How will we measure the response of carbon export in the ocean to climate change?

Ken Johnson

MBARI

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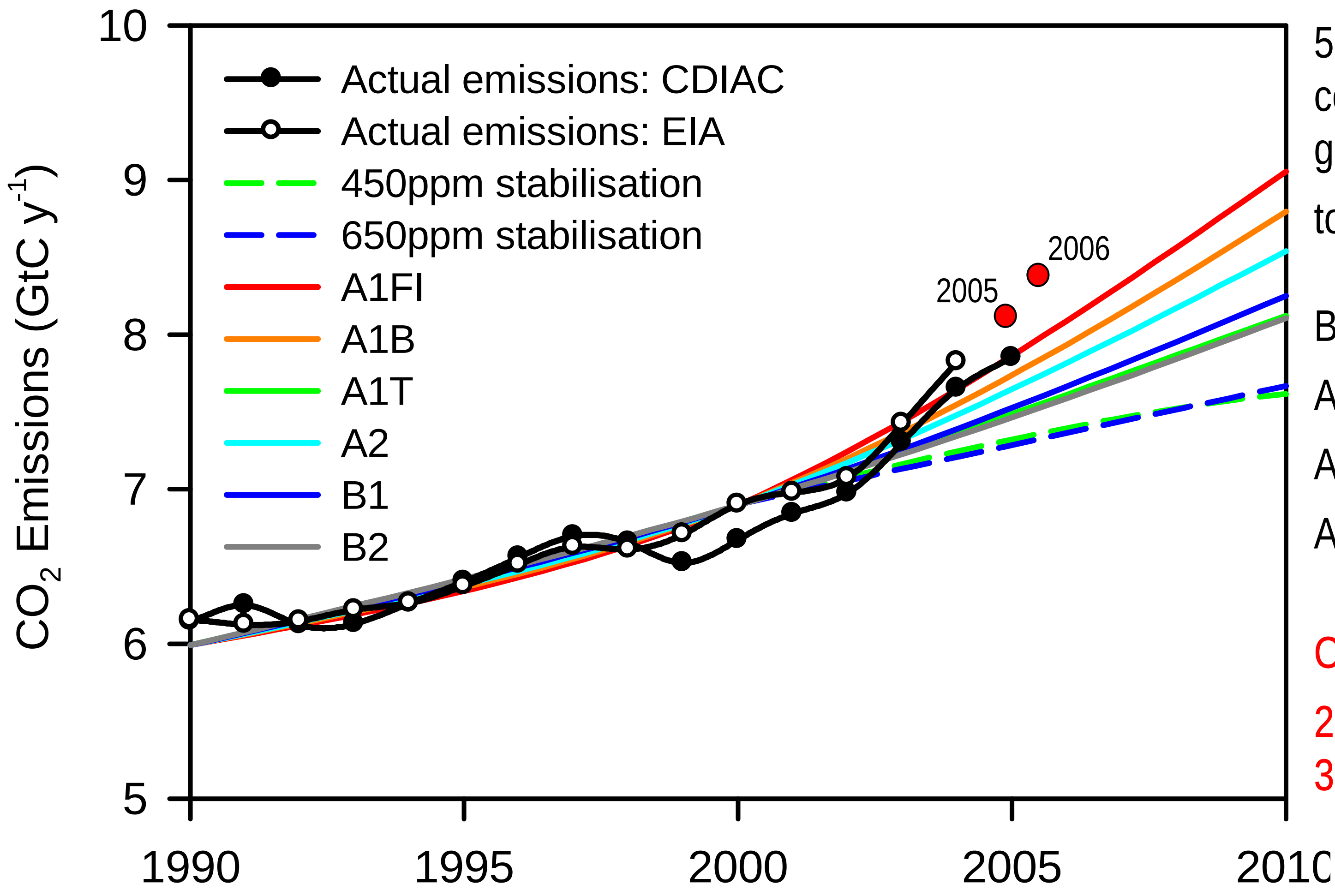
Outline:

- Why care about ocean carbon flux?
- Future changes?
- How would we measure changes globally?
  - Biogeochemical sensors on profiling floats
  - Using float sensors to monitor carbon export on the scale (almost) of an ocean basin

Trajectory of Global Fossil Fuel Emissions



50-year constant growth rates to 2050

B1 1.1%,

A1B 1.7%,

A2 1.8%

A1FI 2.4%

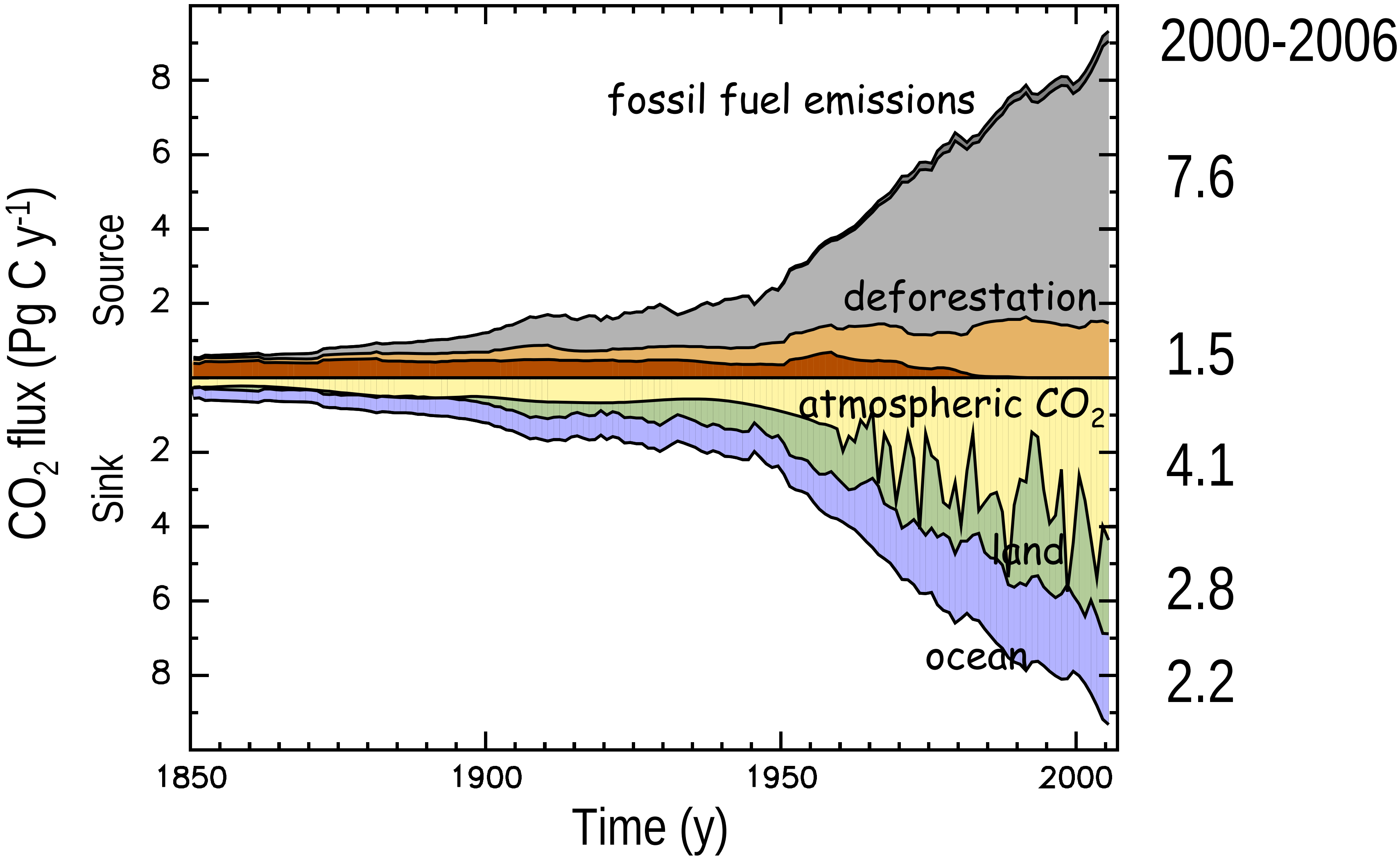
Observed

2000-2006

3.3%

Raupach et al. 2007, PNAS

Perturbation of Global Carbon Budget (1850-2006)



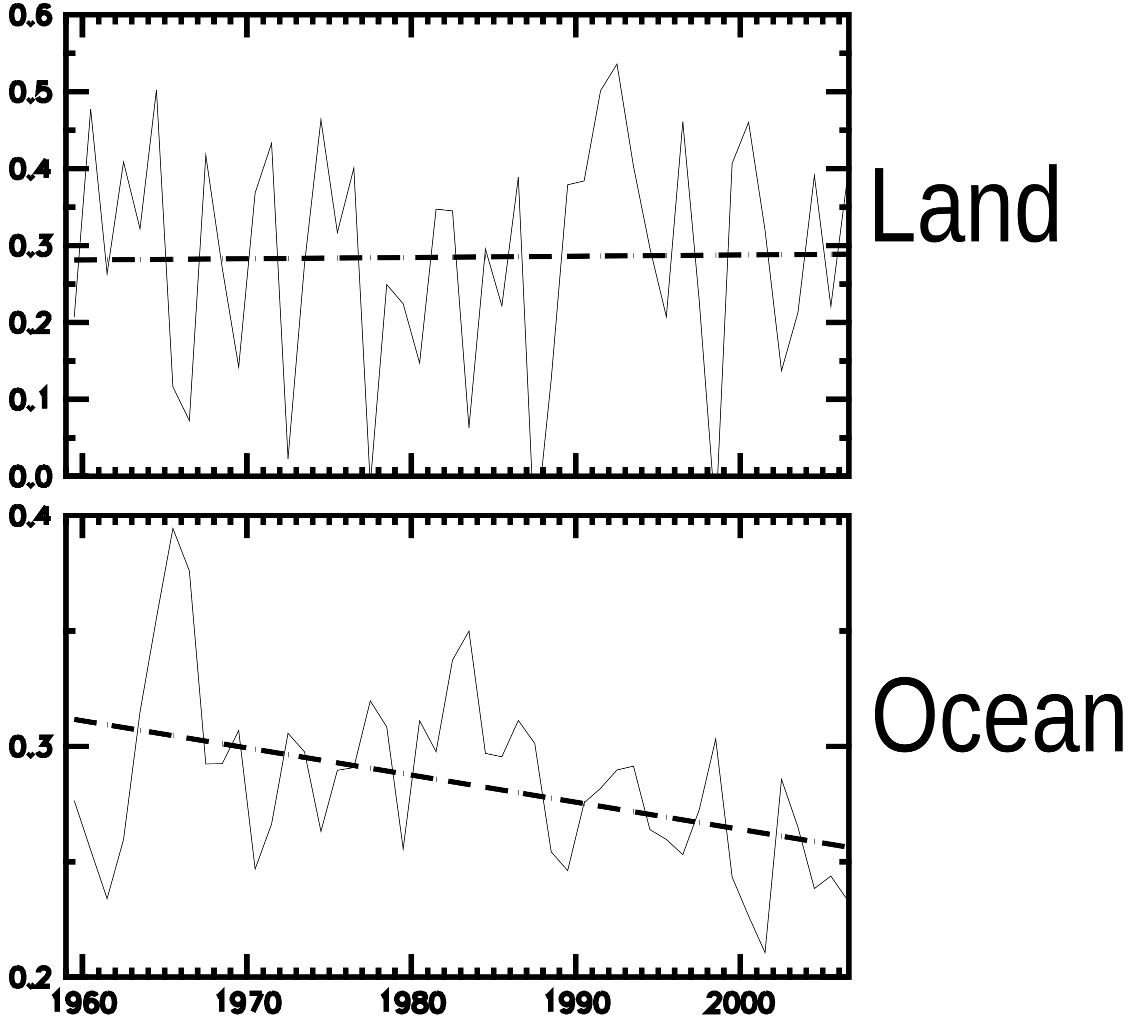
Le Quéré, unpublished; Canadell et al. 2007, PNAS

Saturation of the Southern Ocean CO_2 Sink Due to Recent Climate Change

Corinne Le Quéré,[1,2,3]* Christian Rödenbeck,[1] Erik T. Buitenhuis,[1,2] Thomas J. Conway,[4] Ray Langenfelds,[5] Antony Gomez,[6] Casper Labuschagne,[7] Michel Ramonet,[8] Takakiyo Nakazawa,[9] Nicolas Metzl,[10] Nathan Gillett,[11] Martin Heimann[1]

Based on observed atmospheric carbon dioxide (CO_2) concentration and an inverse method, we estimate that the Southern Ocean sink of CO_2 has weakened between 1981 and 2004 by 0.08 petagrams of carbon per year per decade relative to the trend expected from the large increase in atmospheric CO_2. We attribute this weakening to the observed increase in Southern Ocean winds resulting from human activities, which is projected to continue in the future. Consequences include a reduction of the efficiency of the Southern Ocean sink of CO_2 in the short term (about 25 years) and possibly a higher level of stabilization of atmospheric CO_2 on a multicentury time scale.

The Efficiency of Natural Sinks: Land and Ocean Fractions



Canadell et al. 2007, PNAS

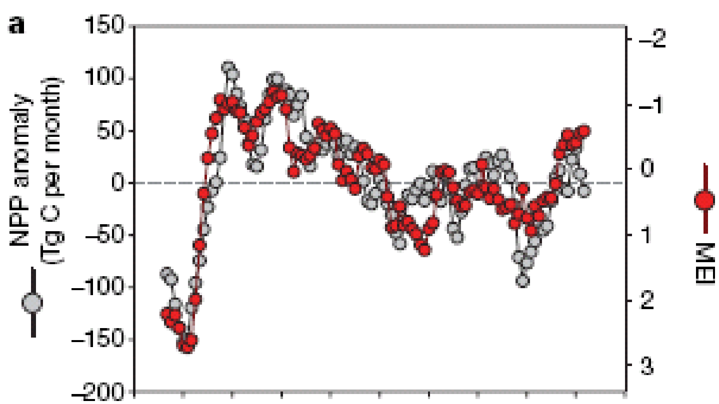
nature Vol 444|7 December 2006|doi:10.1038/nature05317

LETTERS

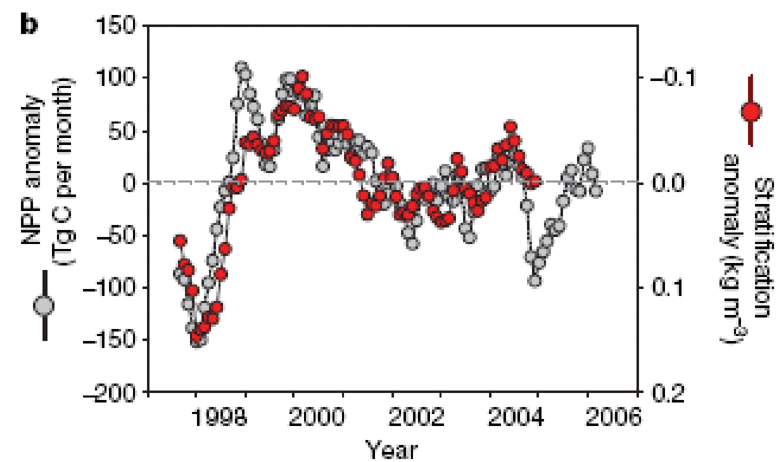
Global satellite time series, but only measure ocean color and infer productivity.

Climate-driven trends in contemporary ocean productivity

Michael J. Behrenfeld[1], Robert T. O'Malley[1], David A. Siegel[3], Charles R. McClain[4], Jorge L. Sarmiento[5], Gene C. Feldman[4], Allen J. Milligan[1], Paul G. Falkowski[6], Ricardo M. Letelier[2] & Emmanuel S. Boss[7]

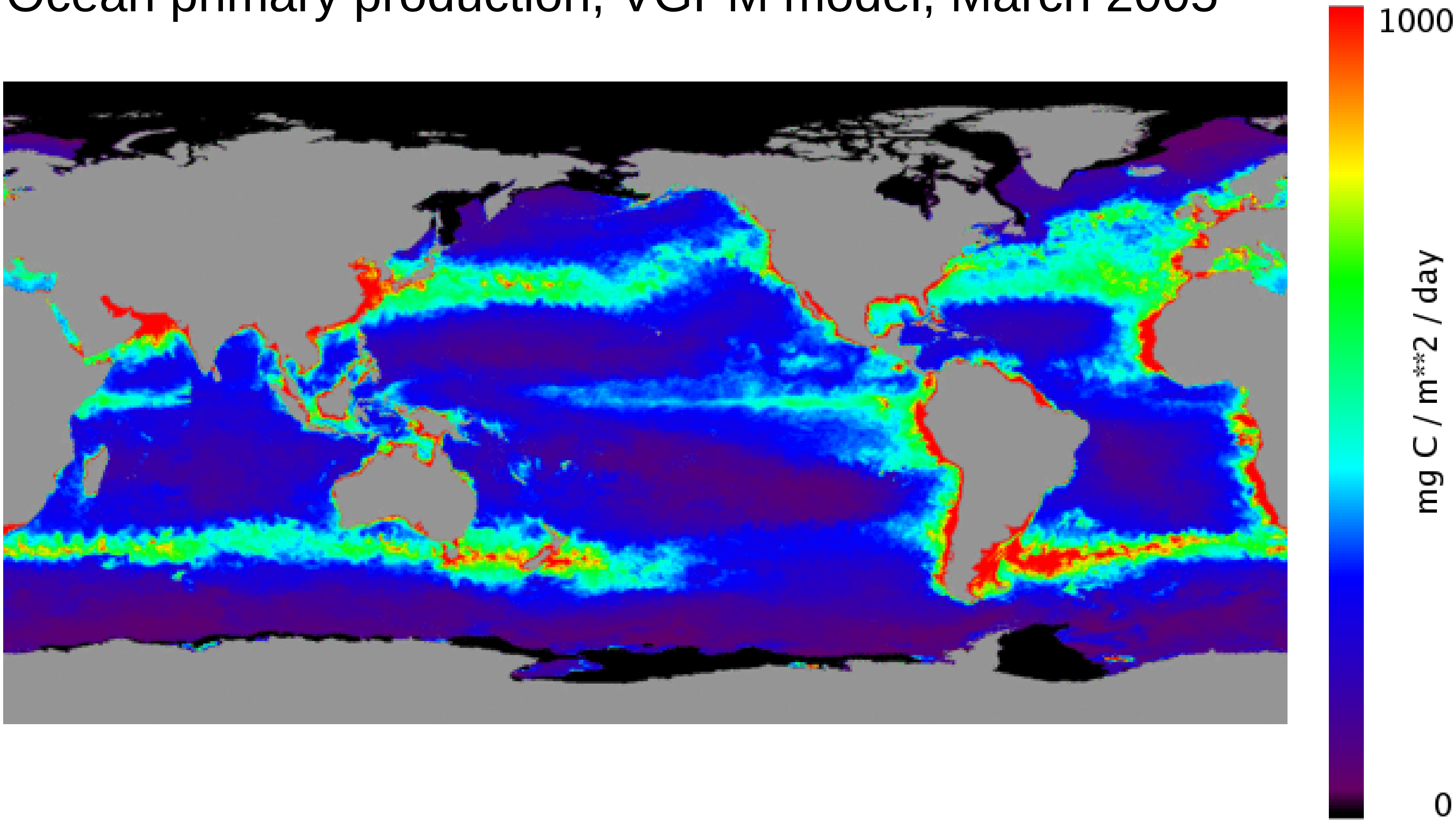


Variation in Pri. Prod and Multi-variate ENSO Index.



Variation in Pri. Prod and surface density gradient of ocean.

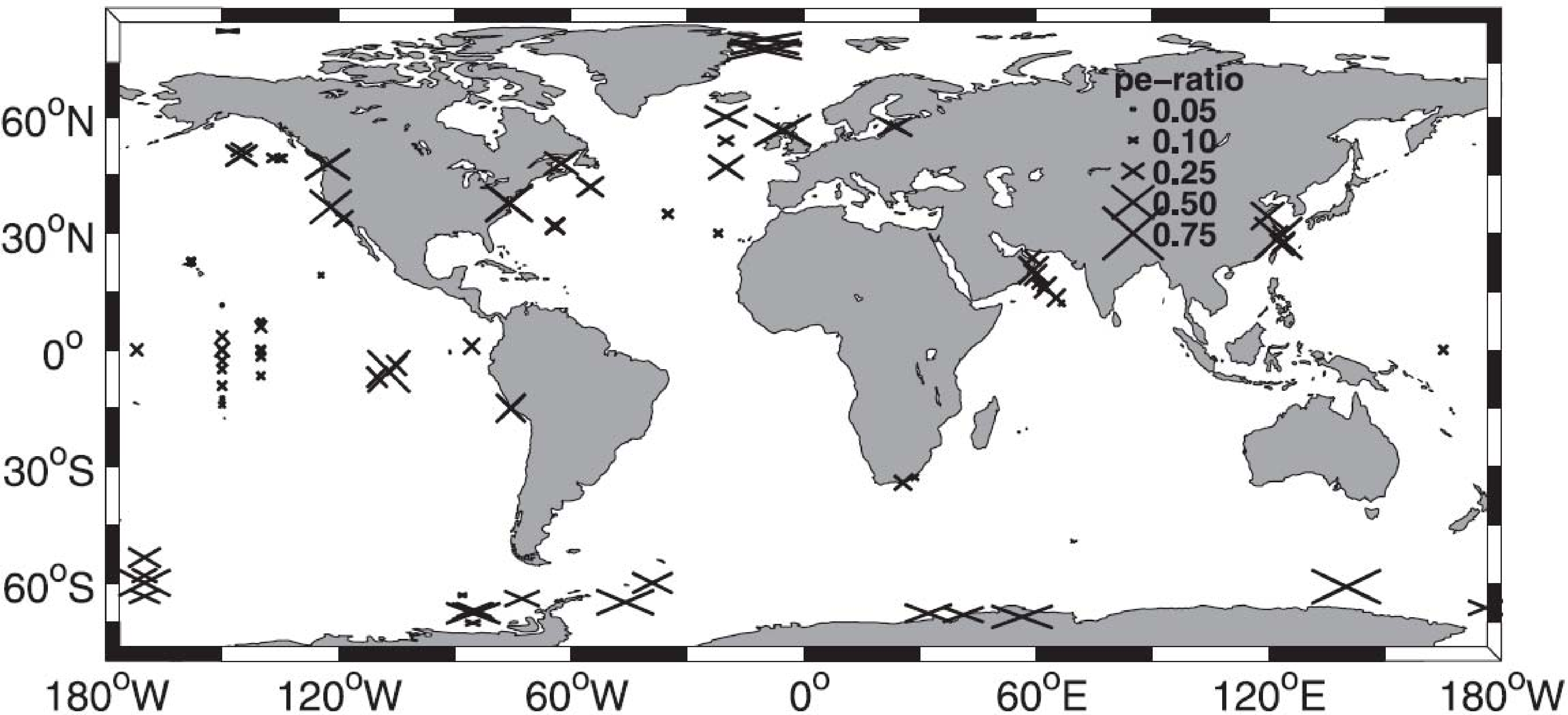
Ocean primary production, VGPM model, March 2005



http://web.science.oregonstate.edu/ocean.productivity/index.php

122 data points with production and export over 20 years using common methods (14C uptake, sediment traps….).

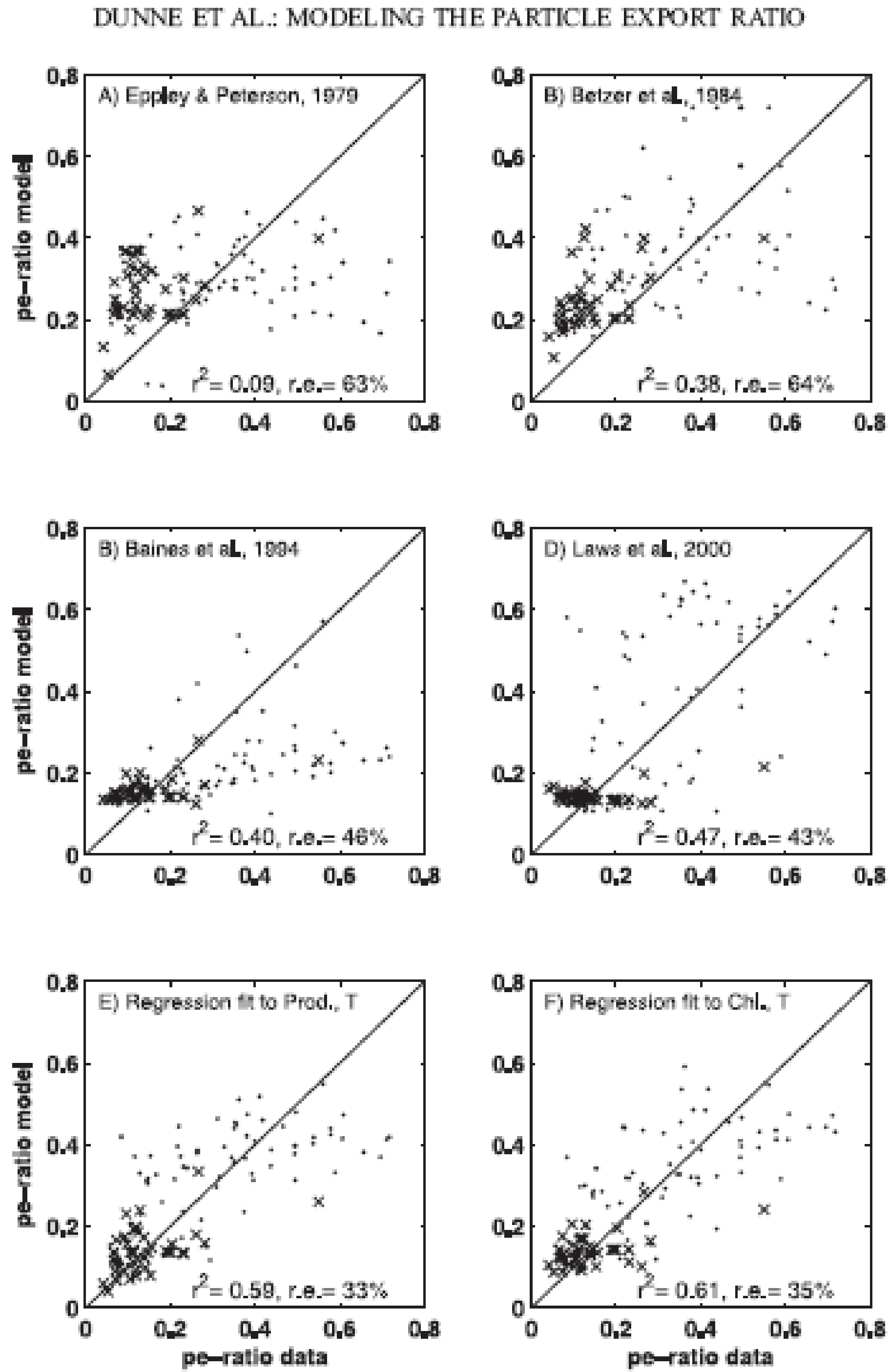
DUNNE ET AL.: MODELING THE PARTICLE EXPORT RATIO



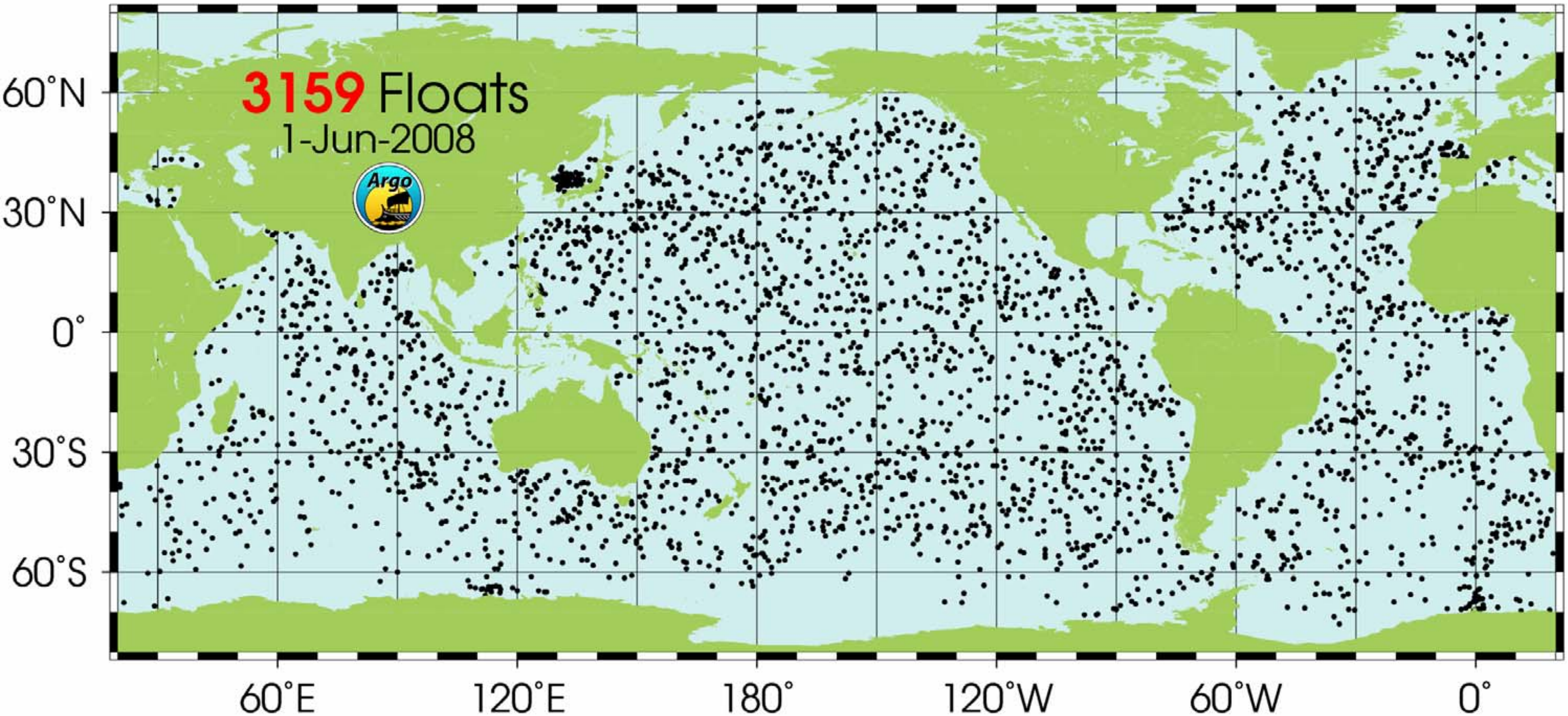
GLOBAL BIOGEOCHEMICAL CYCLES, VOL. 19, GB4026, doi:10.1029/2004GB002390, 2005

Models and satellite observations alone will not provide adequate constraints on changing export.

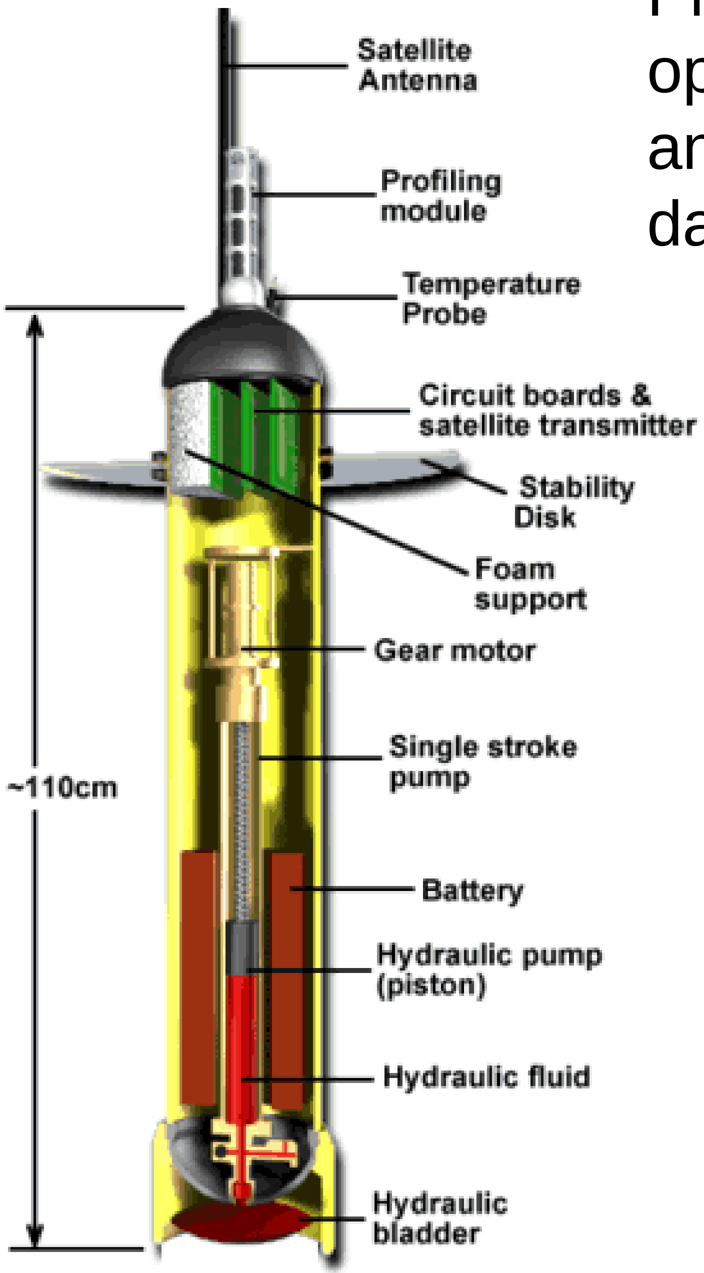
More observations of the changing system are required. We need a new approach to biogeochemical observing at the global scale.

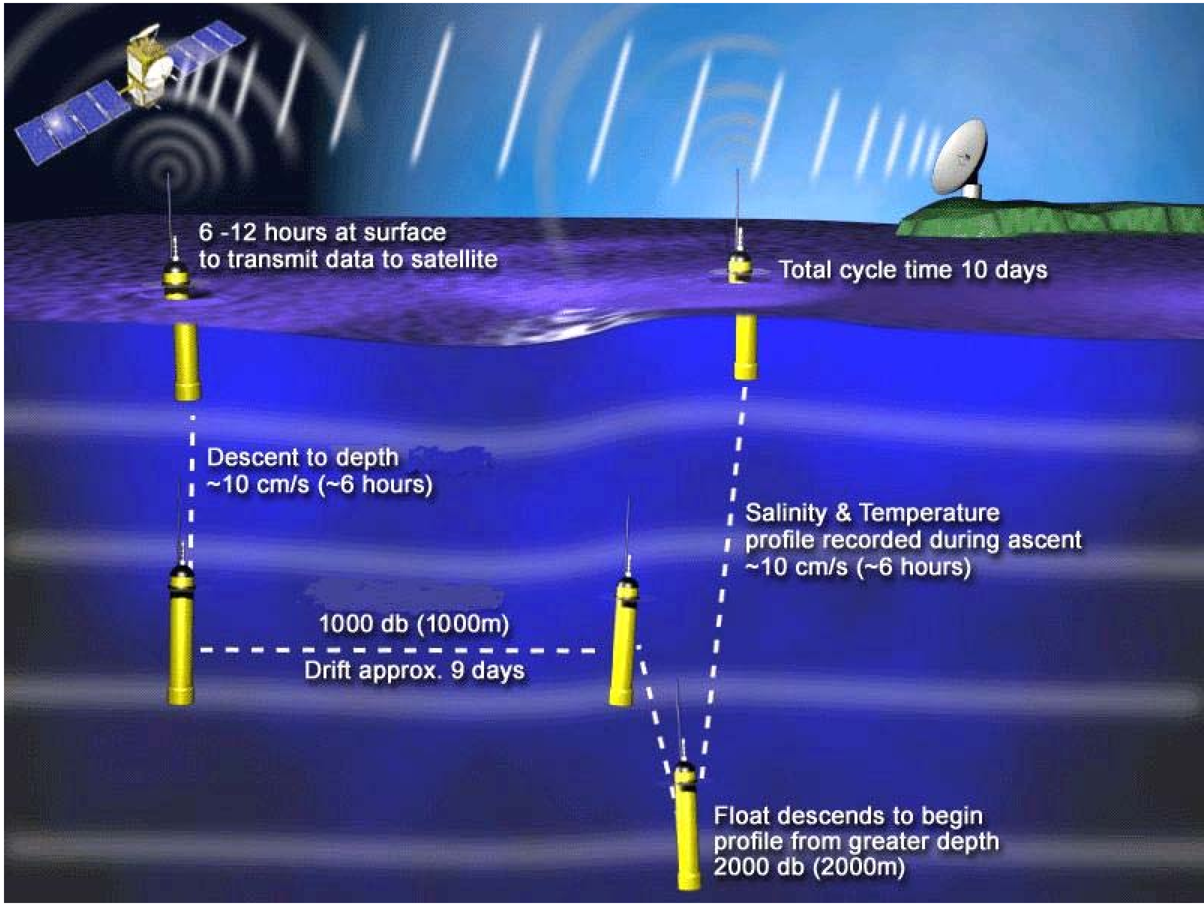


The take home message: it's now possible to instrument the world ocean with a reasonably low-cost chemical sensor network that would give us the spatial and temporal variability of net community production, carbon export, nutrient flux...



Profiling floats provide access to the open ocean. All we need are sensors and the scientific inspiration to use the data.

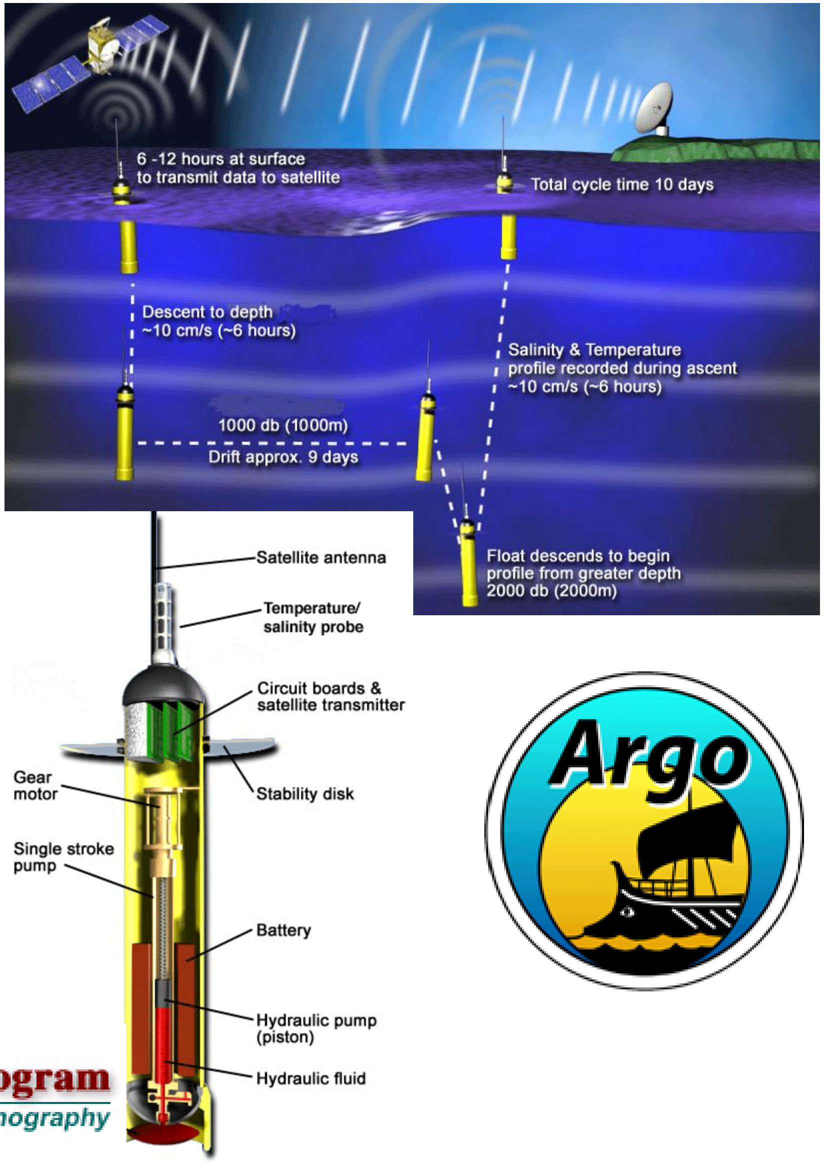




Ocean metabolism observed with oxygen sensors on profiling floats in the Pacific

A collaboration with Steve Riser, UW

- >100 UW oxygen floats deployed in Pacific since 2002

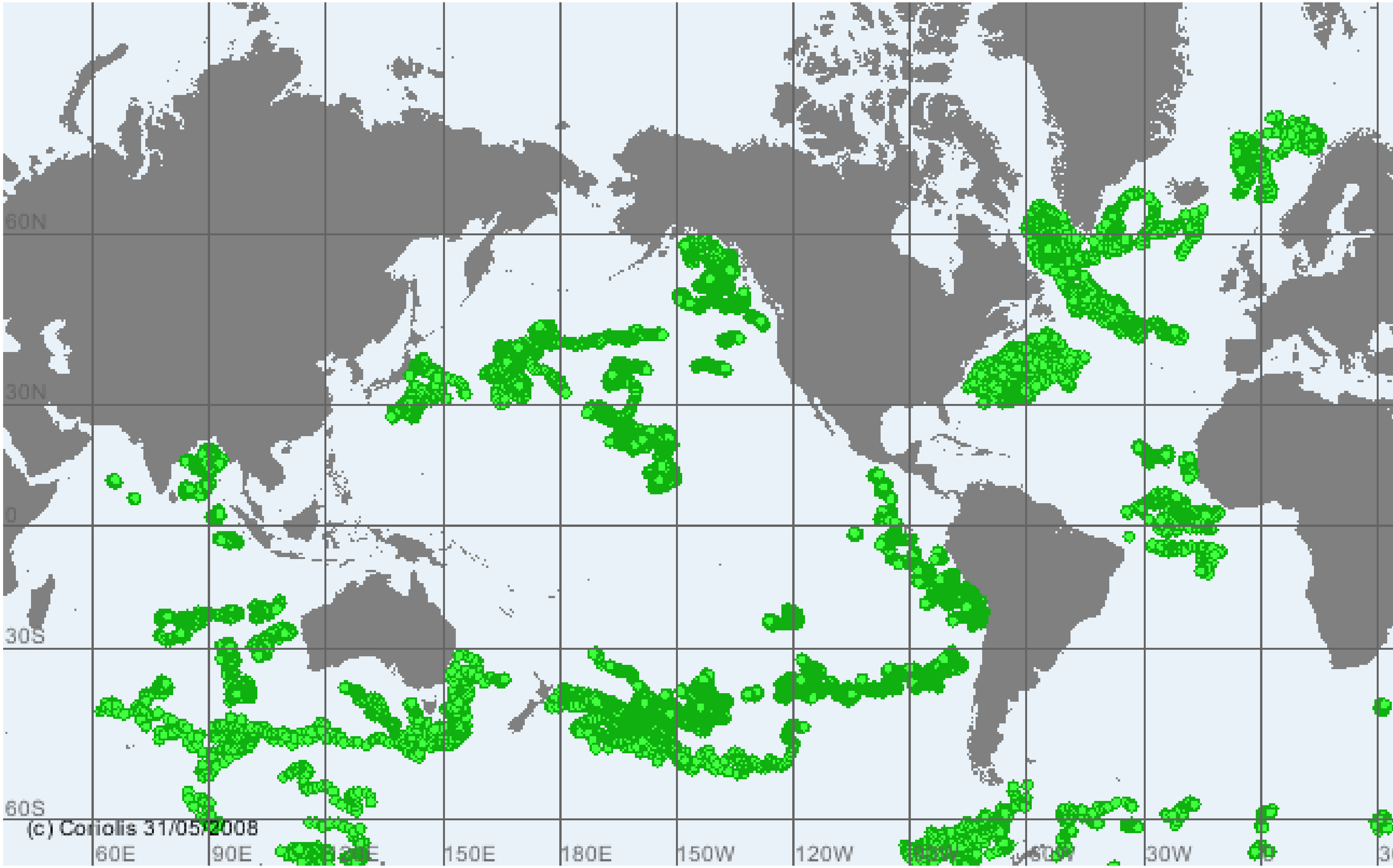


Argo

National Oceanographic Partnership Program

Promoting Partnerships for the Future of Oceanography

5219 Argo profiles with O_2 in the past year by a variety of groups in US, Japan, Canada, Germany, Australia, Chile…..



The Ocean Takes a Deep Breath

Arne Körtzinger,* Jens Schimanski, Uwe Send, Douglas Wallace

The temperature (*T*) and salinity (*S*) of the deep ocean are established at mid- and high latitudes where intermediate and deep waters are formed through subduction and deep convection. These processes also ventilate the deep ocean for atmospheric gases such as oxygen (O_2). Although O_2 is consumed within the ocean by heterotrophic processes, the ocean has no internal oxygen sources. The O_2 concentration in the ocean's interior therefore reflects a balance between supply through circulation and loss through respiration.

We therefore conducted a test deployment of an oxygen sensor mounted on an autonomous profiling float (*5*). Such floats, which report their data by satellite, are being deployed in large numbers (there are presently nearly 1500) to monitor the *T* and *S* structure of the oceans. O_2 measurements from such floats could provide tens of thousands of profiles in a single year, a multiple of all data from the unprecedented, 10-year, ship-based World Ocean Circulation Experiment of the 1990s.

www.sciencemag.org SCIENCE VOL 306 19 NOVEMBER 2004

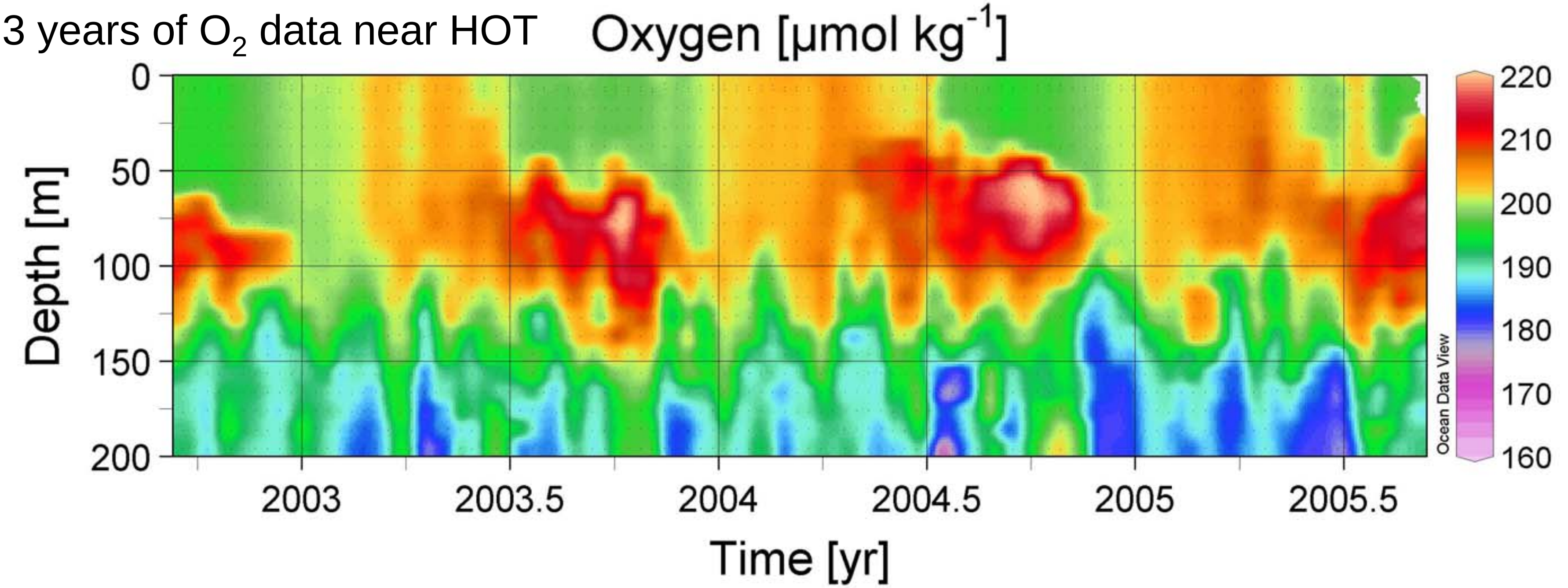
Vol 451|17 January 2008|**doi:10.1038/nature06441** nature

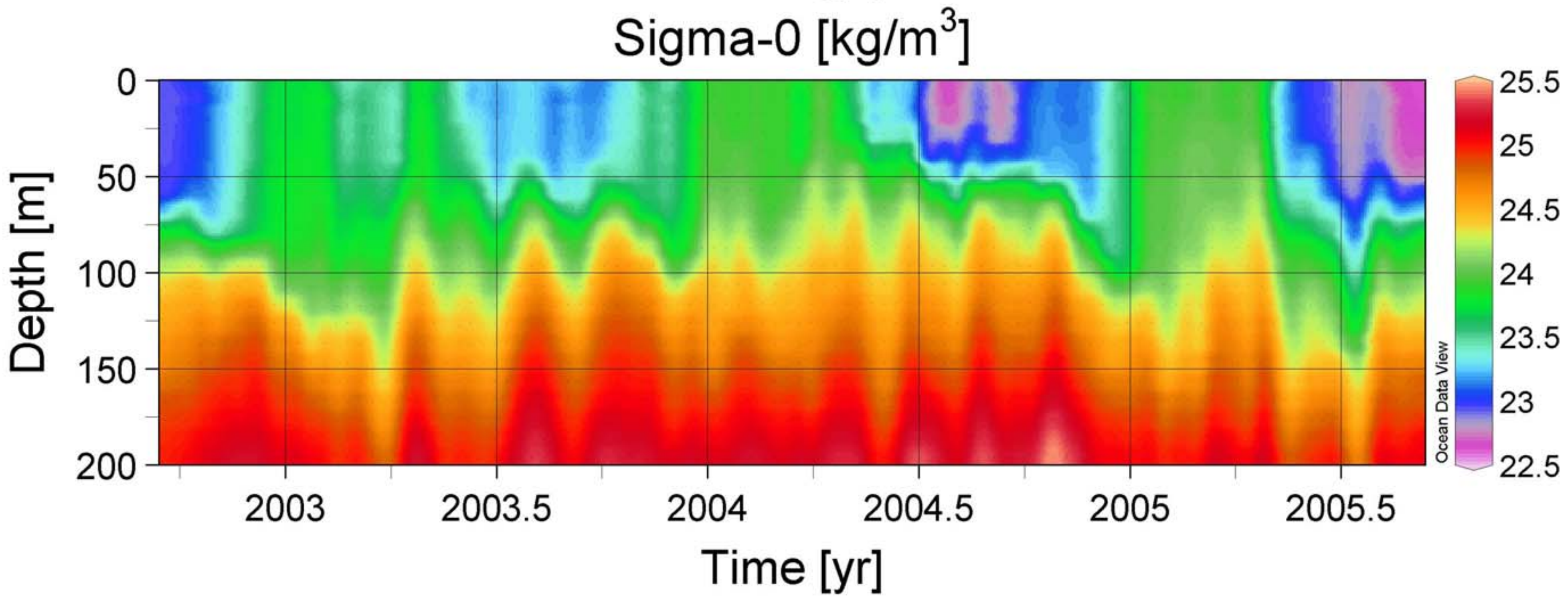
LETTERS

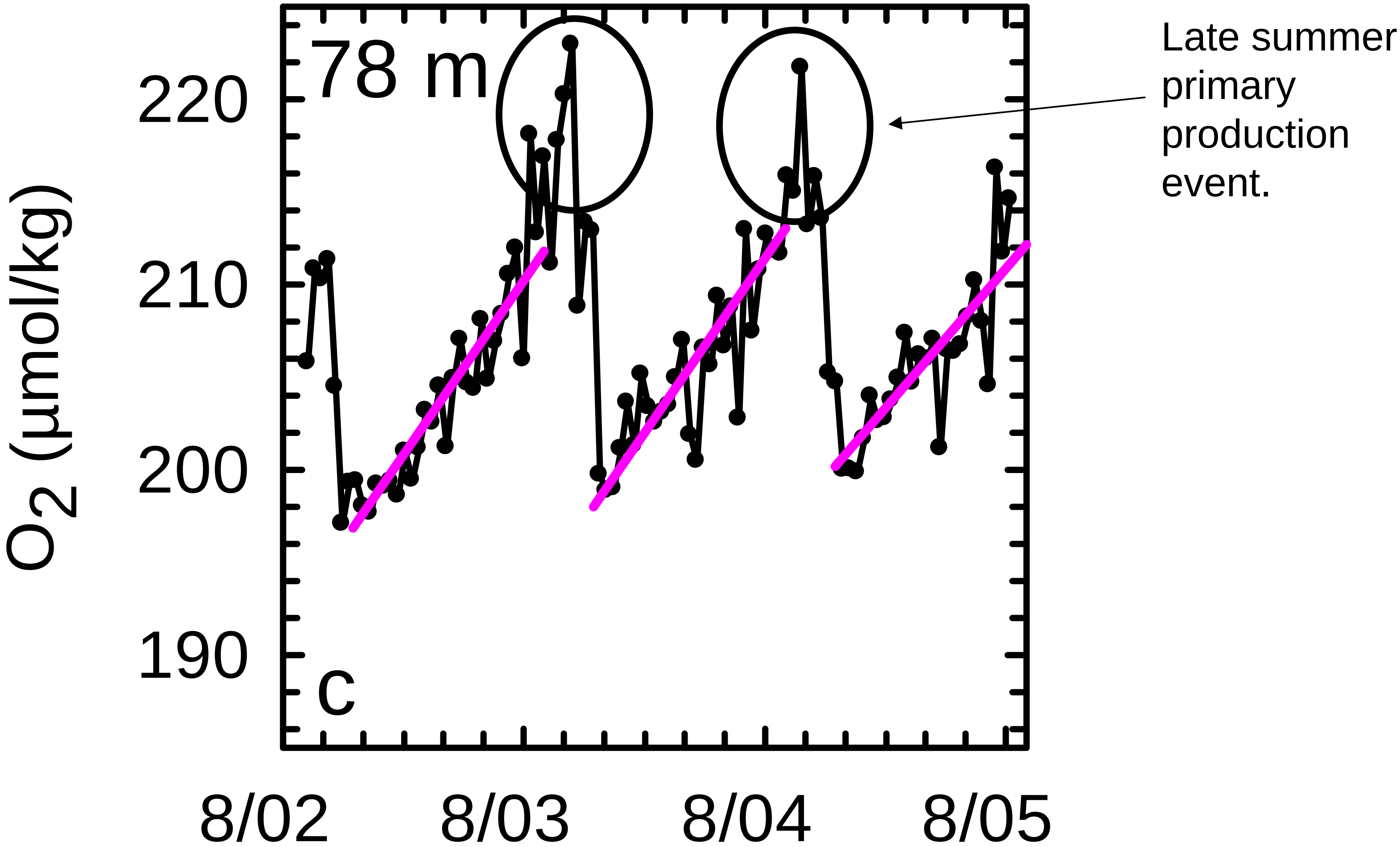
Net production of oxygen in the subtropical ocean

Stephen C. Riser[1] & Kenneth S. Johnson[2]

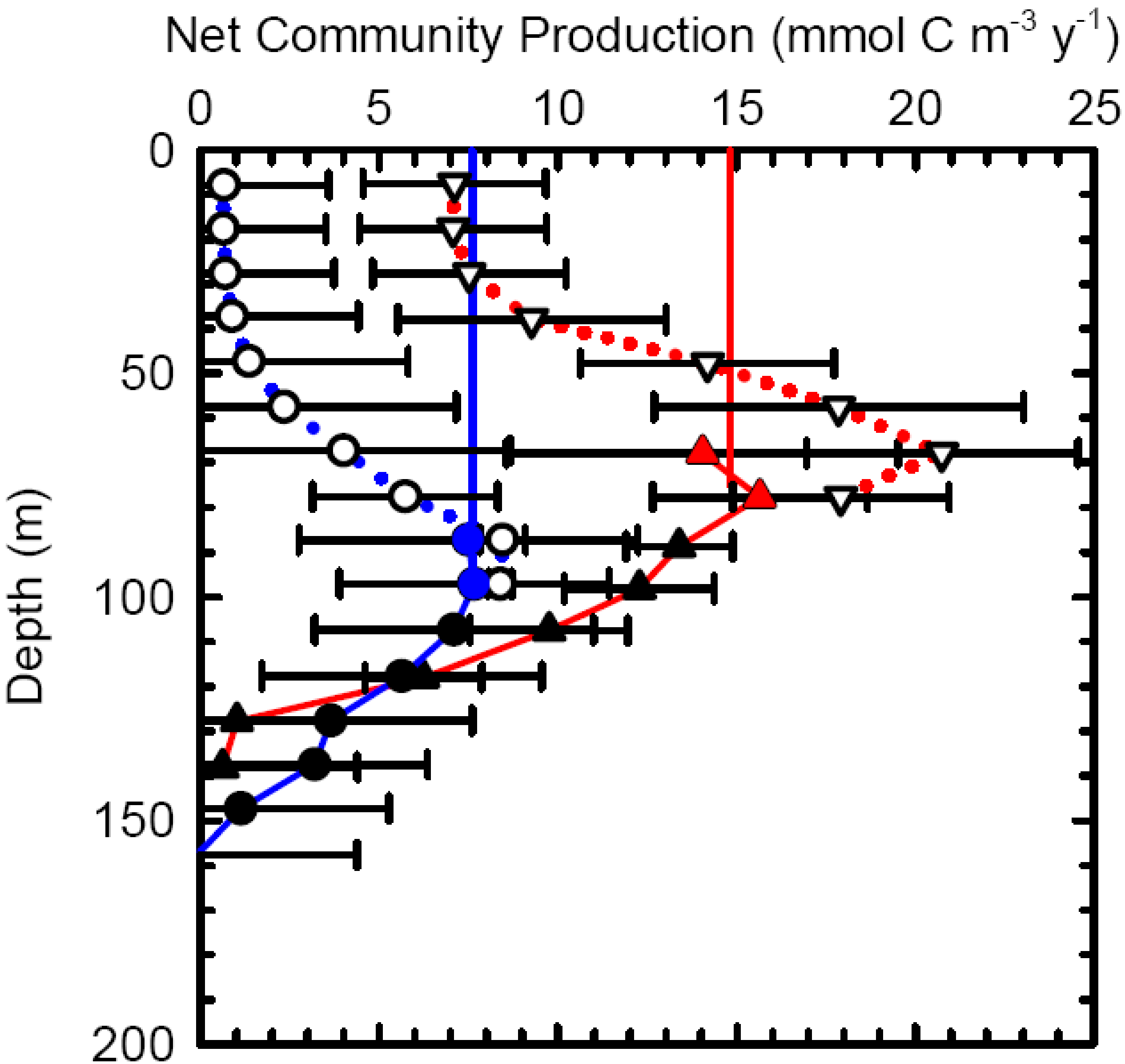
3 years of O_2 data near HOT







78 m
Late summer primary production event.
220
210
200
190
c
O2 (µmol/kg)
8/02
8/03
8/04
8/05



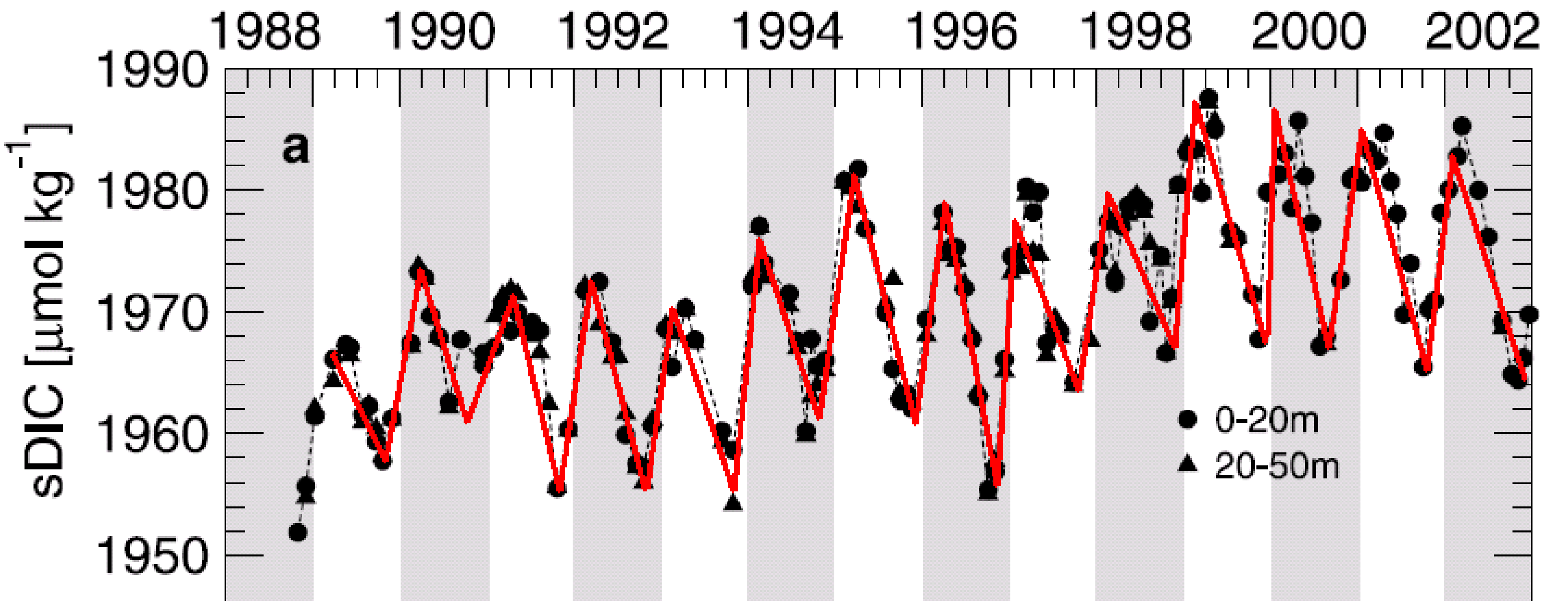
Vertically integrated Net Community Production at HOT = 1.6±0.2 mol C/m²/y.

Keeling et al. (2004) summarized 11 other measurements that average 1.9±0.6 mol C/m²/y.

At 22 S, vertical integral of NCP = 0.9±0.4 mol C/m²/y. About ½ the magnitude of NCP at HOT, as expected.

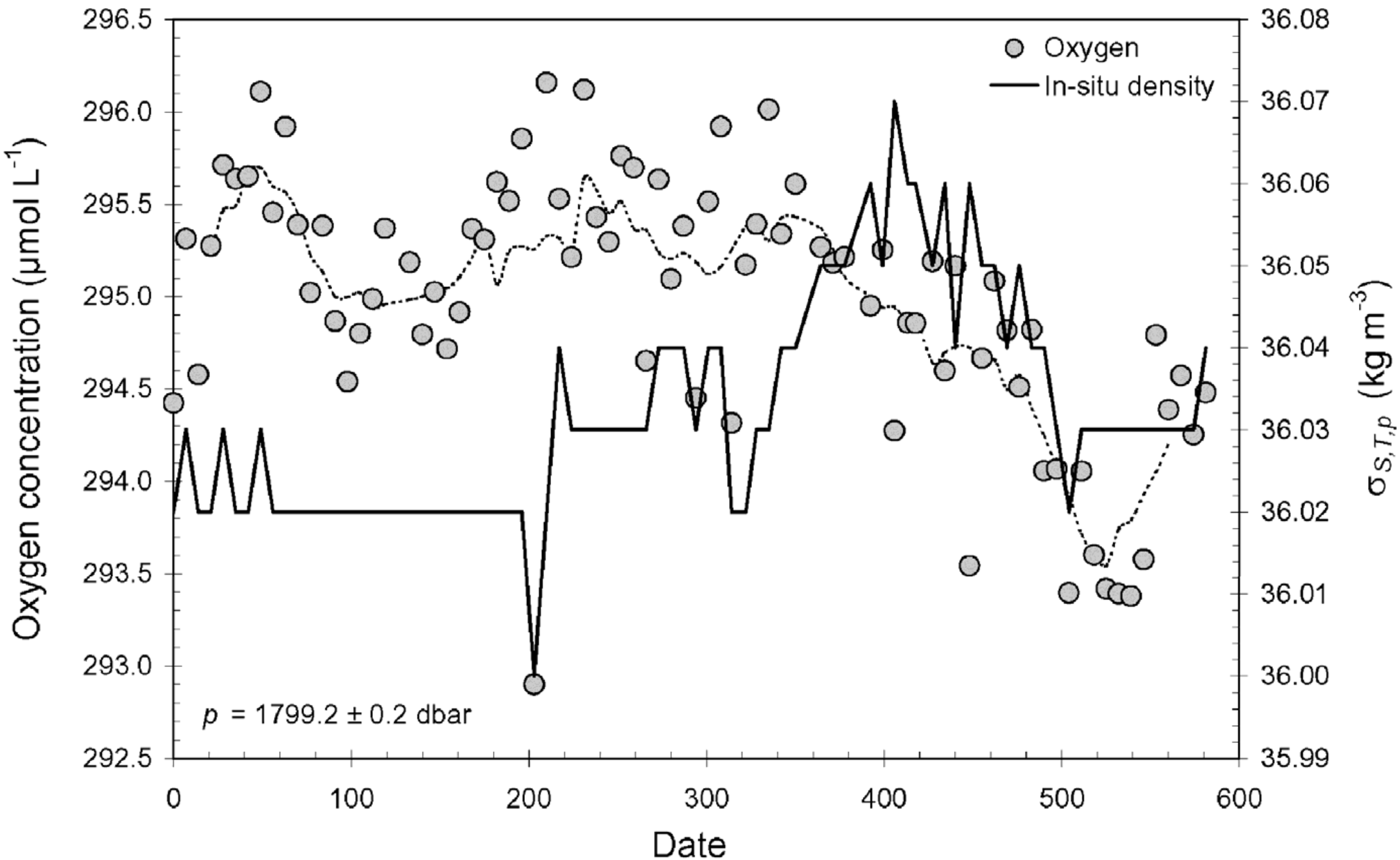
Cycle of Dissolved Inorganic Carbon at surface looks very similar to O_2 cycle below mixed layer. DIC equilibrates with atmosphere 10x more slowly than O_2.

KEELING ET AL.: SEASONAL CYCLES AND TRENDS AT STATION ALOHA

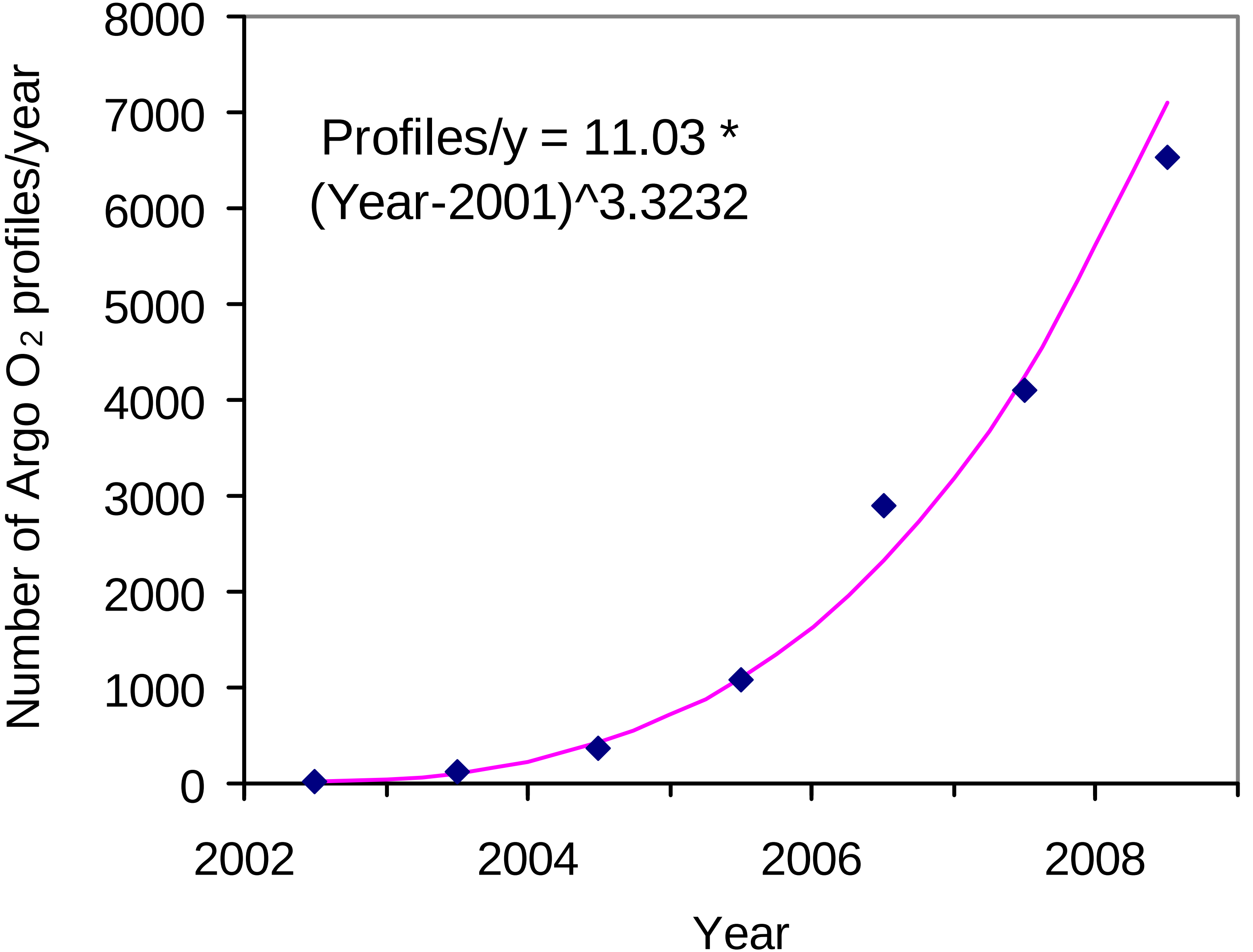


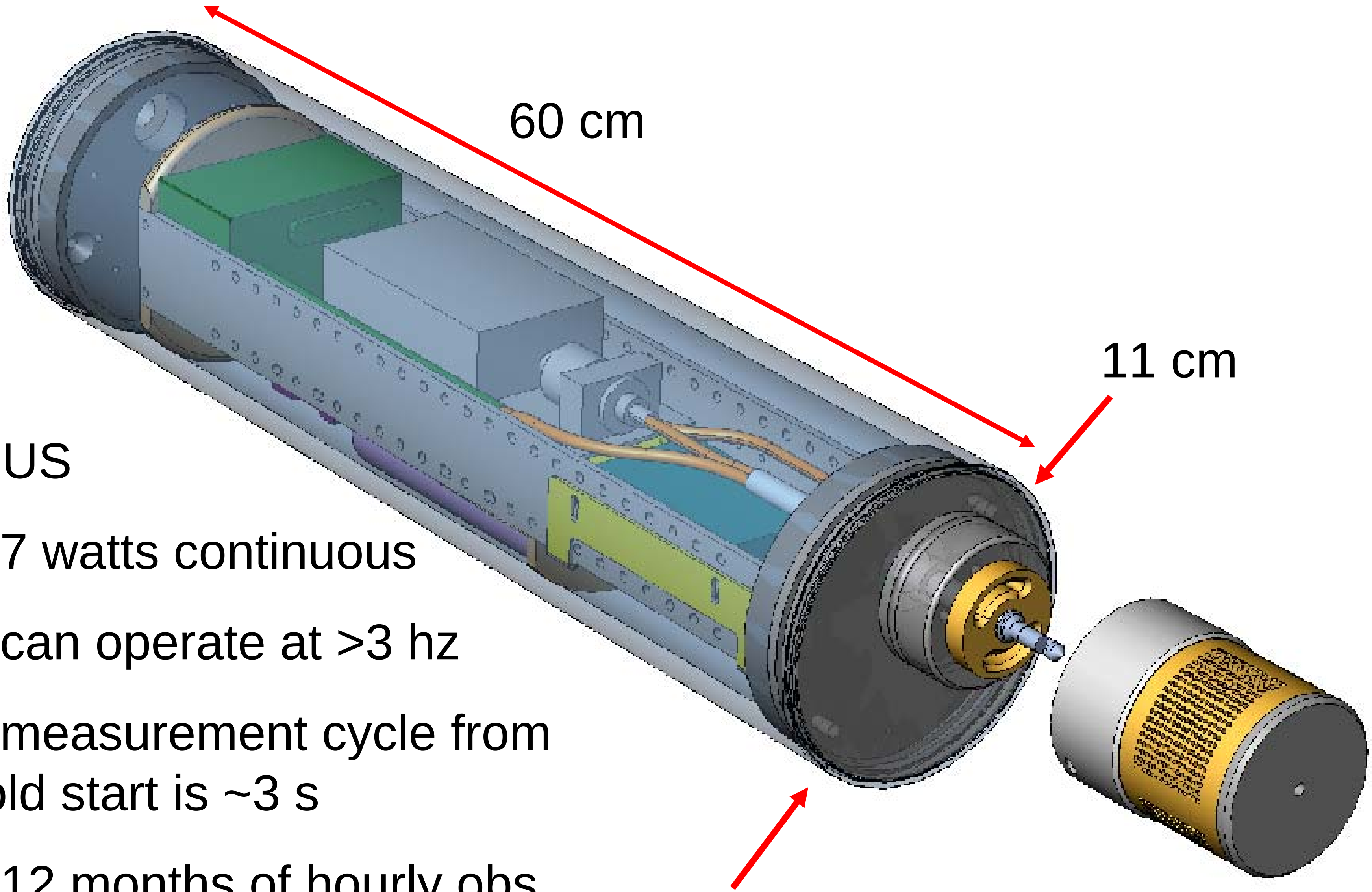
Solution to measuring annual cycles near the surface would be a good pH sensor on a float.

An Aanderaa oxygen optode on a vertical profiling float in the North Atlantic is stable to 295.0±0.7 μmol/L over nearly two years at 1800 m depth (Kortzinger et al., 2006; Tengberg et al., 2006). Much of the oxygen variability may be real!!! These sensors could be precise to 0.1%. That’s fantastic!!!!



Number of O_2 profiles per year in Argo data system is doubling every 15 months





ISUS

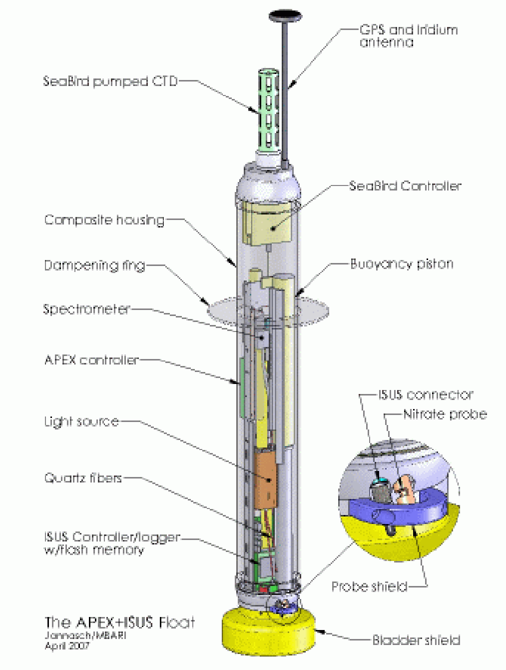
- 7 watts continuous
- can operate at >3 hz
- measurement cycle from cold start is ~3 s
- 12 months of hourly obs.
- precision ~ 0.07 µM (1 sd)

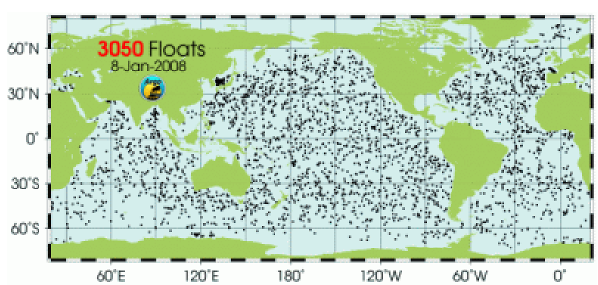
Johnson and Coletti, Deep-Sea Res., 2002

Why measure nitrate? Nitrate is a key phytoplankton nutrient. The concentration of nitrate regulates phytoplankton growth in much of the ocean. In a warming climate, the transport of nitrate from deep water may diminish and reduce primary production in the ocean.

The ISUS nitrate sensor is integrated into the body of a Webb Research Apex profiling float that is of the type used in the Argo array. These floats are designed for an expendable deployment in the ocean.

- Floats park at 1000 m depth and profile to the surface at programmed intervals, typically 5 to 10 days. Measurements are made as the float rises. Results are transmitted to orbiting satellites and then to shore when the float reaches the surface. The float then returns to its parking depth.
- The Apex/ISUS float makes 60 measurements of nitrate and oxygen on each profile, and it measures temperature, salinity and pressure at 2 m intervals.
- Battery life is sufficient for approximately 260 vertical profiles from 1000 m depth.
- At a cycle time of 5 days, each float should profile for nearly four years.
- The precision of the ISUS nitrate sensor is near 0.2 micromoles per liter (1 SD).
- Absolute accuracy is about 0.5 micromoles per liter and can be improved by comparison to laboratory analyses to remove offsets.
- Data is available in real-time.

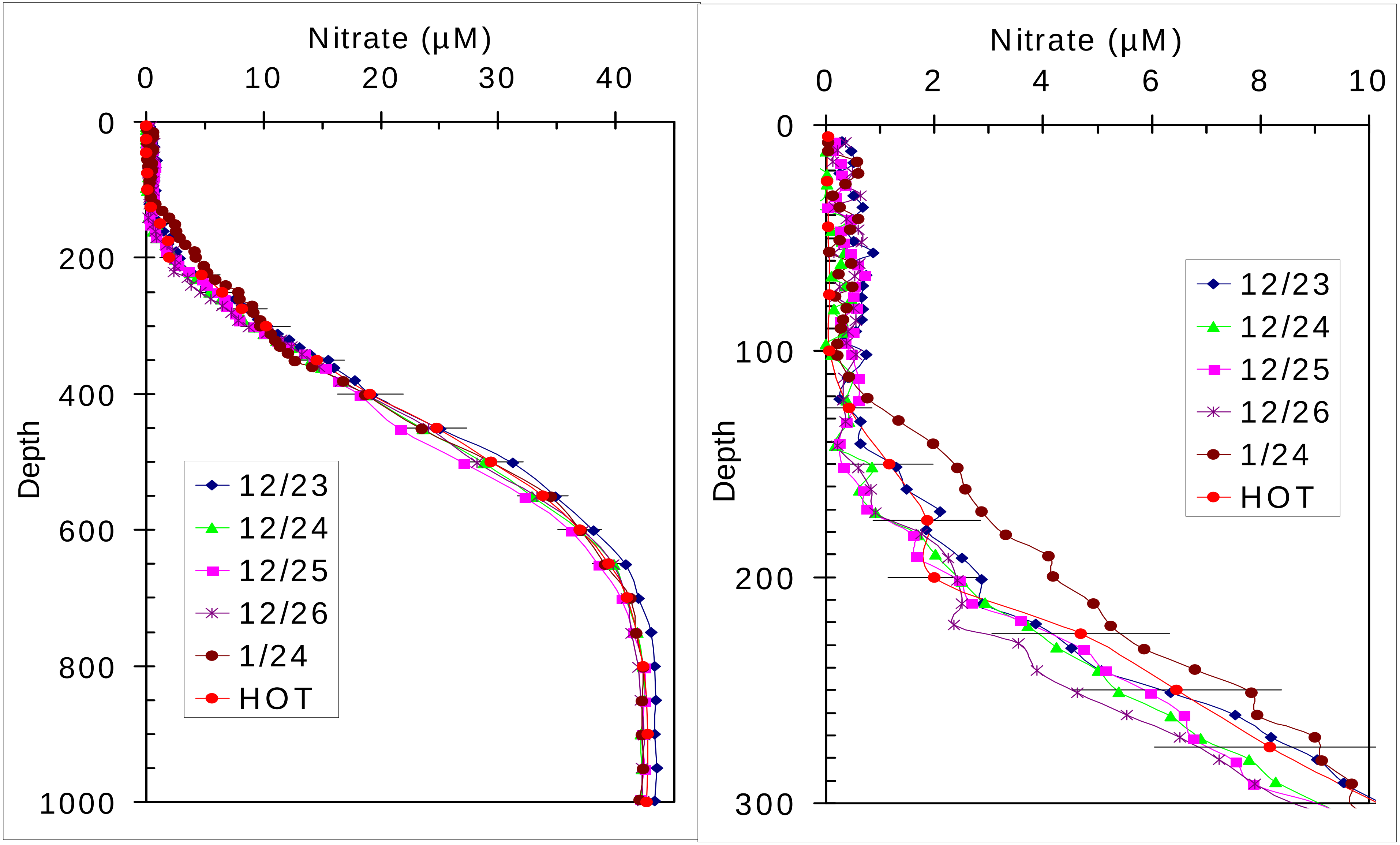




The Argo array consists of approximately 3000 profiling floats that are distributed throughout the world ocean. These floats are used to monitor the heat and salt budget of the ocean. Equipping such an array with biogeochemical sensors would allow scientists to monitor rates of primary production.

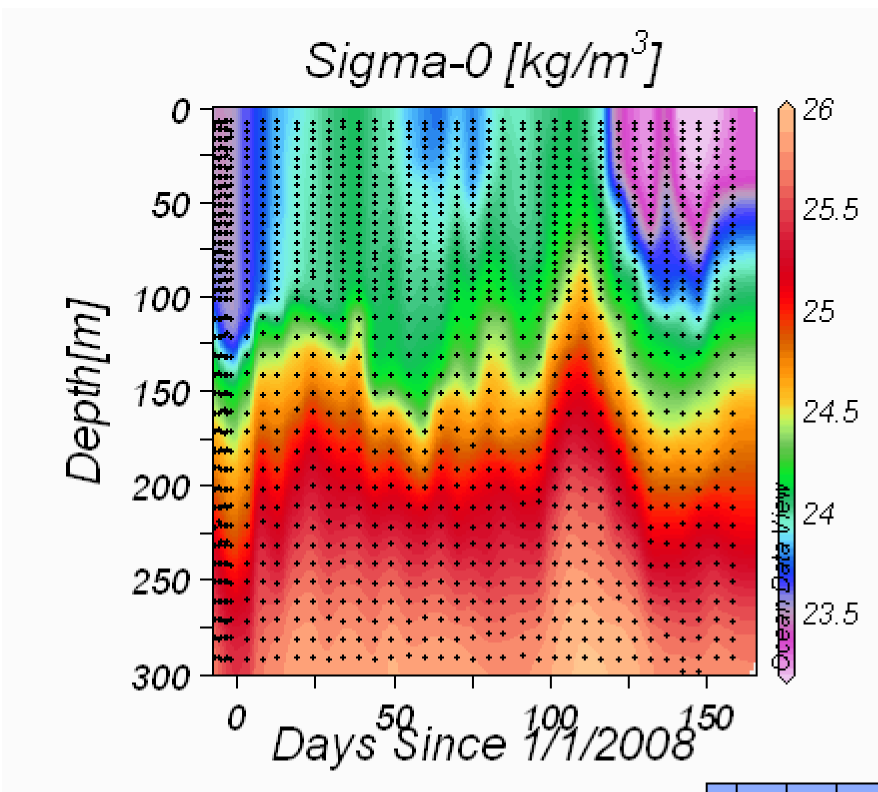
A plan to equip the Argo array with oxygen sensors now exists.

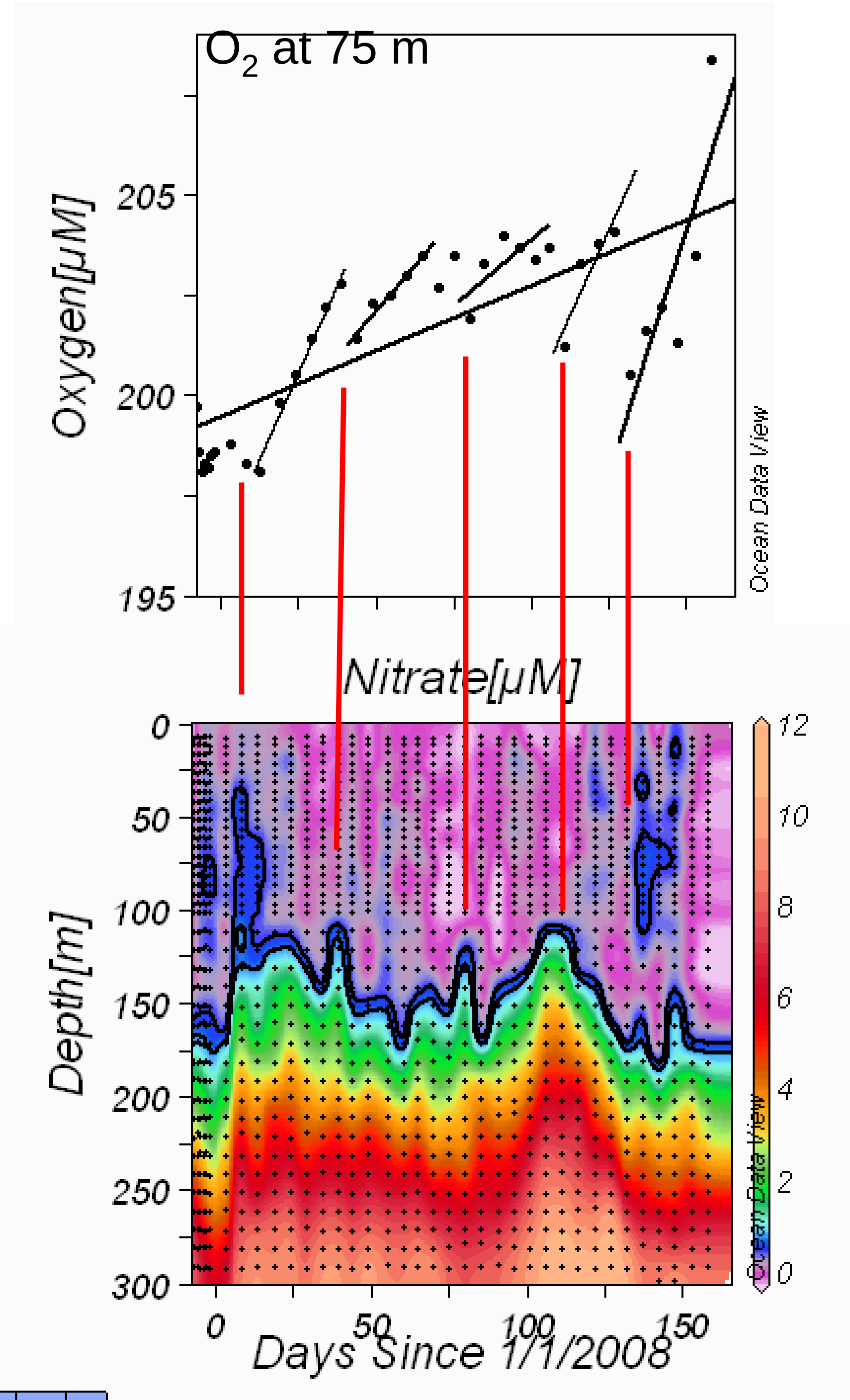
Integration of ISUS into the Webb Apex float was done by Dana Swift (UW), Luke Coletti and Hans Jannasch (MBARI).



Nitrate (µM)
0
10
20
30
40
0
200
400
600
800
1000
Depth
12/23
12/24
12/25
12/26
1/24
HOT
Nitrate (µM)
0
2
4
6
8
10
0
100
200
300
Depth
12/23
12/24
12/25
12/26
1/24
HOT

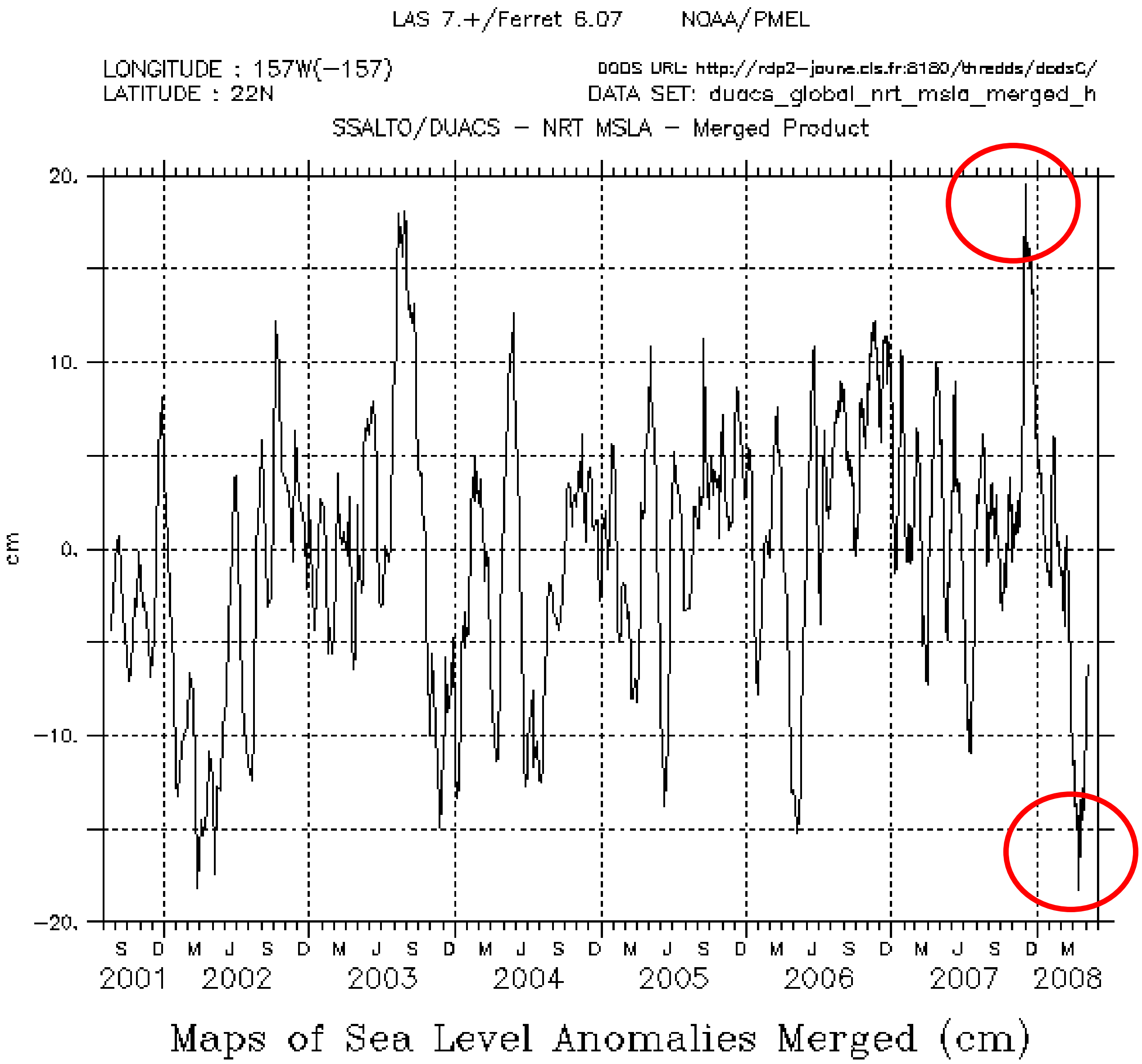
Five nitrate injection events drive increase in oxygen production rate. NO_3^- contours at 0.5 and 0.75 µM = 2 SD and 3 SD of data in upper 100 m. All NO_3^- data corrected for drift using 900 to 1000 m data. Lines on O_2 plot are least squares fits to data in the range spanned by the line. 5 day cycle time barely resolves these events.

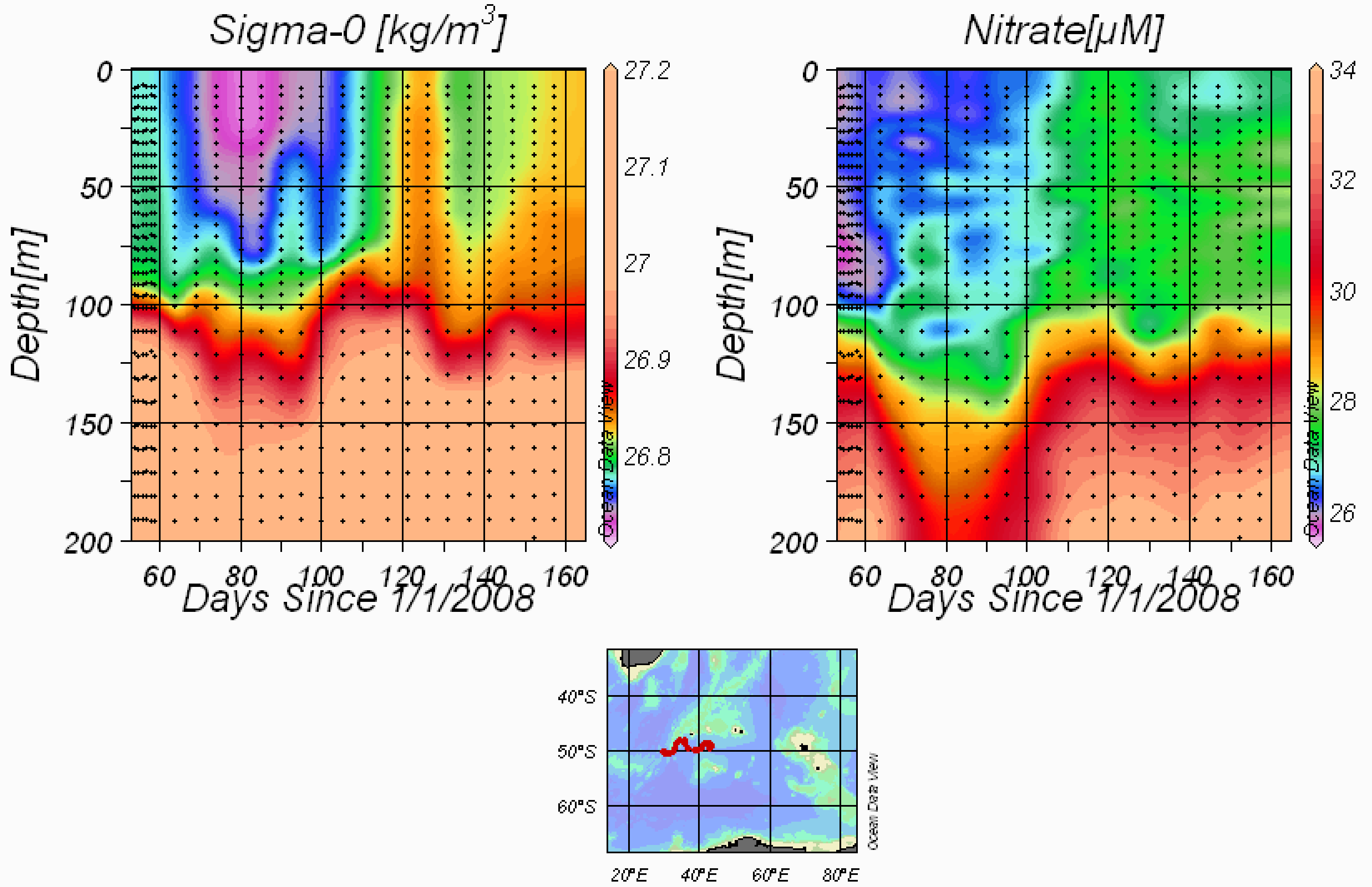




Dec 2007 to April 2008 was a fairly extreme period for mesoscale events.

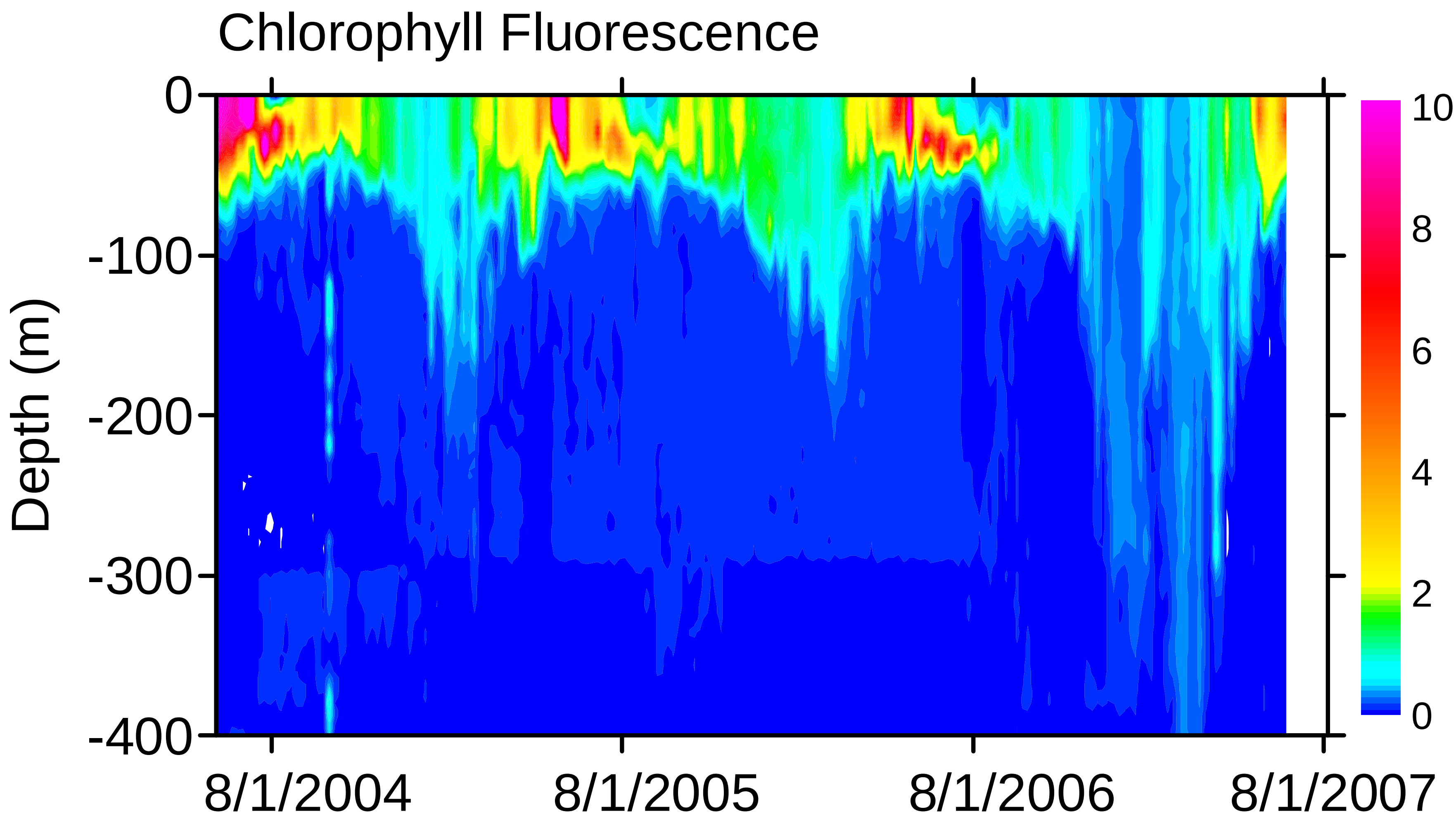
Sea surface height anomaly (cm)



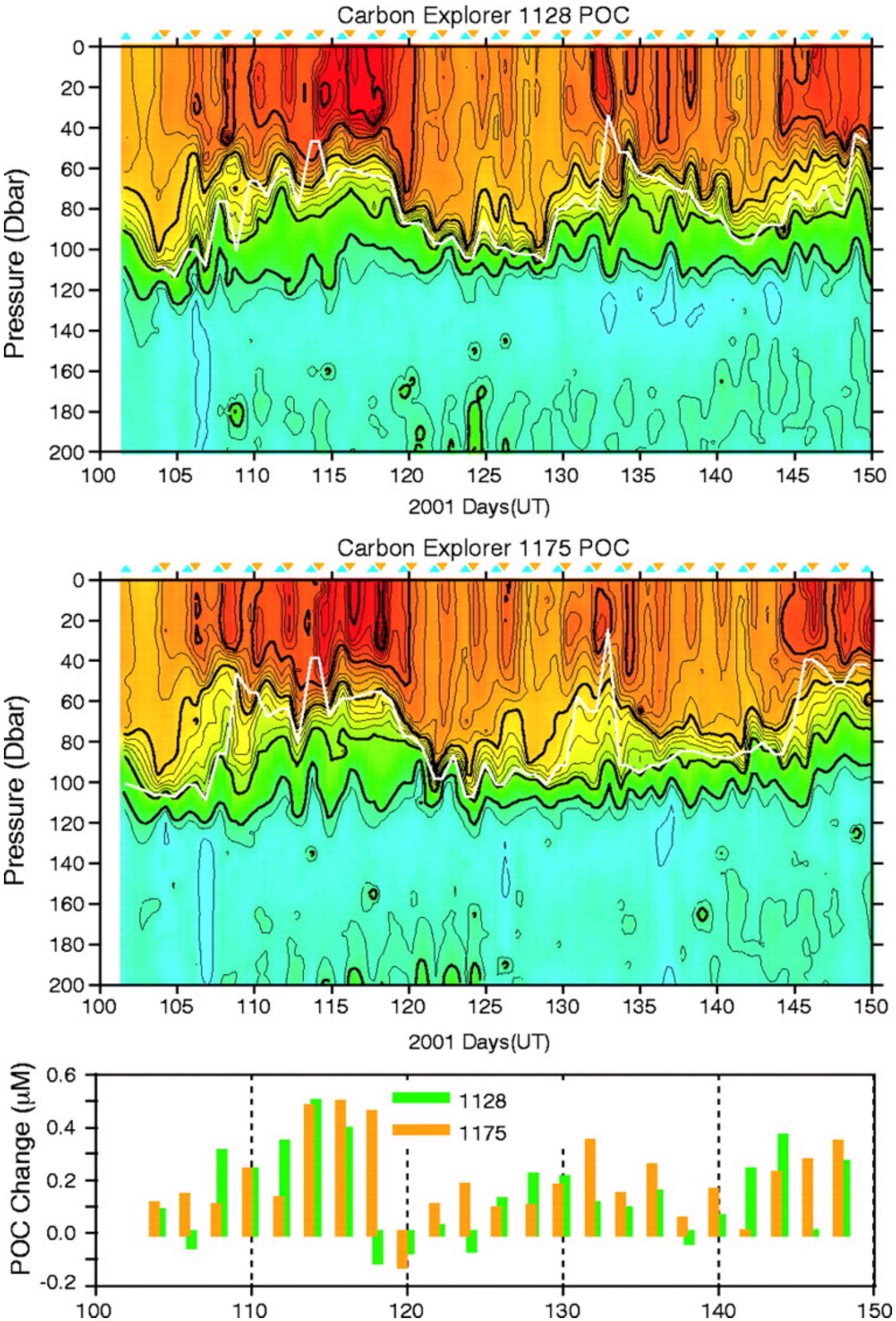


Sigma-0 [kg/m3]
Depth[m]
Days Since 1/1/2008
27.2
27.1
27
26.9
26.8
Ocean Data View
Nitrate[μM]
Depth[m]
Days Since 1/1/2008
34
32
30
28
26
Ocean Data View
40°S
50°S
60°S
20°E
40°E
60°E
80°E
Ocean Data View

E. Boss et al., in press. Show 3 yrs of data for a fluorometer on a profiling float in the Labrador Sea.



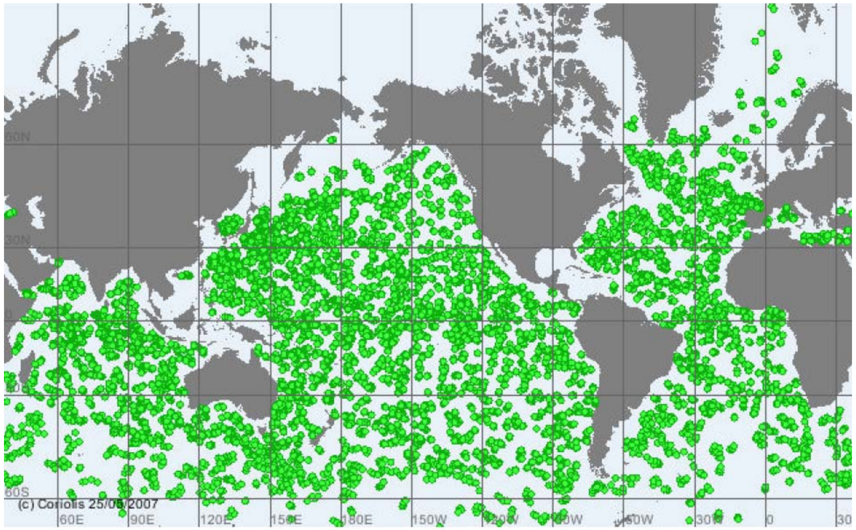
Time series of POC variability from SOLO1128 and SOLO1175 in Subarctic N. Pacific inferred from transmissometer measurements (Bishop et al., 2002).



Bishop, J.K.B., R.E. Davis and J.T. Sherman. 2002. Science, 298: 817-821.

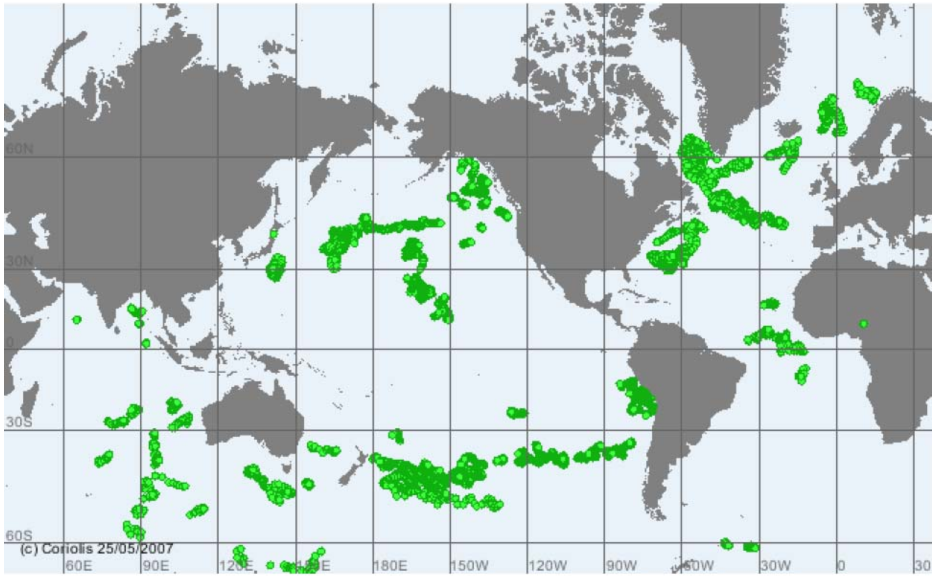
Bishop, J. K. B., T. J. Wood, R. E. Davis and J. T. Sherman. 2004. Science, 304, 417-420.

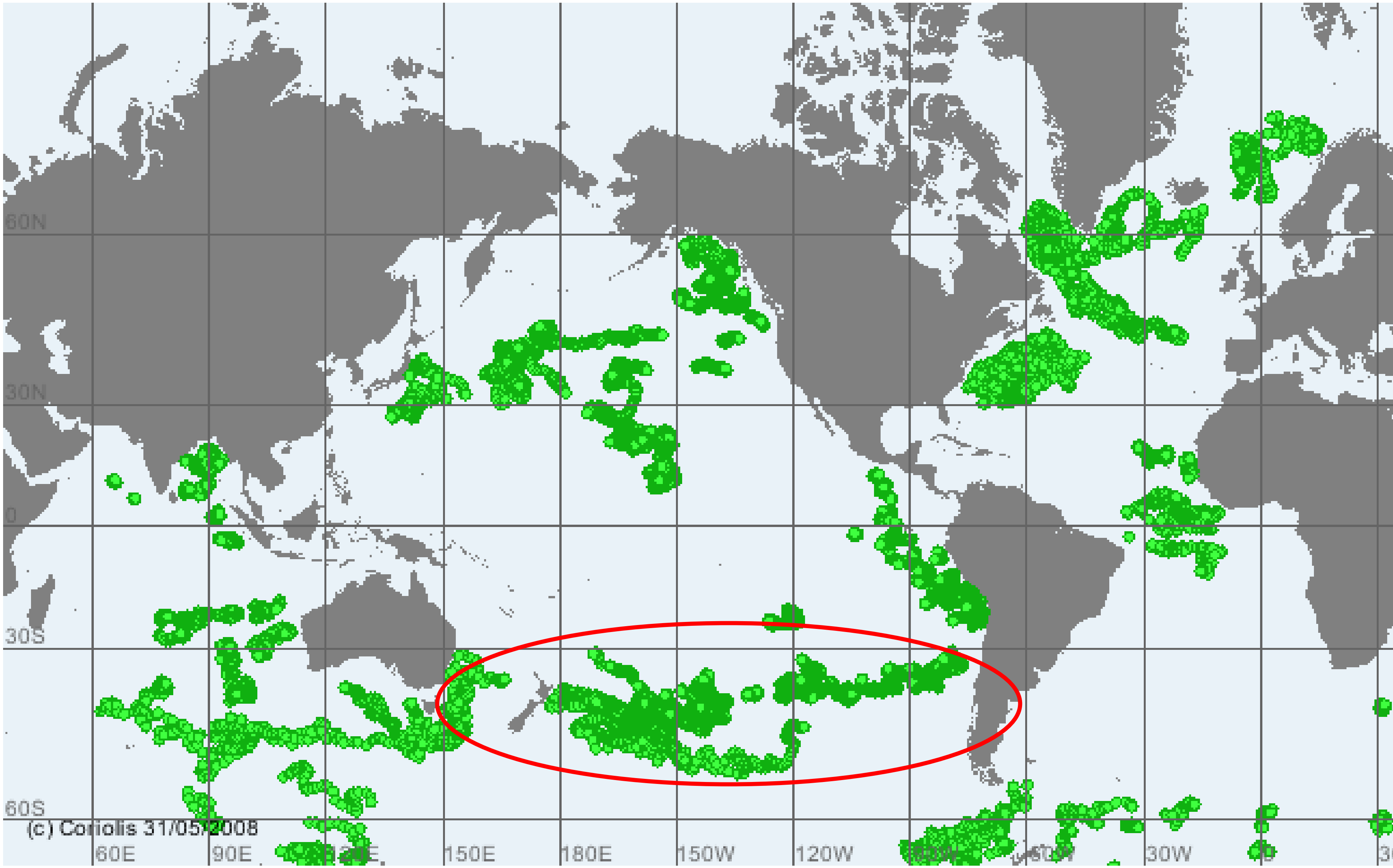
Ocean metabolism observed with oxygen sensors on profiling floats in the South Pacific



- •2852 Active floats
- •100 Oxygen sensors
- •Large spatial coverage of annual oxygen cycle

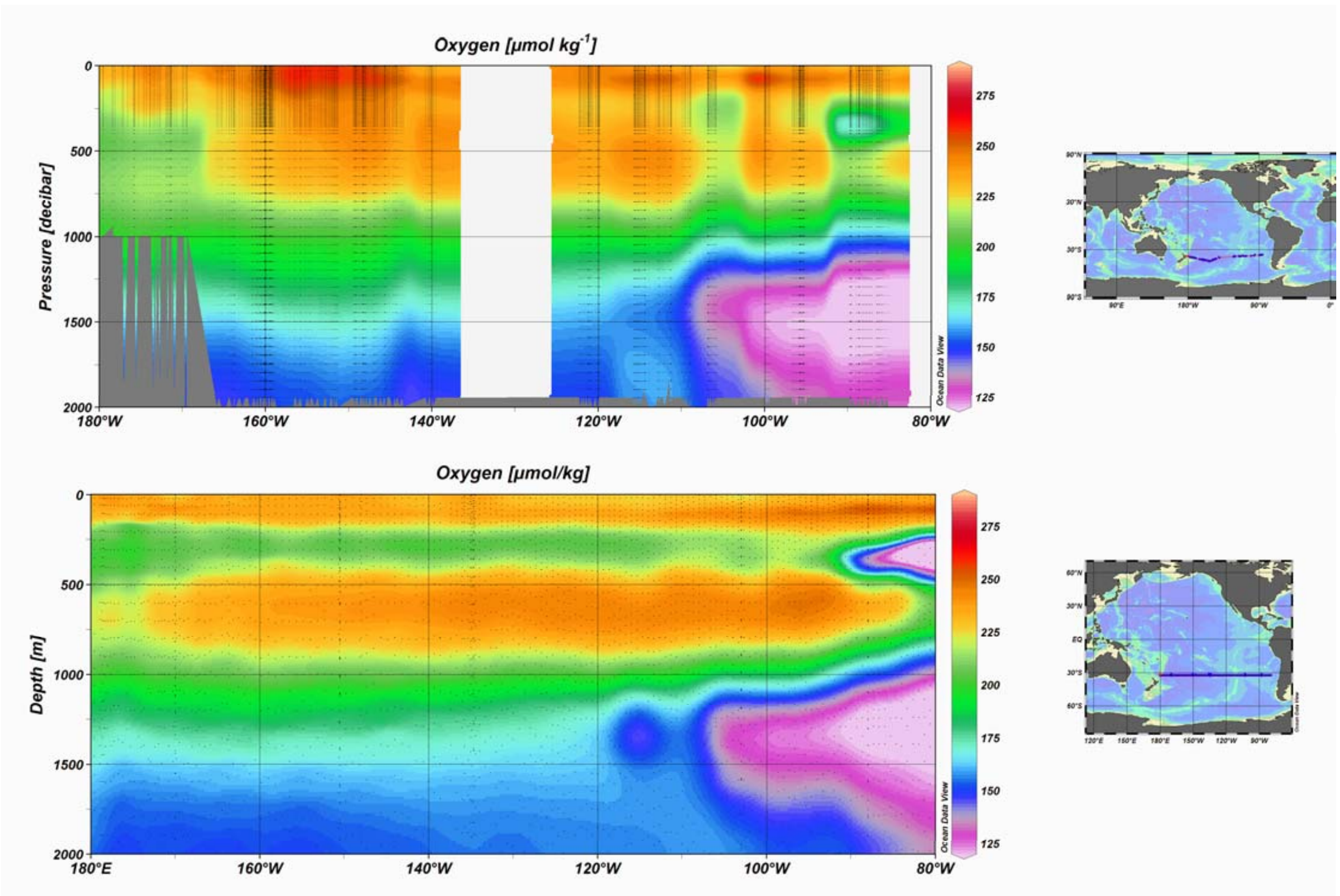
Todd Martz
MBARI
Postdoctoral
Fellow




60N
30N
0
30S
60S
(c) Coriolis 31/05/2008
60E
90E
150E
180E
150W
120W
30W

- 18 floats at 40°S
- 66-72 profiles from Nov 2005 – Apr 2007
- 70 depth intervals per profile
- 1,212 stations; 83,816 measurement points

Argo vs. WOCE

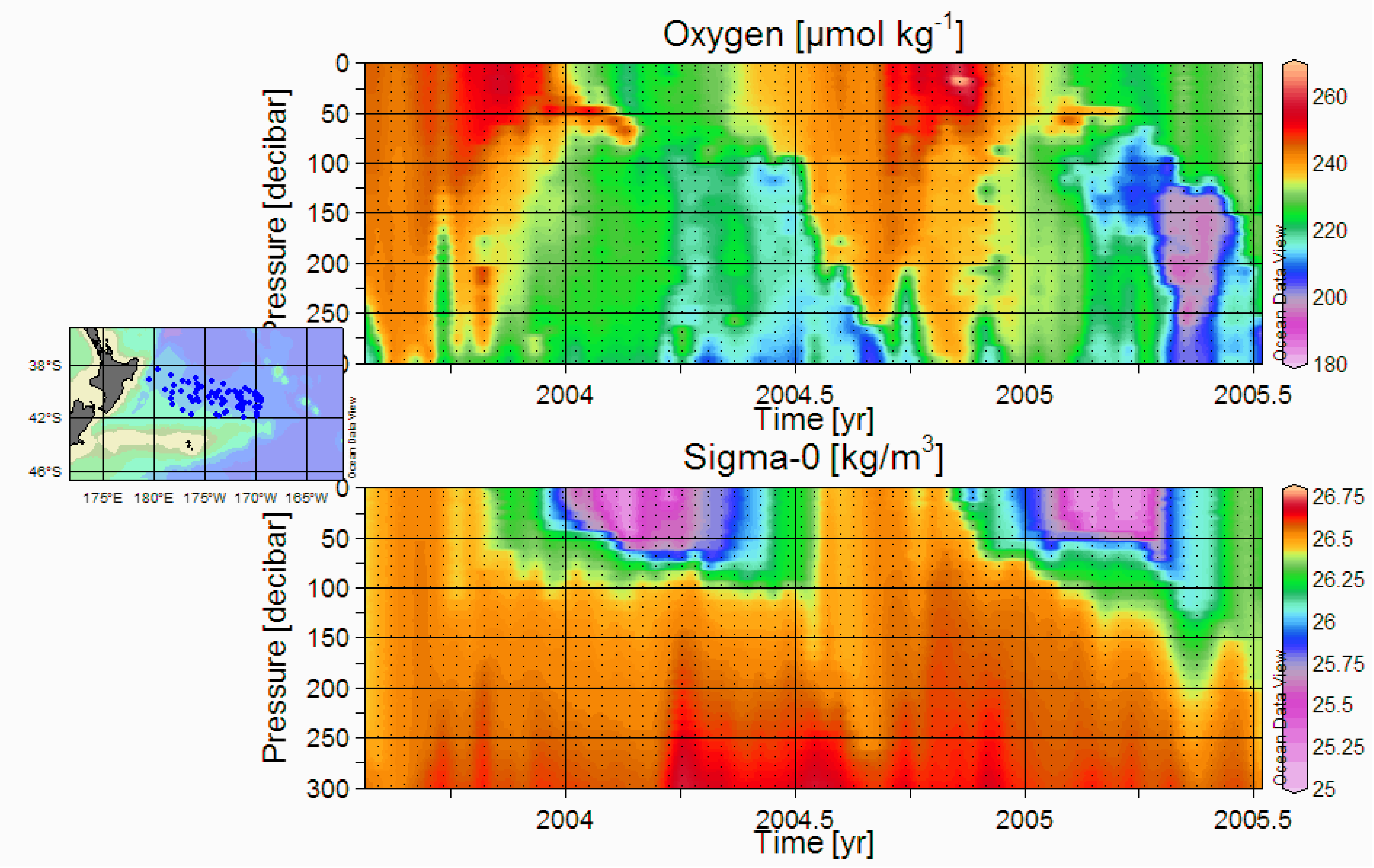


Argo

WOCE P06

32.5°S, 1992

UW Float 5900421

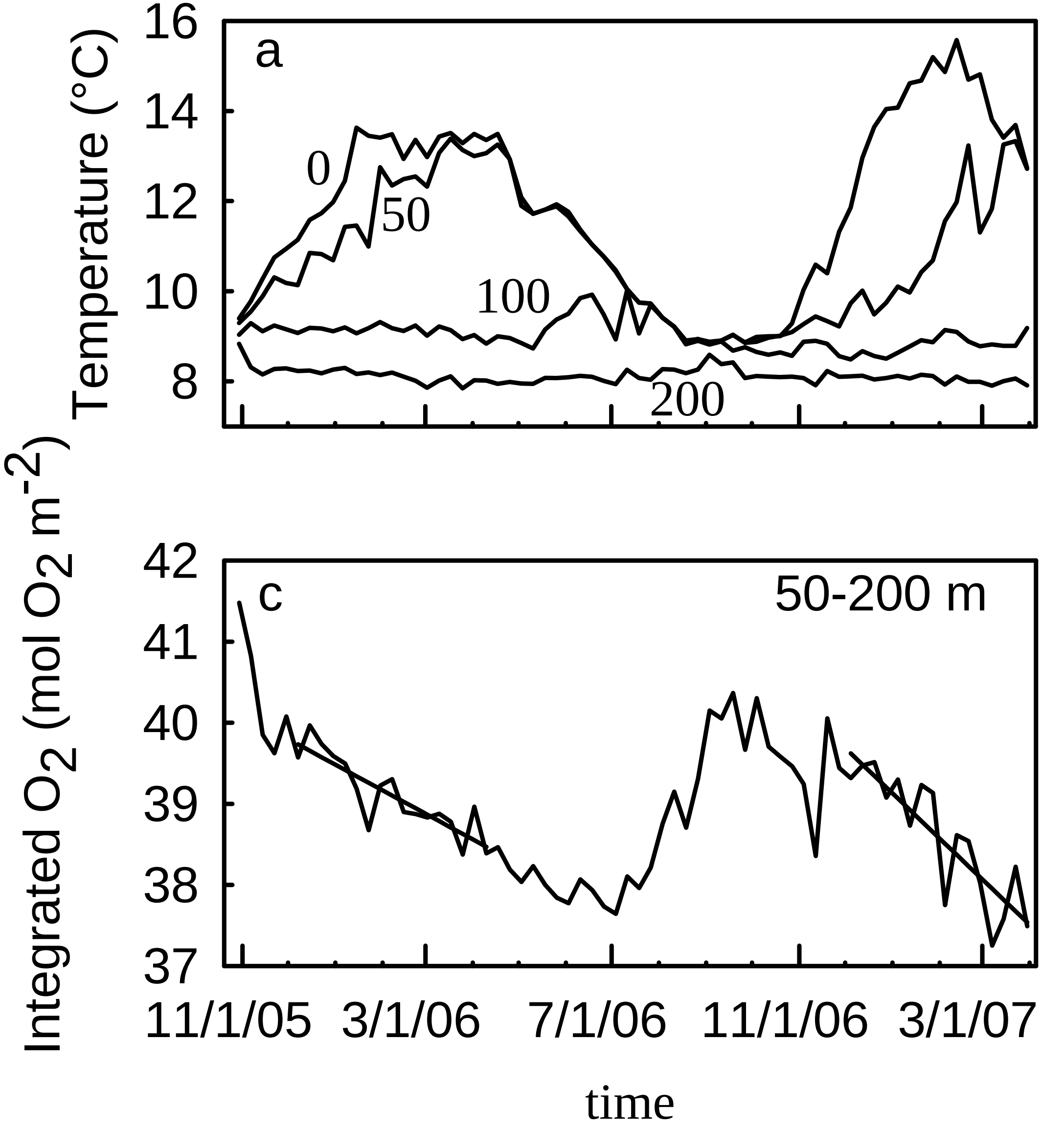


Pacific Argo floats:

annual cycles

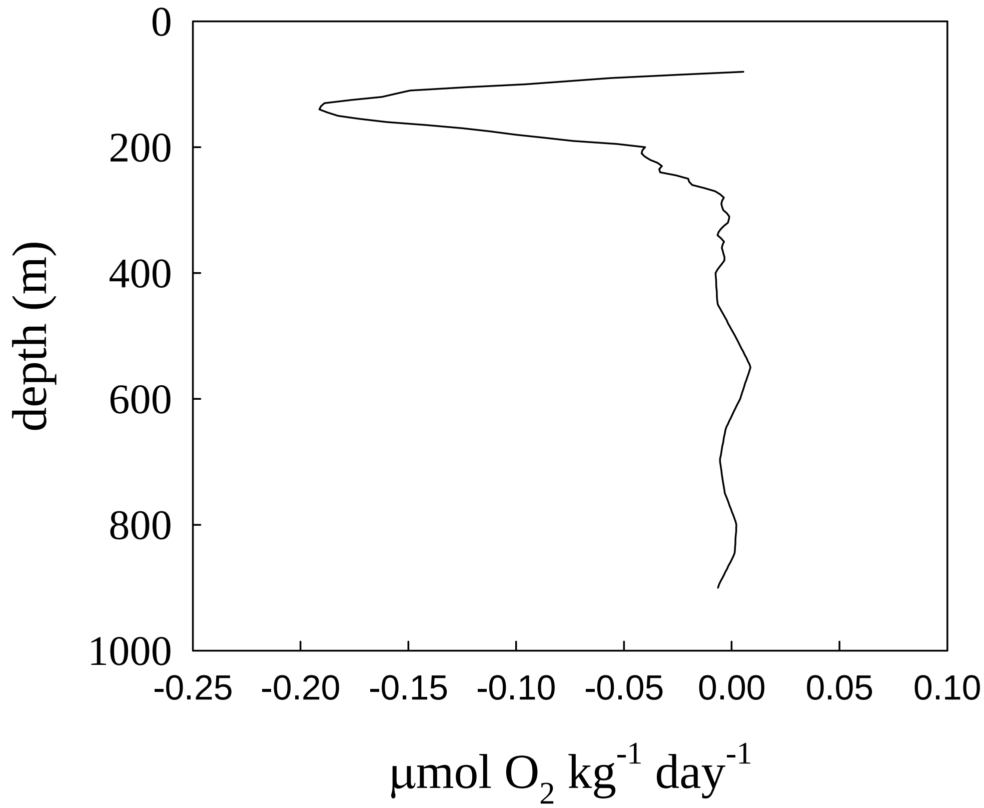
•Oxygen inventory exhibits a Ventilation-Respiration cycle

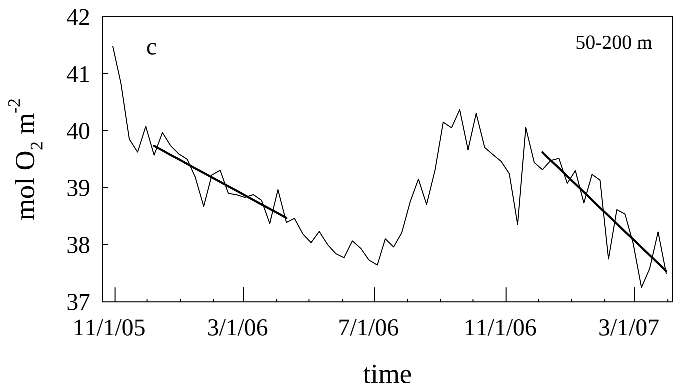
•Rates of remineralization attributed to export production

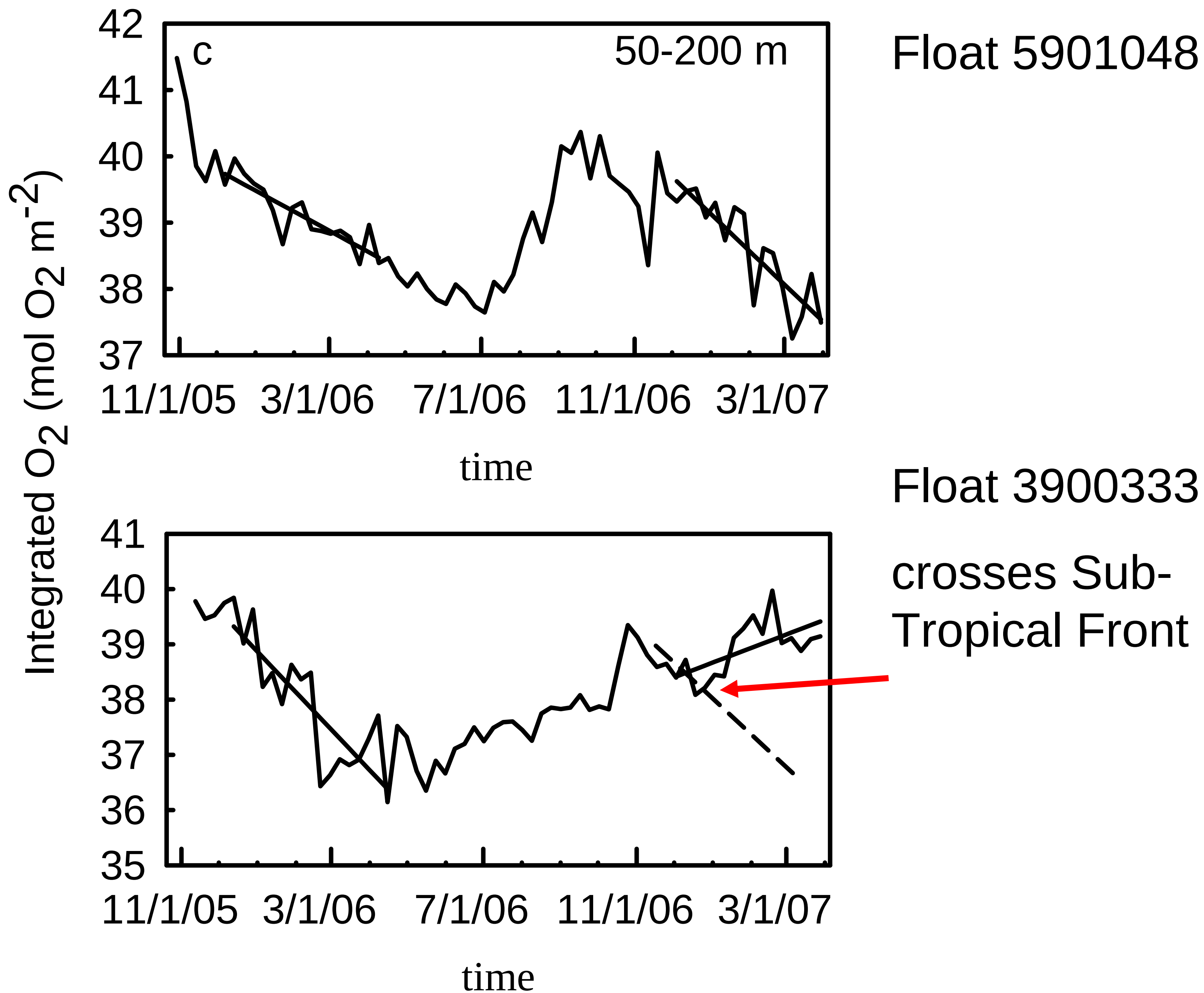


Pacific Argo floats: Oxygen Utilization Rate

- Dec-April rates show a clear negative signal - 4-5 months of export production directly observed by Argo floats.
- Extended to annual rates using satellite seasonality (i.e. no decoupling of EP from PP).
- Zero at Z_c
- s:n ~ 1:1 by 200 m

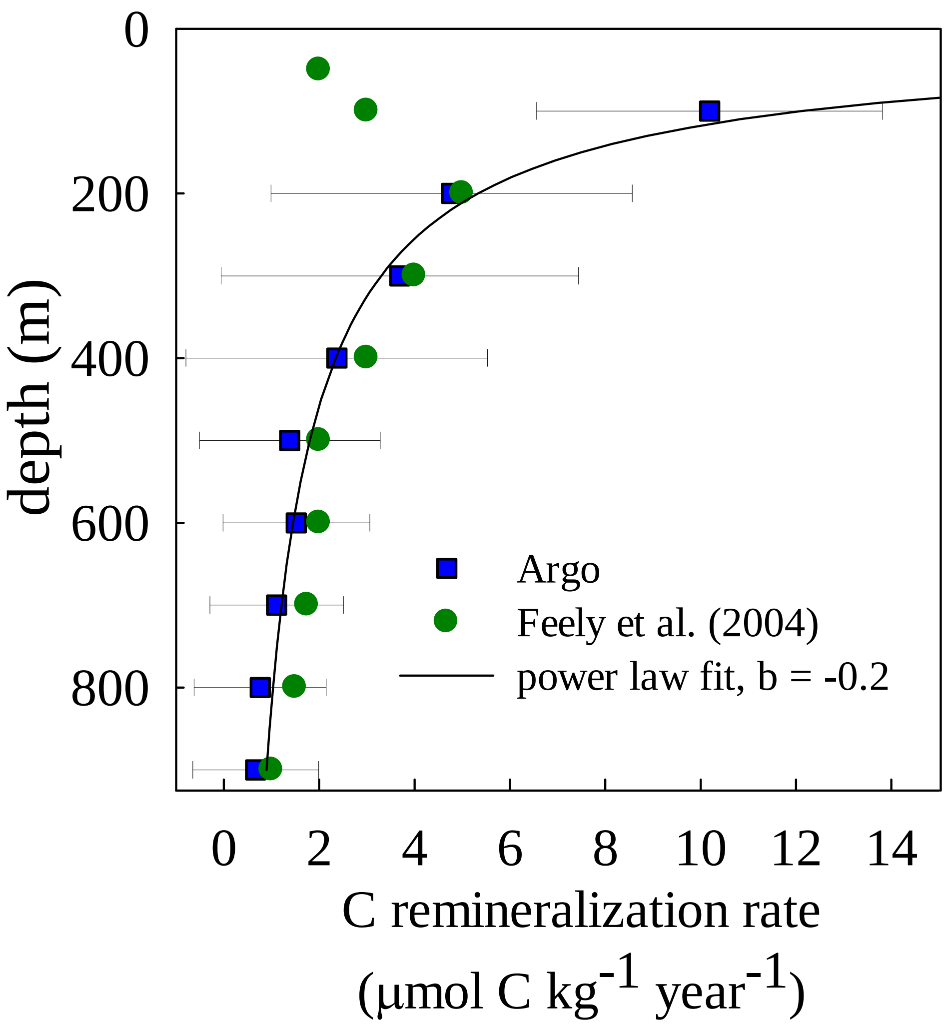






Float 5901048
c
50-200 m
42
41
40
39
38
37
11/1/05
3/1/06
7/1/06
11/1/06
3/1/07
time
Integrated O2 (mol O2 m-2)
Float 3900333
crosses Sub-Tropical Front
41
40
39
38
37
36
35
11/1/05
3/1/06
7/1/06
11/1/06
3/1/07
time

Remineralization rates at 43ºS



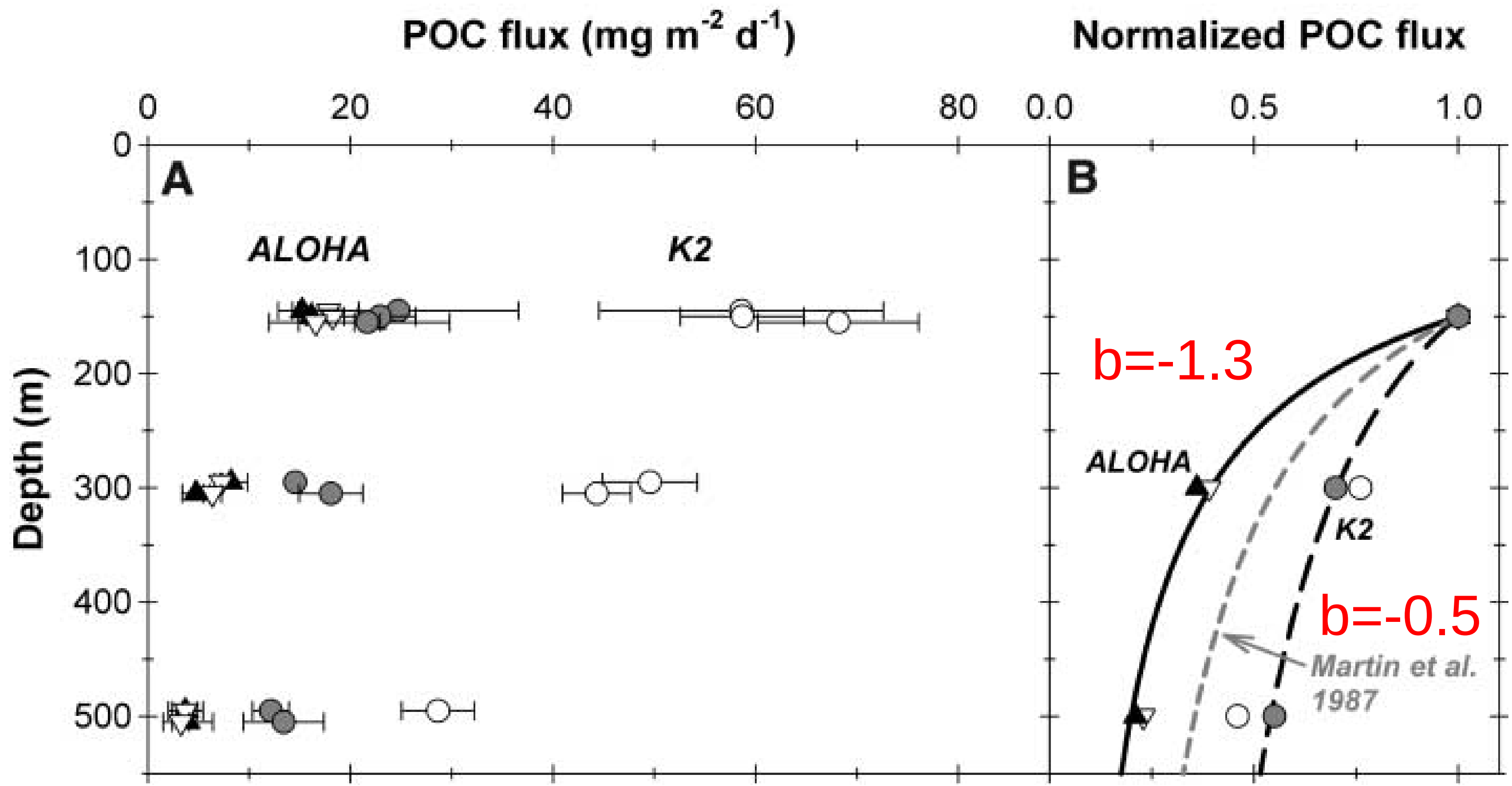
Derivative of the particle flux attenuation function

$$R_z \approx \frac{\partial F}{\partial z} = R_{100}\left(\frac{z}{100}\right)^{b-1}$$

Martin et al. (1987)

Martin 'b' exponent found using binned oxygen rates appears to be larger than trap-based values (usually -1.3 to -0.6).

This can be reconciled by: oxygen gradients, trapping efficiency, active transport.



Revisiting Carbon Flux Through the Ocean's Twilight Zone

Argo
b=-0.2

Ken O. Buesseler,[1*] Carl H. Lamborg,[1] Philip W. Boyd,[2] Phoebe J. Lam,[1] Thomas W. Trull,[3] Robert R. Bidigare,[4] James K. B. Bishop,[5,6] Karen L. Casciotti,[1] Frank Dehairs,[7] Marc Elskens,[7] Makio Honda,[8] David M. Karl,[4] David A. Siegel,[9] Mary W. Silver,[10] Deborah K. Steinberg,[11] Jim Valdes,[12] Benjamin Van Mooy,[1] Stephanie Wilson[11]

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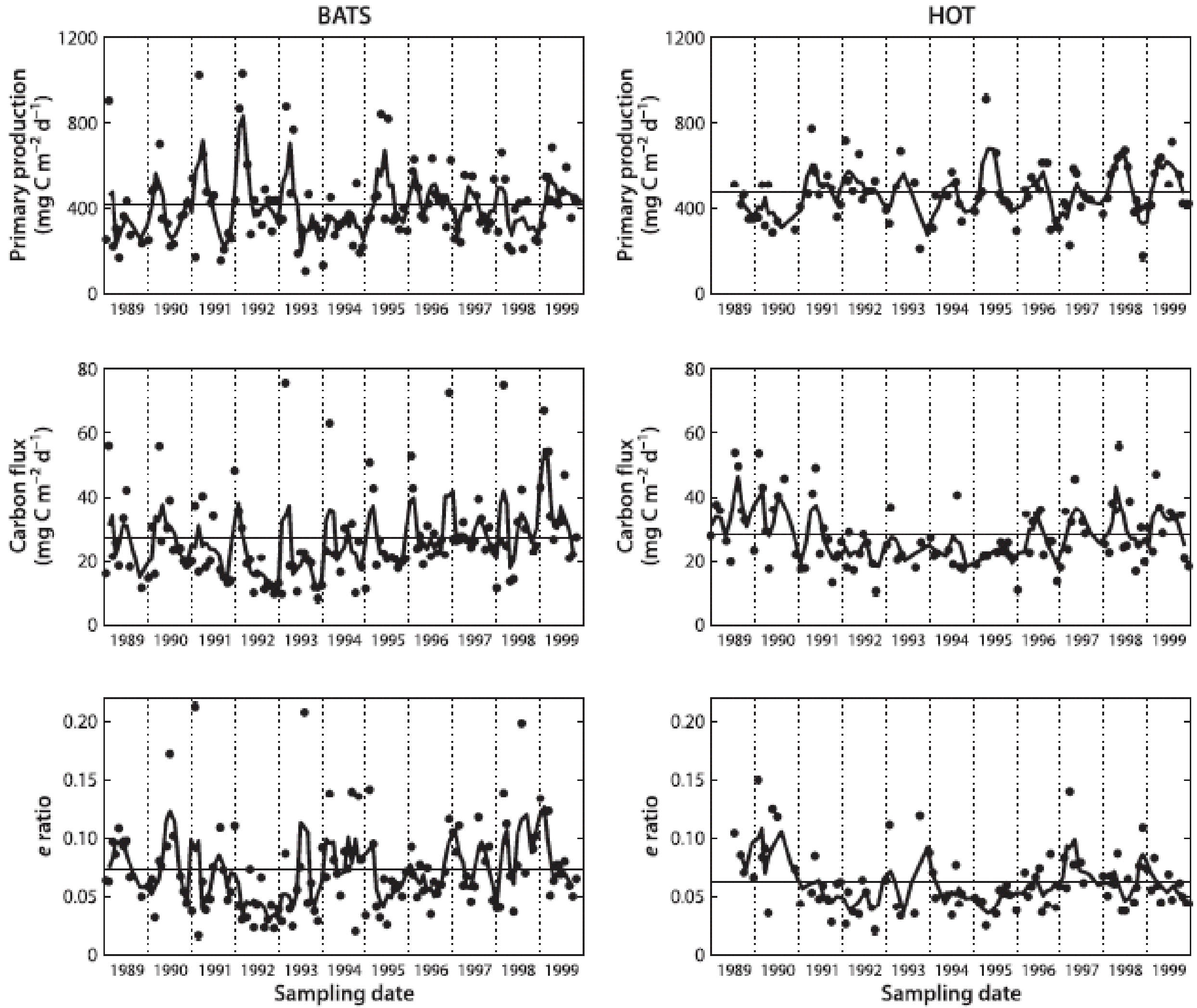

Fig. 10.9. Temporal variations of primary production (measured by the ^{14}C technique) and carbon flux (measured using free-drifting sediment traps positioned at the base of the euphotic zone) for an 11-year period at BATS and HOT time-series sites. Also shown at the *bottom* is the corresponding *e*-ratio (flux ÷ production). The *solid symbols* represent the individual cruise data for each parameter and the *heavy solid line* is the 3-point running mean. *Left:* BATS data sets showing the climatological mean values (*horizontal lines*): primary production = 416 mg C $m^{-2} d^{-1}$, carbon flux = 27.2 mg C $m^{-2} d^{-1}$, and *e*-ratio = 0.072. *Right:* HOT data sets showing the climatological mean values (*horizontal lines*): primary production = 480 mg C $m^{-2} d^{-1}$, carbon flux = 28.3 mg C $m^{-2} d^{-1}$, and *e*-ratio = 0.062

Chapter 10

Temporal Studies of Biogeochemical Processes Determined from Ocean Time-Series Observations During the JGOFS Era

David M. Karl · Nicholas R. Bates · Steven Emerson · Paul J. Harrison · Catherine Jeandel · Octavio Llinás
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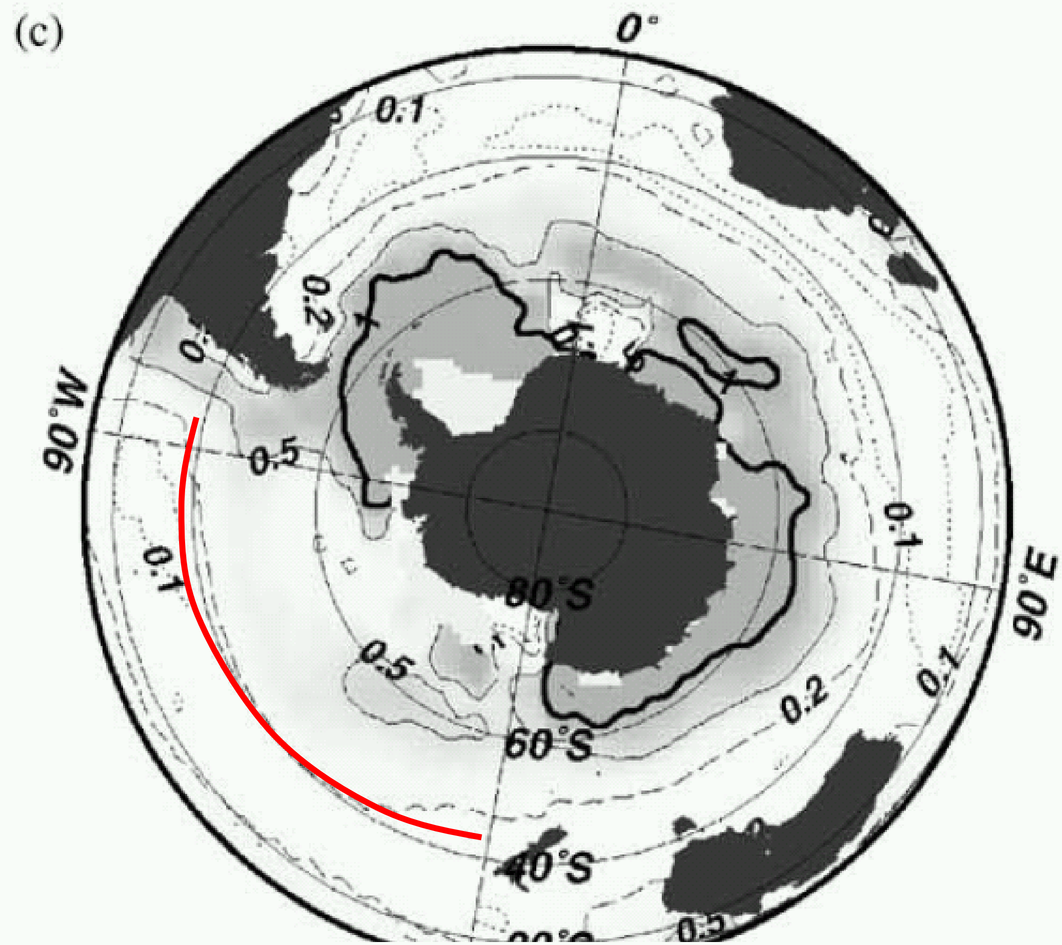
e-ratio (= C-exported/Pri. Prod.) based on an inversion of oxygen and nutrient data collected over decades.

Argo e-ratio = 0.15±0.05 (95% CI)



Part II

PERGAMON

Deep-Sea Research II 49 (2002) 1623–1644

www.elsevier.com/locate/dsr2

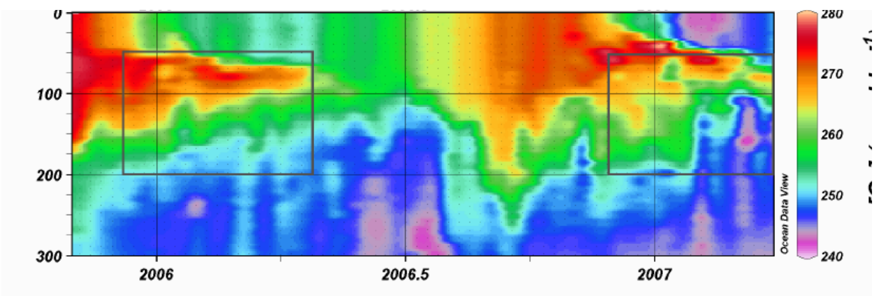
Carbon export fluxes in the Southern Ocean: results from inverse modeling and comparison with satellite-based estimates

Reiner Schlitzer

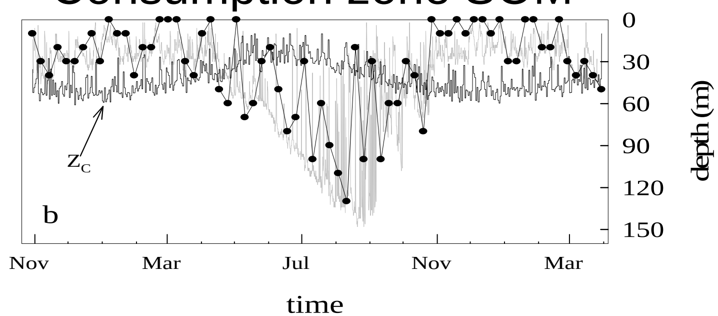
Model/Data synergy

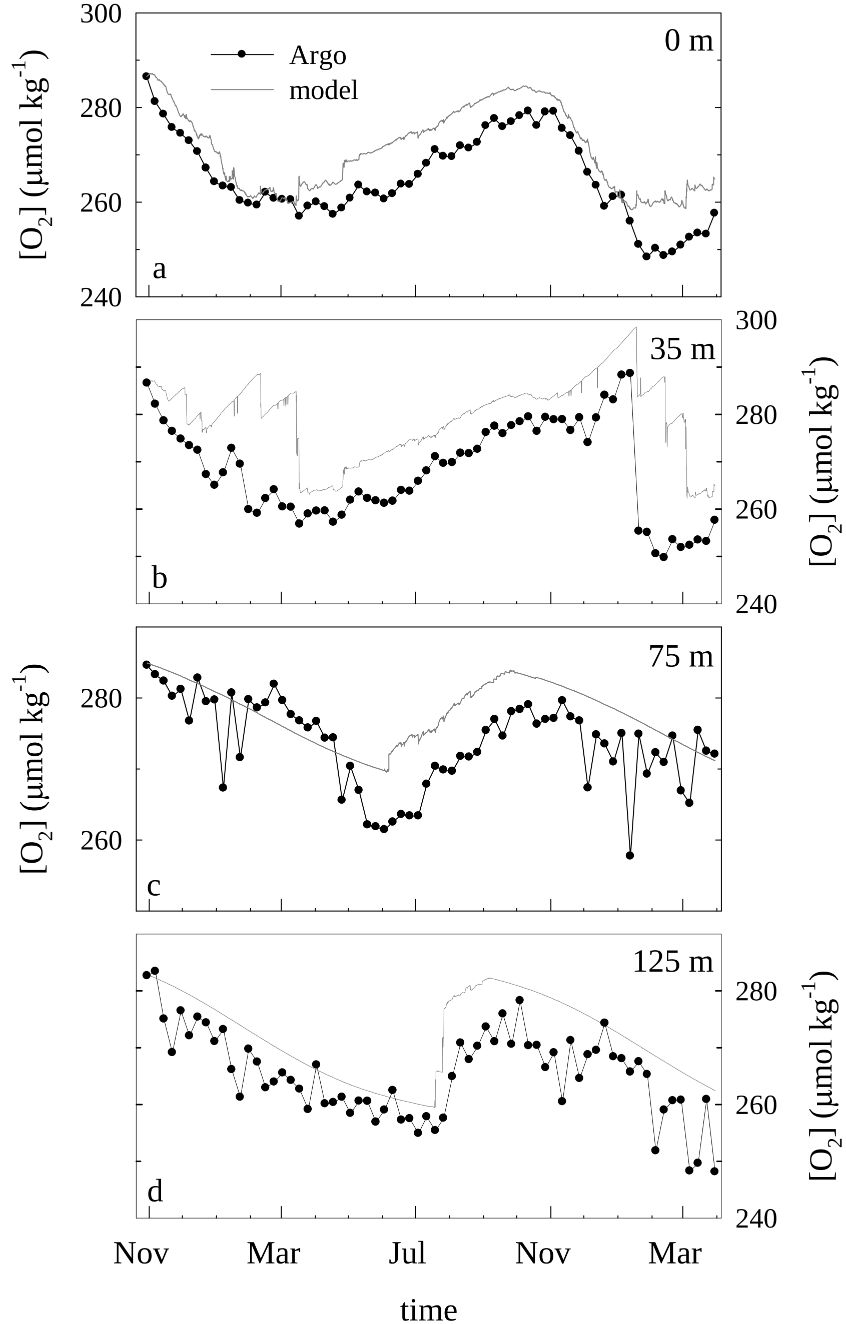
Musgrave et al (1988)
Oxygen & PWP physical model

Model NCP = 2.1 mol C m^{-2} yr^{-1}



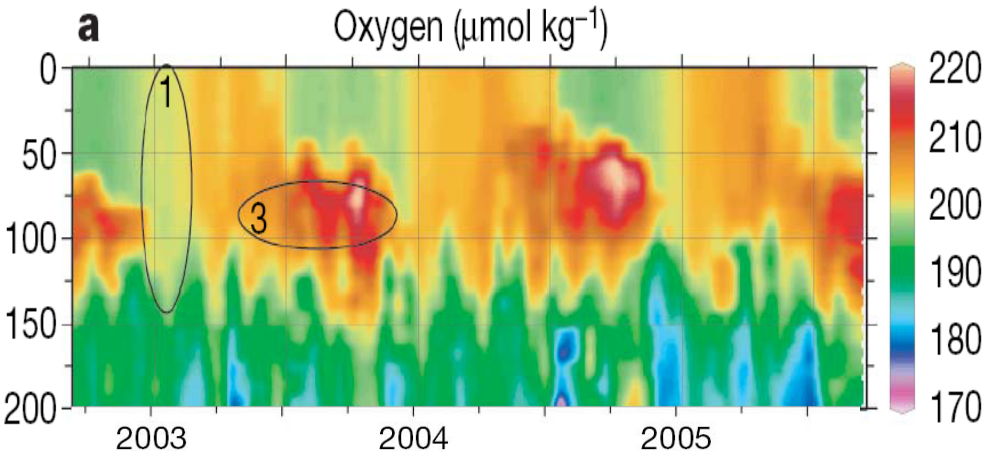
Consumption zone SOM

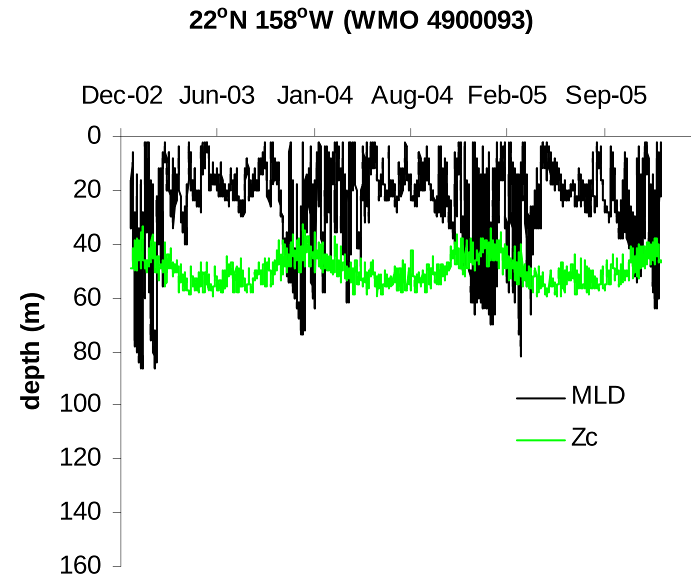




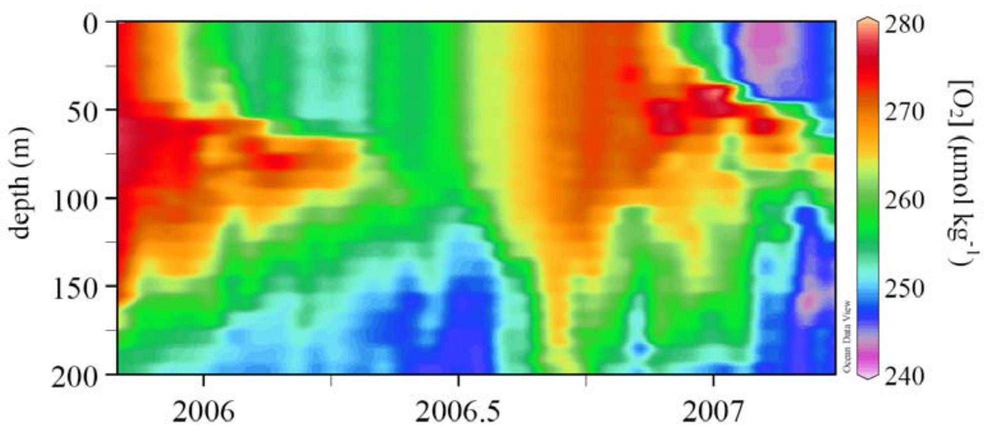
SOM and latitude

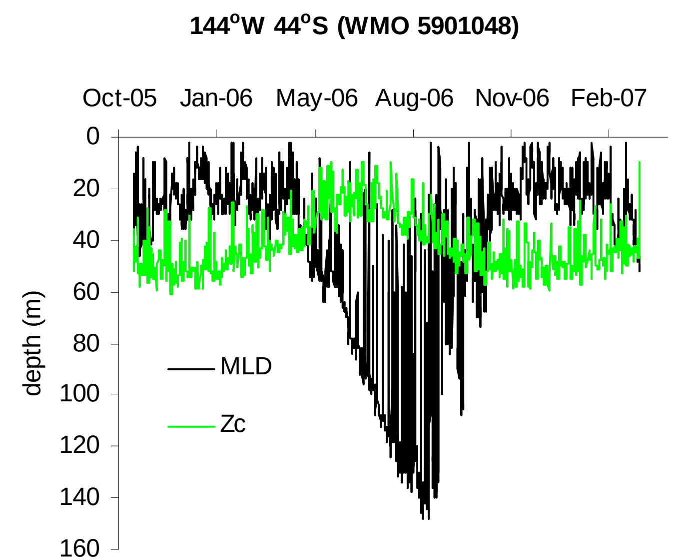
Production zone SOM at 22ºN





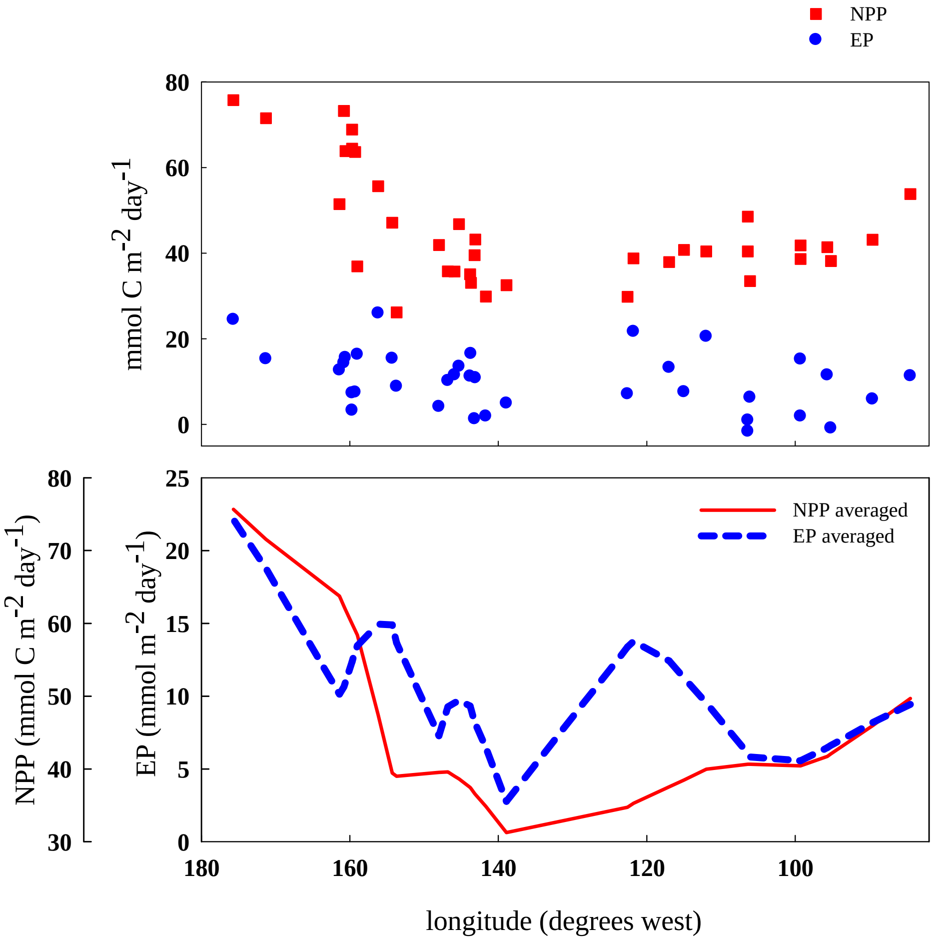
Consumption zone SOM at 43ºS



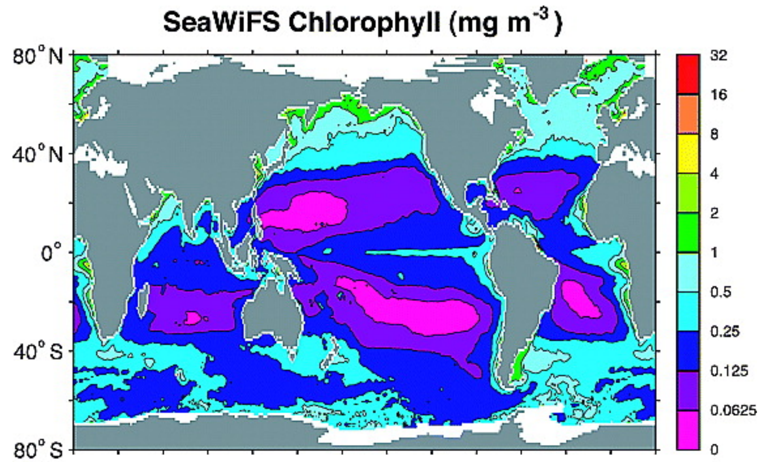


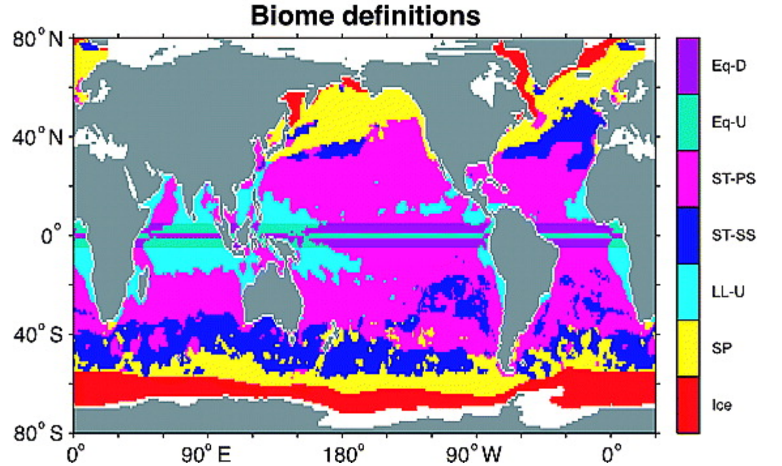
Spatial trends at 42ºS?

Floats are located in a transition region between the permanently stratified, oligotrophic South Pacific subtropical gyre and the seasonally stratified, mesotrophic South Pacific



Sarmiento, J. L.; R. Slater, R. Barber, L. Bopp, S. C. Doney, A. C. Hirst, J. Kleypas, R. Matear, U. Mikolajewicz, P. Monfray, V. Soldatov, S. A. Spall, and R. Stouffer. 2004. Response of ocean ecosystems to climate warming. Global Biogeochem. Cycles. **18**: GB3003, doi:10.1029/2003GB002134.

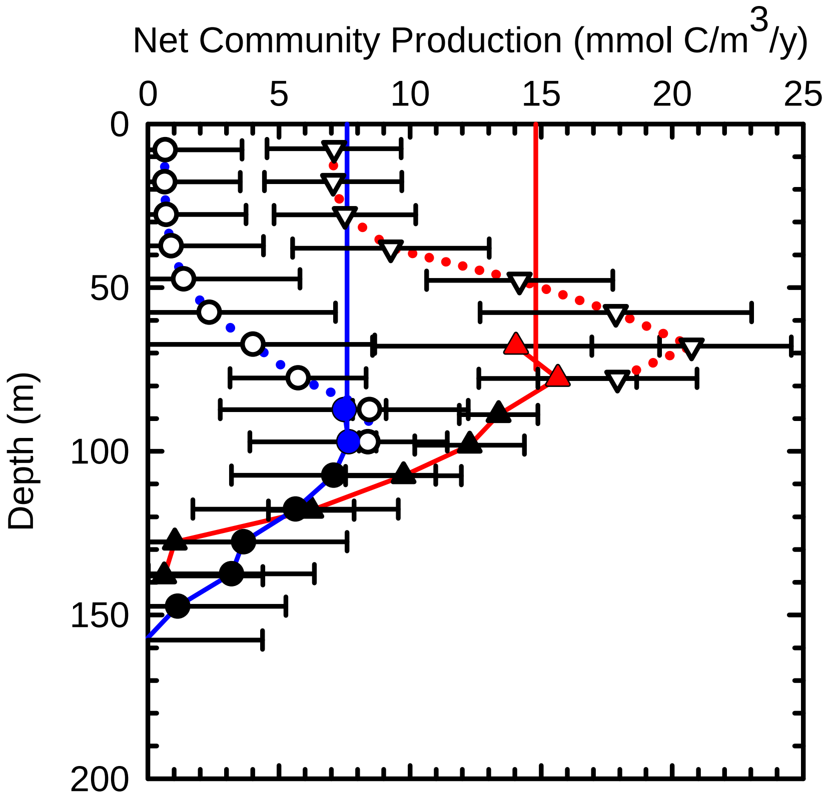


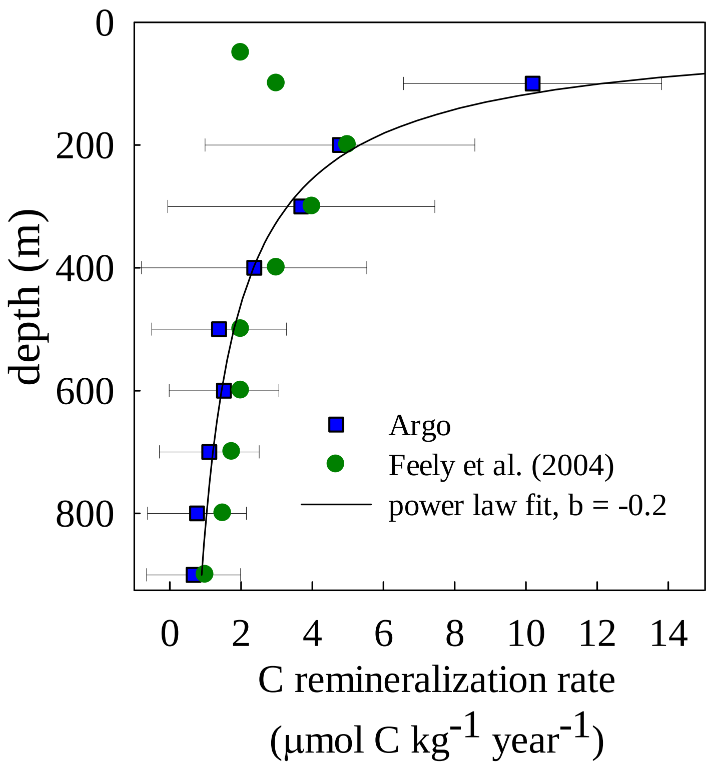


Summary of rates calculated

Low productivity STG

Intense SOM allows estimates of NCP above Z_c





Higher productivity region (STF)

Substantial vertical export/transport of organic matter allows estimates of EP below Z_c

pH sensors allow TCO2 and NCP to be estimated in mixed layer: Ion Selective Field Effect Transistor - ISFET

P. Bergveld / Sensors and Actuators B 88 (2003) 1–20

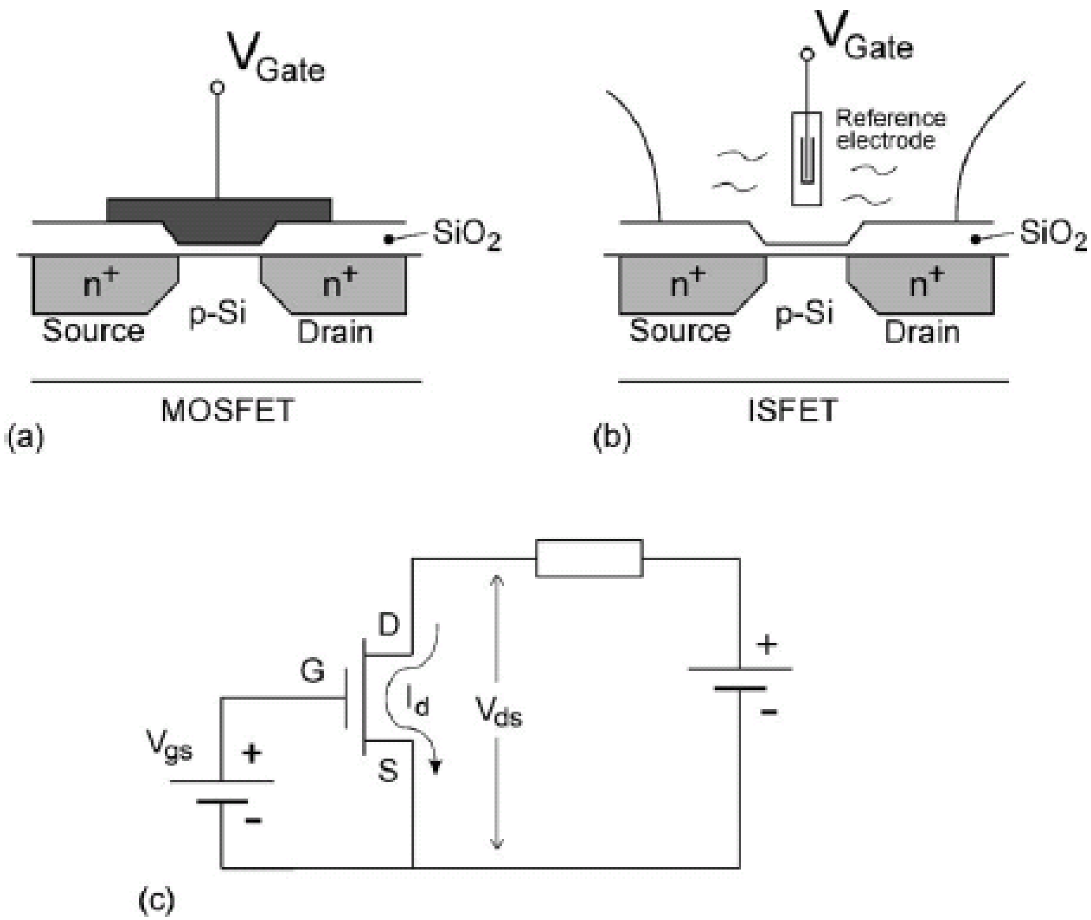
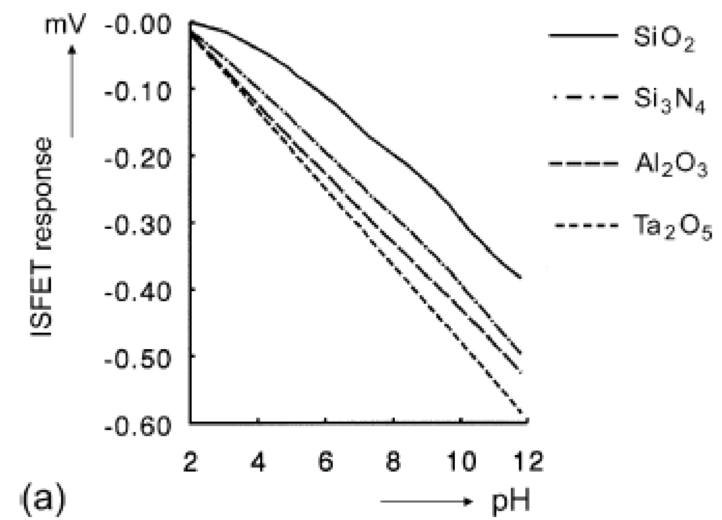
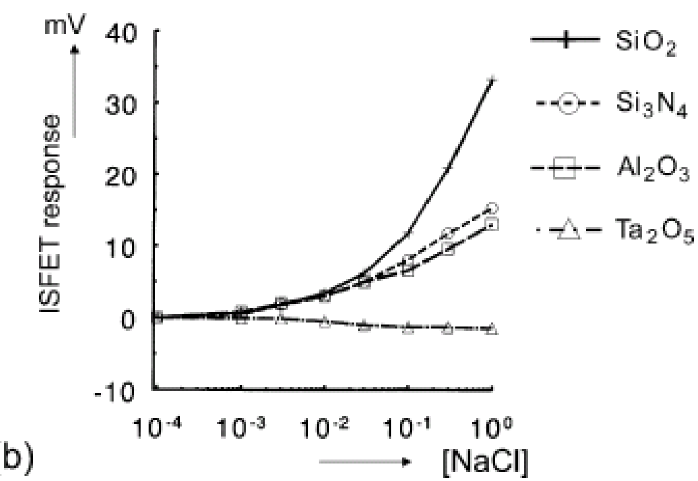
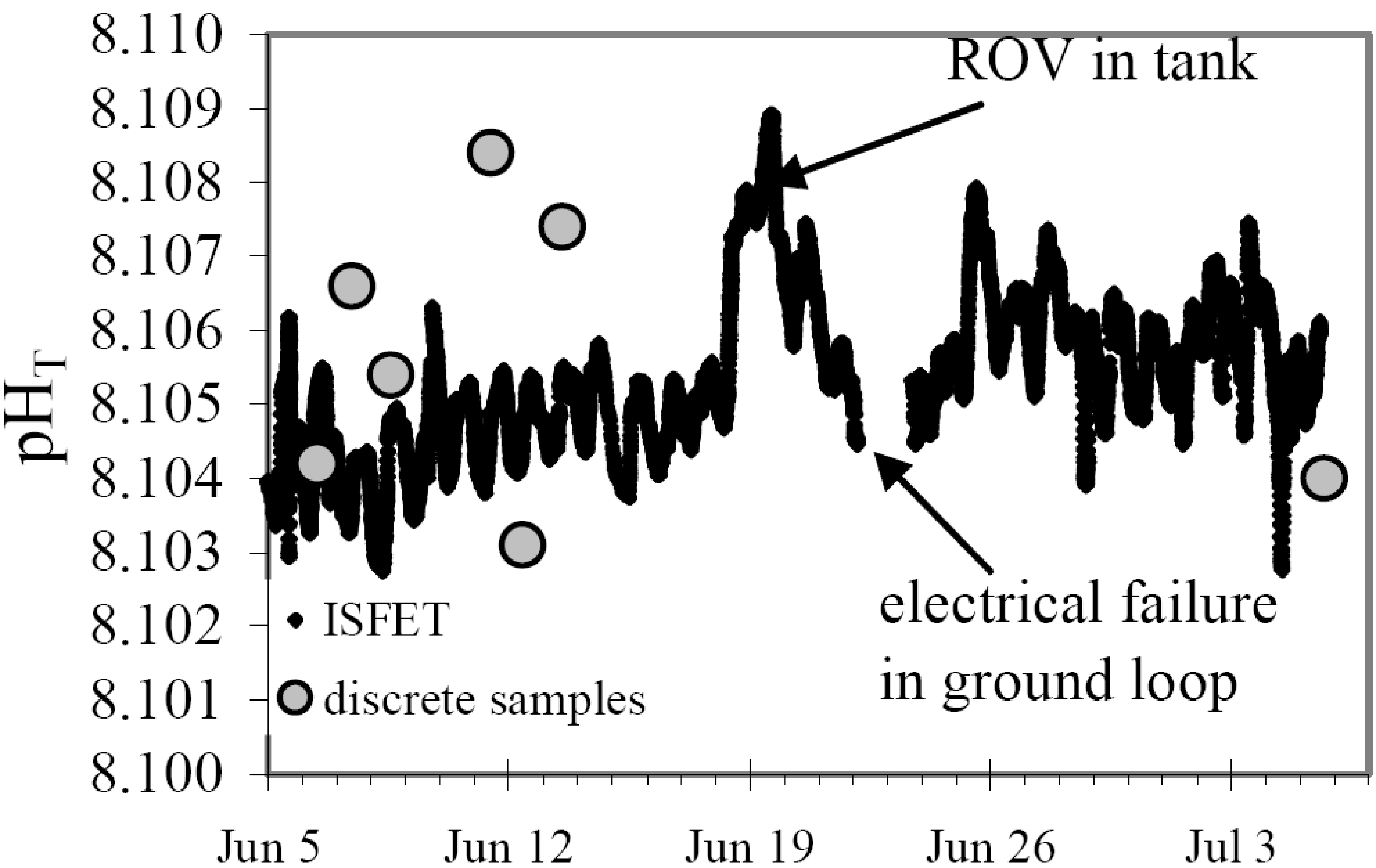


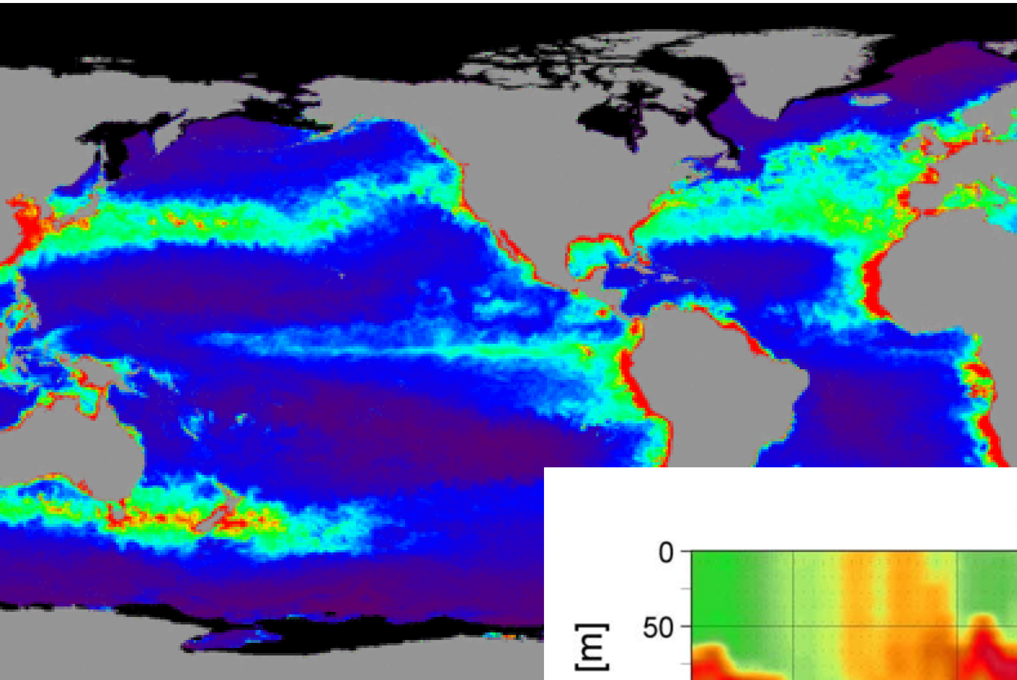
Fig. 3. Schematic representation of MOSFET (a), ISFET (b), and electronic diagram (c).

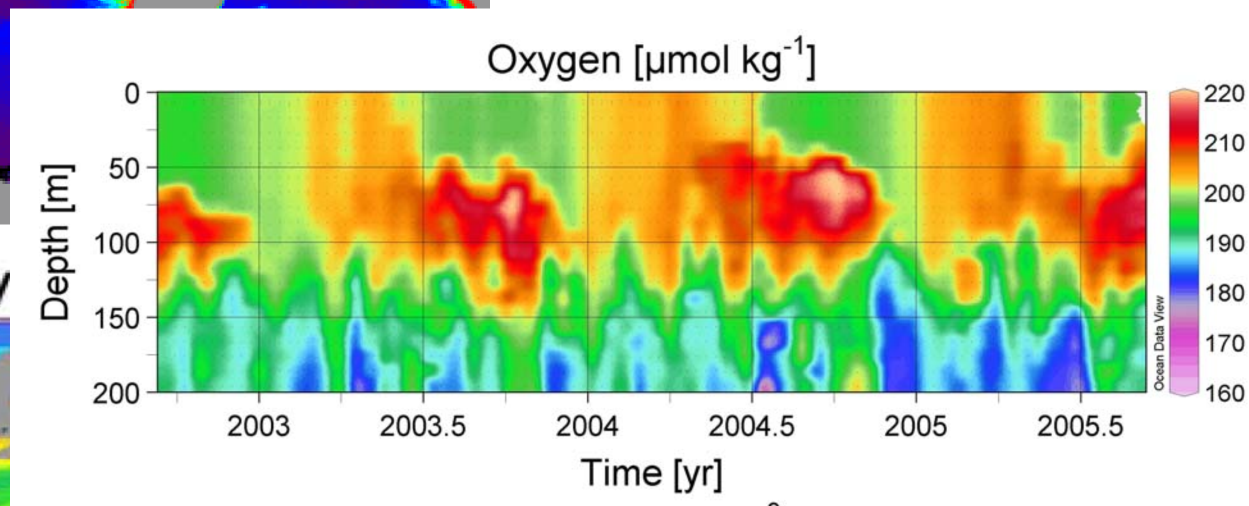


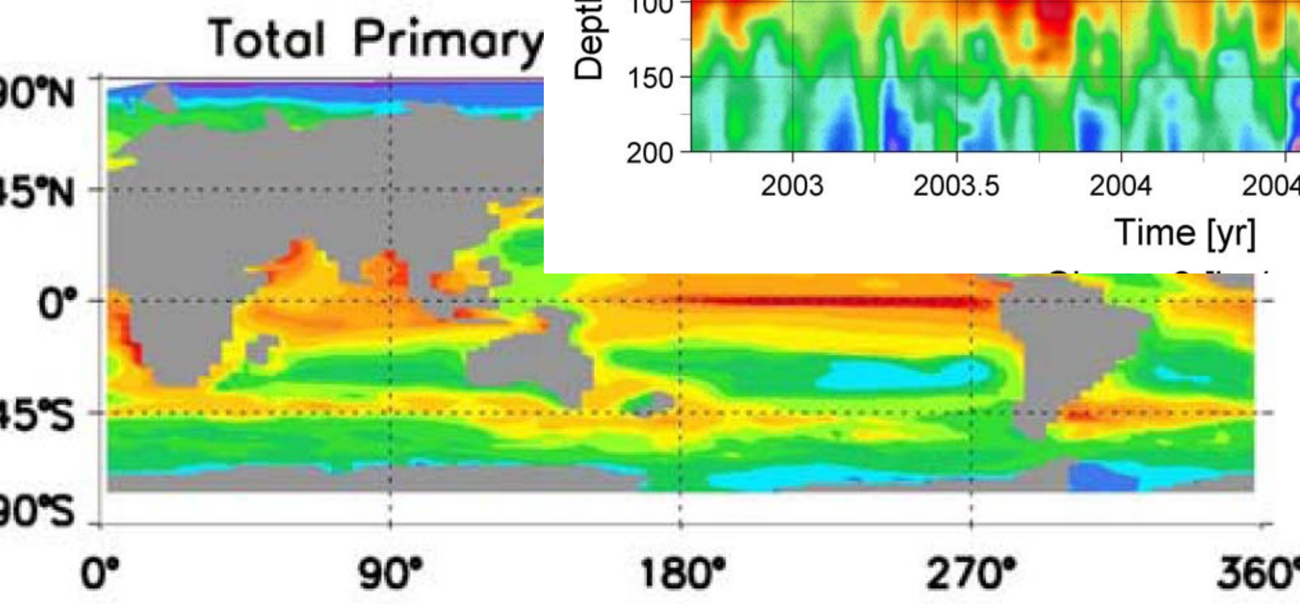



pH$_T$
8.110
8.109
8.108
8.107
8.106
8.105
8.104
8.103
8.102
8.101
8.100
ROV in tank
electrical failure
in ground loop
ISFET
discrete samples
Jun 5
Jun 12
Jun 19
Jun 26
Jul 3

Merged satellite, in situ and model based system would ocean primary production, carbon export …. to be observed with detail not possible before.







A) CCSM Primary Production (0–111m)

What would it cost?

Biological Benefits

- Terrestrial and marine exchanges currently remove more than 4 Gt C yr^{-1} from the atmosphere (55% of anthropogenic emissions)
- This free service provided by the planet constitutes an effective 55% emissions reduction, worth Trillions of $$ per year if we had to provide it through mitigation measurements.

$400 Billion – $400x10^9$

What would it cost per year?

- Current US Argo cost $10,000,000; world is probably double that = $20,000,000

- Adding oxygen to Argo estimate in Friends of Oxygen on Argo Floats report (Gruber et al., 2007) to increase operating costs 50% = $10,000,000

- Adding chlorophyll is probably a similar cost. = $10,000,000

- Adding nitrate would probably be order of 100% = $20,000,000 (or more)

- Total is $60,000,000 and assume US share is $30,000,000


A global, in situ observing system for ocean biogeochemistry that doesn't require a fleet of people on ships all the time is feasible.