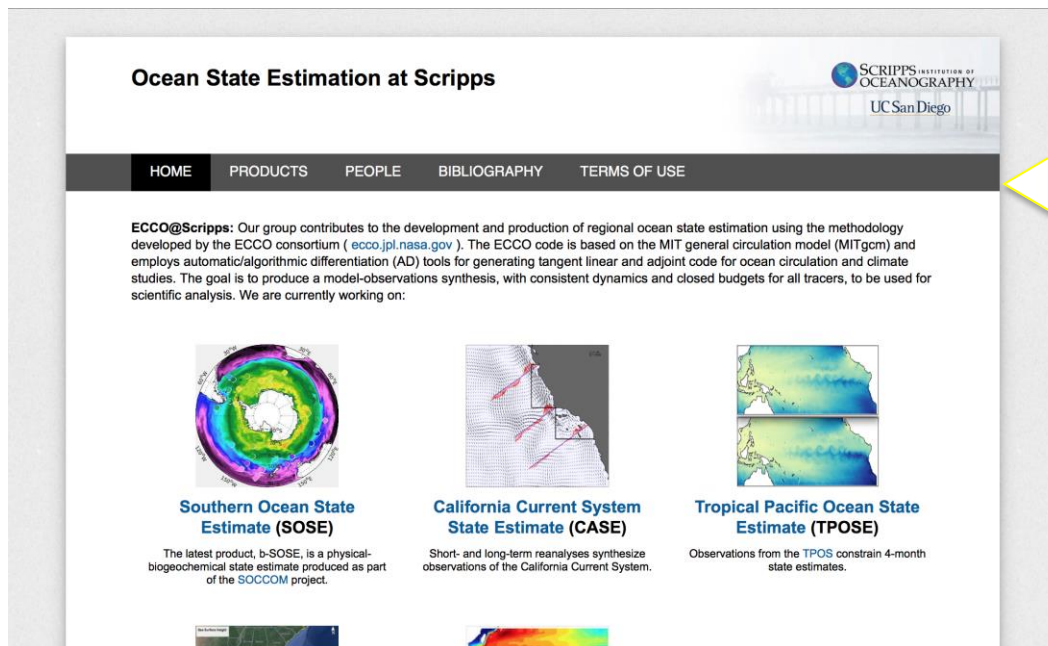


**pCO<sub>2</sub> ( $\mu\text{atm}$ ) at 2 m**



# Getting the products

B-SOSE output: [sose.ucsd.edu](http://sose.ucsd.edu)  
+ validation  
+ documentation



- netCDF
- CF compliant
- **available for model comparisons**

MITgcm BLING model and adjoint: [github.com/MITgcm/MITgcm](https://github.com/MITgcm/MITgcm)

Verdy, A. and M. R. Mazloff (2017), A data assimilating model for estimating Southern Ocean biogeochemistry, J. Geophys. Res. Oceans, 122, 6968– 6988, doi:10.1002/2016JC012650.