

The prospects and rationale for a global biogeochemical Argo system (BGC Argo)

Kenneth S. Johnson, Monterey Bay Aquarium Research Institute, johnson@mbari.org

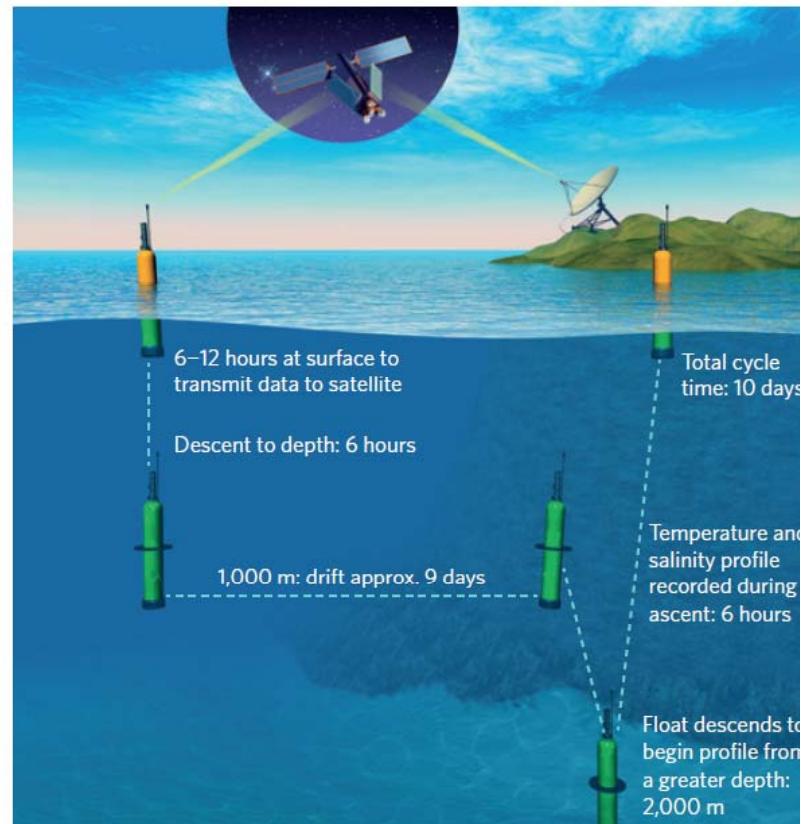
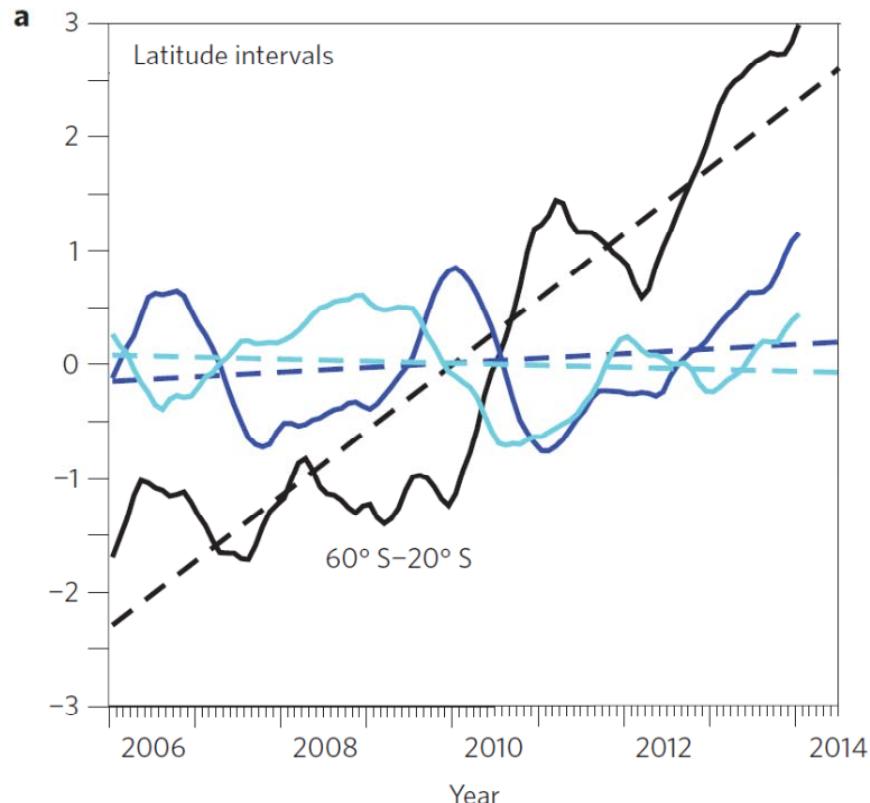
Jorge L. Sarmiento, Princeton University

Hervé Claustre, Laboratoire d'Océanographie de Villefranche



Fifteen years of ocean observations with the global Argo array

Stephen C. Riser¹, Howard J. Freeland^{2*}, Dean Roemmich³, Susan Wijffels⁴, Ariel Troisi⁵, Mathieu Belbéoch⁶, Denis Gilbert⁷, Jianping Xu⁸, Sylvie Pouliquen⁹, Ann Thresher⁴, Pierre-Yves Le Traon¹⁰, Guillaume Maze⁹, Birgit Klein¹¹, M. Ravichandran¹², Fiona Grant¹³, Pierre-Marie Poulain¹⁴, Toshio Suga¹⁵, Byunghwan Lim¹⁶, Andreas Sterl¹⁷, Philip Sutton¹⁸, Kjell-Arne Mork¹⁹, Pedro Joaquín Vélez-Belchi²⁰, Isabelle Ansorge²¹, Brian King²², Jon Turton²³, Molly Baringer²⁴ and Steven R. Jayne²⁵



LETTERS

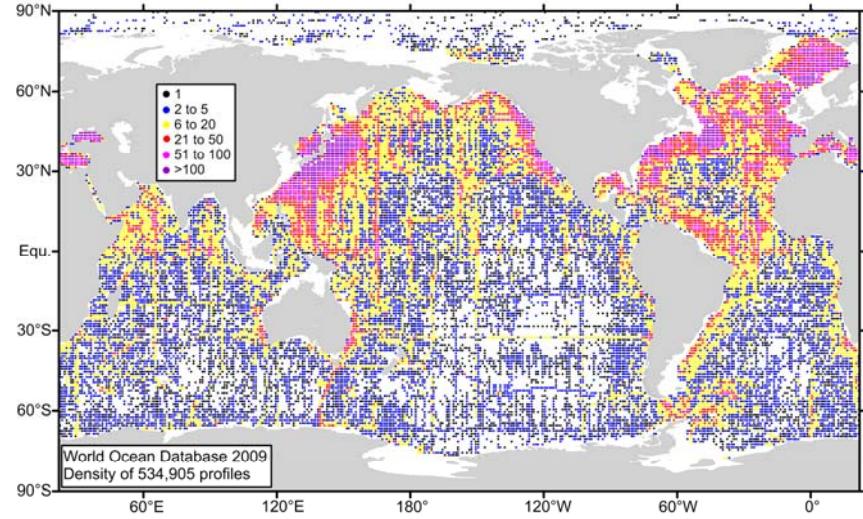
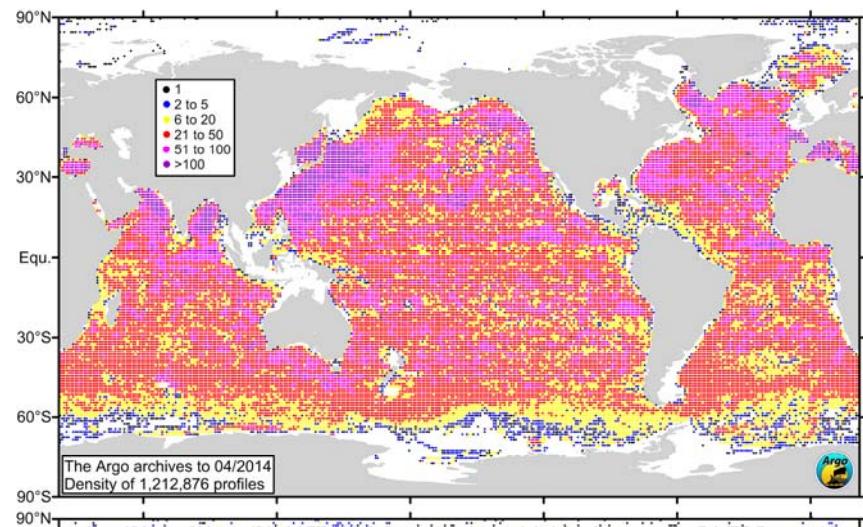
PUBLISHED ONLINE: 2 FEBRUARY 2015 | DOI: 10.1038/NCLIMATE2513

Unabated planetary warming and its ocean structure since 2006

Dean Roemmich^{1*}, John Church², John Gilson¹, Didier Monselesan², Philip Sutton³ and Susan Wijffels²

Argo transformed *global-scale* oceanography into *global* oceanography.

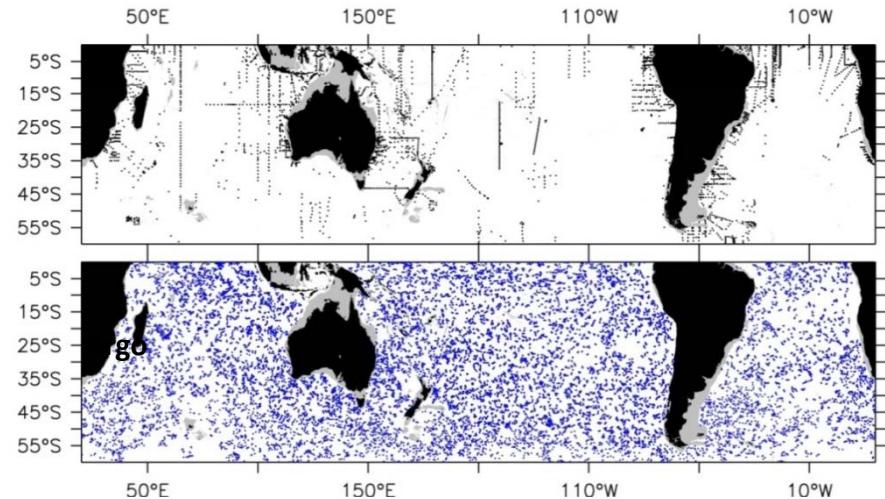
Argo: 1,000,000 T/S profiles milestone achieved in 2012.



20th Century: 500,000 T/S profiles > 1000 m

Argo Floats Do Not Mind Bad Weather

All August T/S profiles (> 1000 m, 1951 - 2000).



5 years of August Argo T/S profiles (2008-2012).

The World Ocean Circulation Experiment was a global survey of 8,000 T/S profiles in 7 years (1991-1997).

Argo is a global survey of 12,000 T/S profiles every month.

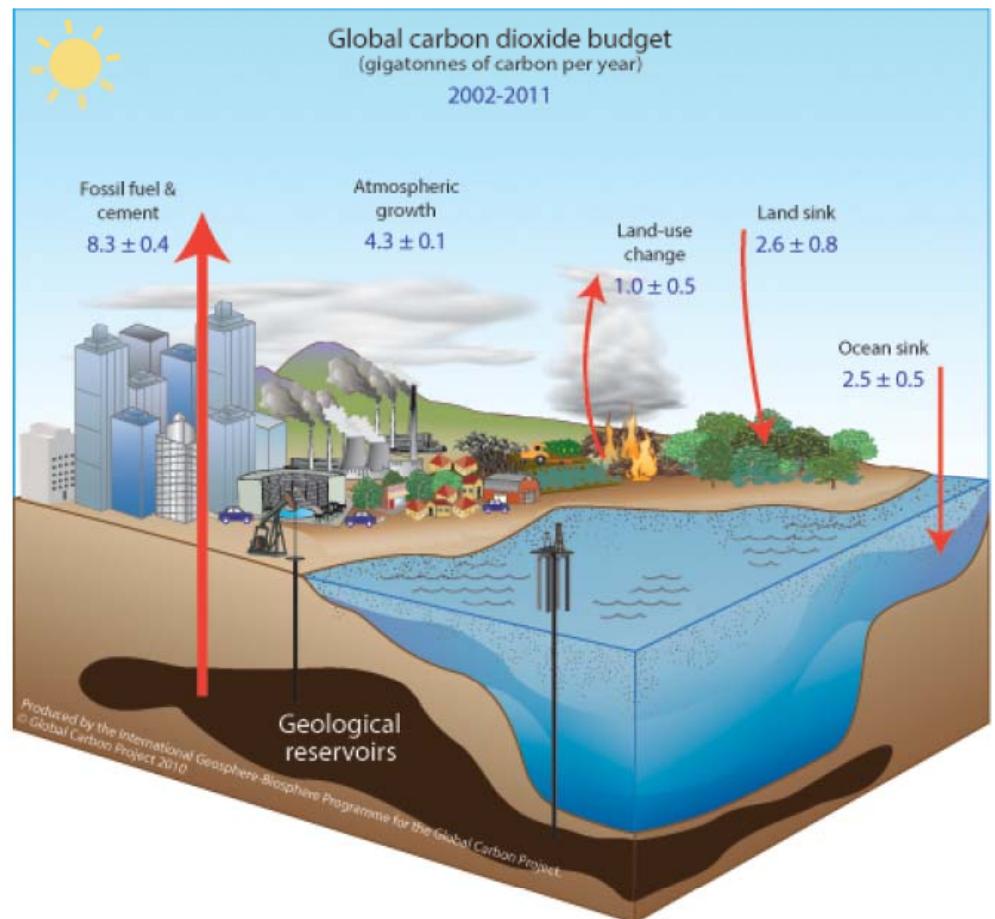
Courtesy S. Piotrowicz

We can now do the same for biogeochemistry/ocean carbon cycling!

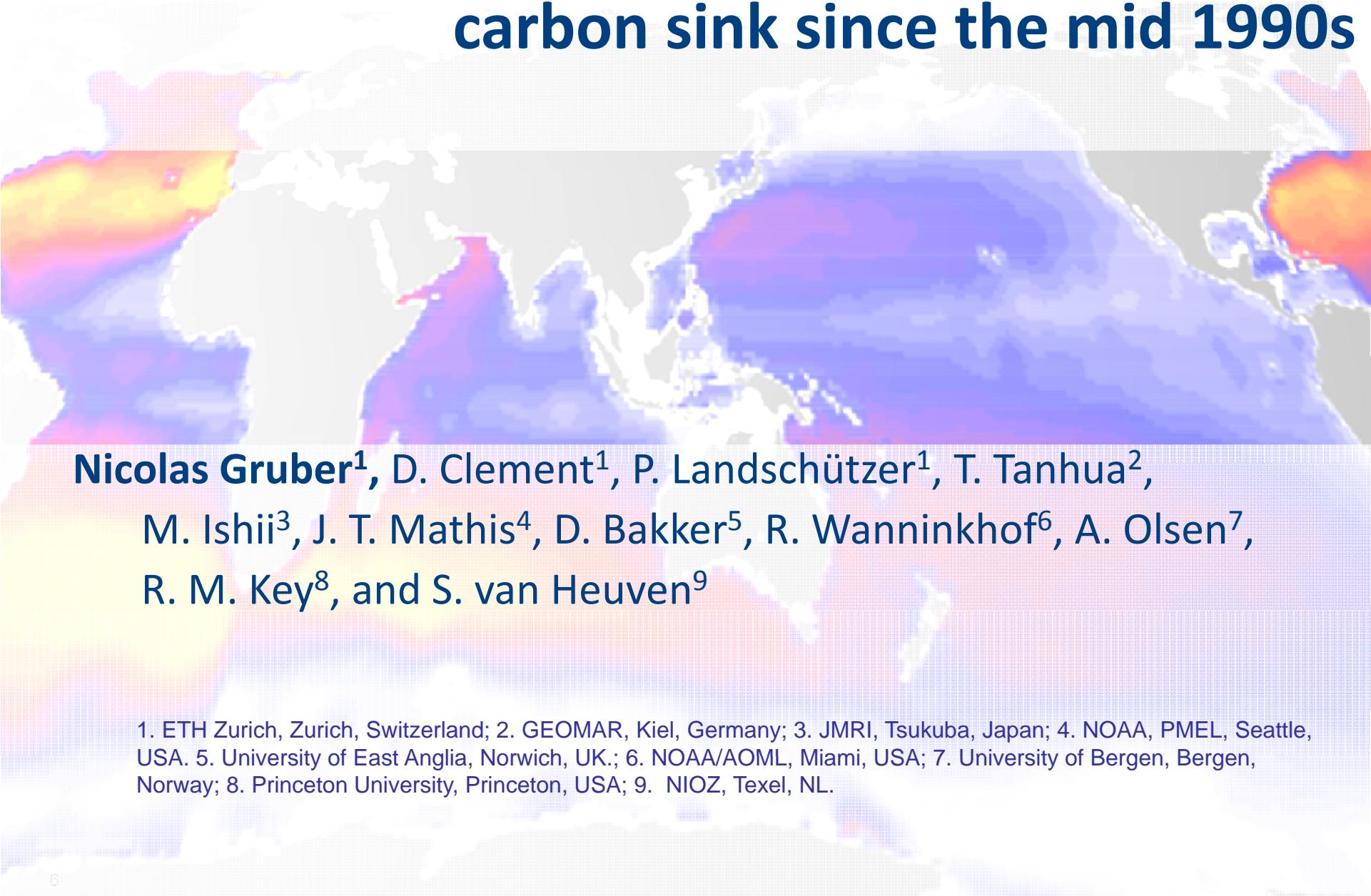
- Why observe carbon/oxygen/nitrate/biooptics?
- Current status of system/sensors.
- Basin-scale experiments and results.
 - SOCCOM – Southern Ocean Carbon and Climate Observations and Modeling
- Linkage to satellite observations.
- The path forward BGC Argo, a global biogeochemical Argo system.

Ocean carbon uptake is a major component of the global carbon budget.

- Biological pump in ocean lowers atmospheric CO₂ ~100 ppm.
- Ocean removes 30% of anthropogenic carbon.
- Net land sink = Fossil Fuels – Atmospheric Growth – Ocean Sink
- Interannual change not well constrained by observations.



Toward a global synthesis of the oceanic carbon sink since the mid 1990s



Nicolas Gruber¹, D. Clement¹, P. Landschützer¹, T. Tanhua²,
M. Ishii³, J. T. Mathis⁴, D. Bakker⁵, R. Wanninkhof⁶, A. Olsen⁷,
R. M. Key⁸, and S. van Heuven⁹

1. ETH Zurich, Zurich, Switzerland; 2. GEOMAR, Kiel, Germany; 3. JMRI, Tsukuba, Japan; 4. NOAA, PMEL, Seattle, USA. 5. University of East Anglia, Norwich, UK.; 6. NOAA/AOML, Miami, USA; 7. University of Bergen, Bergen, Norway; 8. Princeton University, Princeton, USA; 9. NIOZ, Texel, NL.

Anomalous air-sea CO₂ flux versus anomalous storage (1994-2007)

- Numerous studies point to climate and decreasing ocean phytoplankton/productivity links.

GEOPHYSICAL RESEARCH LETTERS, VOL. 30, NO. 15, 1809, doi:10.1029/2003GL016889,

Ocean primary production and climate: Global decadal changes

Watson W. Gregg

Laboratory for Hydrographic Processes, NASA/Goddard Space Flight Center, USA

[1] Satellite-in situ blended ocean chlorophyll records indicate that global ocean annual primary production has declined more than 6% since the early 1980's. Nearly 70% of the global decadal decline occurred in the high latitudes. In

nature

Vol 444 | 7 December 2006 | doi:10.1038/nature05317

LETTERS

Climate-driven trends in contemporary ocean productivity

Michael J. Behrenfeld¹, Robert T. O'Malley¹, David A. Siegel³, Charles R. McClain⁴, Jorge L. Sarmiento⁵, Gene C. Feldman⁴, Allen J. Milligan¹, Paul G. Falkowski⁶, Ricardo M. Letelier² & Emmanuel S. Boss⁷

8

nature

ARTICLES

Global phytoplankton decline over the past century

Daniel G. Boyce¹, Marlon R. Lewis² & Boris Worm¹

In the oceans, ubiquitous microscopic phototrophs (phytoplankton) account for approximately half the production of organic matter on Earth. Analyses of satellite-derived phytoplankton concentration (available since 1979) have suggested decadal-scale fluctuations linked to climate forcing, but the length of this record is insufficient to resolve longer-term trends. Here we combine available ocean transparency measurements and *in situ* chlorophyll observations to estimate the time dependence of phytoplankton biomass at local, regional and global scales since 1899. We observe declines in eight out of ten ocean regions, and estimate a global rate of decline of ~1% of the global median per year. Our analyses further reveal interannual to decadal phytoplankton fluctuations superimposed on long-term trends. These fluctuations are strongly correlated with basin-scale climate indices, whereas long-term declining trends are related to increasing sea surface temperatures. We conclude that global phytoplankton concentration has declined over the past century; this decline will

Reevaluating ocean warming impacts on global phytoplankton

Michael J. Behrenfeld^{1*}, Robert T. O'Malley¹, Emmanuel S. Boss², Toby K. Westberry¹, Jason R. Graff¹, Kimberly H. Halsey³, Allen J. Milligan¹, David A. Siegel⁴ and Matthew B. Brown¹

Is the satellite ocean color signal a reflection of physiological adaptation by phytoplankton to a warmer ocean, and not a change in biomass?

A paradigm shift in ocean observing: Autonomous biogeochemical sensors on profiling floats enable a widely distributed observing system.

- Field developing rapidly:

- Körtzinger, et al. (2005) – O₂

- Tengberg et al. (2006) – O₂

- Bittig et al. (2015) – O₂

- Johnson et al. (2015) – O₂

- Johnson et al. (2010) – Optical nitrate

- Johnson et al. (2013) – Optical nitrate

- Martz et al. (2010) – DuraFET pH

- Johnson et al. (2016) – Deep-Sea DuraFET pH

- E. Boss et al. (2008) – Biooptics (chlorophyll & particles)

- Whitmire et al. (2009) – Biooptics

- Boss and Behrenfeld (2010) – Biooptics

Oxygen



Table 3: Current Observing Networks*

Observing Network	Profiling Floats (PF)	Repeat Hydrography (RH)	Moorings (M)	Gliders (G)	Ship-based Time-Series (STS)	Ship Of Opportunity (SOO)
-------------------	-----------------------	-------------------------	--------------	-------------	------------------------------	---------------------------

Phenomena Addressed	1,2,3,4
---------------------	----------------

Readiness Level of the Observing Network (as defined in the FOO)	Pilot/ Mature
--	------------------

Spatial Scales Currently Captured by the Observing Network	Global every 3°
--	-----------------

Typical Observing Frequency	Bi-weekly to annual
-----------------------------	---------------------

Nitrate

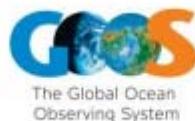


Table 4: Future Observing Networks

Observing Network	Profiling Floats (PF)	Surface Gliders/Drifters (Gsurf/D)	Subsurface Moorings (Msubsurf)	Subsurface Gliders (Gsubsurf)
-------------------	-----------------------	------------------------------------	--------------------------------	-------------------------------

Phenomena Addressed	?
---------------------	---

Readiness Level of the Observing Network (as defined in the FOO)	NO_3 Pilot <u>Other</u> Concept
--	---

Spatial Scales Captured by the Observing Network	10-1000 km
--	------------

Typical Observing Frequency	Weekly to annual
-----------------------------	------------------

pH



The Global Ocean Observing System



Table 4: Future Observing Networks

Observing Network	Profiling Floats (PF)	Surface gliders (Gsurf)	Subsurface moorings (Msubsurf)	Subsurface gliders (Gsub)
Phenomena Addressed	?	?	?	?
Readiness Level of the Observing Network (as defined in the FOO)	pH Pilot ..	pCO_2 Pilot ..	Conceptual	Conceptual

Suspended Particles/ Backscatter



Table 3: Current Observing Networks* (Part 1)

Observing Network	Ship Of Opportunity (SOO)	Gliders (G)	Moorings (M)	Profiling Floats (PF)	Satellites (SAT)	Ship-based Sampling (SS)
Phenomena Addressed	1,2 & possibly 3	1,2	1,2 & possibly 3	1,2,4	1,2,5,6,7	Needed for calibration
Readiness Level of the Observing Network (as defined in the FOO)	Mature (1,2), Concept (3)	Mature	Mature (1,2), Concept (3)	Mature	Mature (1,2), Pilot to mature	Mature

Table 1: Priority List of 10 biological eEOVs defined at the Workshop

Potential eEOV in order of ranking (1= Highest Impact/Highest feasibility)		eEOV Theme
1. Chlorophyll		A. Productivity (Primary) D. Human/Climate impacts
2. Coral Cover		B. Biodiversity C. Ecosystem Services (food supply for populations in tropical latitudes, e buffer) D. Human/Climate impacts
3. Mangrove Area		A. Productivity (Primary) C. ES (Carbon sequestration, ecological flooding) D. Human/Climate impacts

A particular synergism with ocean color remote sensing.

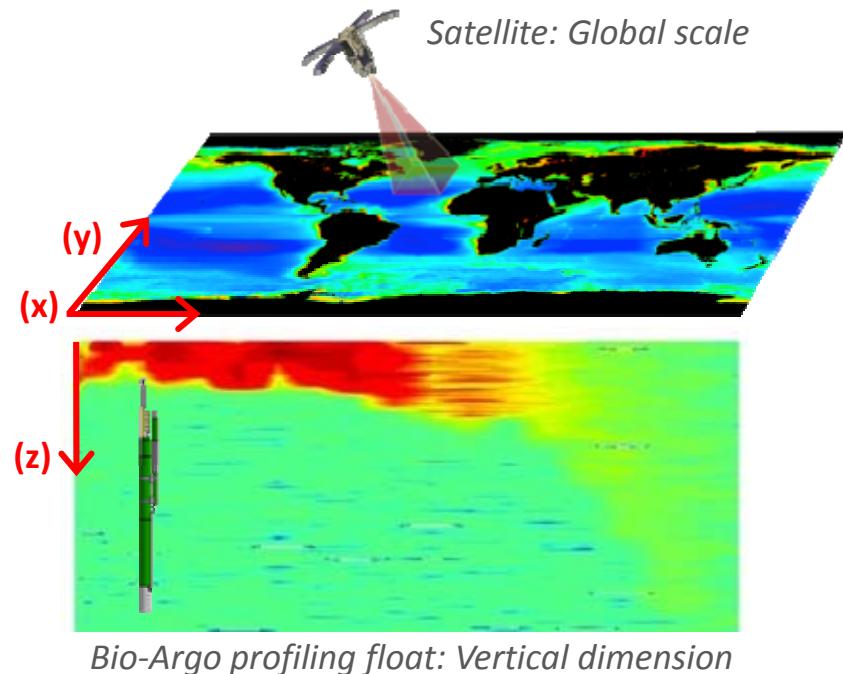
Synergetic Ocean Color remote sensing-profiling float approach

- Floats and ocean color share key biogeochemical variables (matchups & validation):

- ✓ Chla
- ✓ b_{bp} (POC)
- ✓ Kd
- ✓ CDOM

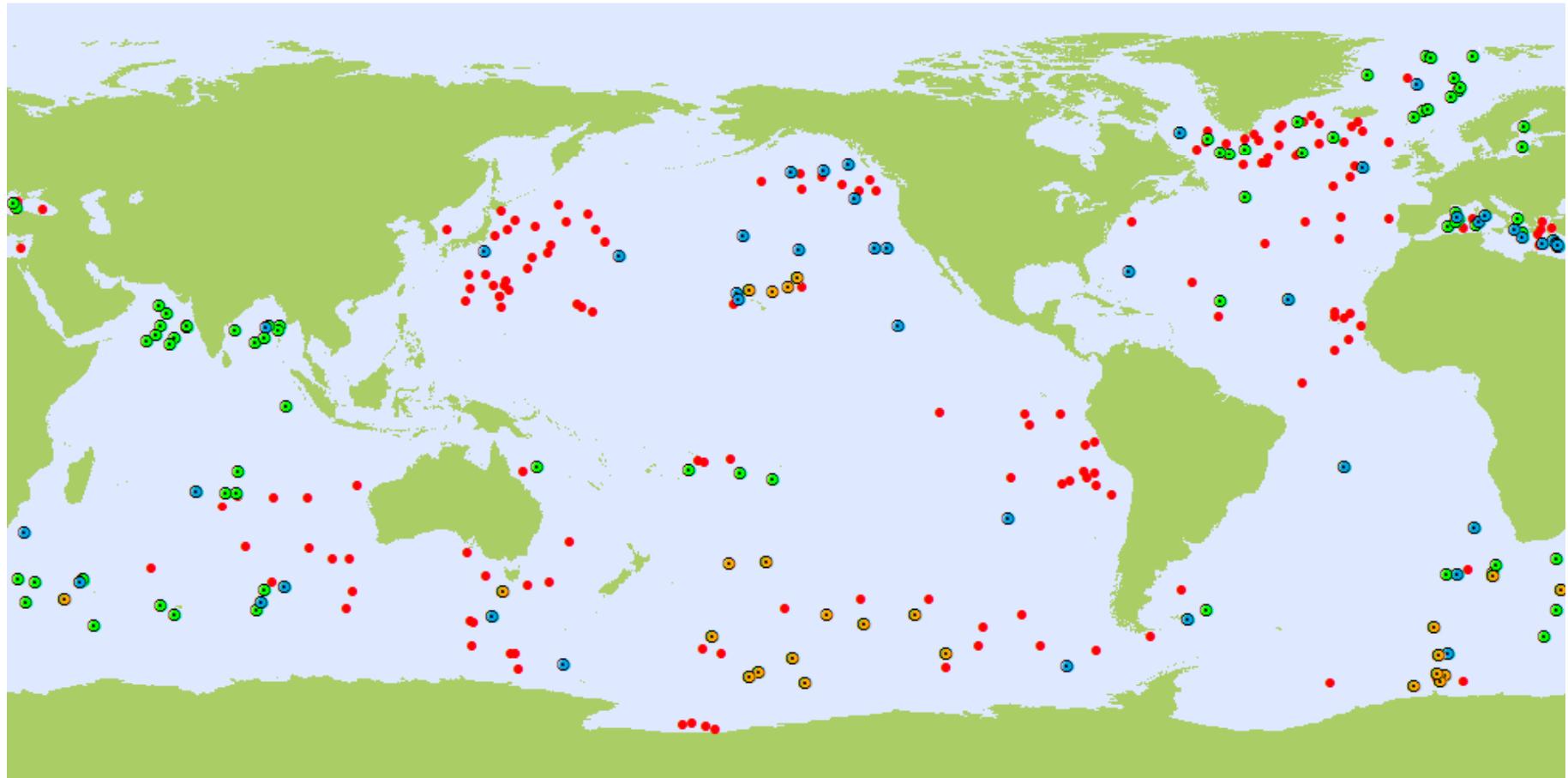
- Benefits of a coupled approach:

- ✓ OC satellites “see” only the 1/5 of the euphotic layer => Profiling floats bring vertical dimension
- ✓ Profiling floats bring observations under cloud cover or no light conditions
- ✓ Remote sensing provides extrapolation to the global ocean



→ 3D/4D OCEAN BIOGEOCHEMISTRY

Biogeochemical (BGC) Argo has grown to a global reach, but so far has no formal structure.



Bio-Argo (271)

- Dissolved Oxygen (280)
- Nitrate (64)
- Bio-optics (115)
- pH (25)

September 2015



[Home](#)

[Proceedings](#)

Preface

Statement

Summary

Published in the
Proceedings of OceanObs'09: Sustained Ocean Observations and Information for Society

PLENARY PAPER

doi:10.5270/OceanObs09.pp.33

Integrating the Ocean Observing System: Mobile Platforms

ADDING OXYGEN TO ARGO: DEVELOPING A GLOBAL IN-SITU OBSERVATORY FOR OCEAN DEOXYGENATION AND BIOGEOCHEMISTRY

Nicolas Gruber⁽¹⁾, Scott C. Doney⁽²⁾, Steven R. Emerson⁽³⁾, Denis Gilbert⁽⁴⁾, Taiyo Kobayashi⁽⁵⁾, Arne Körtzinger⁽⁶⁾, Gregory C. Johnson⁽⁷⁾, Kenneth S. Johnson⁽⁸⁾, Stephen C. Riser⁽³⁾, and Osvaldo Ulloa⁽⁹⁾

⁽¹⁾ Institute of Biogeochemistry and Pollutant Dynamics, ETHZ Zurich, Zurich, Switzerland

BIO-OPTICAL PROFILING FLOATS AS NEW OBSERVATIONAL TOOLS FOR BIOGEOCHEMICAL AND ECOSYSTEM STUDIES: POTENTIAL SYNERGIES WITH OCEAN COLOR REMOTE SENSING.

Hervé Claustre⁽¹⁾, Jim Bishop⁽²⁾, Emmanuel Boss⁽³⁾, Stewart Bernard⁽⁴⁾, Jean-François Berthon⁽⁵⁾, Christine Coatanoan⁽⁶⁾, Ken Johnson⁽⁷⁾, Aneesh Lotiker⁽⁸⁾, Osvaldo Ulloa⁽⁹⁾, Marie Jane Perry⁽¹⁰⁾, Fabrizio D'Ortenzio⁽¹¹⁾, Odile Hembise Fanton D'andon⁽¹²⁾, Julia Uitz⁽¹³⁾

⁽¹⁾ CNRS and University P. & M. Curie, Laboratoire d'Océanographie de Villefranche, 06230 Villefranche-sur-Mer, France, Email: claustre@obs-vlfr.fr

⁽²⁾ Earth Sciences Division, Lawrence Berkeley National Laboratory, One Cyclotron Road, M/S 90-1116,

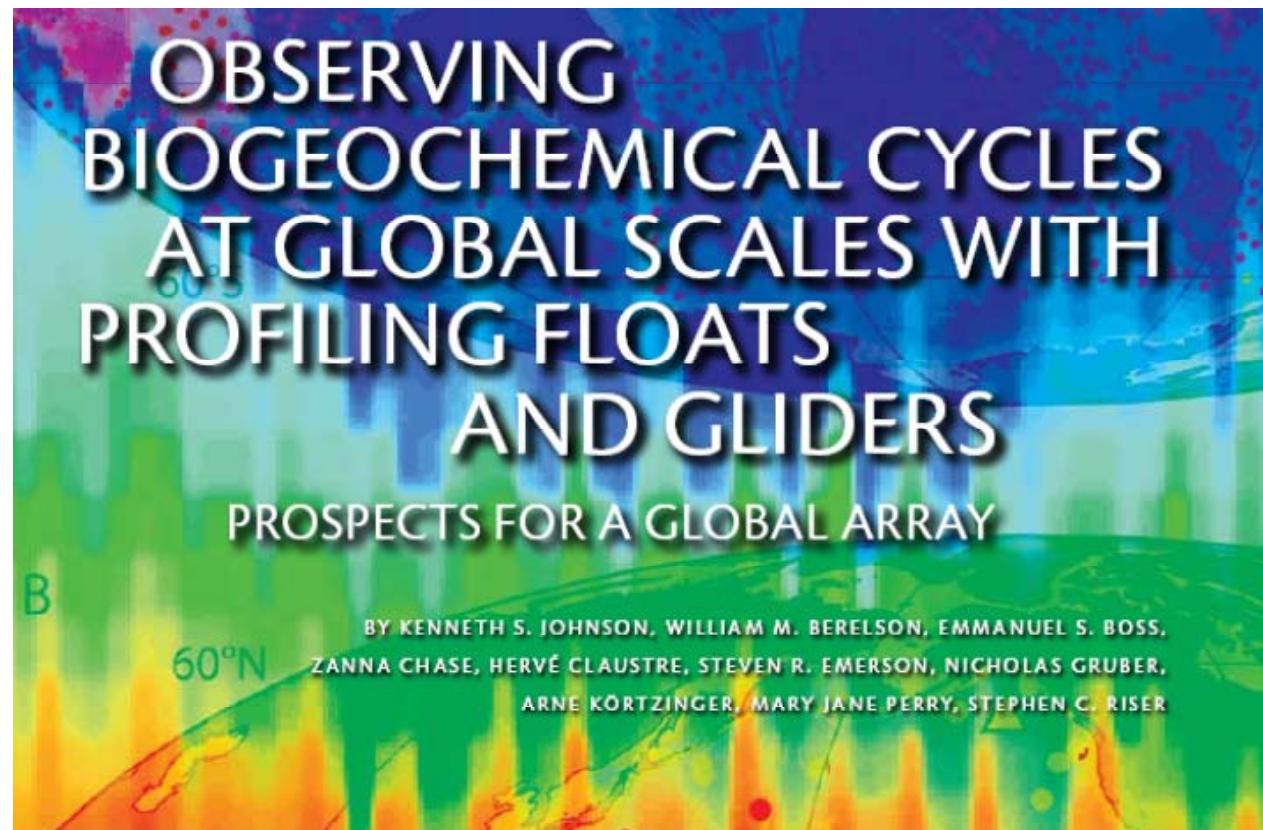
US Ocean Carbon & Biogeochemistry Scoping Workshop

Observing biogeochemical cycles at global scales with floats and gliders

28-30 April 2009, Moss Landing, CA

<http://www.whoi.edu/sites/OCBfloatsgliders>

Planning documents all point to next step: regional/basin scale programs



Sept. 2009 Issue of Oceanography



SOCCOM

Southern Ocean Carbon and Climate Observation and Modeling



What is the role of the Southern Ocean in the global climate system?

1

It accounts for **67-98%** of the excess heat that is transferred from the atmosphere into the ocean each year.

2

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

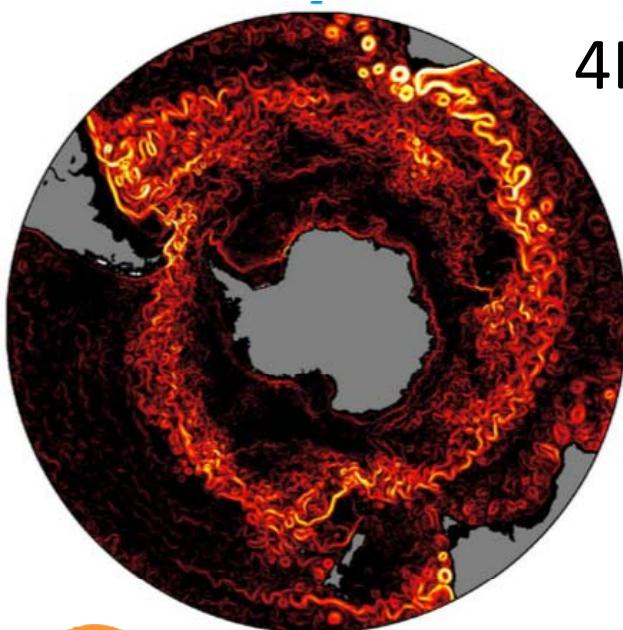
3

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.

200 profiling floats over 6 years with pH, NO_3^- , O_2 , biooptics with calibration tied to GO-SHIP observations



Southern Ocean State
Estimate model to get
4D fluxes



Improved coupled climate model (GFDL) predictions of Southern Ocean role in carbon and climate



SOCCOM

SOCCOM funded by NSF Polar Programs for 6 years with additional support from NOAA and NASA

Directorate



Jorge Sarmiento,
Princeton

Theme I
Observations



Lynne Talley,
SIO

Theme II
Modeling



Joellen Russell,
U. Arizona

Theme III
Education & Outreach



Heidi Cullen,
Climate Central



Ken Johnson



Steve Riser, U. W.



Biooptics (Emmanuel
Boss, Maine)

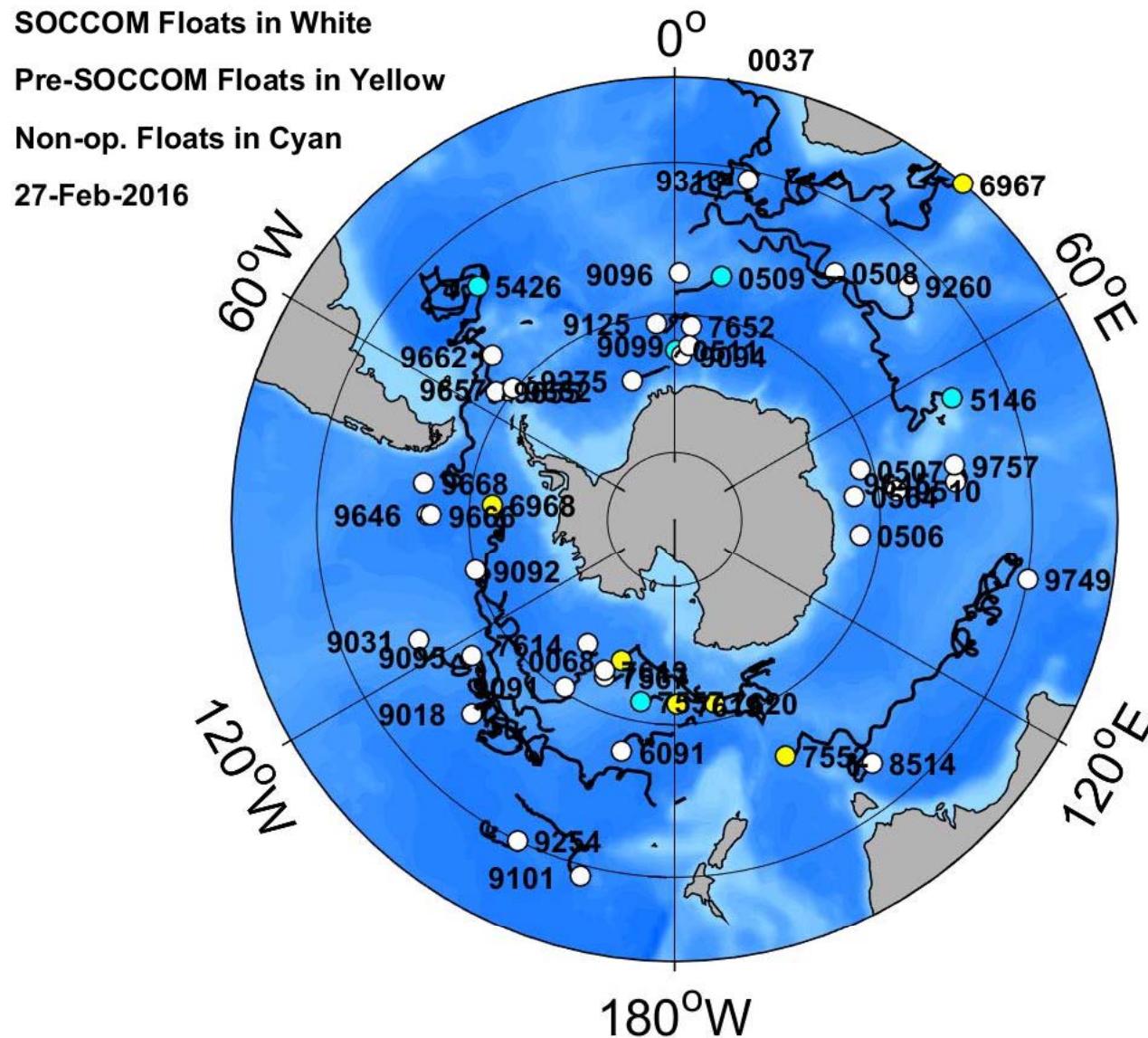


SOCCOM

23 senior researchers at 11 institutions



Institution	Collaborators	Contribution
CSIRO Australia	Tom Trull, Zanna Chase, Steve Rintoul, Bernadette Sloyan, Susan Wijffels, Peter Strutton, Bronte Tillbrook	Float deployment and calibration support on one cruise in Year 1 and three Indian Ocean cruises in Year 2; processing of carbon samples
AWI Germany	Olaf Boebel, Gerd Rohardt	Float deployment and calibration support on 2014-15 Polarstern cruise; CTD/salinity data sets
NERC U.K.	Yvonne Firing	Float deployment and calibration on Drake Passage cruise in Year 2
GO-SHIP Internat.		P16S (Year 1), I08S and P15S (Year 2) float deployment support and full calibration chemistry

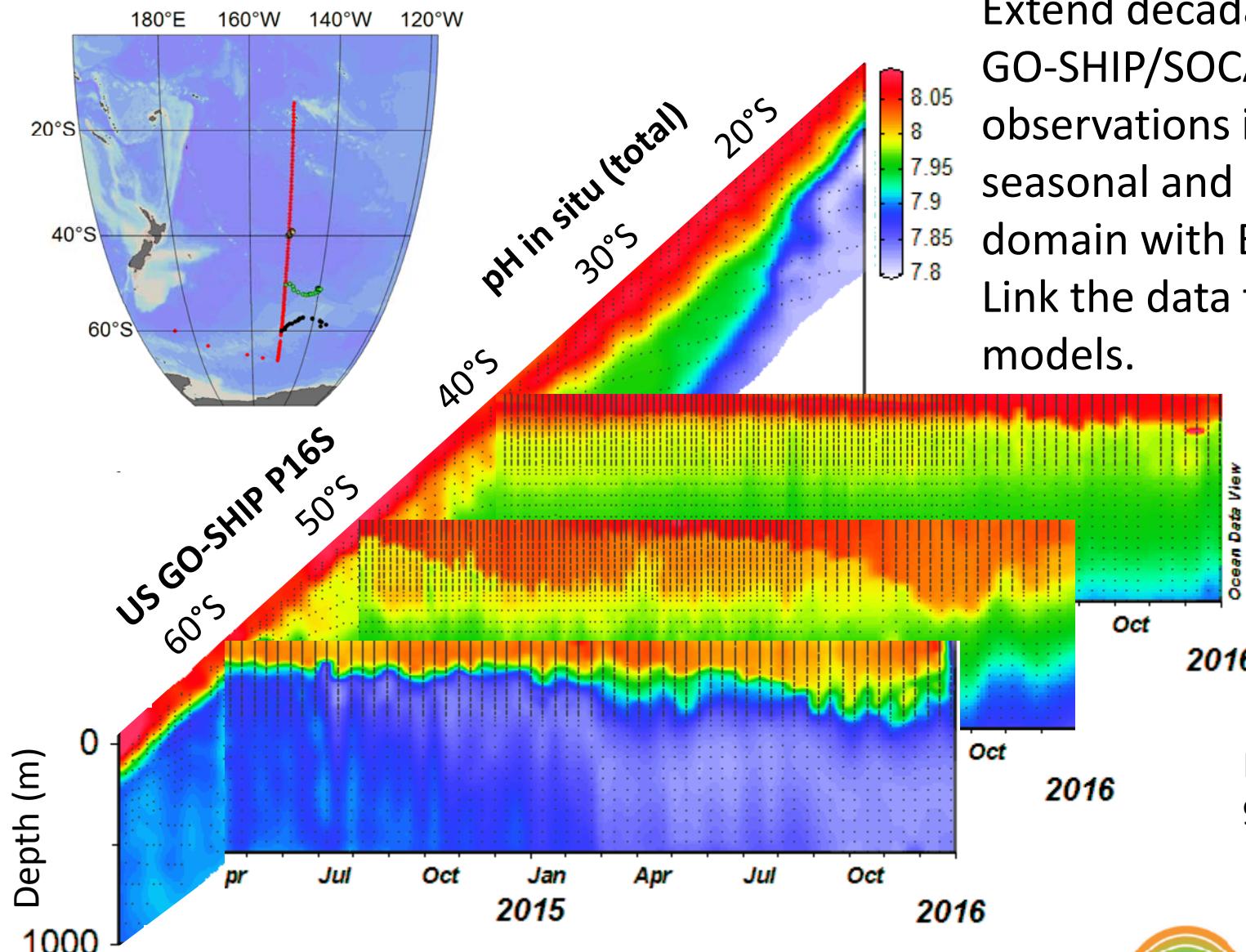


- 37 BGC floats deployed from March 2014 to date
 - 16 more deployments in 2016 (I8S, P15S)
 - ~37 in construction for 2016/17 season
 - Funded for ~100 more 2017/2020.

All data public in real time at soccom.princeton.edu



SOCOM



Extend decadal-scale
GO-SHIP/SOCAT carbon
observations into the
seasonal and interannual
domain with BGC floats.
Link the data to high res.
models.



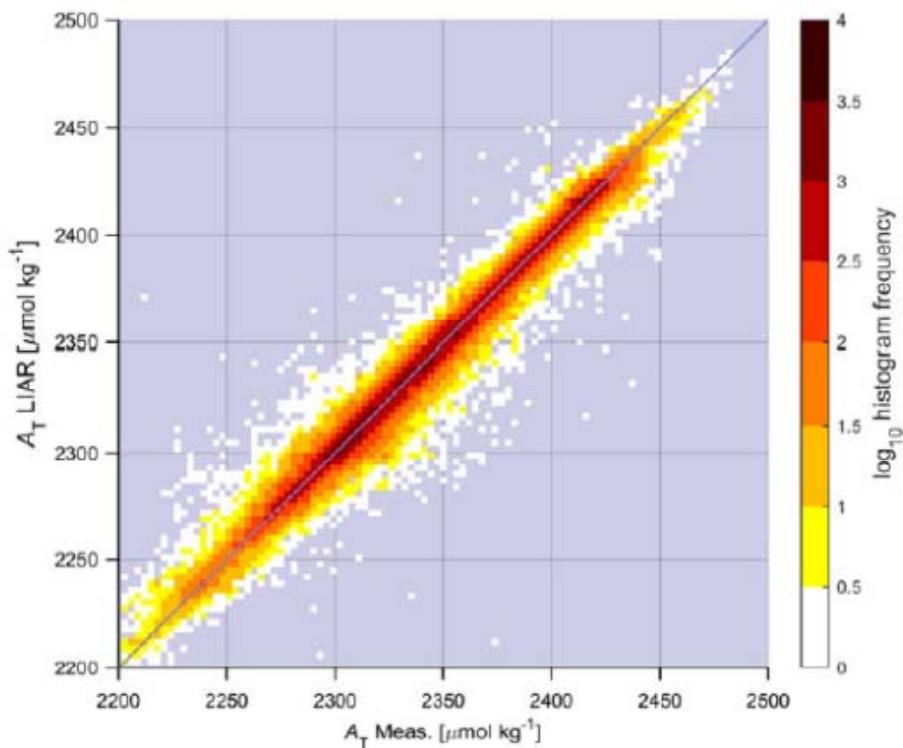
Locally interpolated alkalinity regression for global alkalinity estimation

B. R. Carter,^{*1,2} N. L. Williams,³ A. R. Gray,⁴ R. A. Feely²

$$\text{Alk}_{\text{est}} = f(S, \theta, \text{AOU})$$

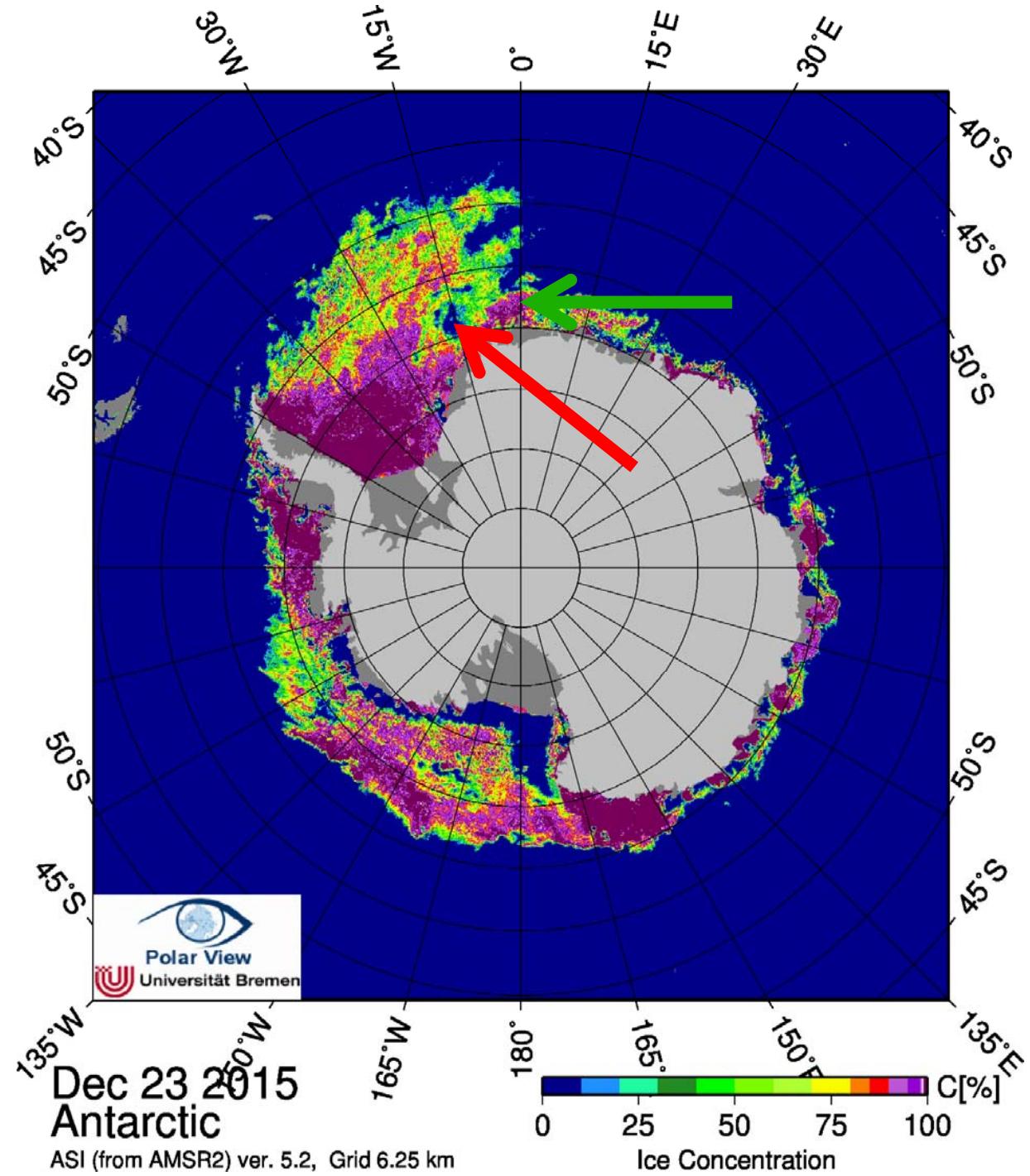
Algorithm trained using
bottle data

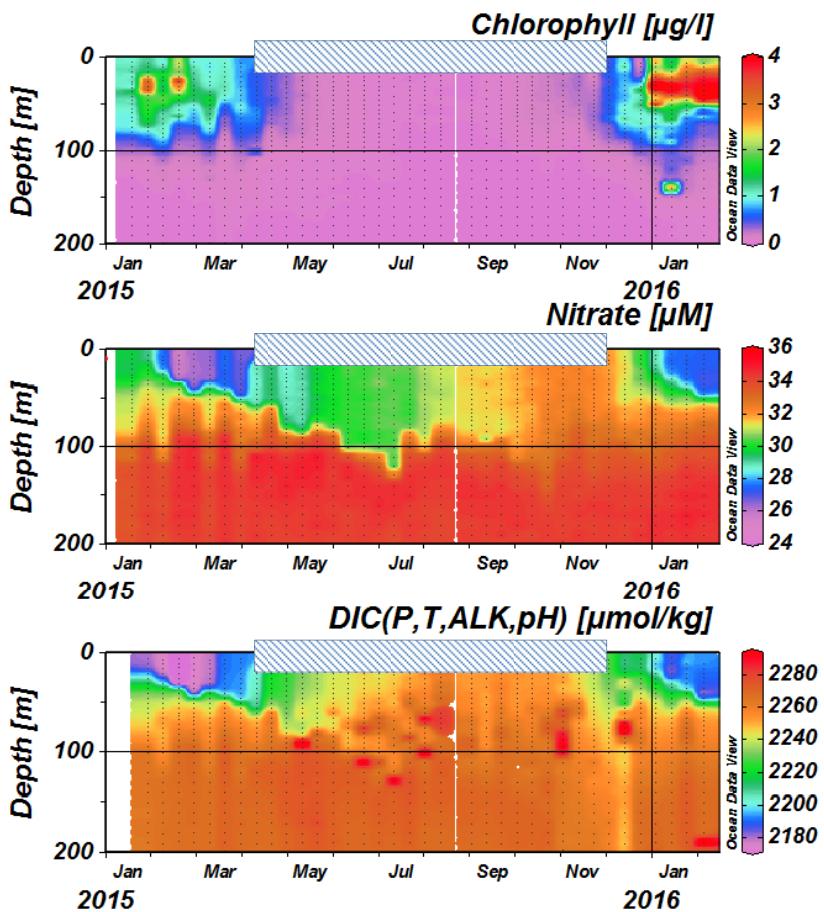
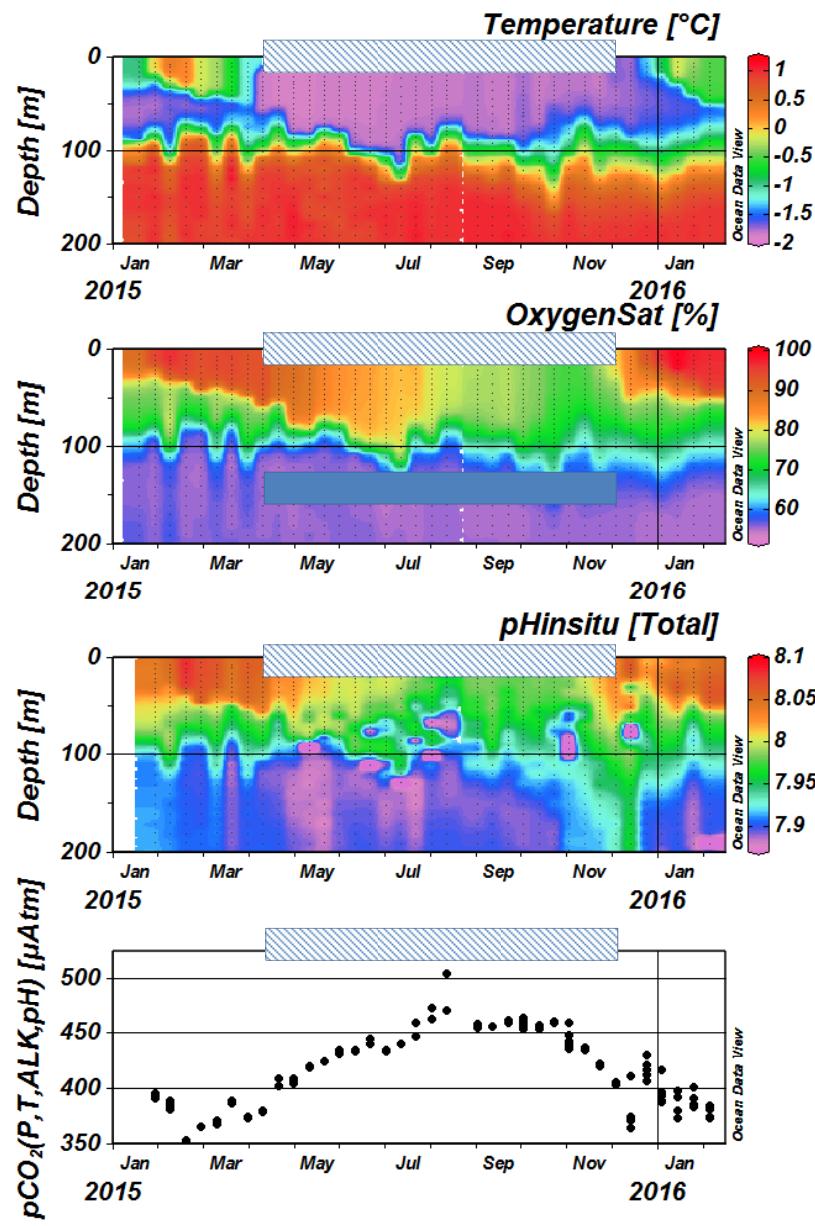
GLODAPv1 + PACIFICA +
CARINA



SOCCOM

SOCCOM float
9275 launched
18 Jan. 2015 at
 67°S , 0°E from
the German
R/V Polarstern.
Reappeared 23
Dec. 2015 at
 68.5°S , 15°W
after winter
under ice.





Float
9275



SOCOM

Mixed layer $\Delta p\text{CO}_2$

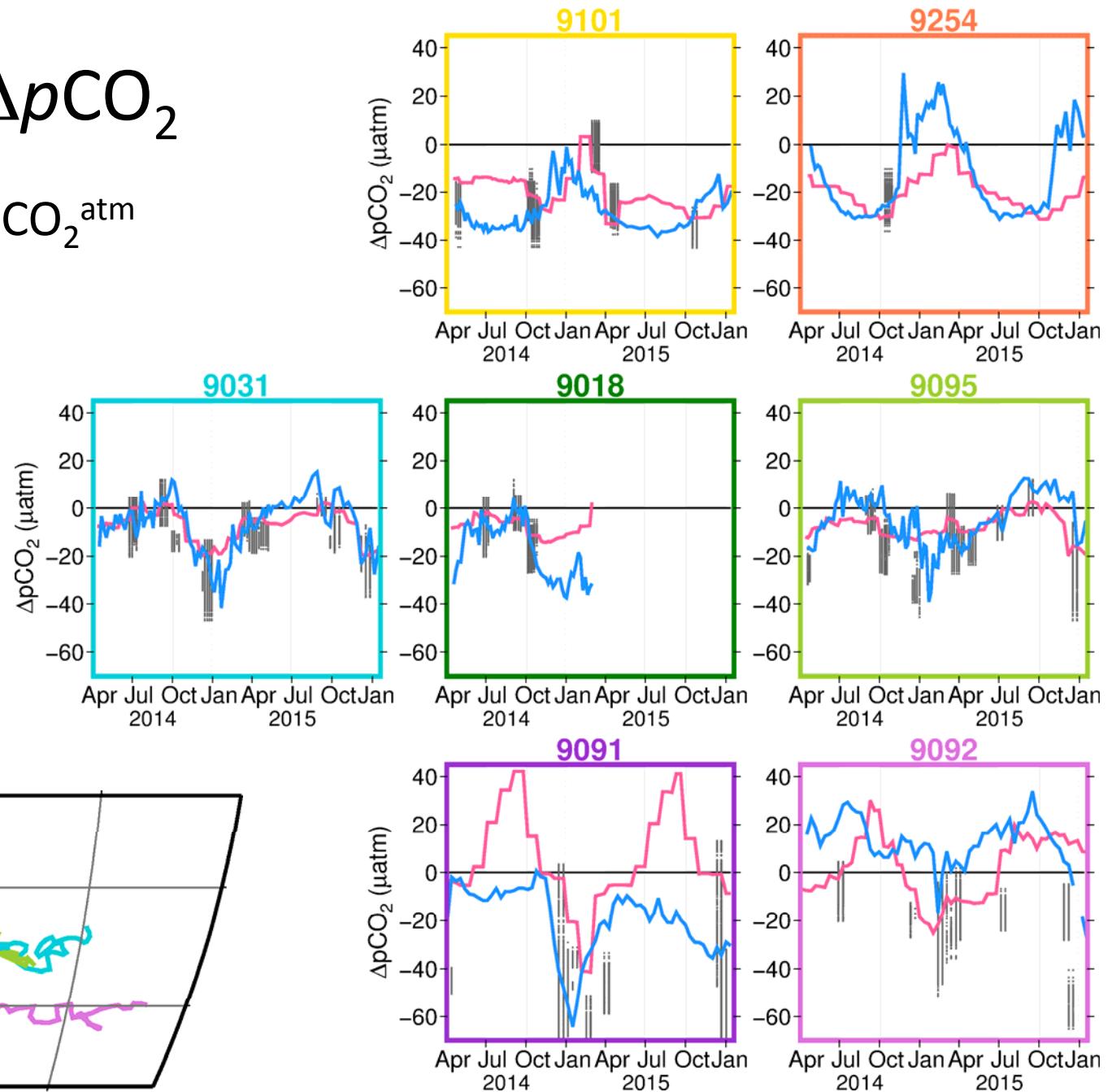
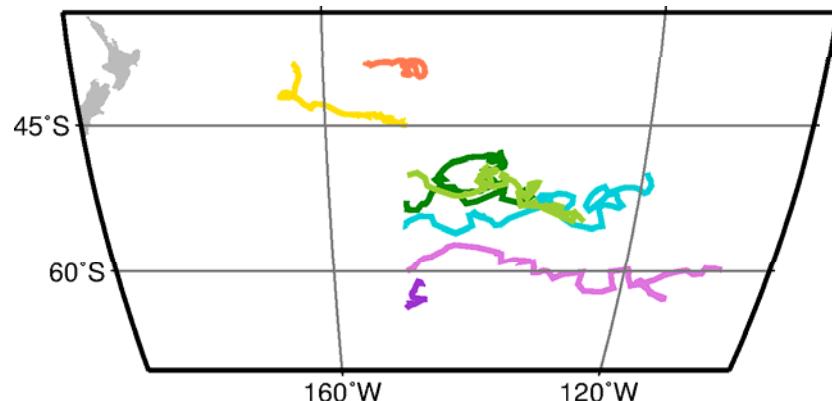
$$\Delta p\text{CO}_2 = p\text{CO}_2^{\text{ocn}} - p\text{CO}_2^{\text{atm}}$$

Float

Takahashi et al. 2009

SOCAT v3 observations

Alison Gray,
Princeton



Cumulative CO₂ Uptake

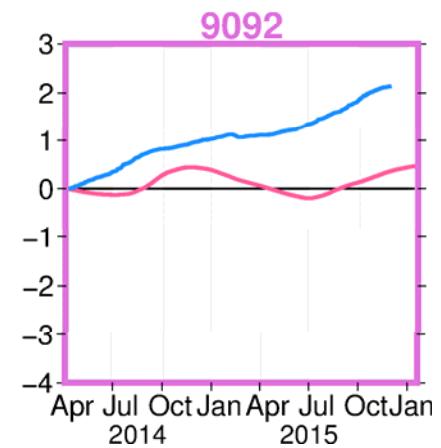
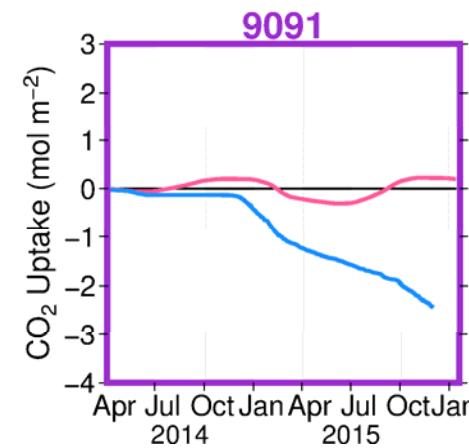
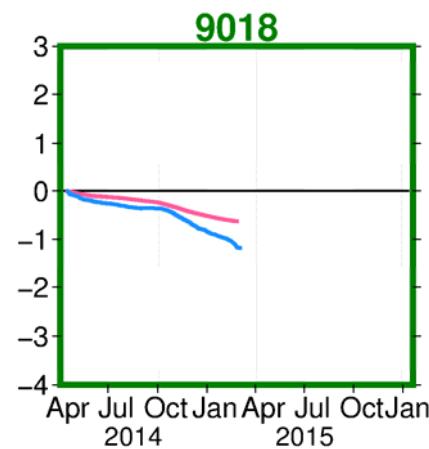
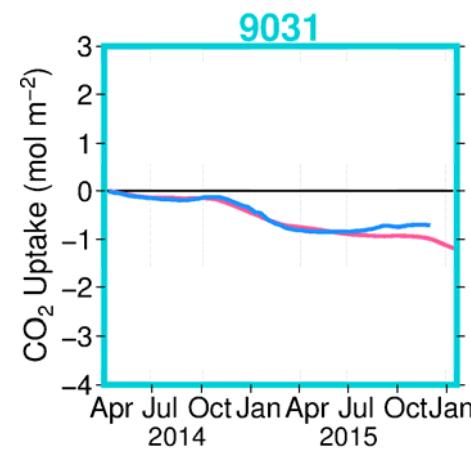
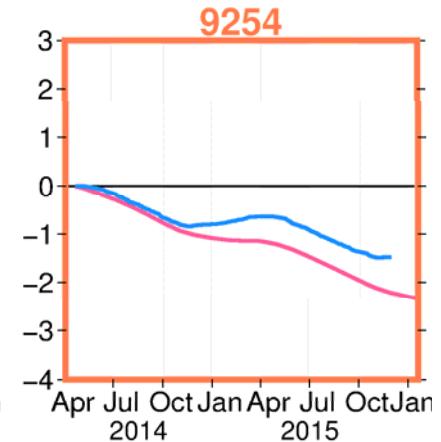
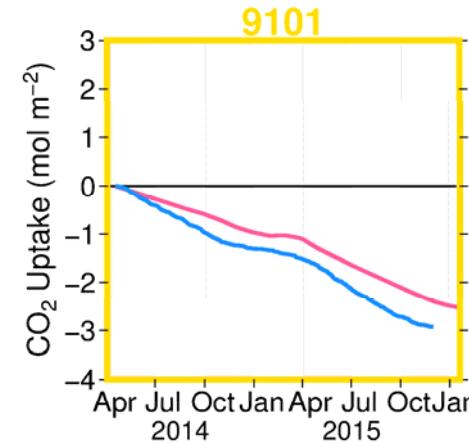
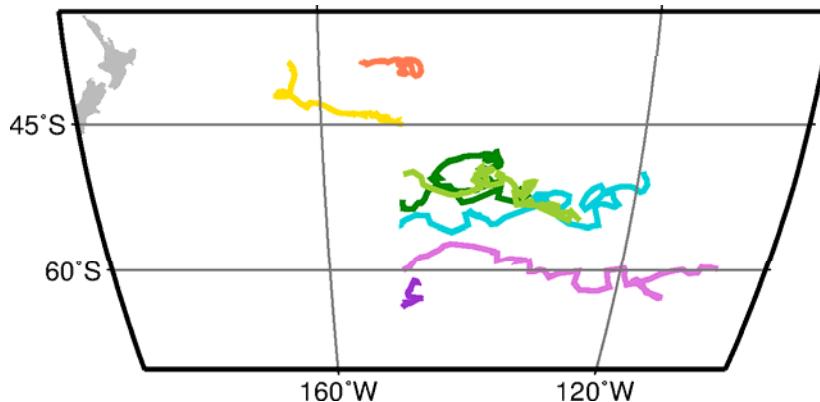
(-) into the ocean

ERA-Interim 6-hour winds

Wanninkhof 2014 coefficient

Alison Gray,
Princeton

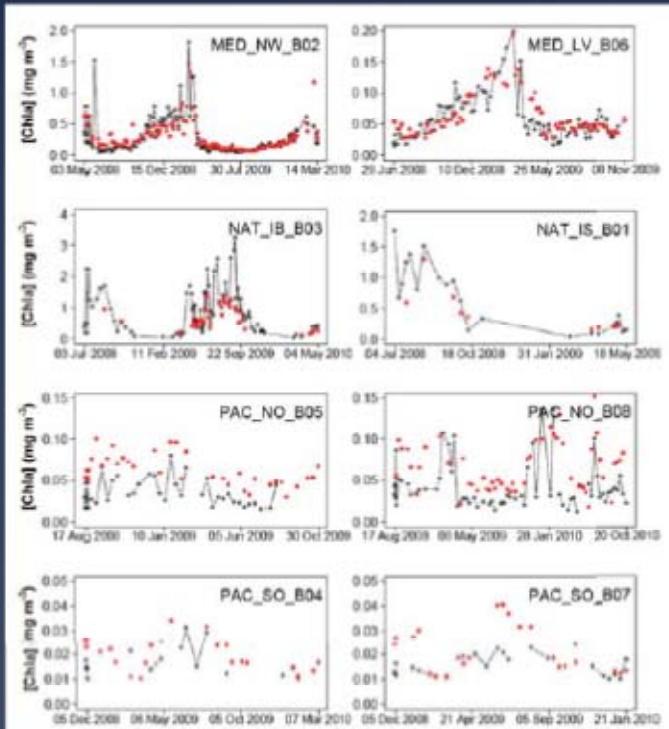
Float
Takahashi et al. 2009



“Bio-data” management issues and perspectives #3

*Delayed mode procedure are being developed
(combination of sensors)*

Chlorophyll a



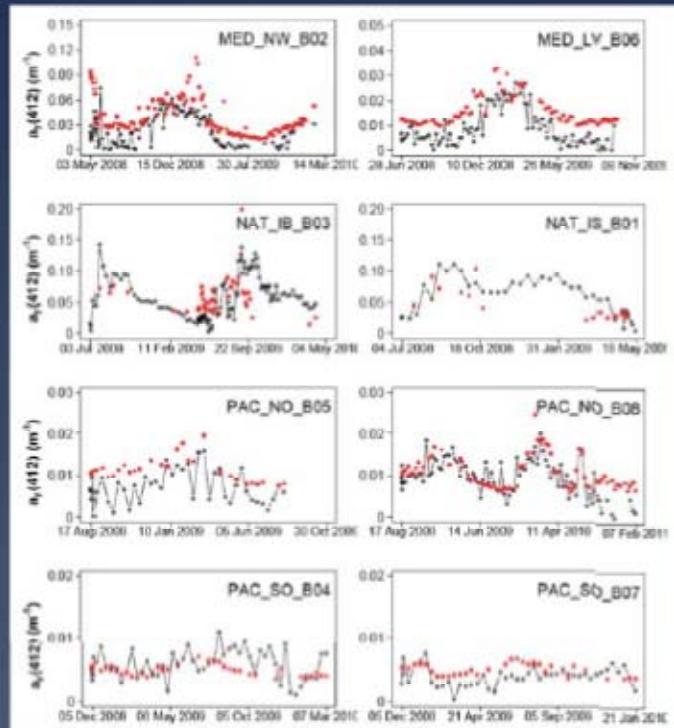
Med Sea

North Atlantic
sub-polar gyre

North Pacific
sub-tropical gyre

South Pacific
sub-tropical gyre

CDOM



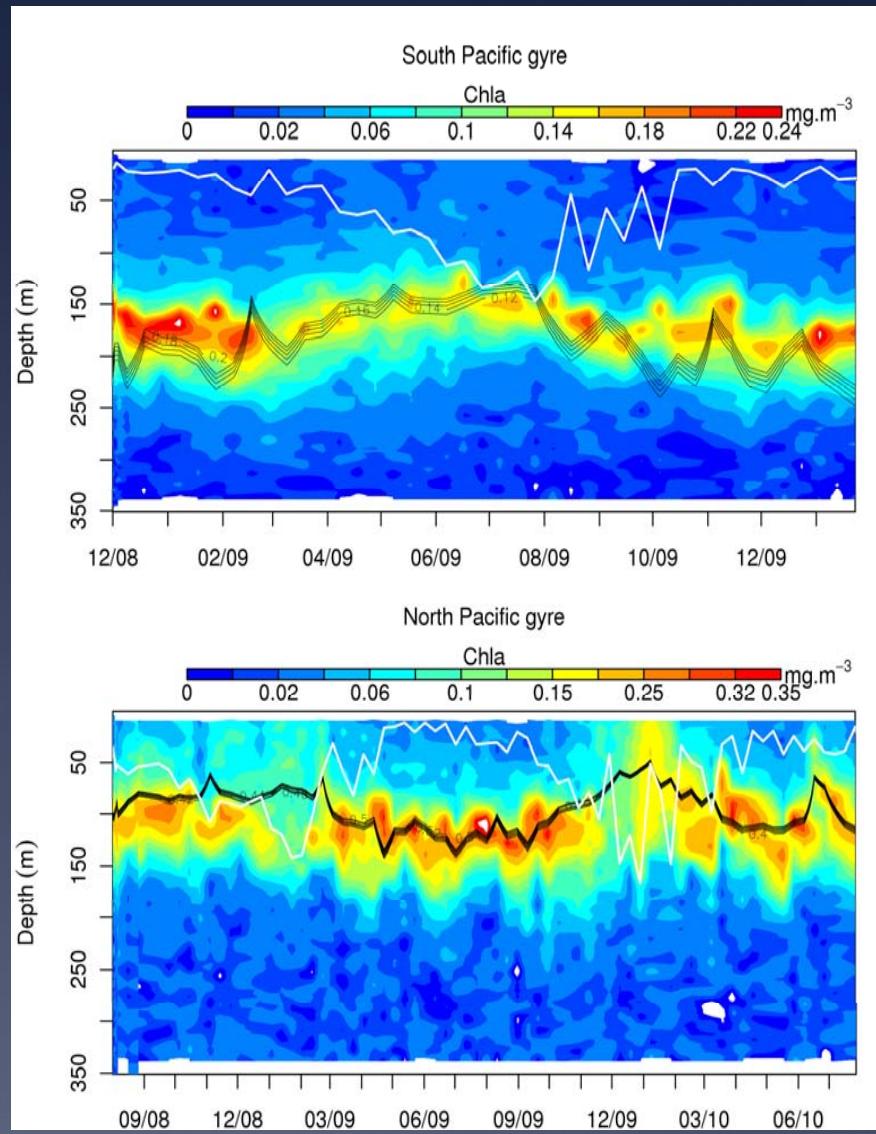
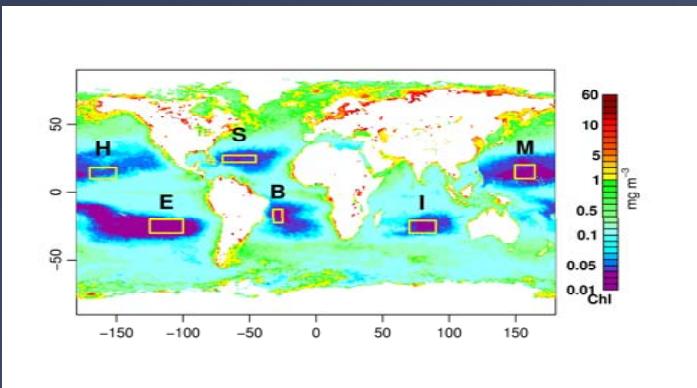
surface float / MODIS

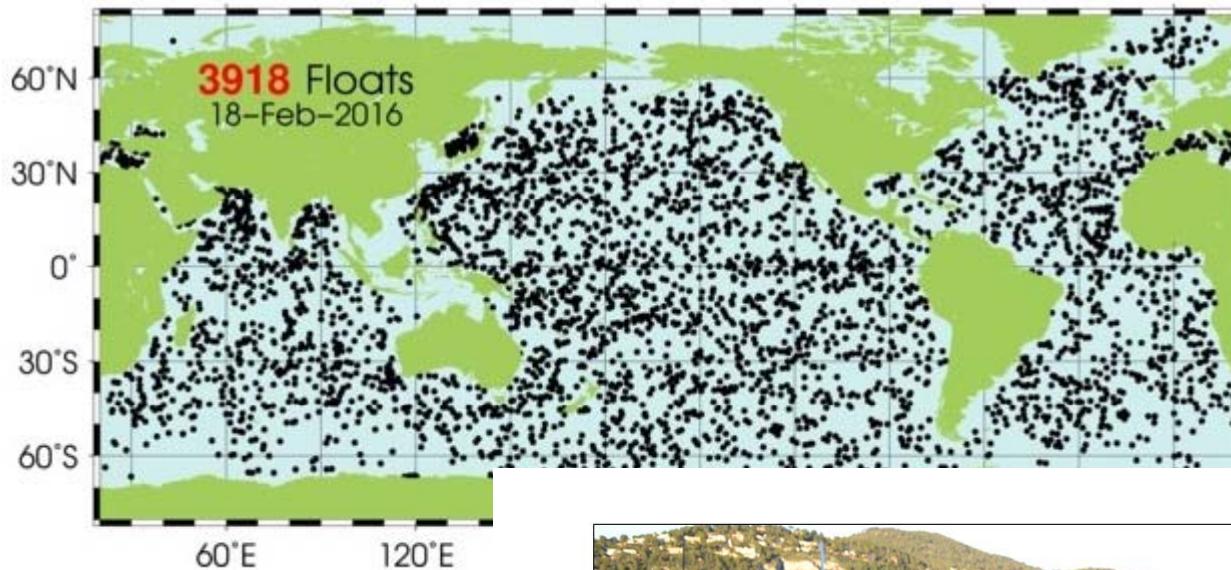
Xing, X., et al. (2011). *Journal of Geophysical Research*, 116, C06020, doi: 10.1029/2010JC006899

Xing, X., et al. (submitted), *Journal of Geophysical Research*, submitted

sub-tropical gyres

- 40% of the global ocean.
- primary production (NCP): controversial
 - ✓ classical (incubation) methods & models: 2-3 times lower than:
 - ✓ «non-intrusive» techniques (O₂ isotopes; O₂ floats budget)
- inter-gyre variability :
 - ✓ N limitation (North & South Pacific) vs P limitation (North Atlantic)
 - ✓ seasonal





Draft implementation plan being written.

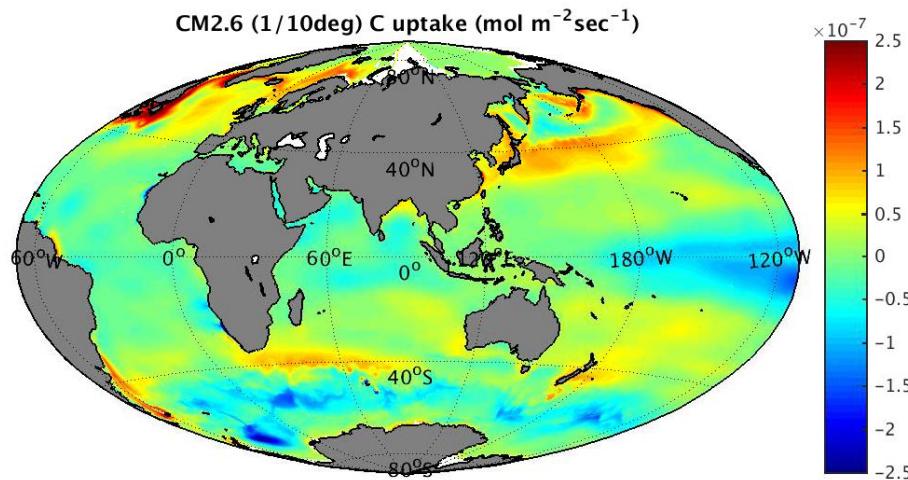
Planning for a global network has begun.
First meeting in Villefranche-sur-Mer, 11-13 January.



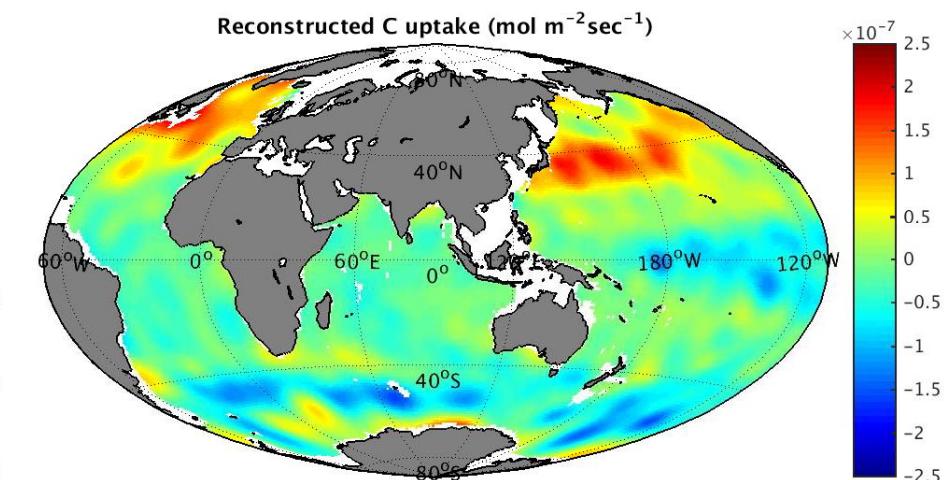
Biogeochemical-Argo Network - Group photo

Reconstruction of the CO₂ flux

- Reconstruction recovers the large-scale structure
- “Shallow” (<1km) and ice-covered regions are not sampled well by Argo; some of them are important for the CO₂ uptake.



Model-simulated CO₂ flux ($\text{mol m}^{-2} \text{sec}^{-1}$)
on the model (~1/10°) grid.
Total uptake: 2.7 Gt CO₂ year⁻¹.



Reconstructed CO₂ flux ($\text{mol m}^{-2} \text{sec}^{-1}$),
from 1000 floats, on the 1°x1° grid.
Total uptake: 2.9 Gt CO₂ year⁻¹.

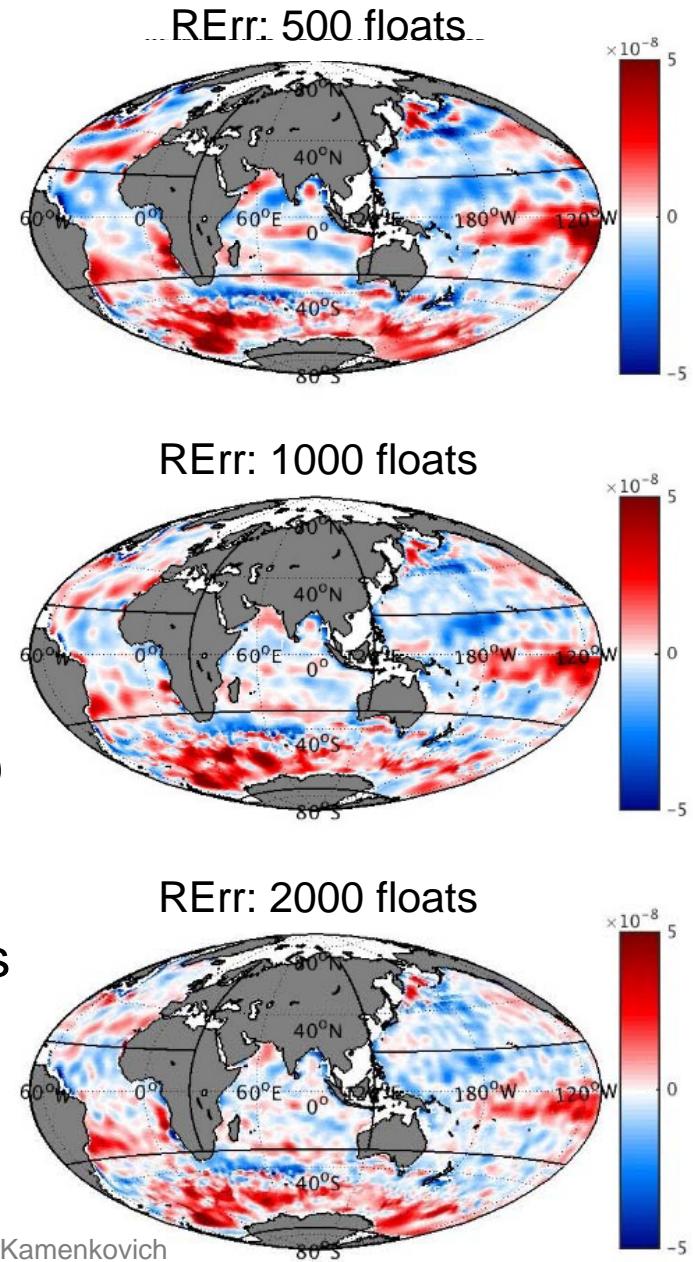


SOCCOM

Reconstruction Errors (RErr): Difference between reconstructed and original fields for air-sea CO₂ flux

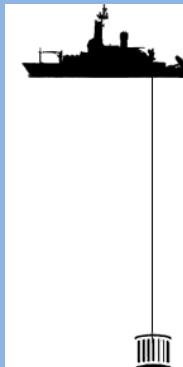
- Reconstruction skill increases with an increasing number of floats
- Changes are most pronounced between 500 and 1000 floats – less additional benefit from 2000 floats
- Reconstruction near coasts and at high latitudes is most challenging (few Argo profiles!)
- Argo array cannot (and was not designed to) resolve sharp gradients, so RErr are large in ACC fronts and near western boundary currents (see also Kamenkovich et al. 2009)
- Patterns are consistent with previous studies

Units are mol m⁻² sec⁻¹



- BGC Argo is an extension of Argo. It follows main Argo philosophy.
 - A BGC Argo float carries O_2 /pH/ NO_3^- chemical sensors, chlorophyll fluorescence, optical backscatter, & downwelling radiance sensors.
 - It profiles to near 2000 m depth.
 - Target array size is ~1000 BGC floats.
 - All data are public in real time.
-
- With a 4 year lifetime, 250 floats/yr will be required
 - \$25,000,000/year at \$100,000/float lifetime cost!!!!
 - BGC Argo should be a sub-committee that reports to the Argo Steering Team.

Global BGC Argo

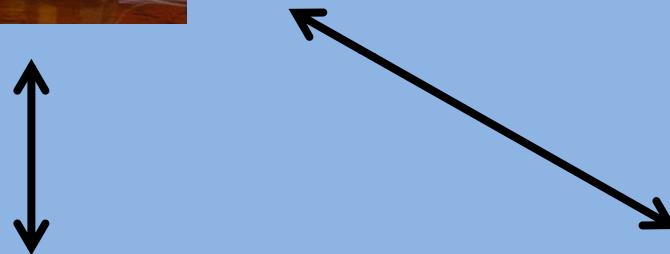


GO-SHIP

TOWARDS A SUSTAINED GLOBAL SURVEY OF THE OCEAN INTERIOR

GO-SHIP brings together scientists with interests in physical oceanography, the carbon cycle, marine biogeochemistry and ecosystems, and other users and collectors of hydrographic data to develop a globally coordinated network of sustained hydrographic sections as part of the global ocean/climate observing system.

GO-SHIP is a major contributor to WCRP's [Climate Variability and Predictability Experiment \(CLIVAR\)](#) and [International Ocean Carbon Coordination Project](#).
GO-SHIP is part of the [Global Climate Observing System / Global Ocean Observing System \(GCOS / GOOS\)](#).



Ocean color, SST, Altimetry, LIDAR

