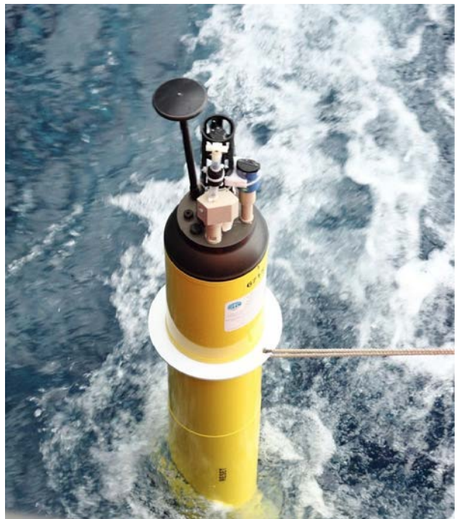
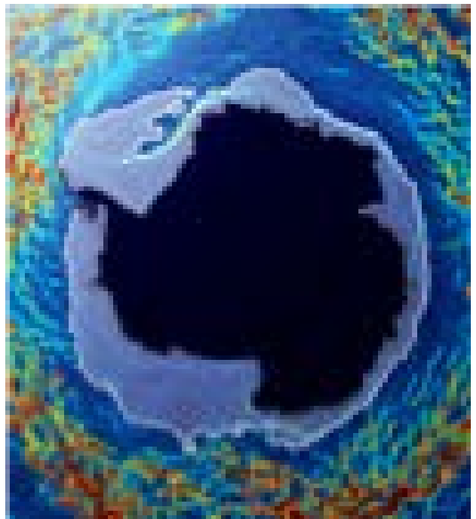
SOCCOM

Southern Ocean Carbon and Climate Observations and Modeling

Jorge Sarmiento, Princeton University

2017 GFDL Symposium





Modeling results suggest the Southern Ocean has a central role in the earth system:

1

It accounts for about **three-quarters** of heat uptake by the ocean

2

It accounts for **up to half** of the annual oceanic uptake of anthropogenic carbon dioxide from the atmosphere.

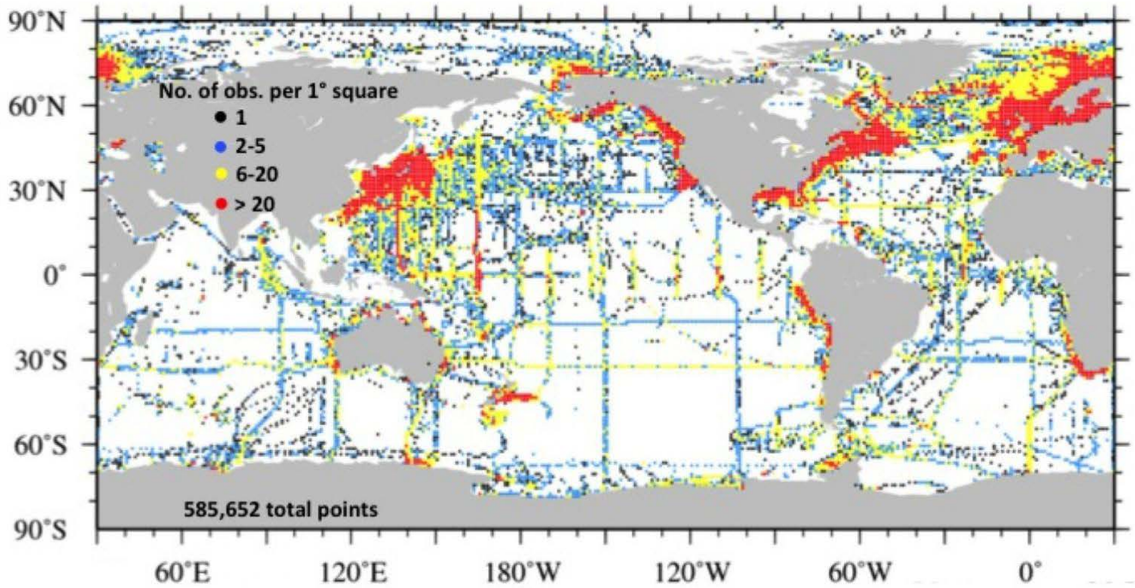
3

Vertical exchange in the Southern Ocean is responsible for supplying nutrients that fertilize **three-quarters** of the biological production in the global ocean north of 30°S.

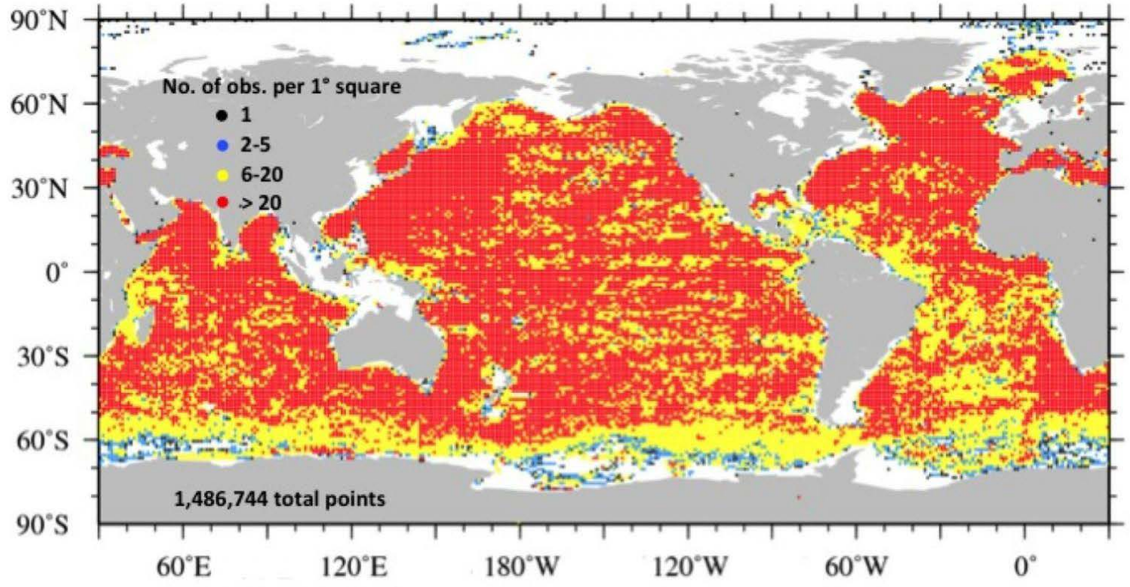
Frölicher et al. (2015) Gruber et al. 2009, Landschützer et al. 2015 Sarmiento et al. 2004

Impact of Argo floats on T profiles (1999–2015)

Shipboard
World Ocean database
585,652 total



Argo
1,485,744 total

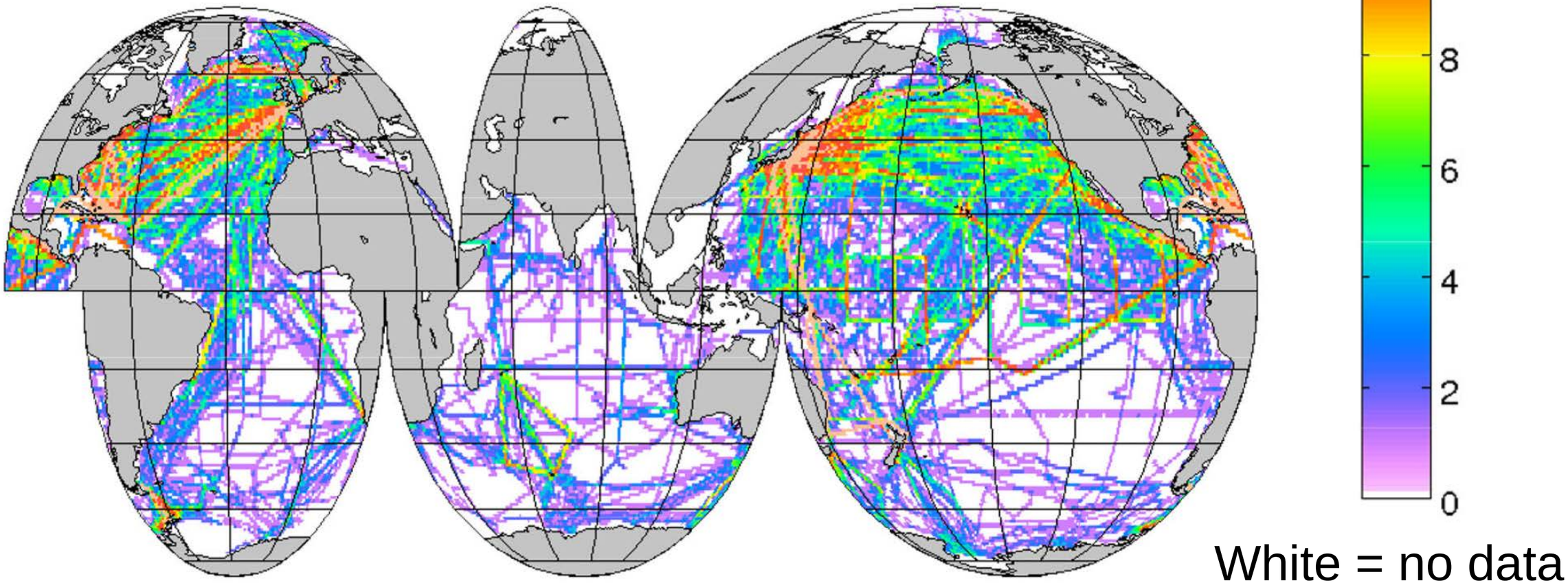


Number of profiles per 1° square

Undersampling of pCO_2

Months of year with surface pCO_2 measurements

- based on all measurements between 1970 to 2011
- binned in 1° squares.



White = no data

SOCAT compilation, Bakker et al. (2014)

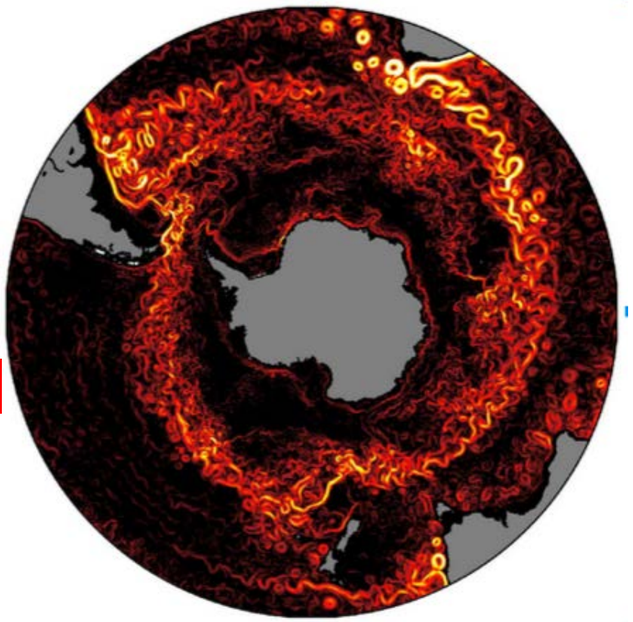
SOCCOM Strategy

200 profiling floats over 6 years with pH, NO_3^-, O_2, & biooptical sensors

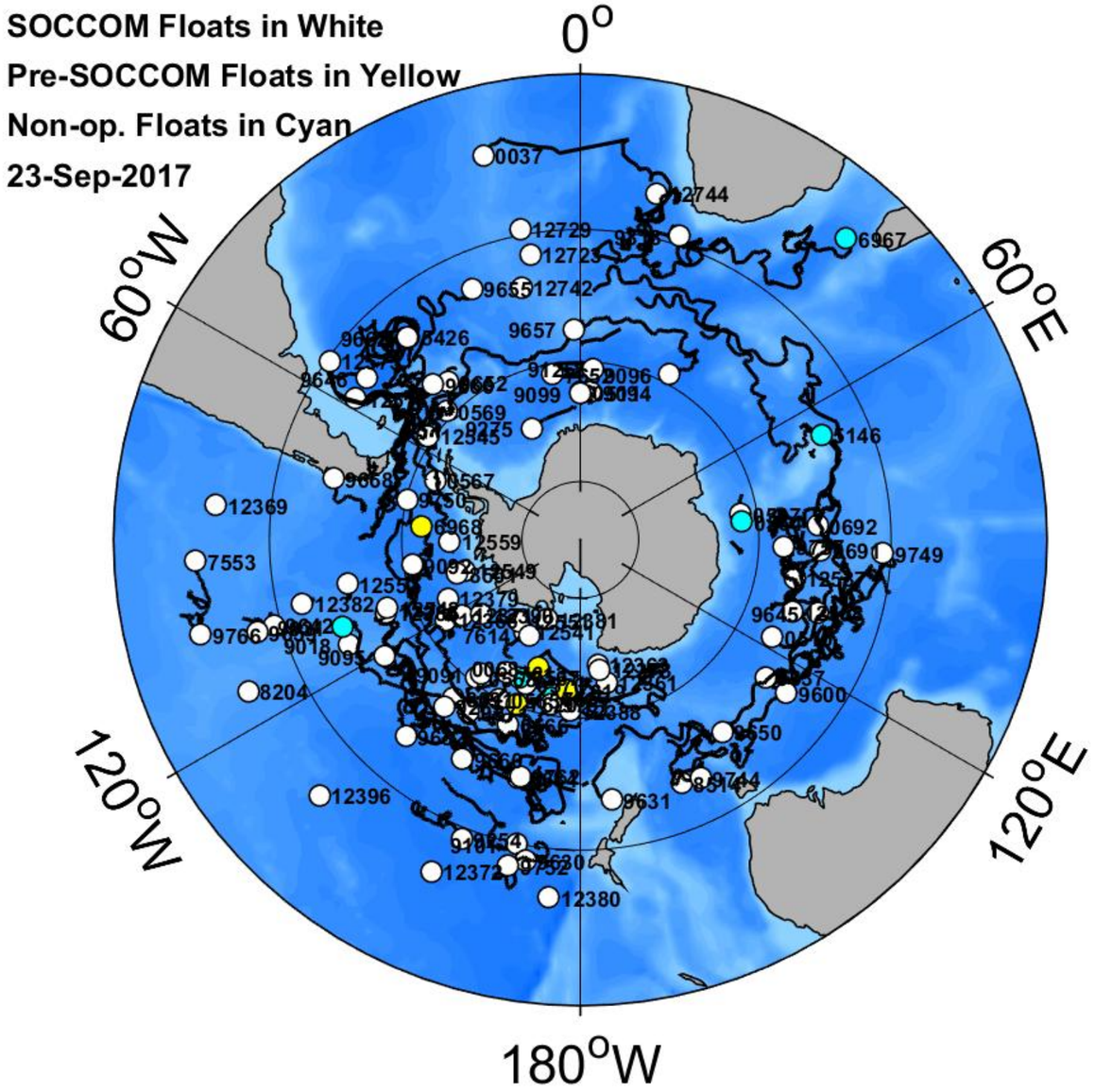
Southern Ocean State Estimate (SOSE) to get 4D fields & fluxes

Improved Earth System (GFDL) model simulations of future Southern Ocean health and role in carbon and climate

GFDL CM2.6 current velocities

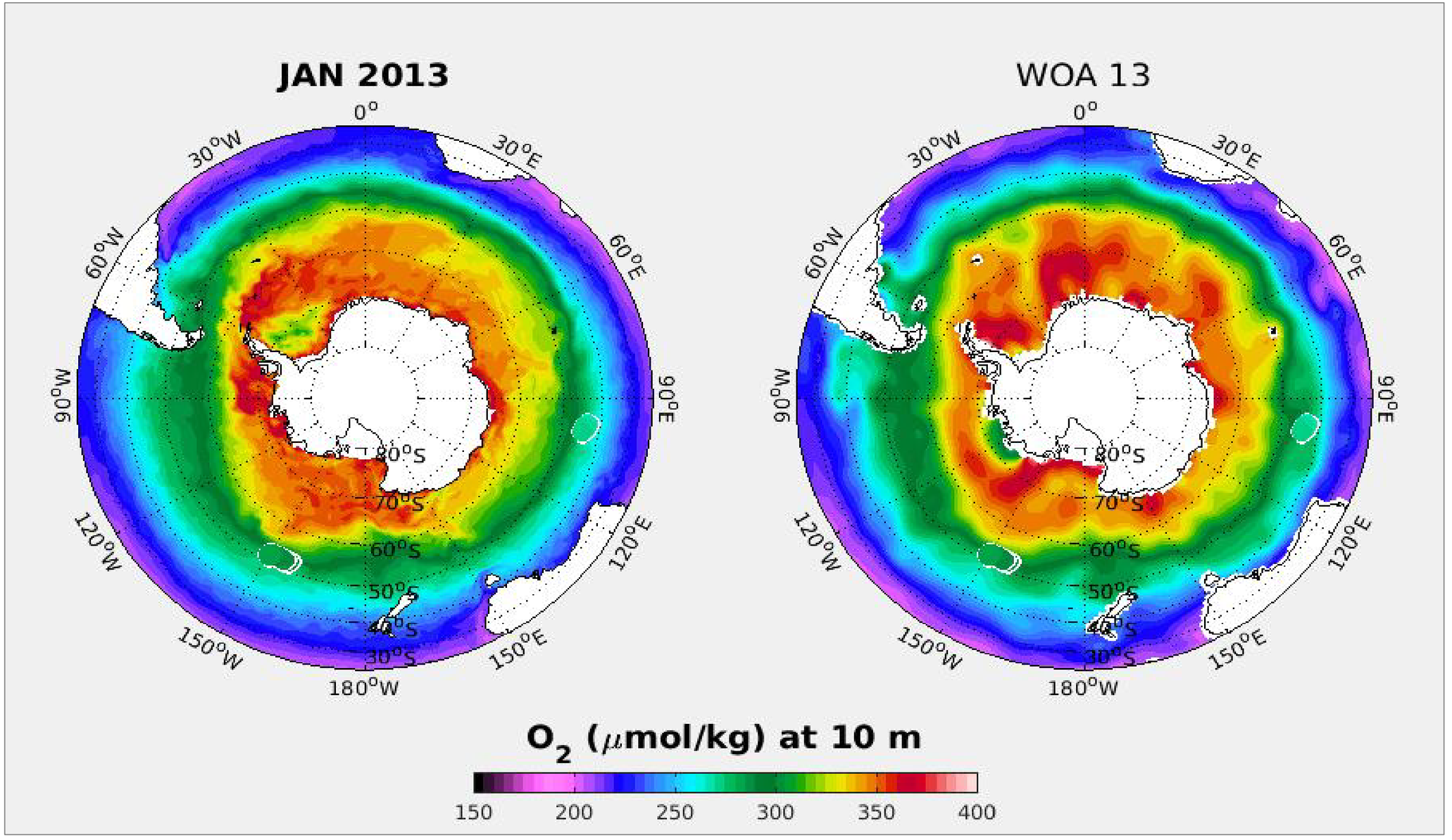


Progress Report



91 operational floats

- NOAA provides 50% of Argo floats. We add BGC sensors (NSF funded)
- 80% of floats include NASA supported optical sensors
- Ice avoidance software allows profiling to continue under ice
- Float and shipboard data available in near real-time


JAN 2013
WOA 13
0°
30°W
30°E
60°W
60°E
90°W
90°E
120°W
120°E
150°W
150°E
180°W
80°S
70°S
60°S
50°S
40°S
30°S
O2 (μmol/kg) at 10 m
150
200
250
300
350
400

Deep Dive: Seasonal cycle of CO_2 flux

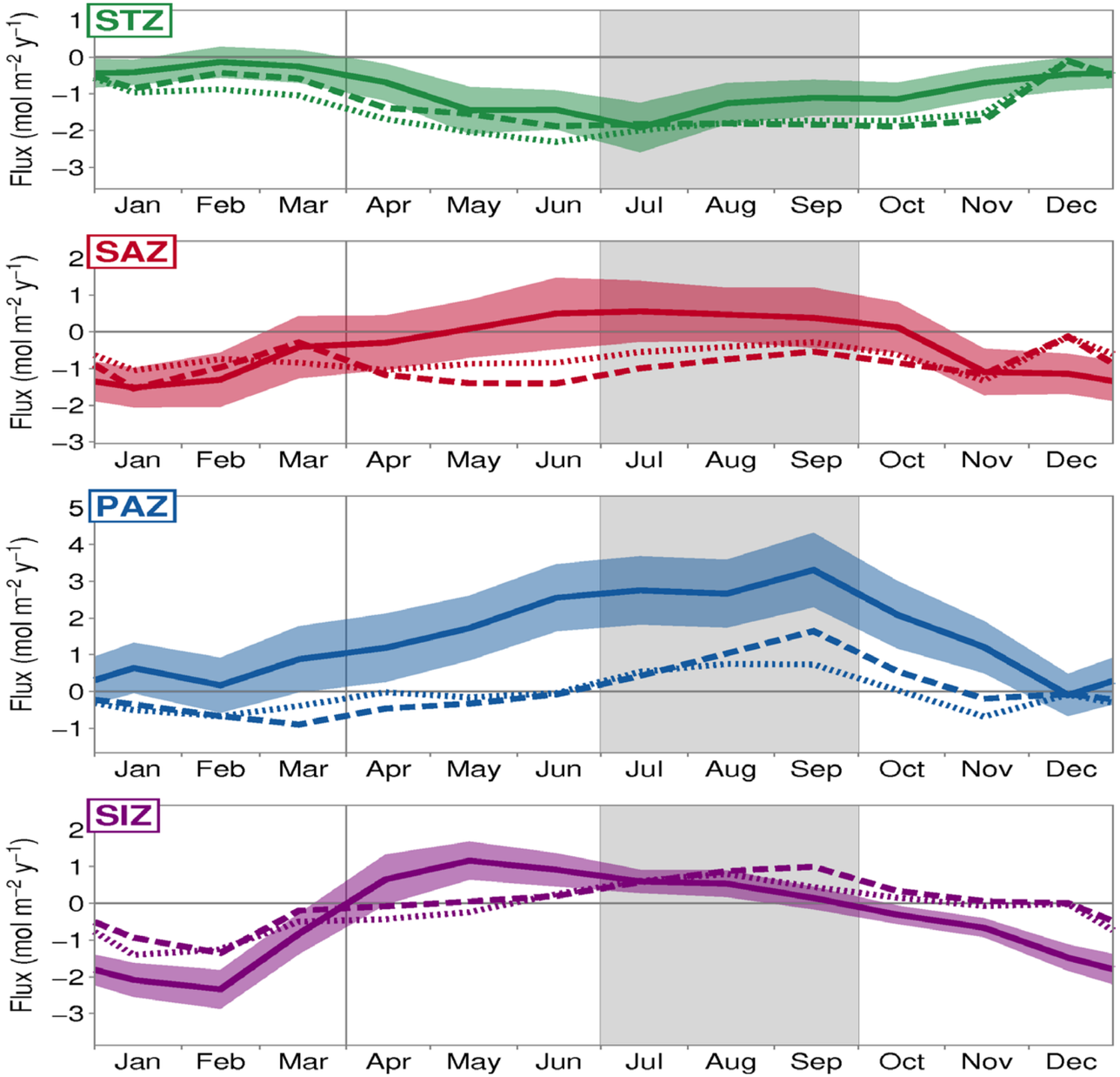
Landschützer and Takahashi estimates miss fall and winter outgassing in PAZ

—— This estimate

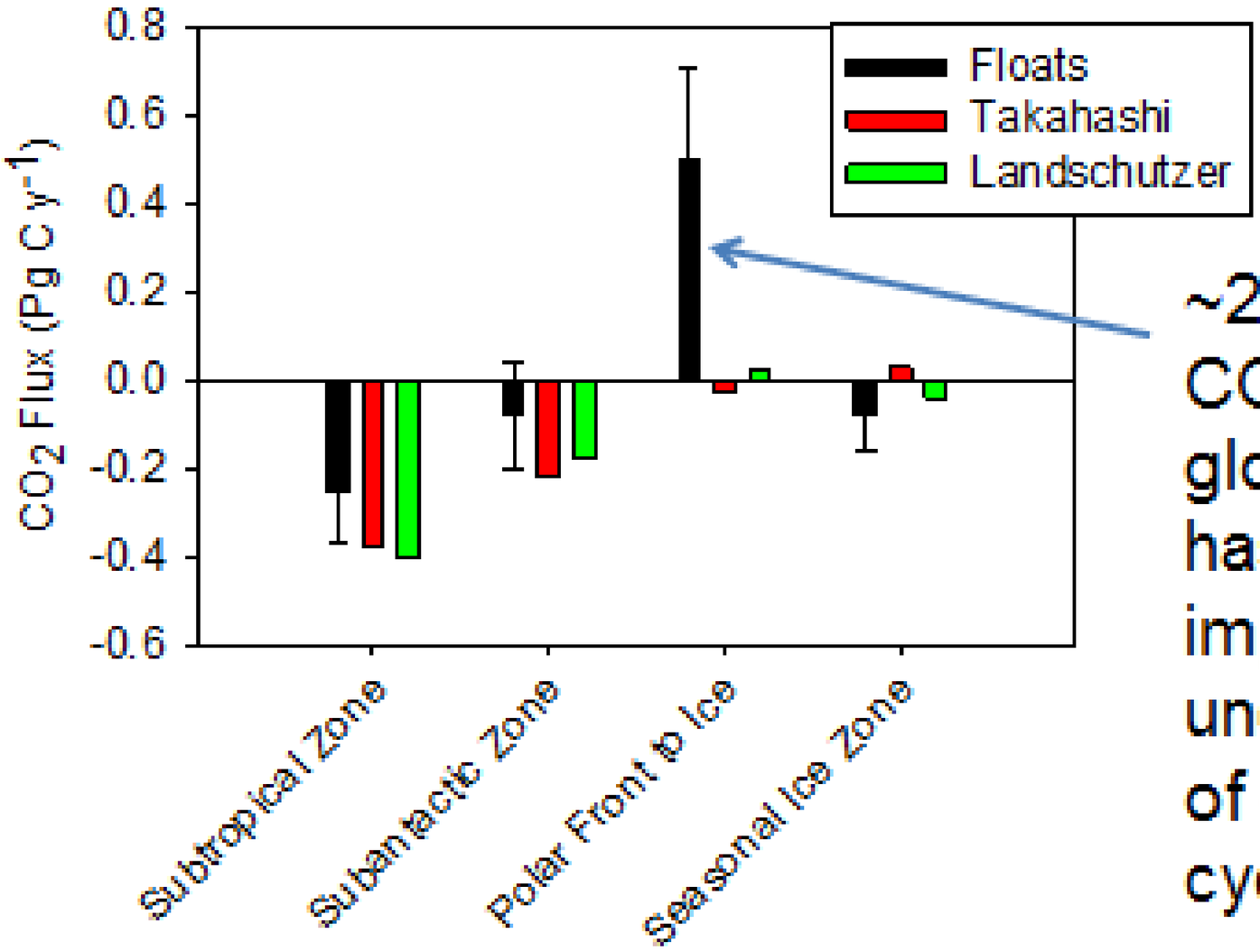
- - - - Takahashi et al. 2009

..... Landschützer et al. 2014 2002-2011 mean

+ Outgassing
– Uptake



Mean from 36 floats



~20% of net CO_2 uptake by global ocean has profound implications for understanding of global C cycle.

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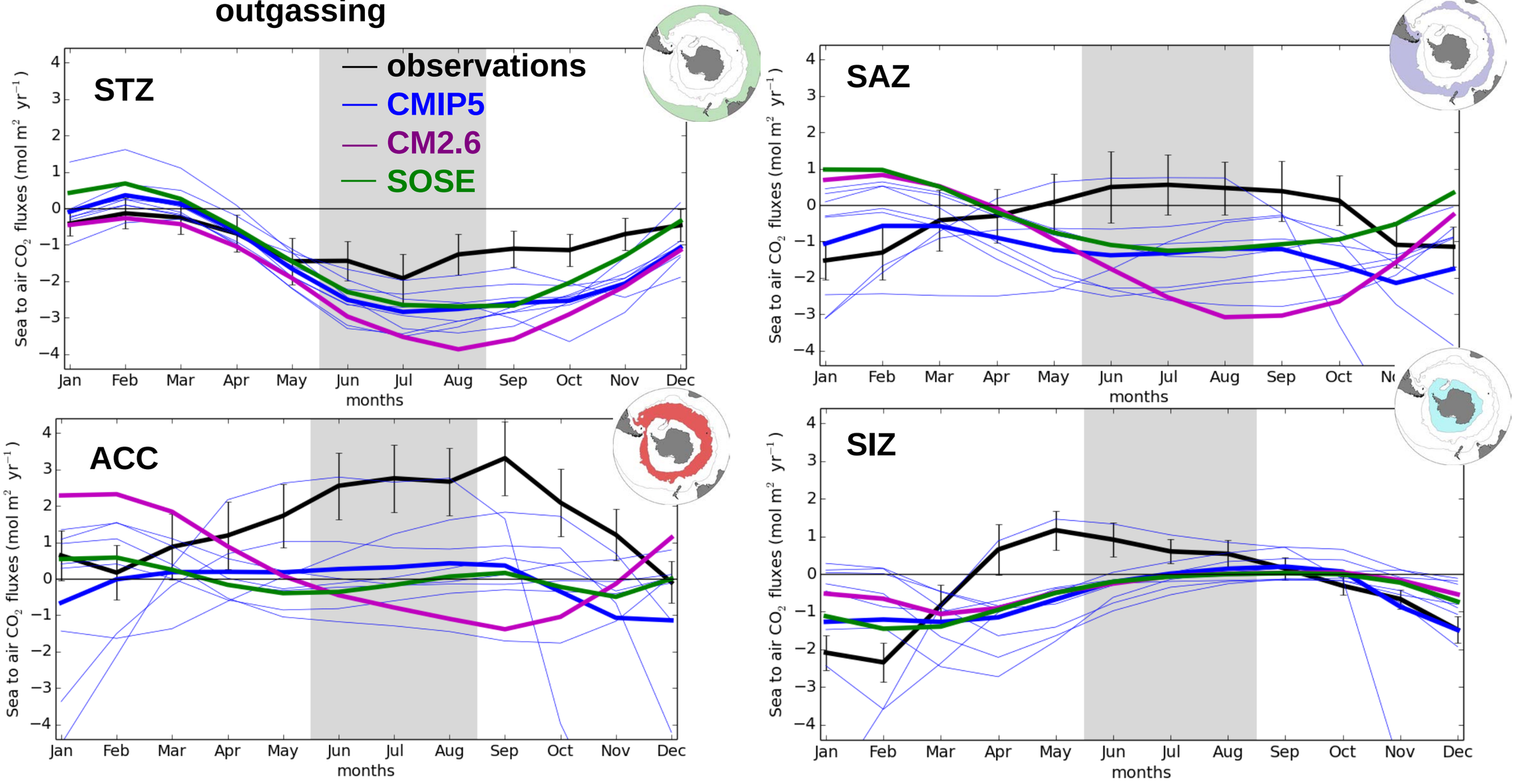
Alison Gray et al., in review, Nature

Results: seasonal CO_2 fluxes

↑ outgassing



SOCCOM Modeling Goals & Accomplishments

METRICS

Metrics for the evaluation of the Southern Ocean in coupled climate models and Earth System models (Russell et al., in press)

SOMIP

IPCC 6, Southern Ocean Models Intercomparison Project

ESMValTool.org:

Development of Earth System Model evaluation tool

CLIMATE HACK

#Great Antarctic Climate Hack led by Russell to grow the community using observations to evaluate earth system model simulations

Global Ocean Health Initiative (GOHI): Proposal for worldwide array of 1000 Biogeochemically-sensored floats

THE FUTURE

- This new generation of robotic floats with cutting-edge sensors developed with Federal support now allow the community to build the first real-time, high-resolution, system to observe ocean health and changing biogeochemical cycles: the Global Ocean Health Initiative (GOHI).
- GOHI will allow us to track threats and provide critical guidance for sustainable ocean management.

SOCCOM

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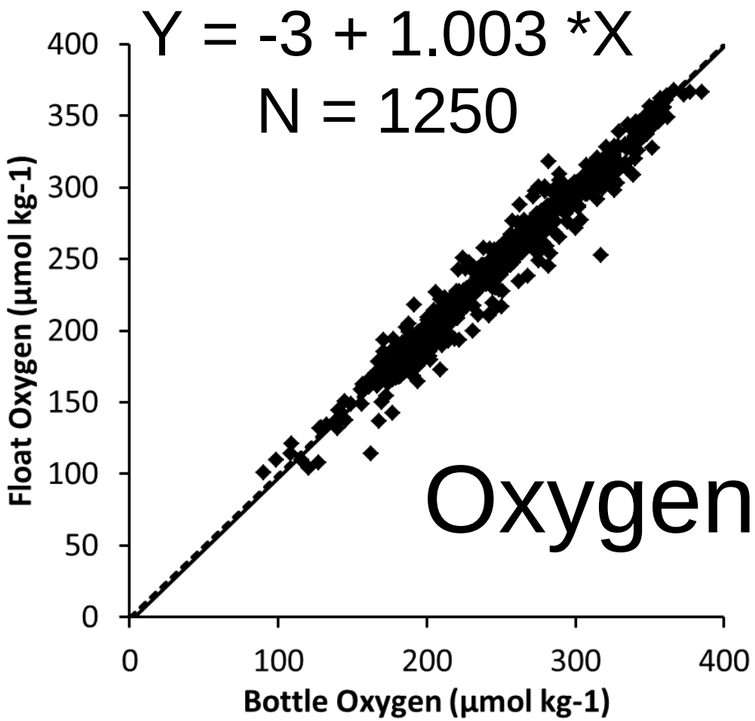
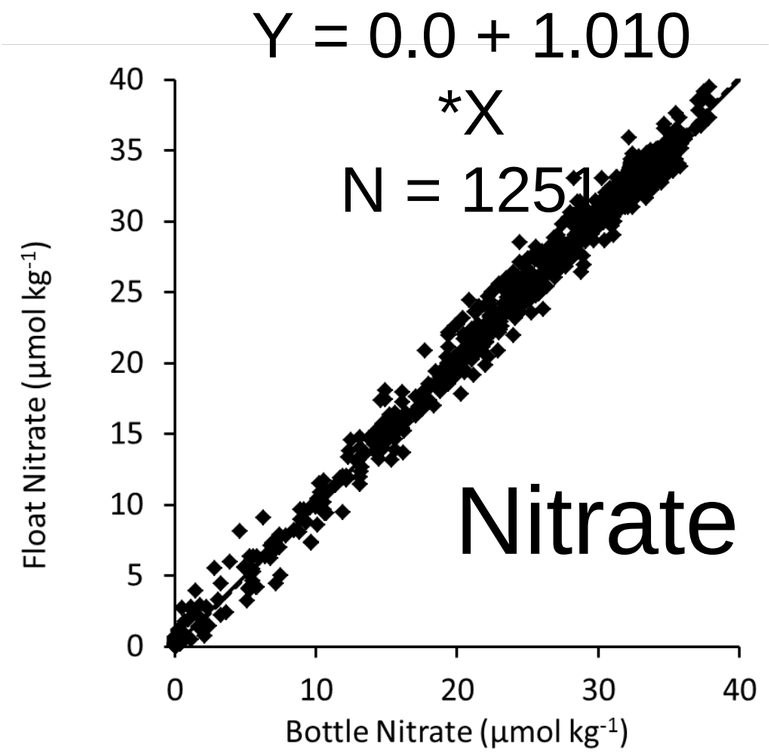
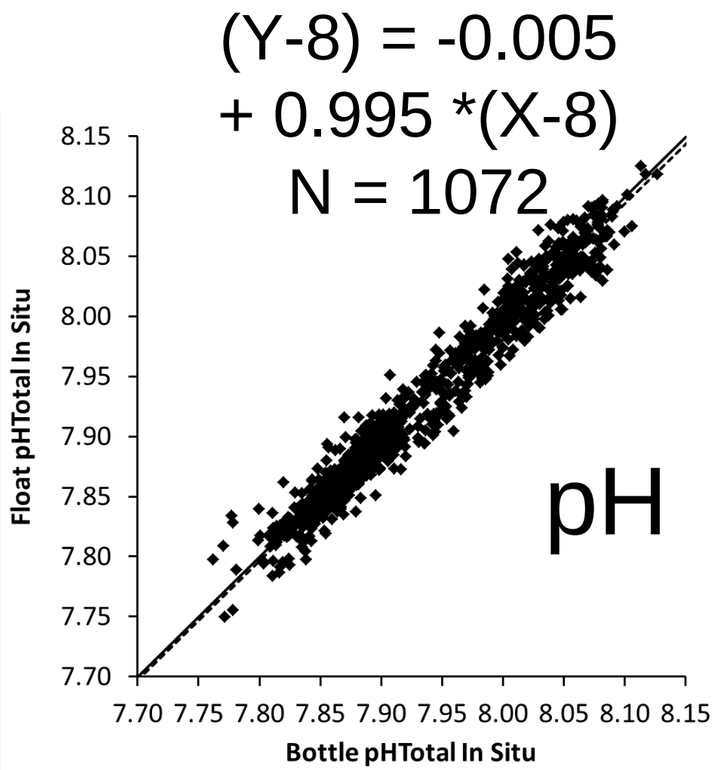
Photo: O. Schofield

The End

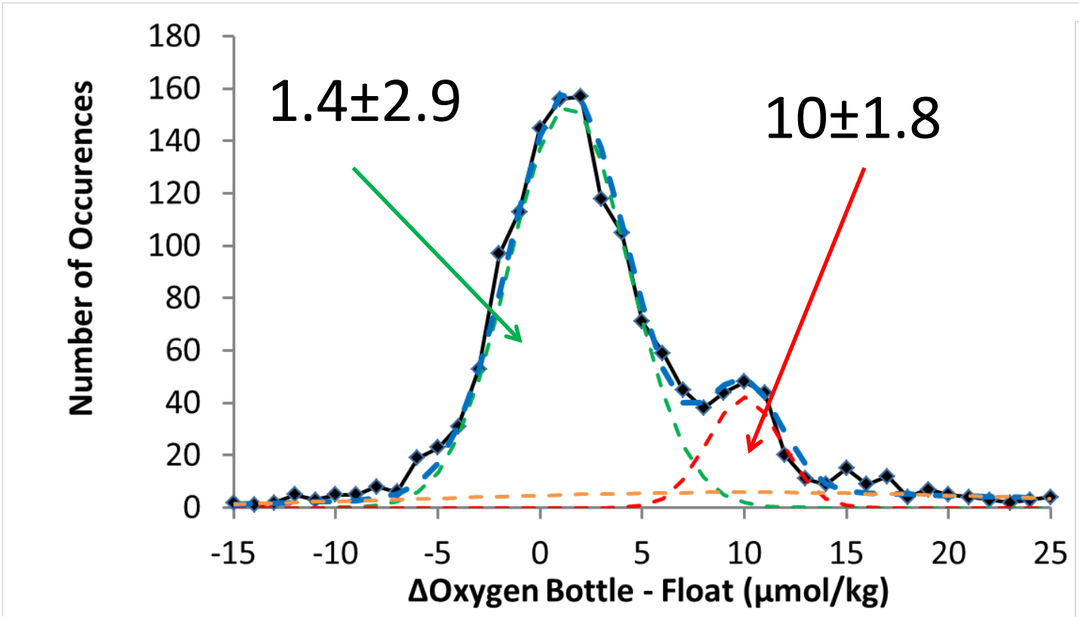
Sensor validation

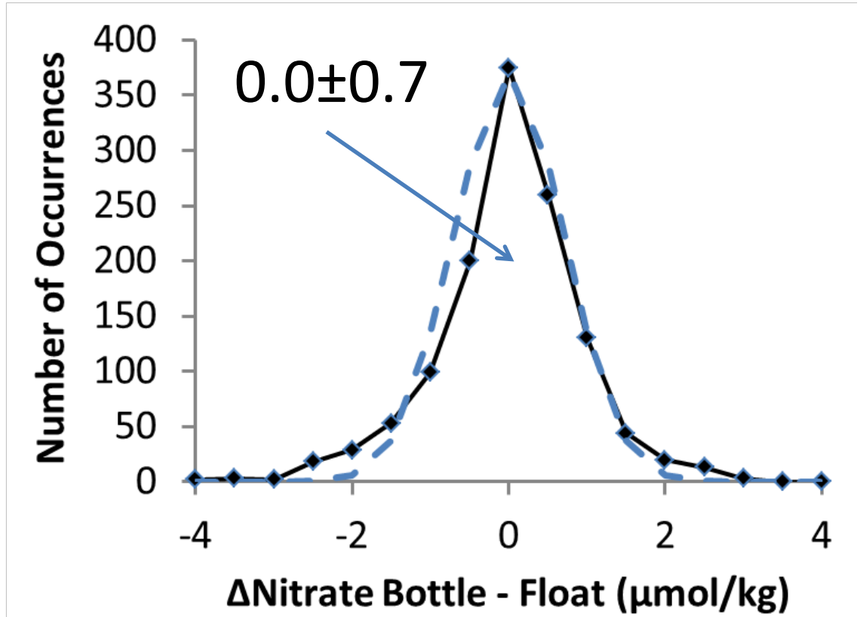






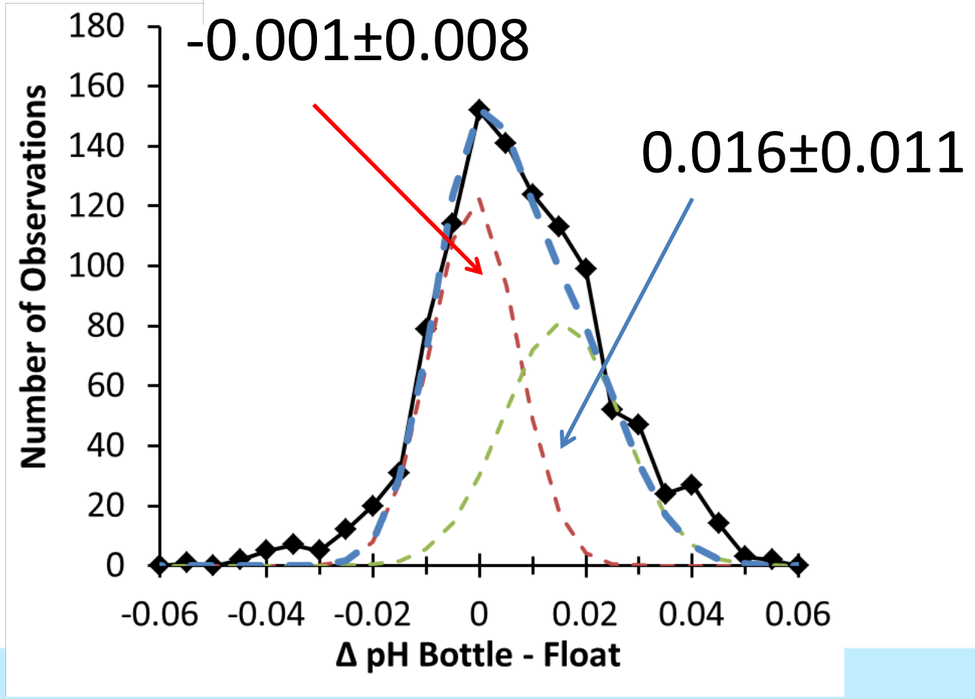
SOCCOM





>1100 bottle-float sensor comparisons.

- Bulk of the data is very high quality.
- Identifies a few cruise or sensor issues in O_2 and pH, which are correctable.

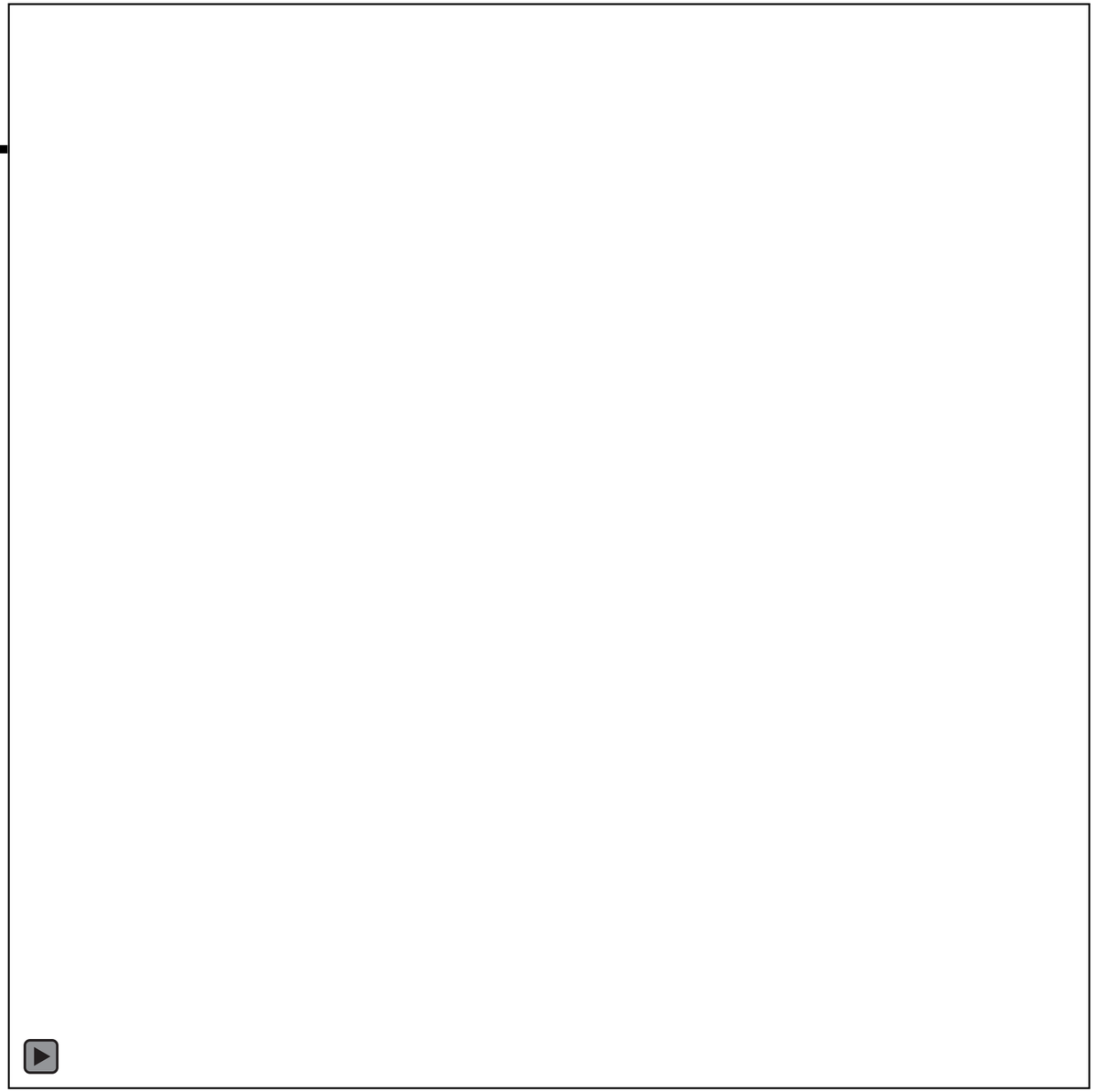


SOCCOM pH measurements (2014 – 2017)

Background pH is from CM2.6 simulation

Symbols show float measurements

- White is Fall & Winter
- Black is Spring & Summer



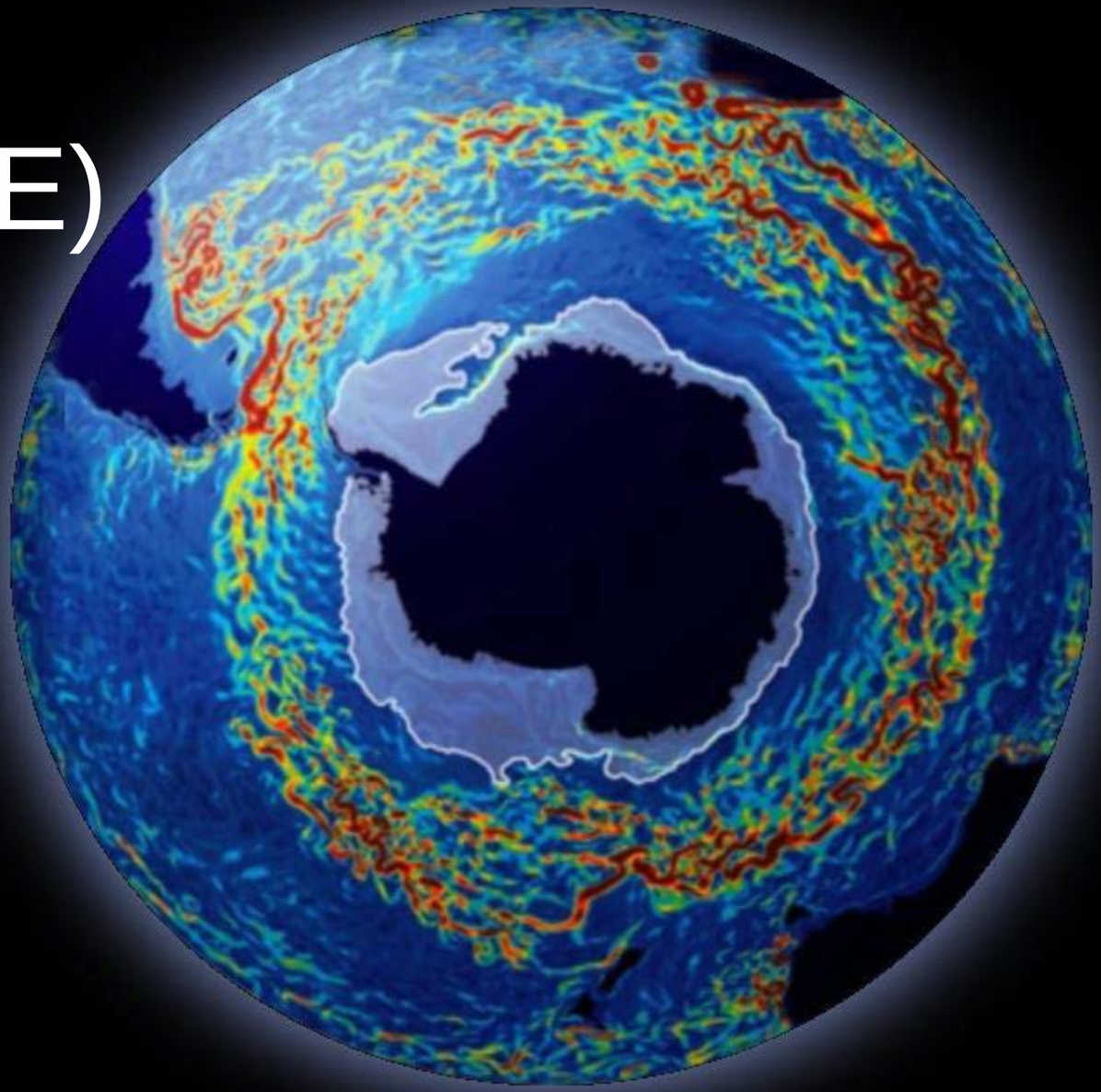
Courtesy: R. Slater

The Southern Ocean State Estimate (SOSE)

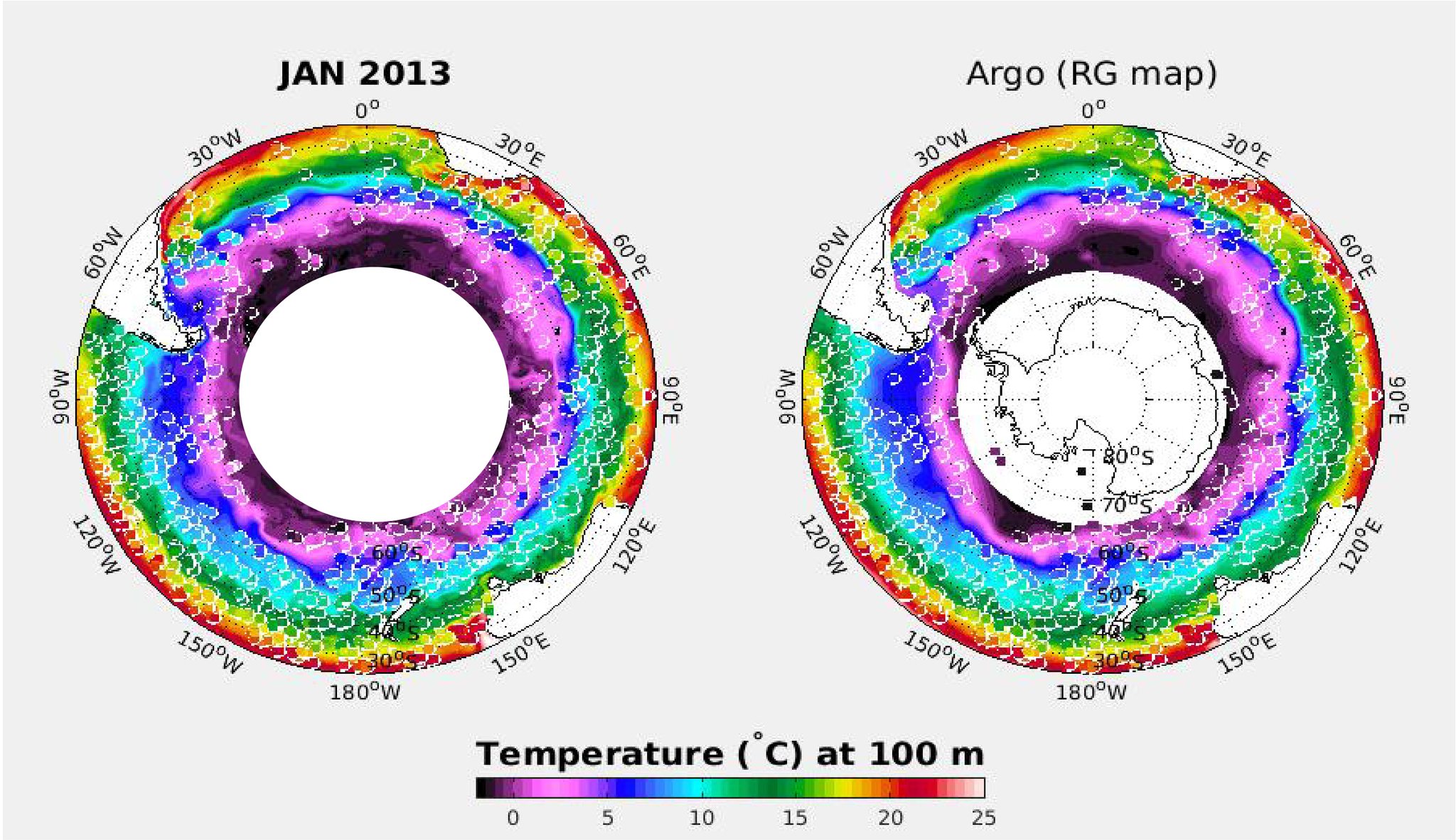
A modern general circulation model, the MITgcm, is least squares fit to all available ocean observations.

SOSE is being produced by Matthew Mazloff as part of the ECCO consortium and funded by the National Science Foundation.

Nominal Resolution is 1/6°

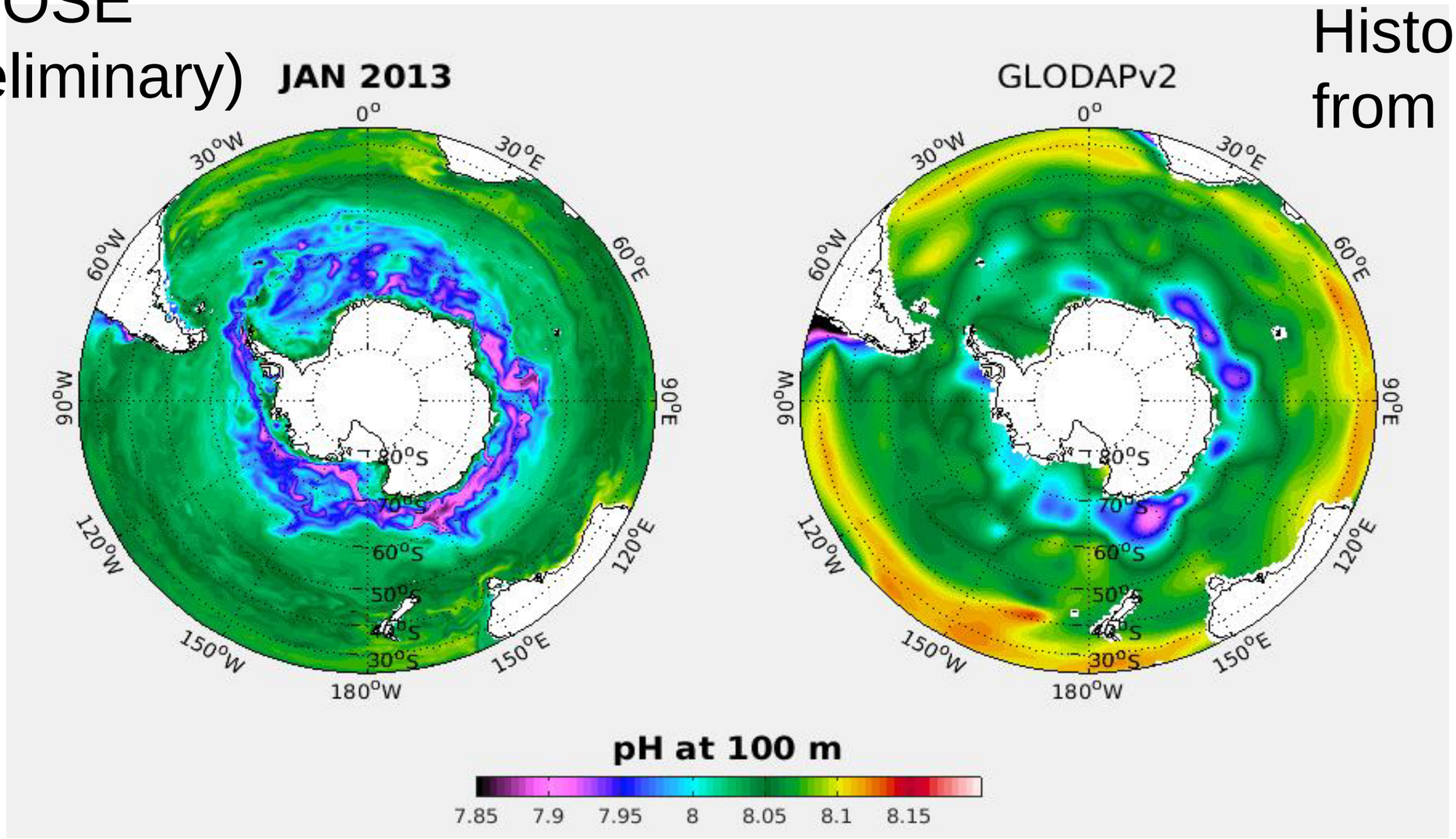


Mazloff et al. 2010; http://sose.ucsd.edu/


JAN 2013
Argo (RG map)
0°
30°W
30°E
60°W
60°E
90°W
90°E
120°W
120°E
150°W
150°E
180°W
80°S
70°S
60°S
50°S
40°S
30°S
Temperature (°C) at 100 m
0
5
10
15
20
25

pH measurements at 100 m (2013 –2016)

B-SOSE (preliminary)



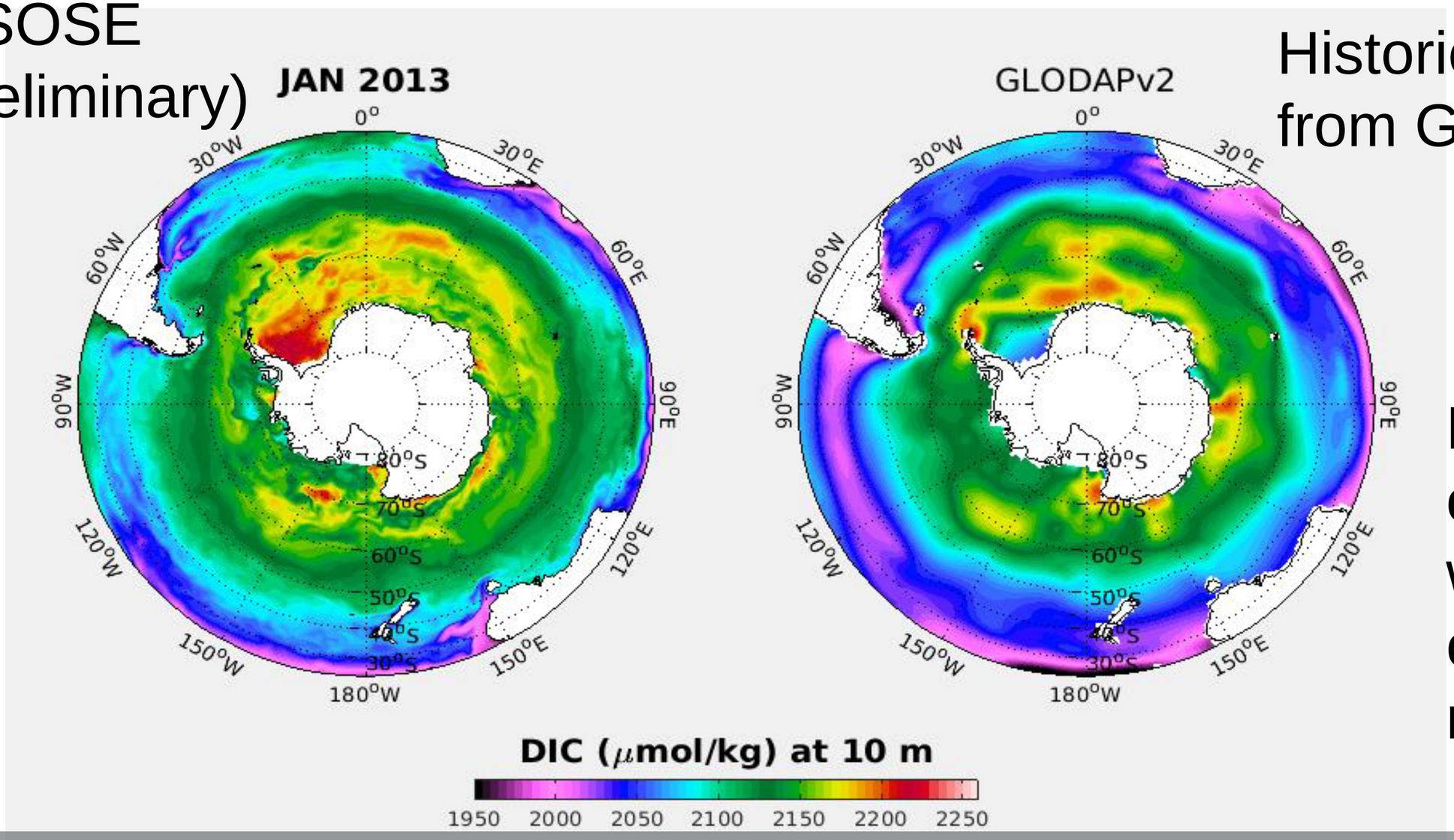
Historic Shipboard from GLODAPv2

Float data outlined in white, pH colored as in maps

M. Mazloff & A. Verdy (Personal Communication)

DIC estimates at 10 m (2013 –2016)

B-SOSE (preliminary)

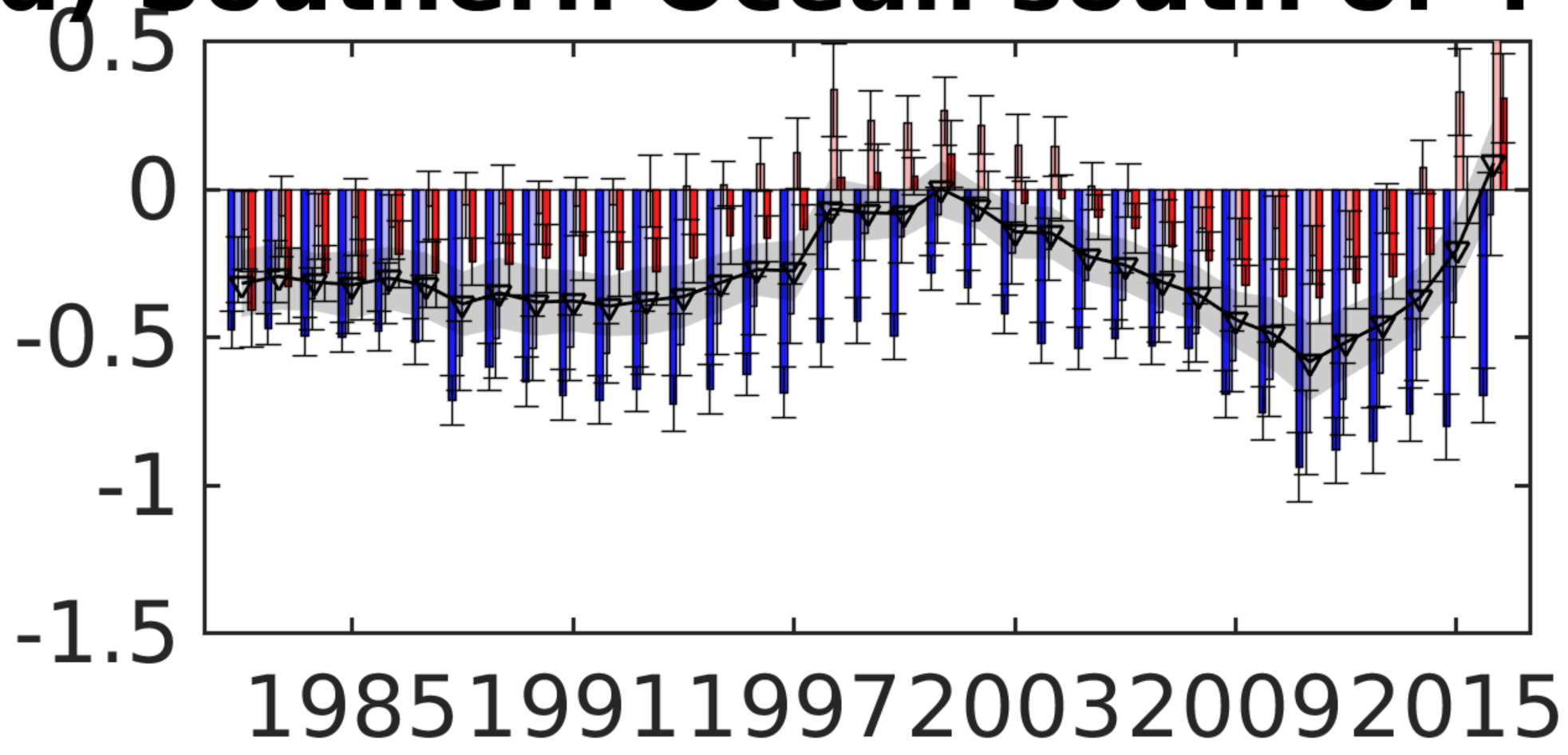


Historic Shipboard from GLODAPv2

Float data outlined in white, pH colored as in maps

M. Mazloff & A. Verdy (Personal Communication)

(d) Southern Ocean south of 44 ° S

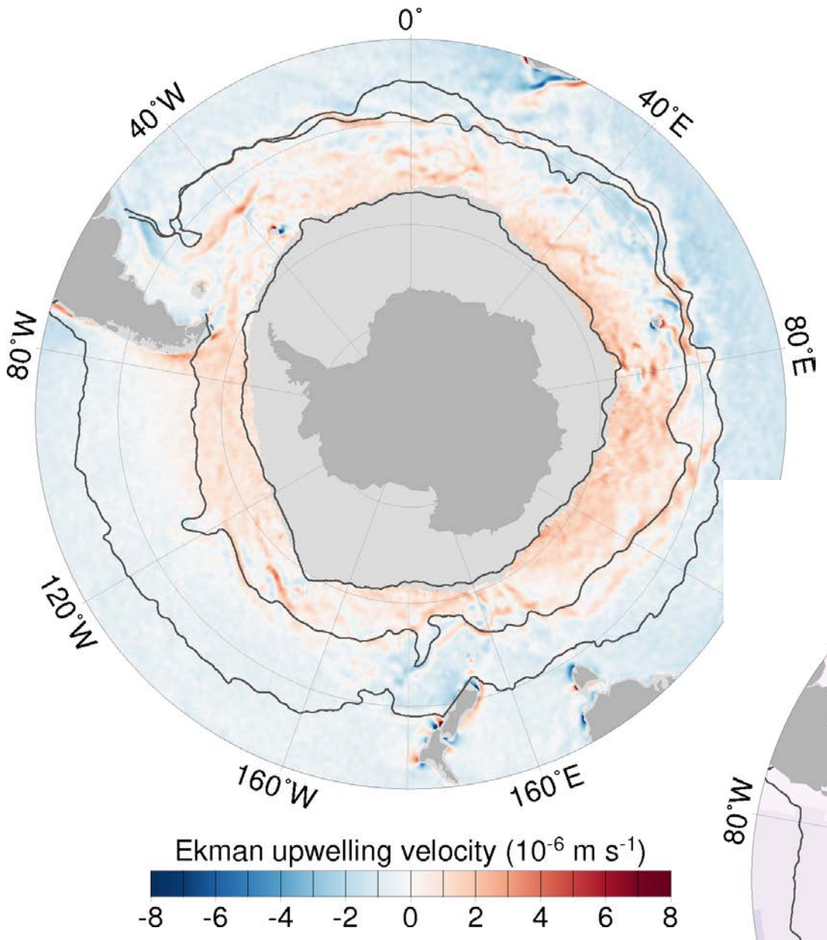


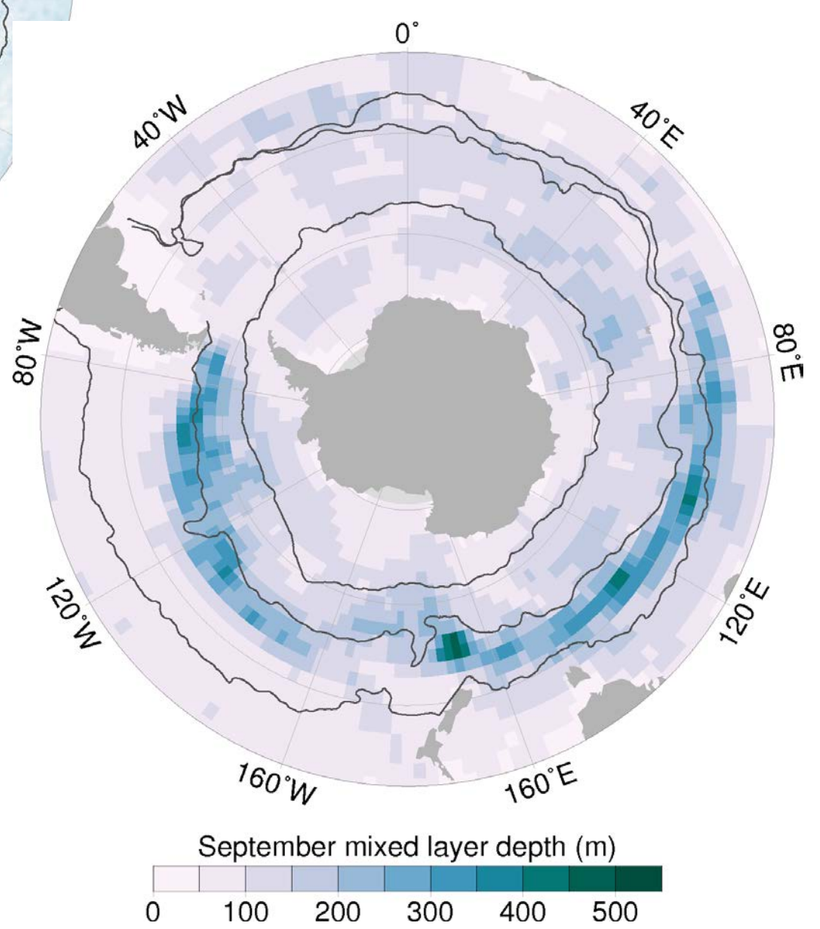
Getting oriented

Four zones are defined by the fronts:

- GRAY – Seasonal Ice Zone (SIZ)
- PINKish – Polar Frontal-Antarctic Zone (PAZ) – upwelling & ACC
- BLUEish – Subantarctic Zone (SAZ) – deep MLDs
- Subtropical Zone (STZ) to north

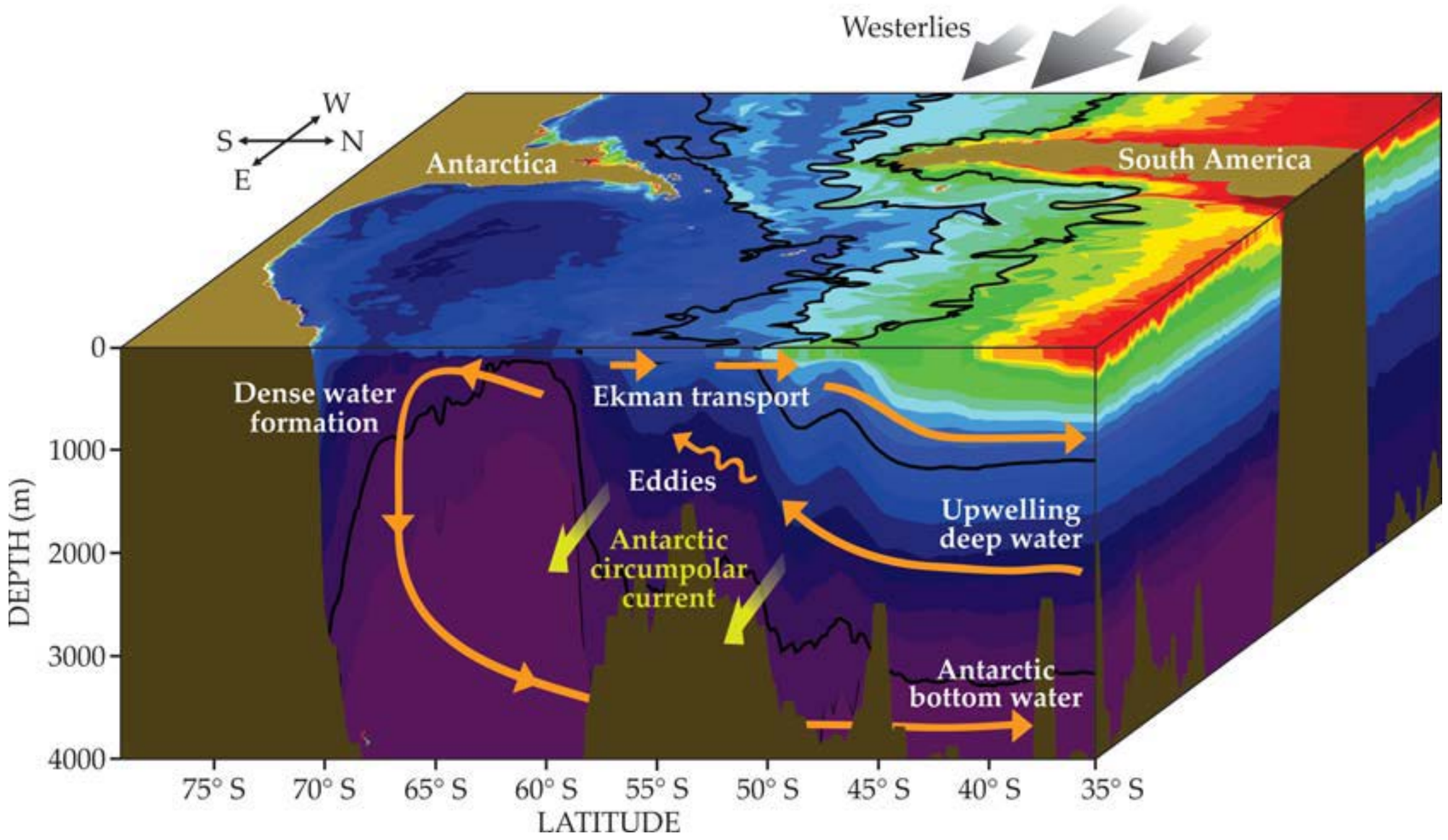
- Ekman velocity is from QuikSCAT 1999-2009 winds (Risien and Chelton 2011).
- MLDs from de Boyer-Montégut et al. (2004) climatology (>250 in upper figure purple line)





Draining the deep ocean

- Direct upwelling from very deep waters to the sea surface over a very large region
- The Southern Ocean upwelling accounts for ~80% of the deep ocean drainage



Morrison et al. (2015) based on Talley & Olbers (2014, after Speer et al. 2000, and NRC 2011)

PROPOSAL FOR A GLOBAL OCEAN HEALTH INITIATIVE RESEARCH PROGRAM (GOHI)

SUMMARY

The ocean provides critical services to all life on land, absorbing 93% of the heat from global warming and a quarter of human carbon dioxide emissions. Yet these services come at a price: ocean temperatures rise; pH and oxygen levels fall. This deteriorating ocean health bleaches corals, harms shellfish, changes where fish live and fishery yields. It alters biogeochemical cycles of key elements such as oxygen, carbon, and nitrogen.

- Scientists and policymakers are **racing to understand and prevent irreparable harm to our largest global commons**.
- Until recent years, **we have been flying blind with respect to change in the open ocean**.
- The **prohibitive cost of obtaining observations from ships** left scientists unable to closely monitor ocean health in the vast areas beyond the populated coasts.
- Satellite remote sensing of **ocean color was our only tool with a global reach**.
- The long-term investments of Federal agencies and private foundations has **now enabled direct observation of biogeochemical cycling and ocean health with in situ sensors**.
- A new generation of **robotic floats with cutting-edge sensors** developed with Federal support now allow the community to build **the first real-time, high-resolution, system to observe ocean health and changing biogeochemical cycles**: the Global Ocean Health Initiative (GOHI).
- GOHI will allow us to **track threats and provide critical guidance for sustainable ocean management**. All that is needed is funding to implement this revolutionary but proven system is funding.

GOHI = Semi-finalist in MacArthur Foundation

….. But no cigar

SOCCOM Modeling Goals & Accomplishments

• METRICS: Metrics for the evaluation of the Southern Ocean in coupled climate models and Earth System models (Russell et al., in press)

• SOMIP: IPCC 6, Southern Ocean Models Intercomparison Project

• ESMValTool.org: Development of Earth System Model evaluation tool

• CLIMATE HACK: #Great Antarctic Climate Hack led by Russell to grow the community using observations to evaluate earth system model simulations

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- GOHI will allow us to track threats and provide critical guidance for sustainable ocean management.

Metrics Paper

1 **Metrics for the Evaluation of the Southern Ocean in Coupled Climate Models**
2 **and Earth System Models**

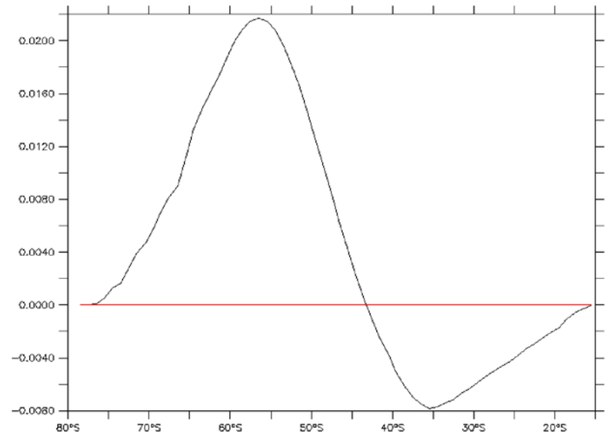
3

4 **Joellen L. Russell[1], Igor Kamenkovich[2], Cecilia Bitz[3], Raffaele Ferrari[4], Sarah T. Gille[5],**
5 **Paul J. Goodman[1], Robert Hallberg[6], Karina Khazmutdinova[10], Kenneth Johnson[7], Irina**
6 **Marinov[8], Matthew Mazloff[5], Stephen Riser[3], Jorge L. Sarmiento[9], Kevin Speer[10], Lynne**
7 **D. Talley[5] and Rik Wanninkhof[11]**

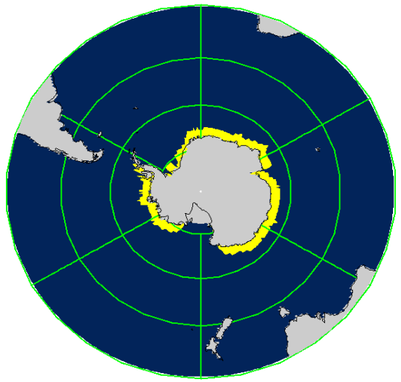
8 [1]University of Arizona, Tucson, Arizona, [2]Rosenstiel School of Marine and Atmospheric
9 Science, University of Miami, Miami, Florida, [3]University of Washington, Seattle, Washington,
10 [4]Massachusetts Institute of Technology, Cambridge, Massachusetts, [5]Scripps Institution of
11 Oceanography, University of California, San Diego, La Jolla, California, [6]National Oceanic and
12 Atmospheric Administration, Geophysical Fluid Dynamics Laboratory, Princeton, New Jersey,
13 [7]Monterey Bay Aquarium Research Institute, Moss Landing, California, [8]University of
14 Pennsylvania, Philadelphia, Pennsylvania, [9]Princeton University, Princeton, New Jersey,
15 [10]Florida State University, Tallahassee, Florida, [11]National Oceanic and Atmospheric
16 Administration, Atlantic Oceanographic and Meteorological Laboratory, Miami, Florida.
17

IPCC6: Southern Ocean Model Intercomparison Project

PLAN: The initial phase will be to perform idealized experiments trying to understand the differences in models' response to common changes in forcings, especially the relationship between wind forcing and stratification influences on the circulation and heat (and carbon) uptake in and by the Southern Ocean.



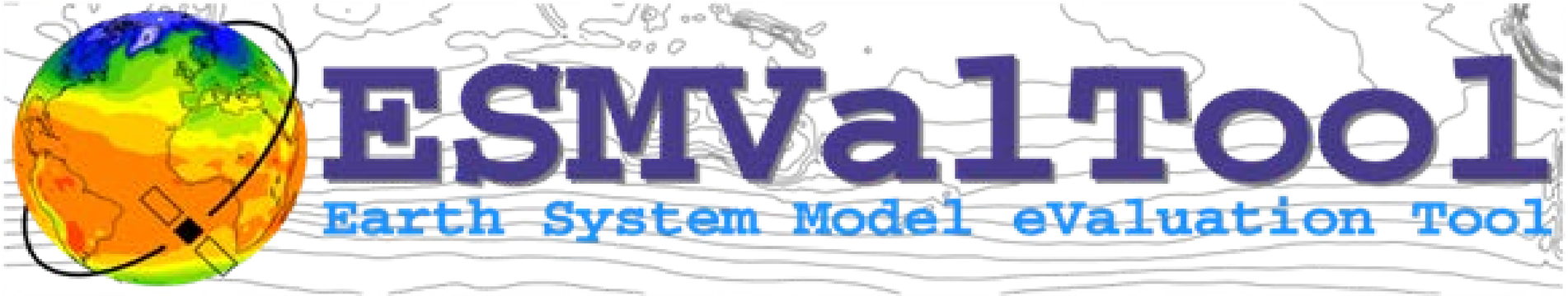
Proposal: Wind and Fresh water perturbations



3 EXPERIMENTS (300-900 years) :

1) An experiment that increases the winds over the Southern Ocean and shifts them poleward. Implications: 1 run (100-300 years).
2) An experiment where the stability of the Southern Ocean is changed via an external source of fresh water (so-called water hosing). Implications: 1 run (100-300 years).
3) An experiment will use both the increased wind forcing and the water hosing described above. Implications: 1 run (100-300 years).

Shared Metrics: ESMValTool



The Earth System Model eValuation Tool (ESMValTool) is a **community diagnostics and performance metrics tool for the evaluation of Earth System Models (ESMs)** that allows for routine comparison of single or multiple models, either against predecessor versions or against observations. Priority has been to focus on selected Essential Climate Variables, a range of known systematic biases common to ESMs, such as coupled tropical climate variability, monsoons, Southern Ocean processes, continental dry biases and soil hydrology-climate interactions, as well as atmospheric CO2 budgets, tropospheric and stratospheric ozone, and tropospheric aerosols.

https://www.esmvaltool.org/

Goals: 1) Grow the community using observations to evaluate climate simulations

2) Antarctic & SO metrics for ESMValTool

#GreatAntarcticClimateHack will be held October 9-12, 2017 at the Scripps Institution of Oceanography Forum, La Jolla, CA. Our first-ever Climate Hack will focus on bringing Antarctic and Southern Ocean observations to bear on evaluating the latest generation of climate and earth system models, producing new climate model metrics for the 21st century.

#GreatAntarcticClimateHack will bring observational and simulation scientists together to use observational datasets to interrogate CMIP model results, thereby creating new model metrics and validation tools. The aim of the workshop is to facilitate preparation for the next IPCC report for a much broader science community, increase non-traditional climate modeling publications, and learn to apply/utilize data sets that help develop model validation skills

http://www.scar.org/antclim21/climatehack

Global Ocean Health Initiative (GOHI):

Proposal for worldwide array of 1000 Biogeochemically-sensored floats

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Photo: O. Schofield

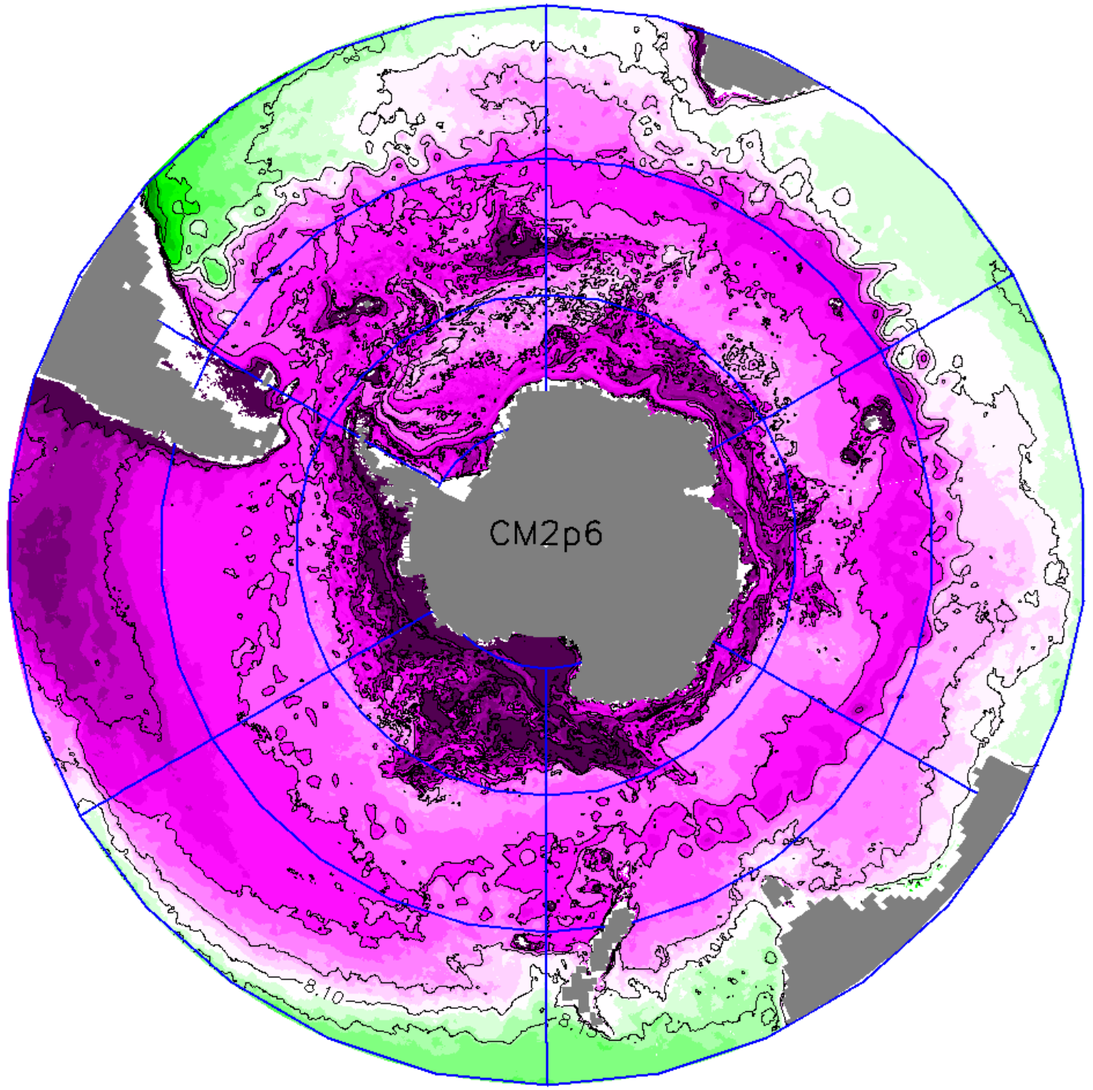
GUIDANCE FROM RAM:

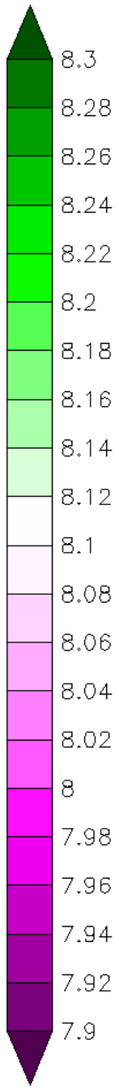
In order for a smooth flow with the rest of the day's talks and the Panel discussions coming up after this talk, and consistent with the central element of the Symposium viz. progressing towards a
Comprehensive, integrative modeling of the Earth System, and Unified modeling system for seamless predictability across time and space scales.,it would be useful for the SOCCOM talk to focus on:

- the chief scientific objective of SOCCOM (carbon-climate; why this was undertaken?)
- benefits from GFDL's hi-res climate and ESM simulations, and integrating with observations,
- perhaps, the principal result from SOCCOM so far,
- how the obs and modeling are pointing to future directions in Earth System Science (even if ambitious at this point e.g., very hi-res incl ocean biogeochem)

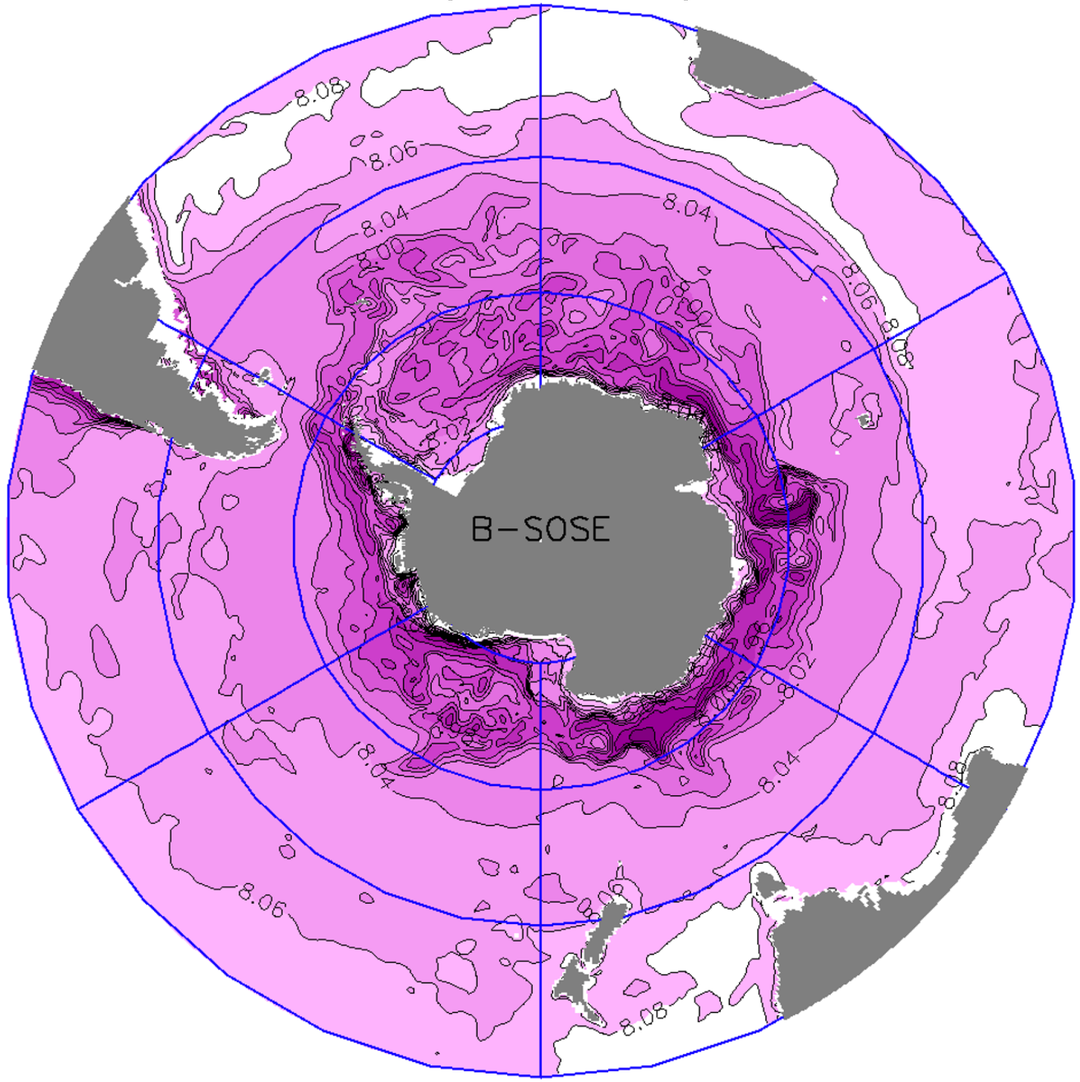
Annual-mean pH (at 105m)

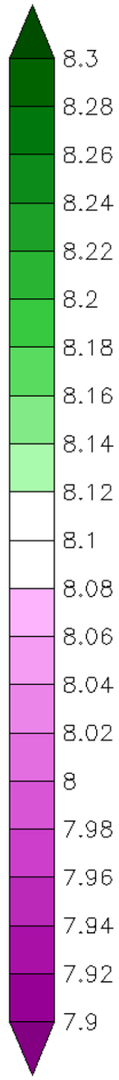
GFDL-CM2.6
(from algorithm using T, S, O_2)





B-SOSE
(2008-2012)





Russell et al. (submitted)

Conclusion: Southern Ocean CO_2 flux to atmosphere is greater than previous estimates

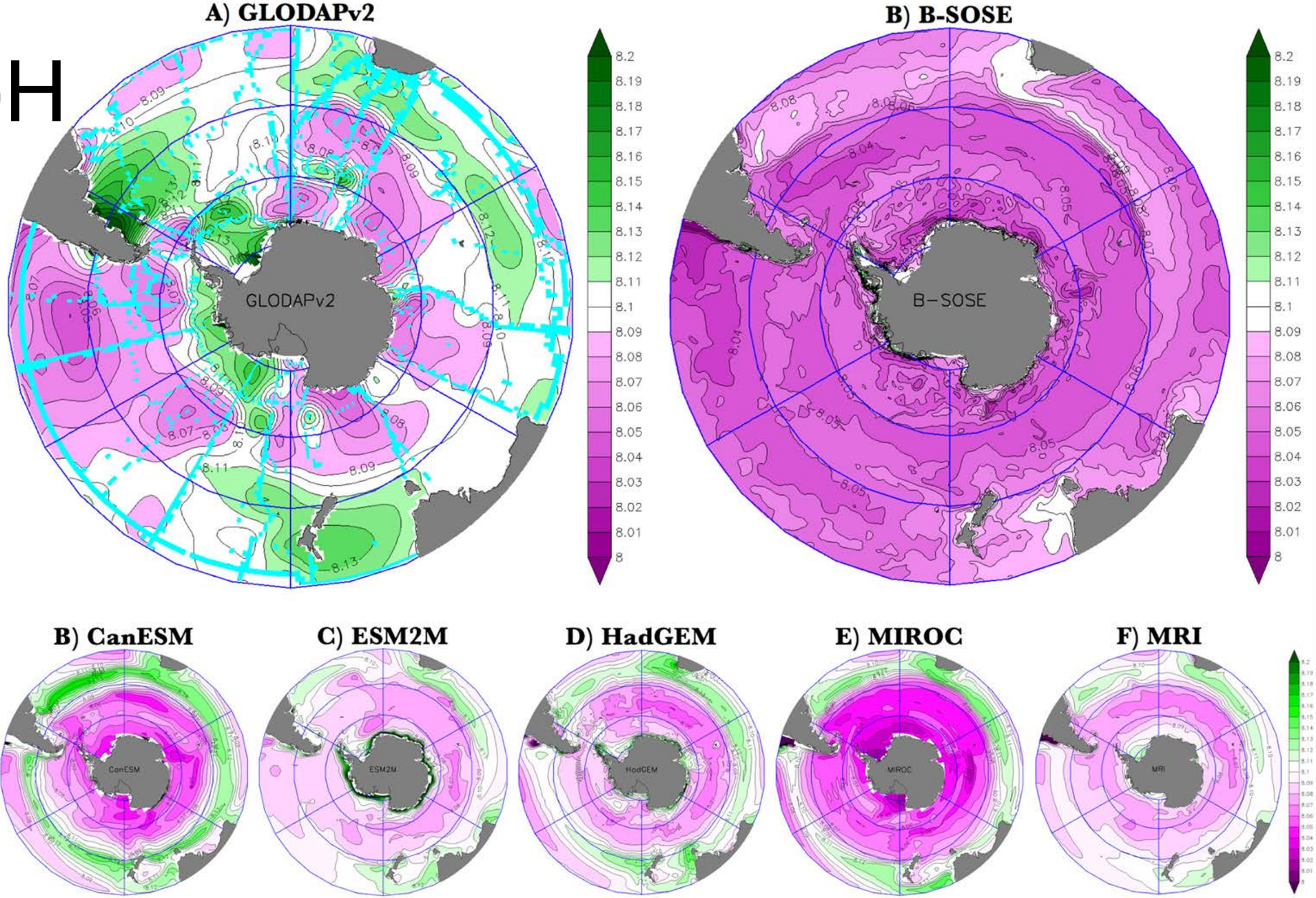
- Hypothesis 1: flawed methodology
  - Small number of floats is worrisome, but
  - Good agreement when shipboard data is available is reassuring
  - Method for converting pH to pCO_2 looks good.

- Hypothesis 2: Climatological baseline should have a stronger Southern Ocean source
  - but is this due to pre-industrial component or anthropogenic component, or both?
  - Maintaining a large global ocean anthropogenic carbon sink requires a larger carbon uptake elsewhere to compensate the smaller carbon uptake in the Southern Ocean

- Hypothesis 3: Interannual variability: 2014-present is anomalous
  - This appears to be the case, but past history suggest this can only explain ~0.5 Pg C y^{-1} of 0.9 Pg C y^{-1} anomaly we find

Surface pH

0-50m average, Annual Mean

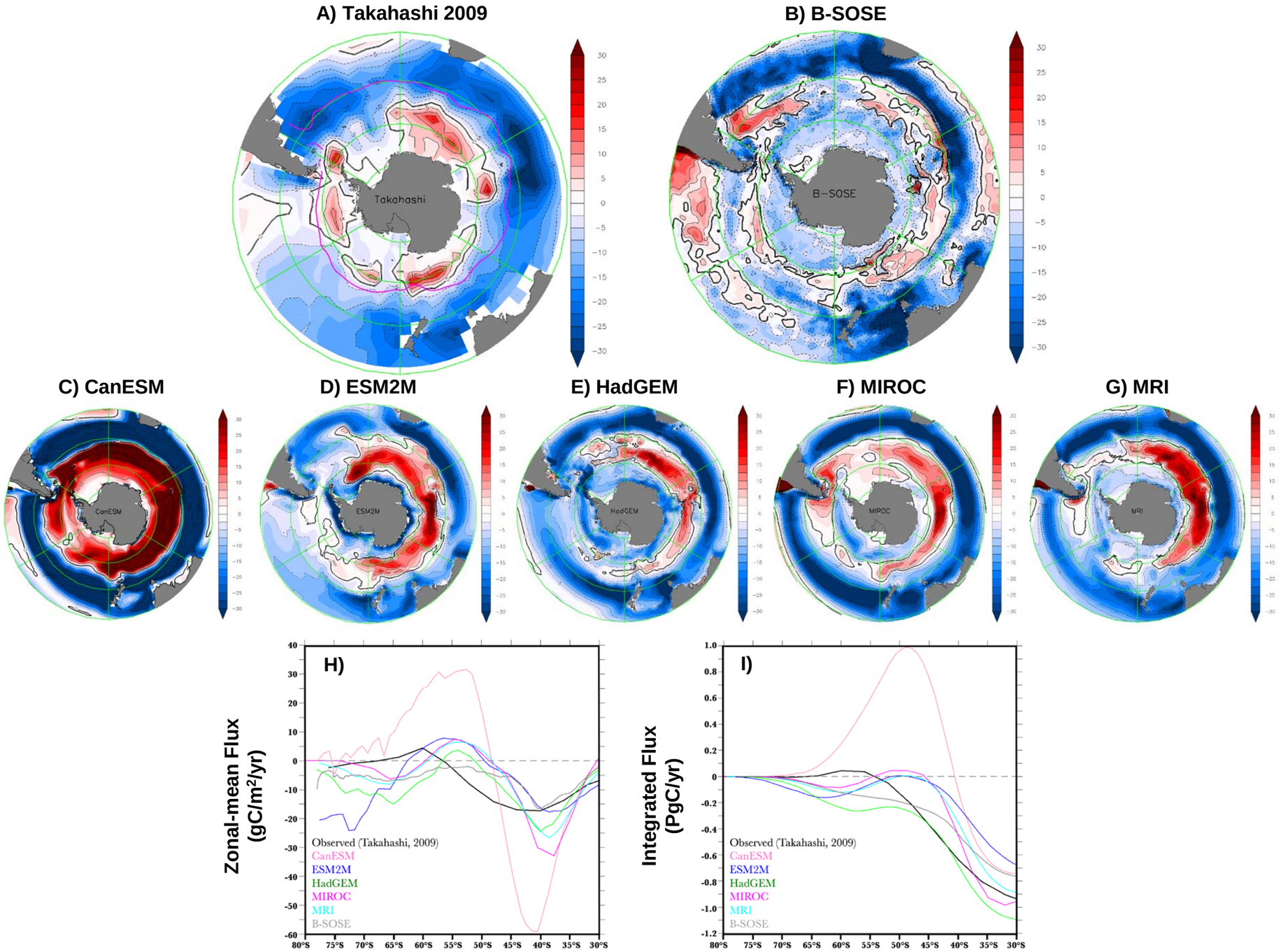


pH is explicitly simulated by these Earth System Models

Russell et al. (submitted)

Sea to Air CO_2 Flux ($gC/m^2/yr$)

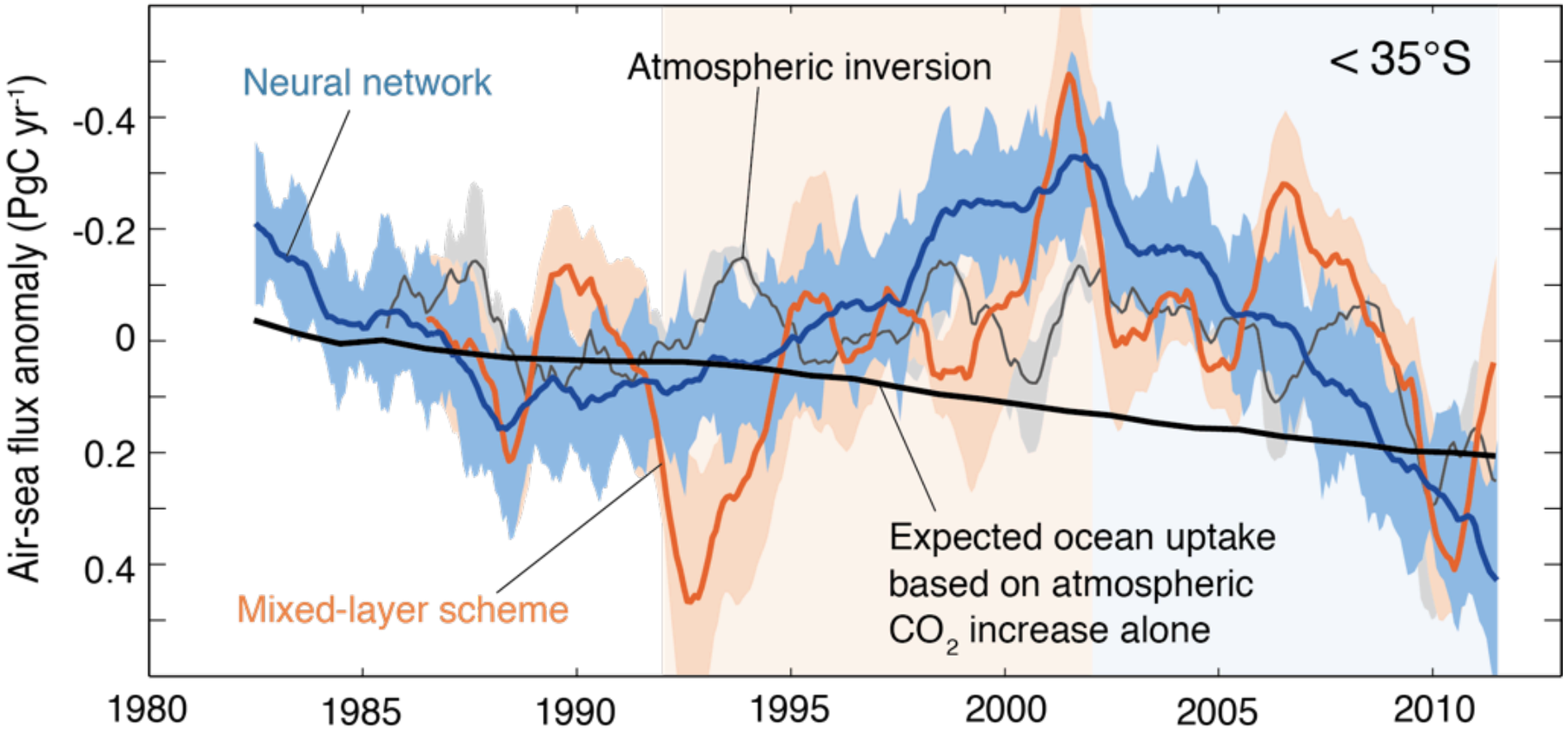
Red is outgassing,
Blue is uptake



Accomplishments Years 1-3

Theme	Topic	Significant results
Observations	Floats	• 91 operational • Bio-optical sensors on 87% of floats
	Cruises	• 16 cruises in 3 ocean basins
	Data availability	• Float data available in near real-time from MBARI, also being uploaded to Argo; “snapshots” with doi archived at Scripps
	State Estimation	• ⅓ degree biogeochemical solution now available for 2008-2012; assimilation of SOCCOM float data underway
Modeling	Metrics	• Adaptation to ESMValTool underway
	OSSEs	• Reconstruction skill completed • Effective resolution of array assessed
	Algorithms	• Algorithms required to convert observed nitrate and/or oxygen and pH into pCO_2 published
	Model Assessment	• Atlas in progress, heat and carbon uptake, biogeochemistry, resolution, budgets
Broader Impacts	SOMIP	• Protocol finalized, initial simulations underway
	Outreach	• Multimedia resources, adopt-a-float program, undergrad teaching resources, virtual special issue of JGR-Oceans

Recent CO_2 flux trend into the Southern Ocean



Le Quéré et al. (2007, Science): Saturation of Southern Ocean CO_2 sink?

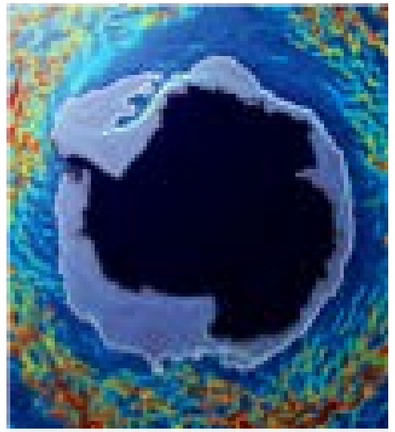
Landschützer et al. (2015, Science): Reinvigoration of Southern Ocean carbon sink

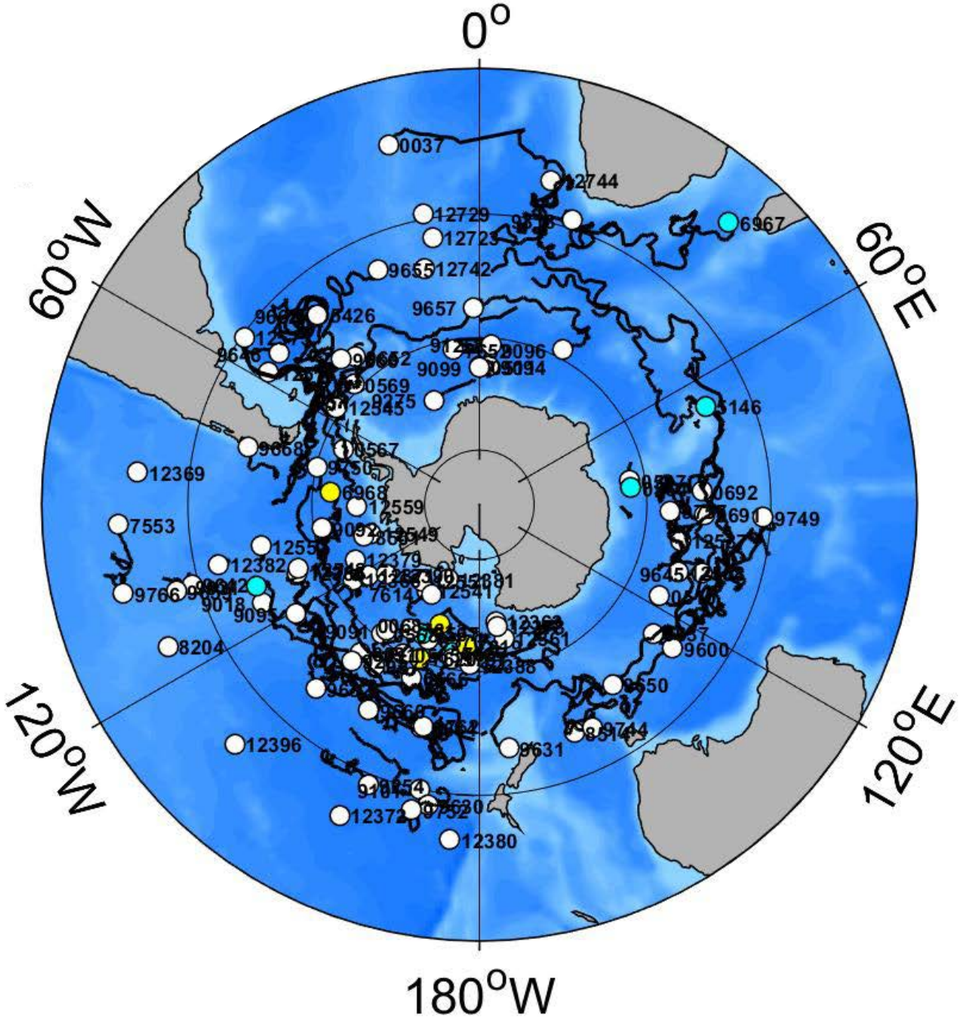
SOCCOM

Southern Ocean Carbon and Climate Observations and Modeling

Jorge Sarmiento

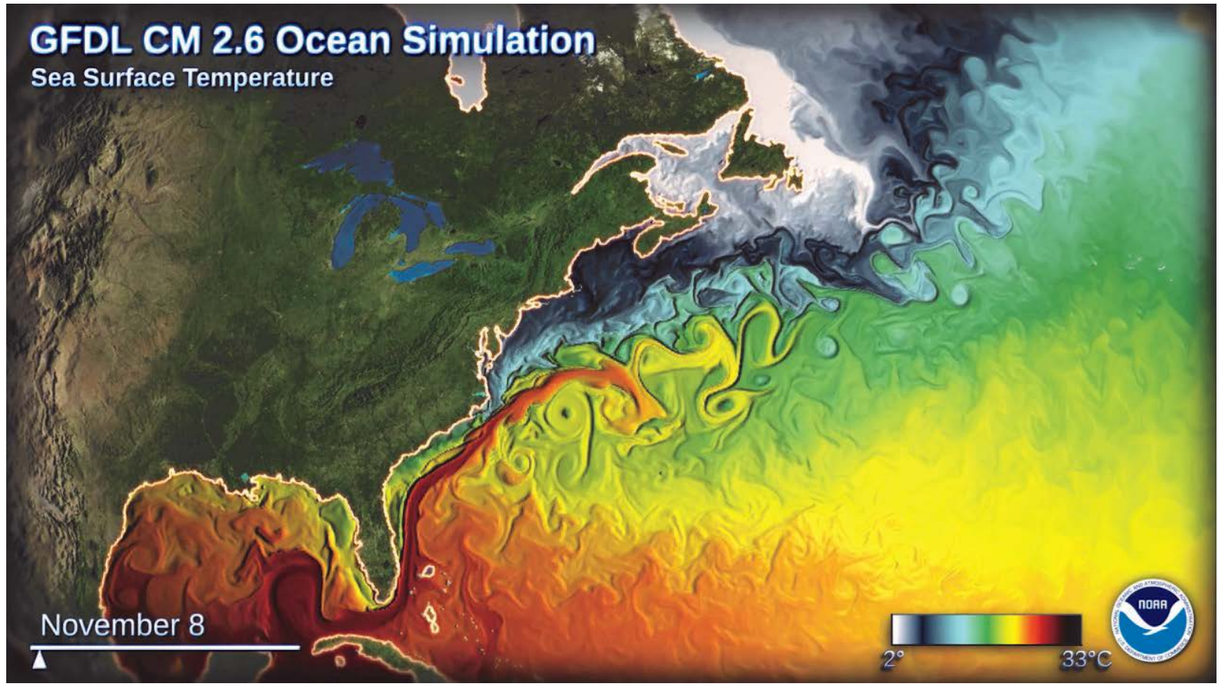
2017 GFDL Symposium



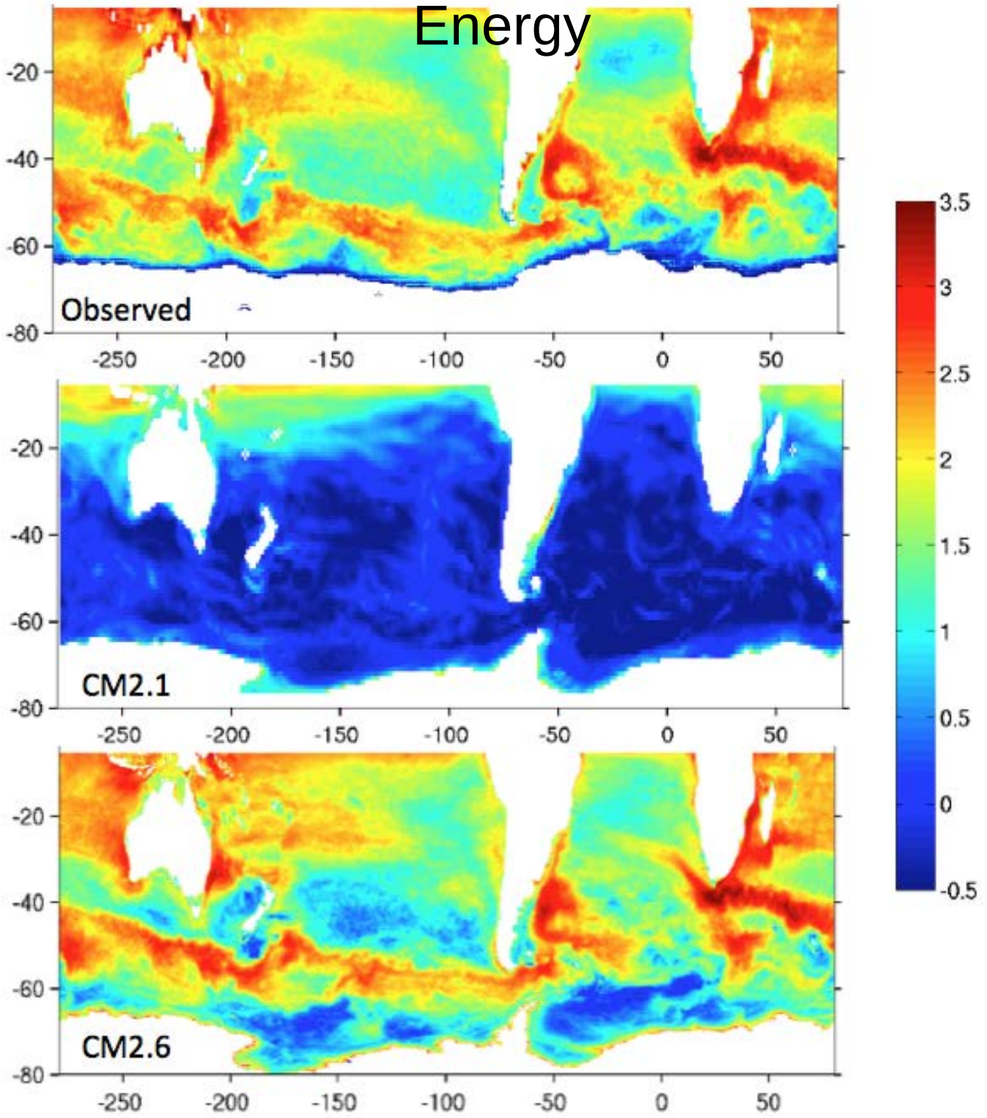


GFDL-CM2.6

- **ocean** - eddy resolving with resolution of 0.1° (5-11km), 50 levels
- **atmosphere** – 50km resolution, 32 levels
- plus **land** (LM3) and **sea ice**
- **MiniBLING biogeochemistry**



Eddy Kinetic Energy



Delworth et al., 2012

Southern Ocean carbon dioxide fluxes estimated from SOCCOM biogeochemical profiling float measurements

Conclusions

- *Float data based estimates suggest there is a large CO_2 flux from the ocean to the atmosphere in the PAZ – Polar Frontal-Antarctic Zone (characterized by upwelling & ACC) a region currently thought to be a sink*
- *Our working hypothesis is that the PAZ has been missed because it occurs largely in the wintertime when previous observations are insufficient*

Implications

- *The PAZ flux anomaly is of order 1 PgC/yr, equivalent to about 50% of the total ocean carbon sink, 15% of fossil fuel emissions.*
- *There must be a sink elsewhere. A possibility is the Southern Hemisphere subtropical gyre*

Models & simulations used in analysis

	center	name	vertical coordinate	ocean resolution	scenario (time period)
CMIP5 models	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)

ANNUAL NET AIR-SEA CO_2 FLUX

+ Outgassing
– Uptake

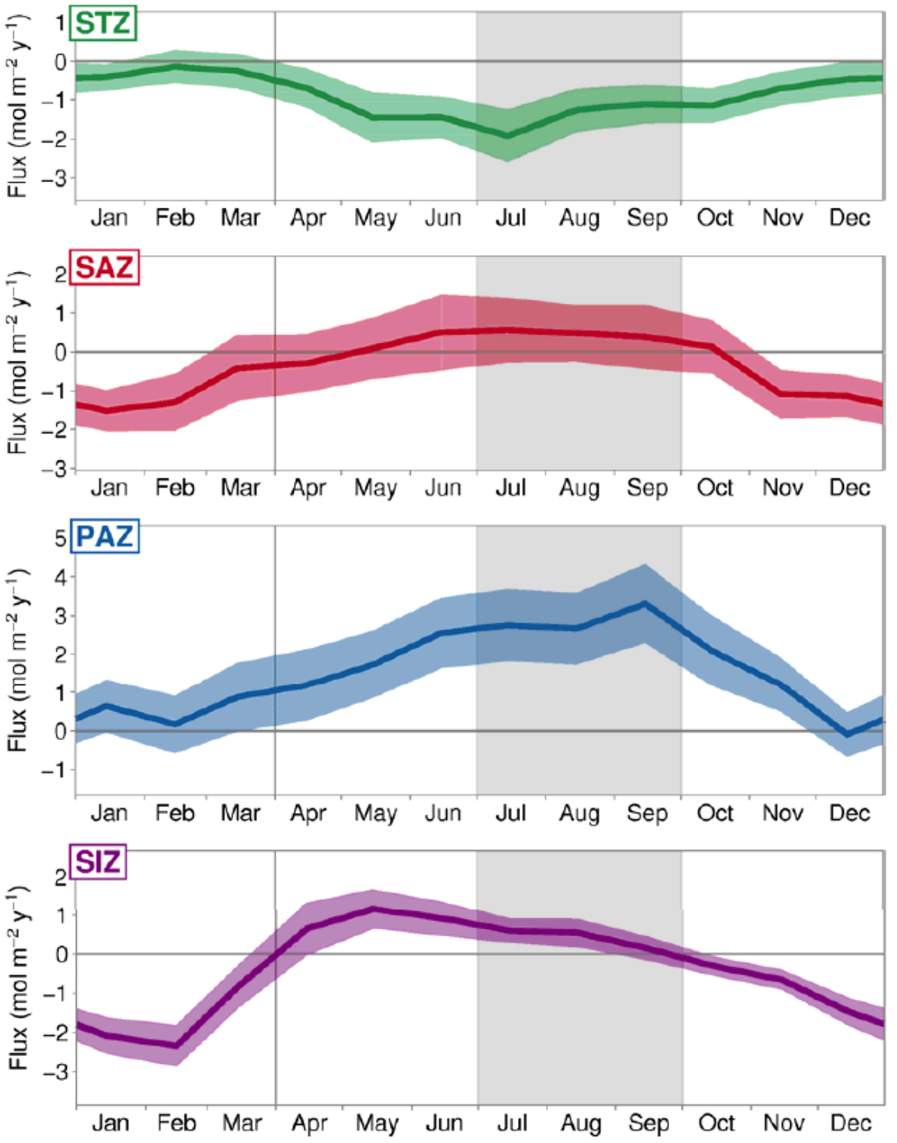
Mean (mol m^{-2} y^{-1})

STZ: -0.9 ± 0.5

SAZ: -0.3 ± 0.7

PAZ: 1.6 ± 0.8

SIZ: -0.3 ± 0.4

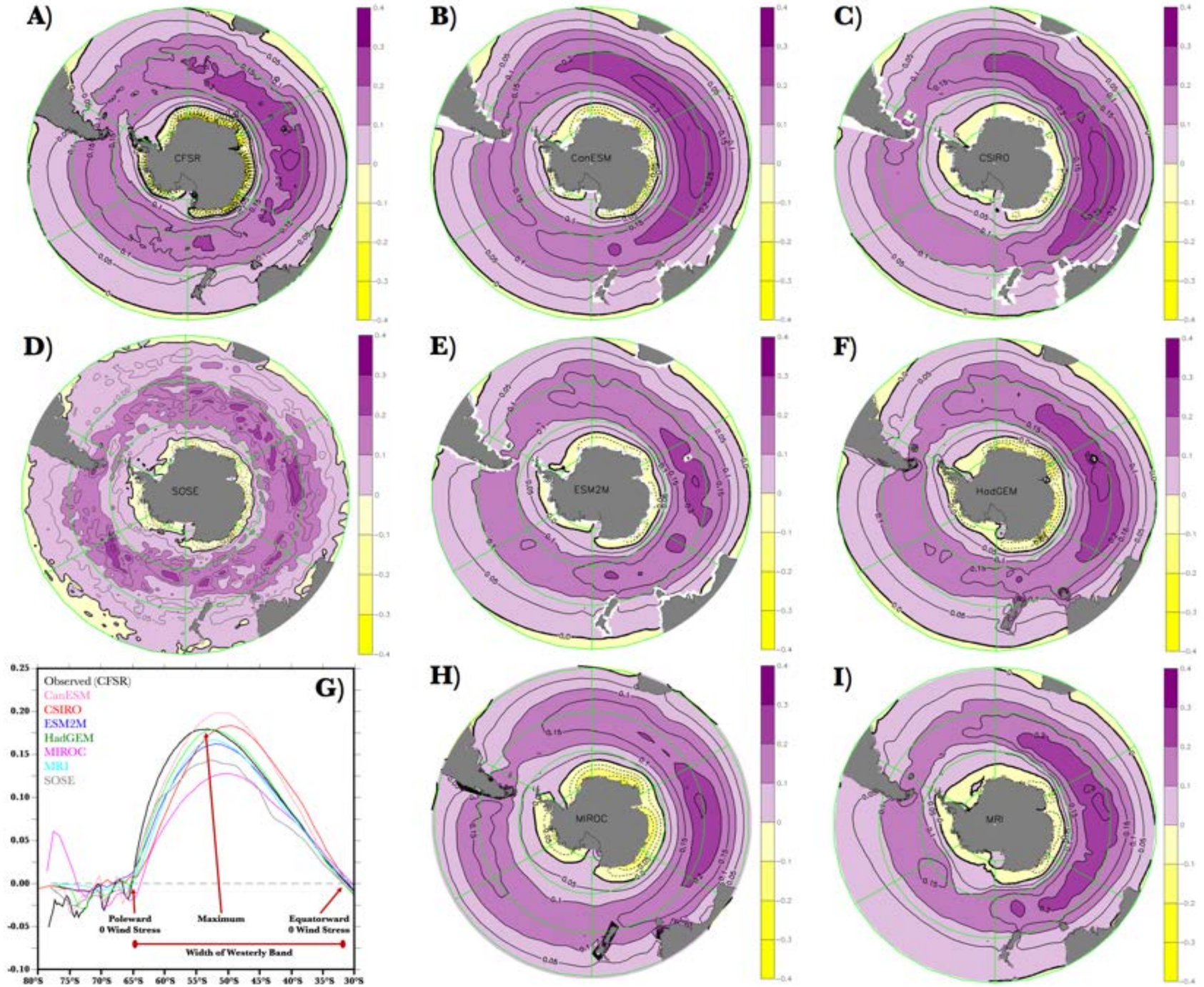


Average global anthropogenic CO_2 uptake = -0.46 ± 0.14 mol m^{-2} y^{-1}

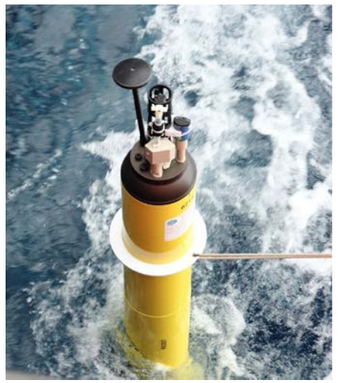
Zonal Wind Stress (N/m^2, Annual Mean)

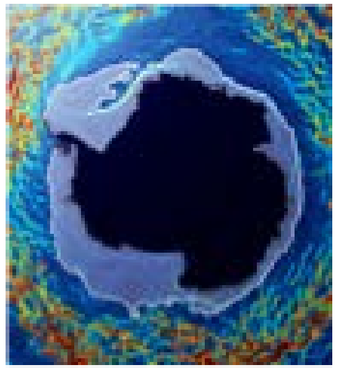
Purple (positive) is clockwise (westerlies)

All the simulations have their strongest mean winds in the South Pacific sector (around Kerguelen), but each has its peak winds too far equatorward



What is SOCCOM?





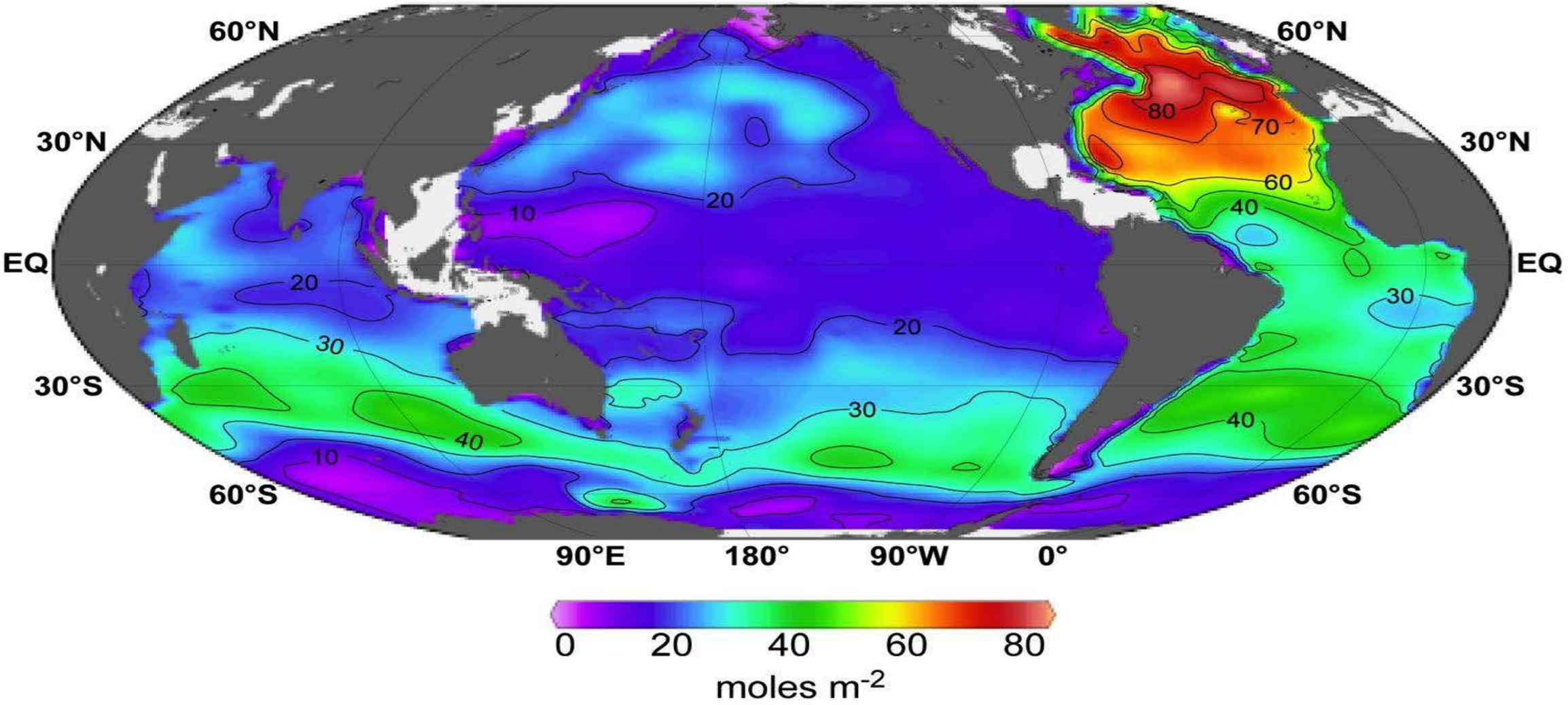
- SOCCOM's mission is to drive a transformative shift in our understanding of the role of the Southern Ocean in climate change and biogeochemistry by:

Extending sparse Southern Ocean biogeochemical observations by deploying a robotic observing system composed of ~200 autonomous BGC Argo floats that will provide nearly continuous coverage in time and horizontal space over the entire Southern Ocean, as well as vertical coverage deep into the water column.

Using these observations to analyze and improve a new generation of high resolution (1/10°) earth system models to both increase our understanding of the Southern Ocean's current workings and make better projections of the future trajectory of the Earth's climate and biogeochemistry.

Educating a new generation of ocean scientists trained in both ocean observation and simulation, and develop a sophisticated outreach effort to disseminate results to the broadest possible community.

Carbon Absorption



SOCCOM

Feely and Sabine, http://www.pmel.noaa.gov/co2/PressConference.html