Autonomous observing at time series stations using moorings, gliders & floats

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the David & Lucile Packard Foundation

NSF

The goals of autonomous, time-series observations might be:

- measure carbon cycle rates with sufficient precision to detect interannual and decadal changes,

- extend the footprint of time series beyond a few stations to “oceanic”

- enable linked in situ observations/satellite observations/numerical models to increase the power, skill, and spatial extent of predictions.

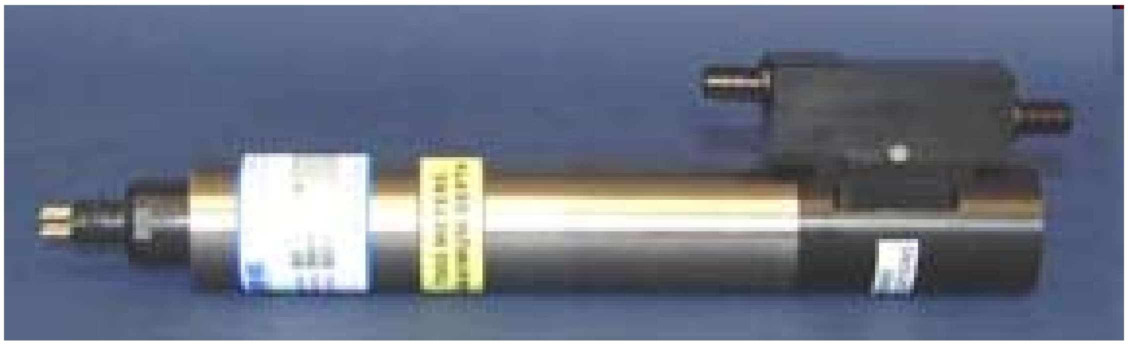
Outline

The focus is on sensors that are capable NOW of long-term, time-series observations:

- Oxygen
- Inorganic carbon (pCO_2 and pH)
- Nitrate
- Biooptics/acoustics

Demonstrate potential for these systems to make “calibrated” rate measurements that could be used to assess interannual variability

Oxygen



Tengberg et al. *Lifetime-based optode to measure oxygen*

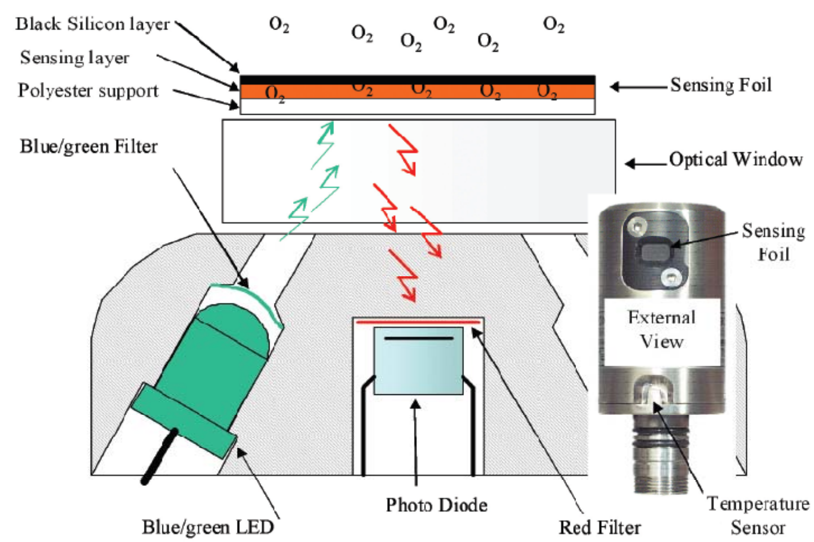
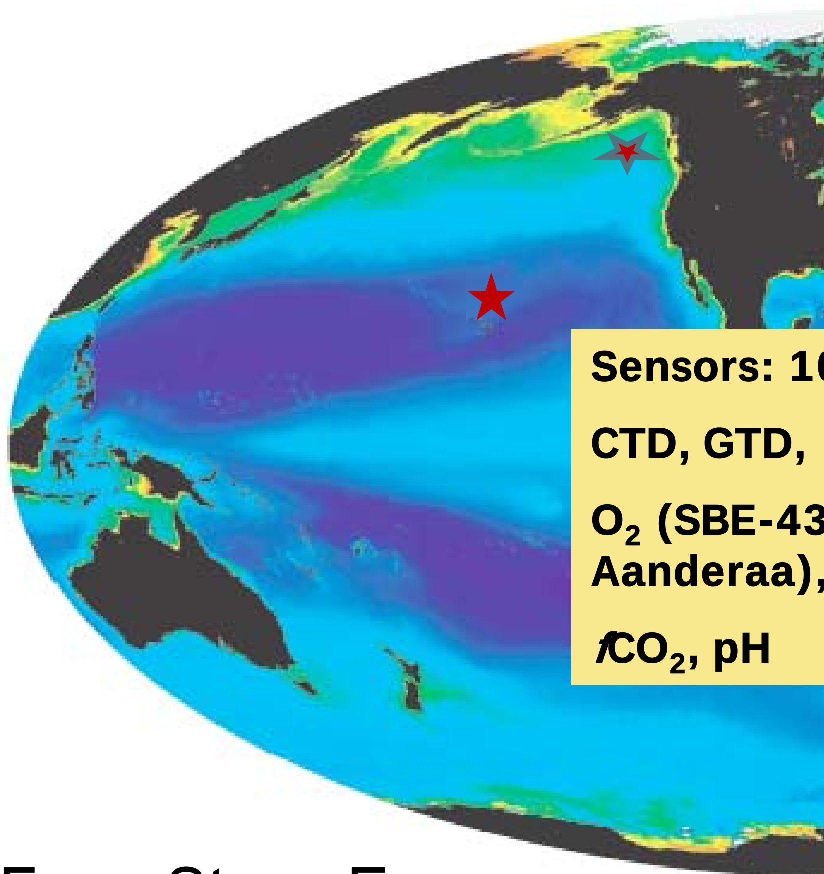
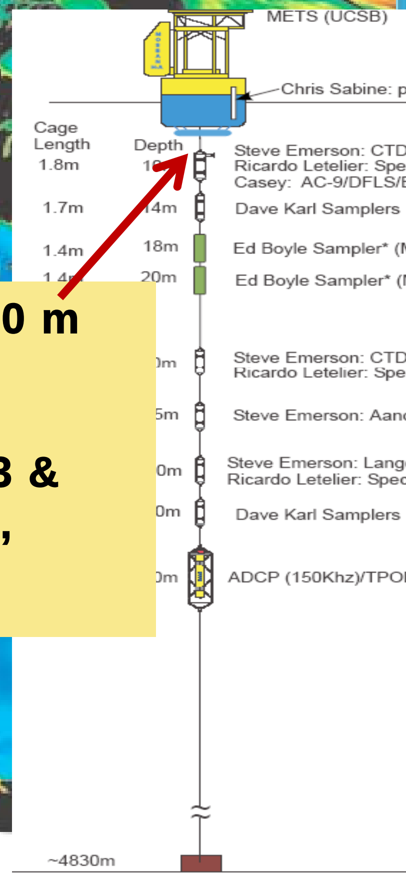


Fig. 1. Optical design and an outside view of the evaluated optode-based oxygen sensor.

IN SITU MEASUREMENTS OF NET BIOLOGICAL OXYGEN PRODUCTION

COLLABORATORS: Roo Nicholson, Chuck Stump U.W.
Meghan Cronin,Chris Sabine, PMEL
Mike DeGranpre, U.Montana; Marie Robert IOS, BC, CA
Tommy Dickey, HOT Scientists





Sensors: 10 m

CTD, GTD,

O_2 (SBE-43 & Aanderaa),

fCO_2, pH

From Steve Emerson

GLOBAL BIOGEOCHEMICAL CYCLES, VOL. 22, GB3023, doi:10.1029/2007GB003095, 2008

Net biological oxygen production in the ocean: Remote in situ measurements of O_2 and N_2 in surface waters

Steven Emerson,[1] Charles Stump,[1] and David Nicholson[1]

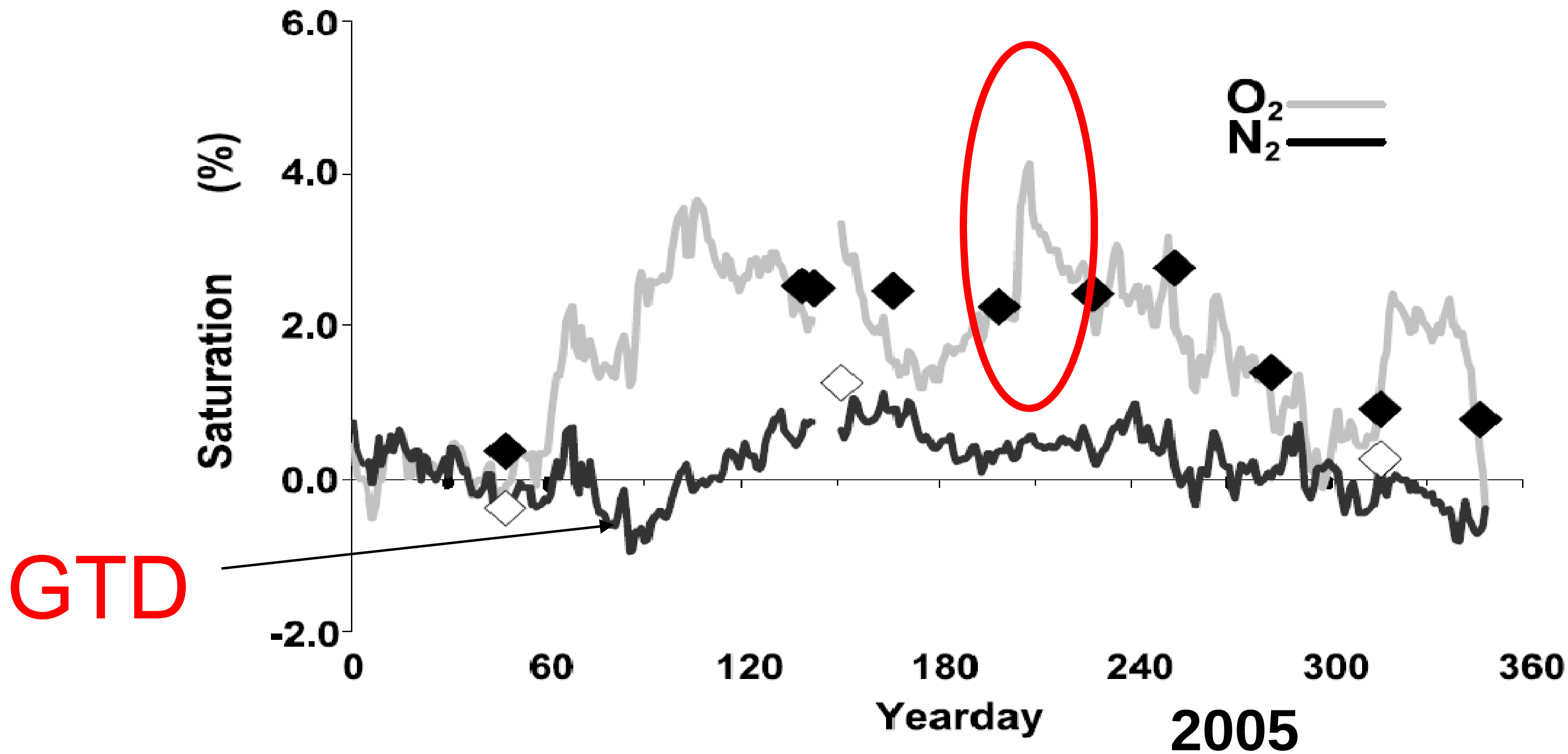


Figure 3. Mean daily oxygen (light line) and nitrogen (dark line) supersaturation (in percent) at 10 m on the MOSEAN mooring at HOT. Dark symbols are oxygen

Gas exchange rate large. Requires very accurate oxygen measurements. Either in situ O_2 calibration needed, or periodic ship visits (Emerson et al. 2008).

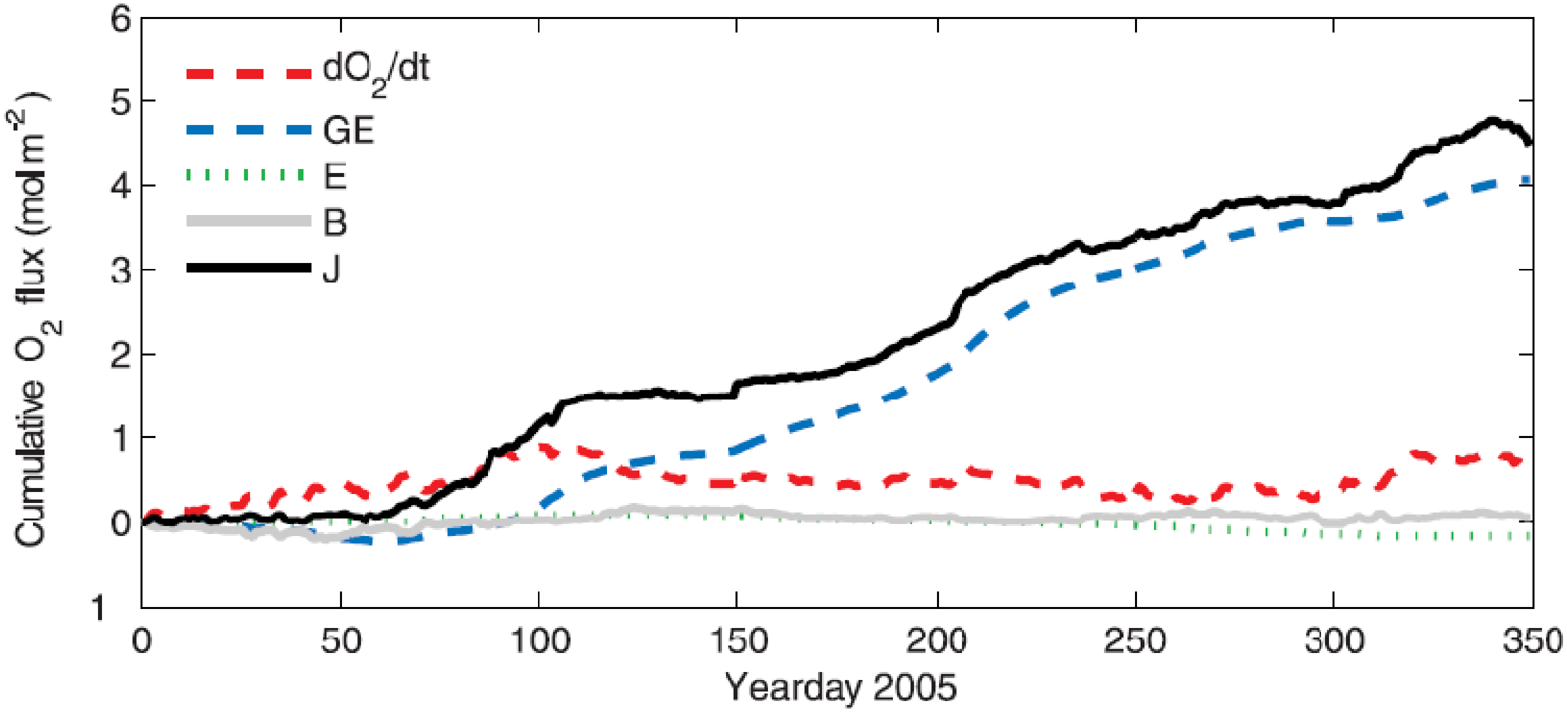


Figure 6. The cumulative biological oxygen production calculated from equations (9) and (10) and the data presented in Figure 3. Different lines are the individual components of the oxygen mass indicated in equation (2): $J = d[O_2]/dt - GE_{A-W} - B - E$, wherein J is the biological oxygen production, $d[O_2]/dt$ is

GLOBAL BIOGEOCHEMICAL CYCLES, VOL. 22, GB3023, doi:10.1029/2007GB003095, 2008 presents bubble fluxes, and

Net biological oxygen production in the ocean: Remote in situ measurements of O_2 and N_2 in surface waters

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CONCLUSION: O_2 and Organic C export is at least as great at HOT as it is at Stn P –

Model and Satellite Export estimates are poorly calibrated!

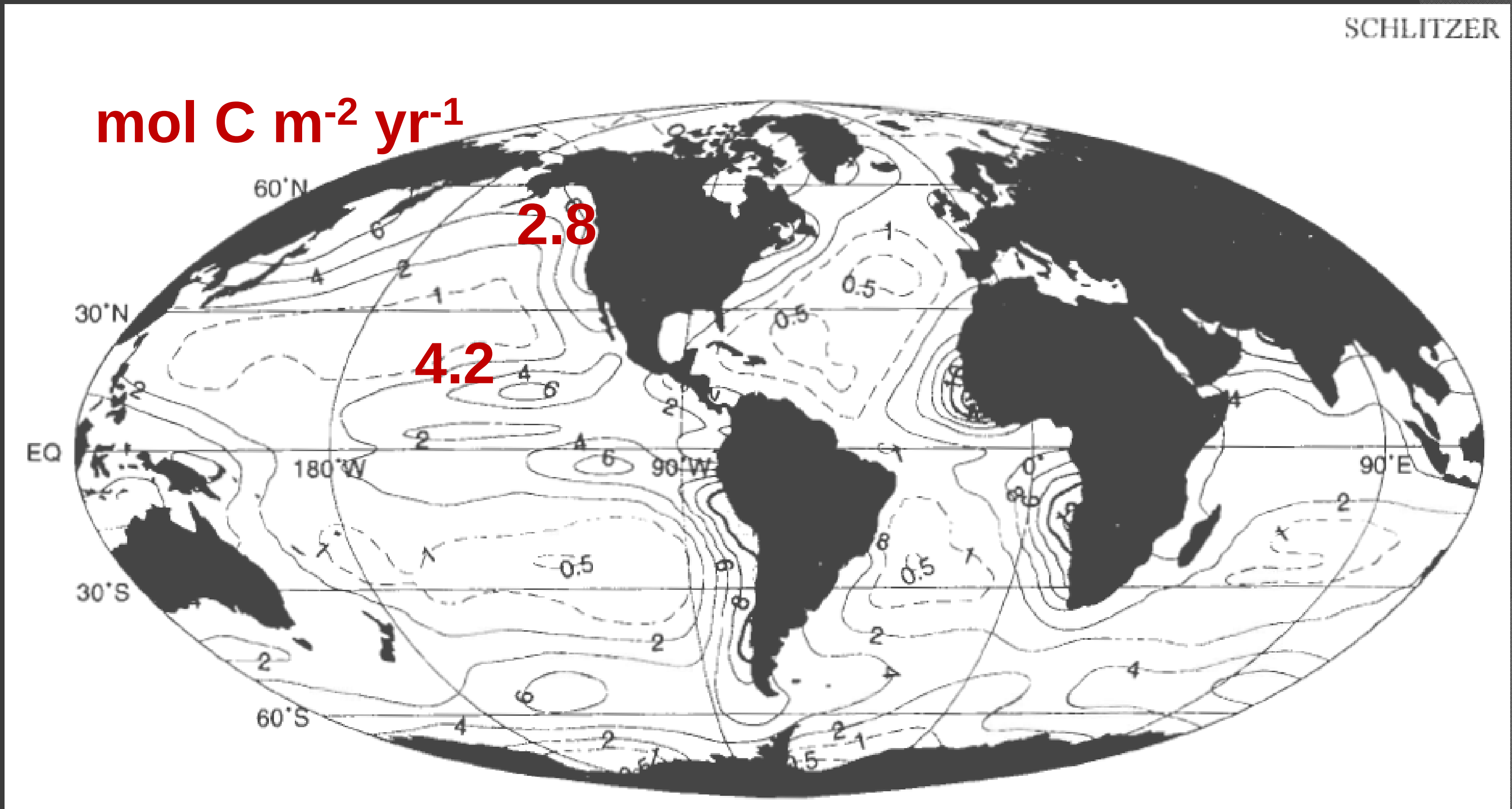


Figure 9. Export production of particulate organic matter (POM) [mol C m^{-2} yr^{-1}] for the global model.

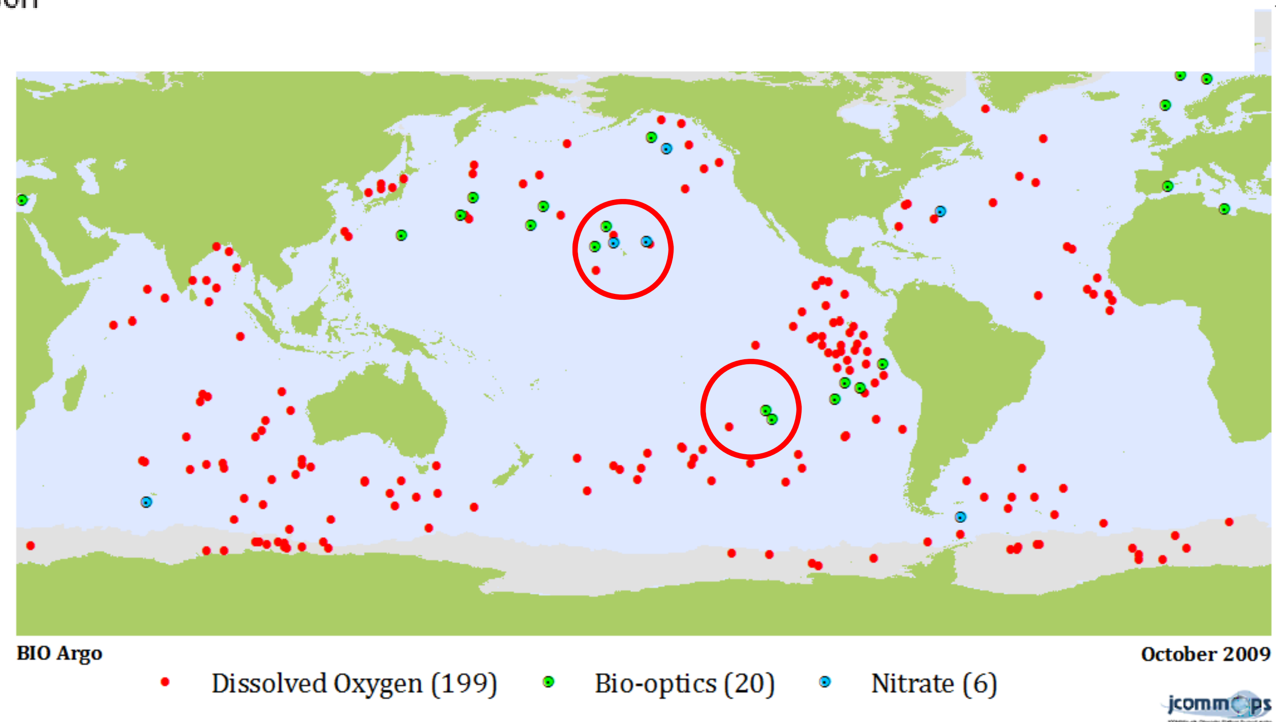
Oxygen sensors now deployed on ~200 Argo floats.

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

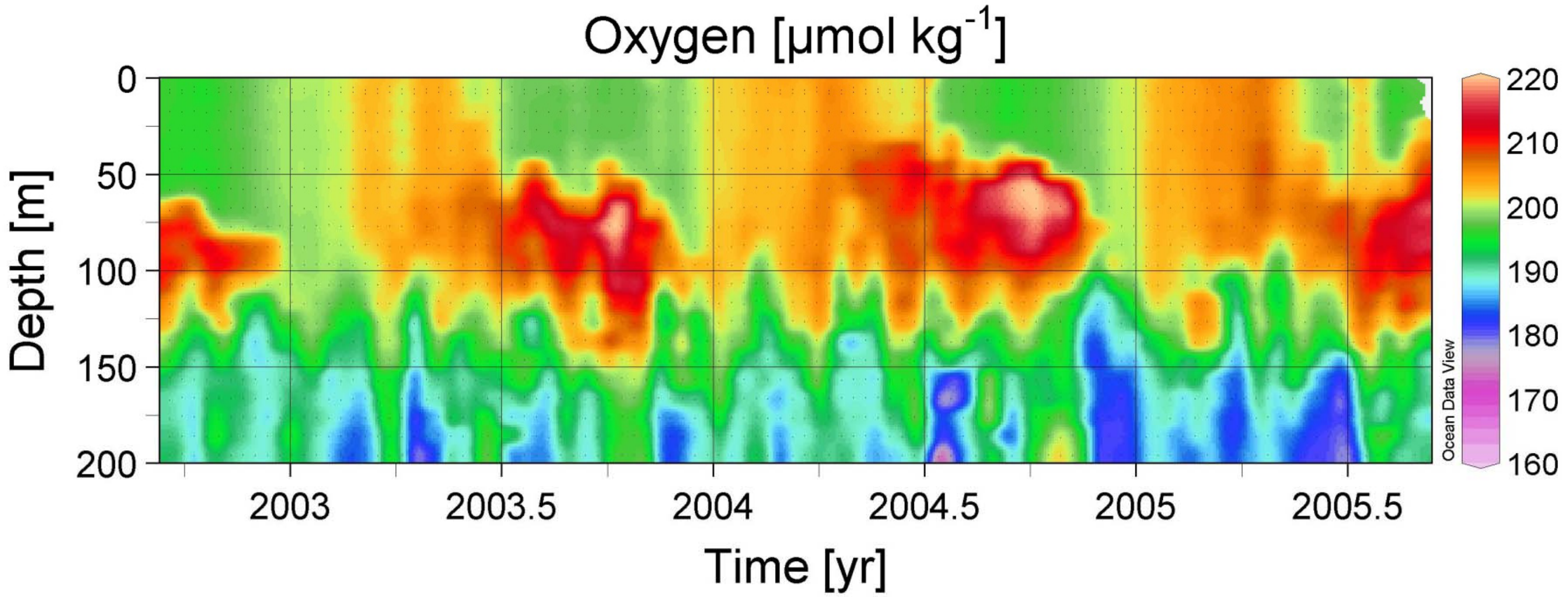
LETTERS

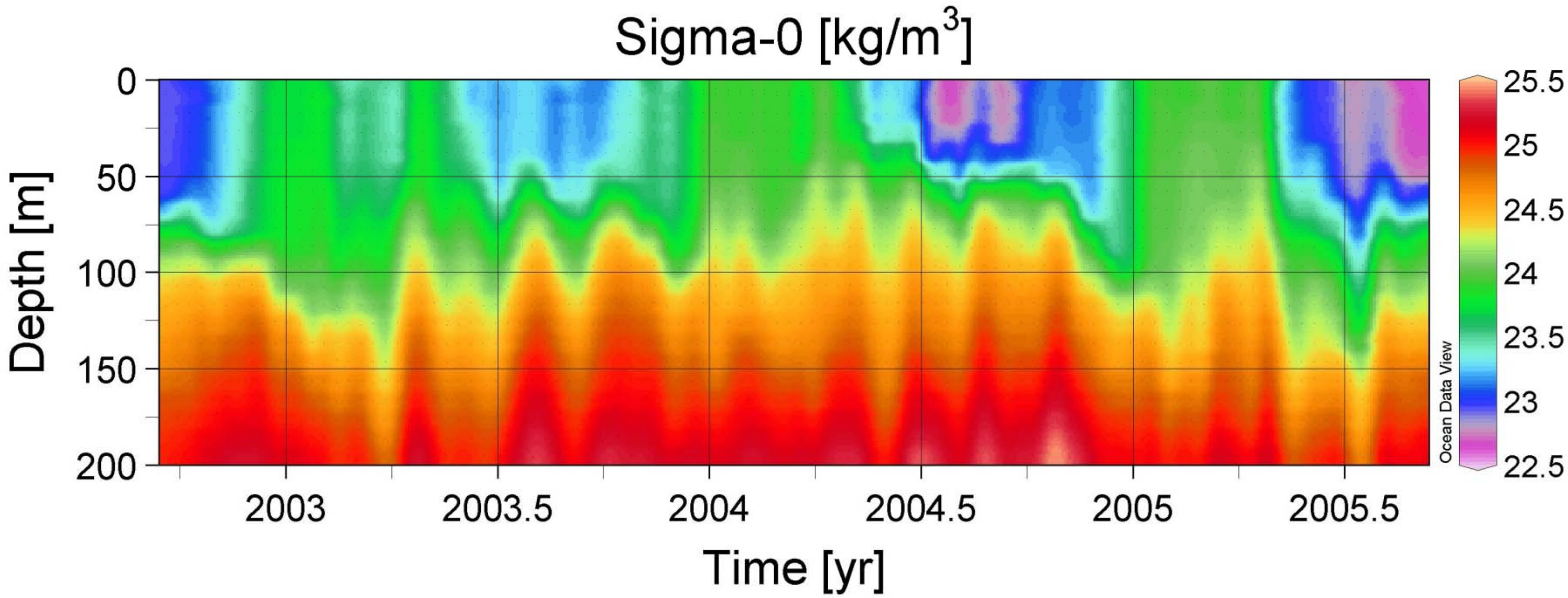
Net production of oxygen in the subtropical ocean

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

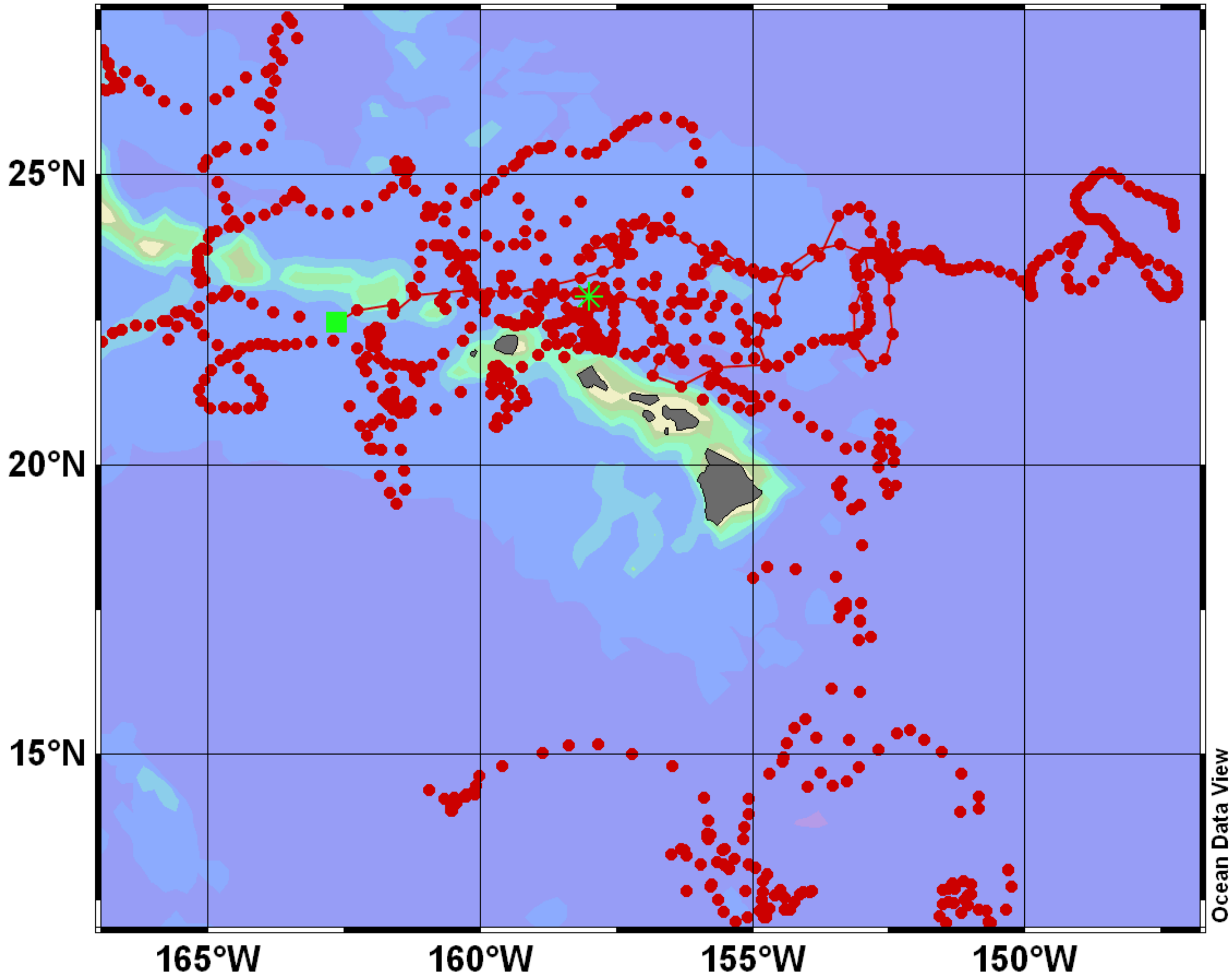


3 years of O_2 data near HOT. Oxygen increases during summer each year, below mixed layer. Must be due to biological production. Net autotrophic.





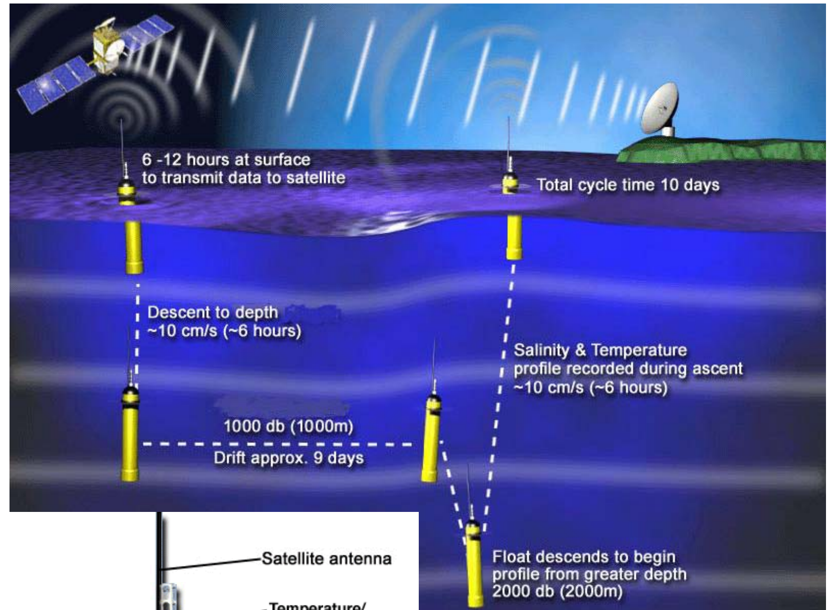
Nine profiling floats with O2 sensors have been deployed near Hawaii. > 1000 vertical profiles. All data is in the public domain.

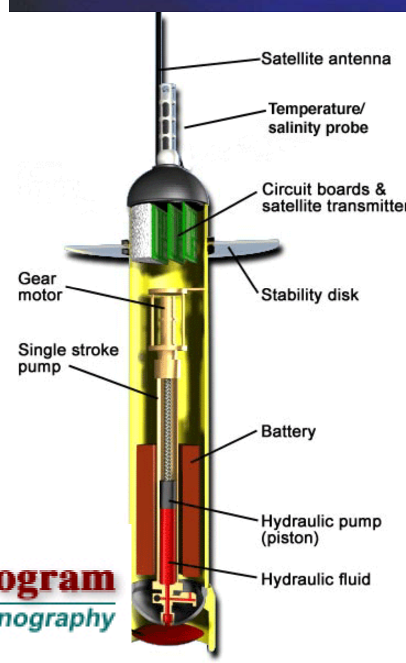


Ocean metabolism observed with oxygen sensors on profiling floats in the Pacific

A collaboration with Steve Riser, UW

- ~100 UW oxygen floats deployed since 2002



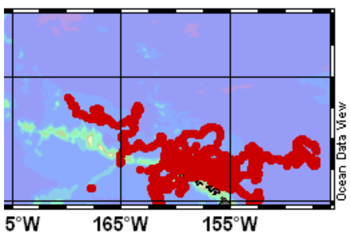


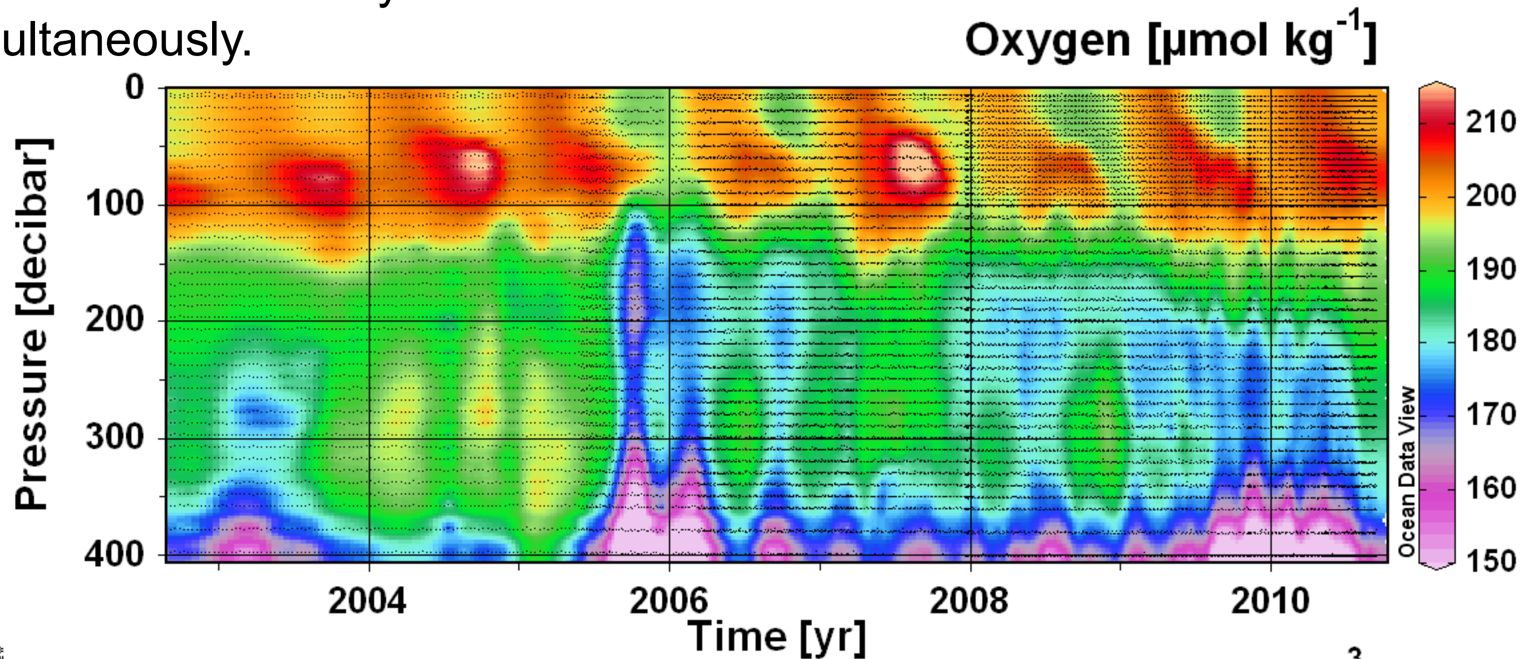
Argo

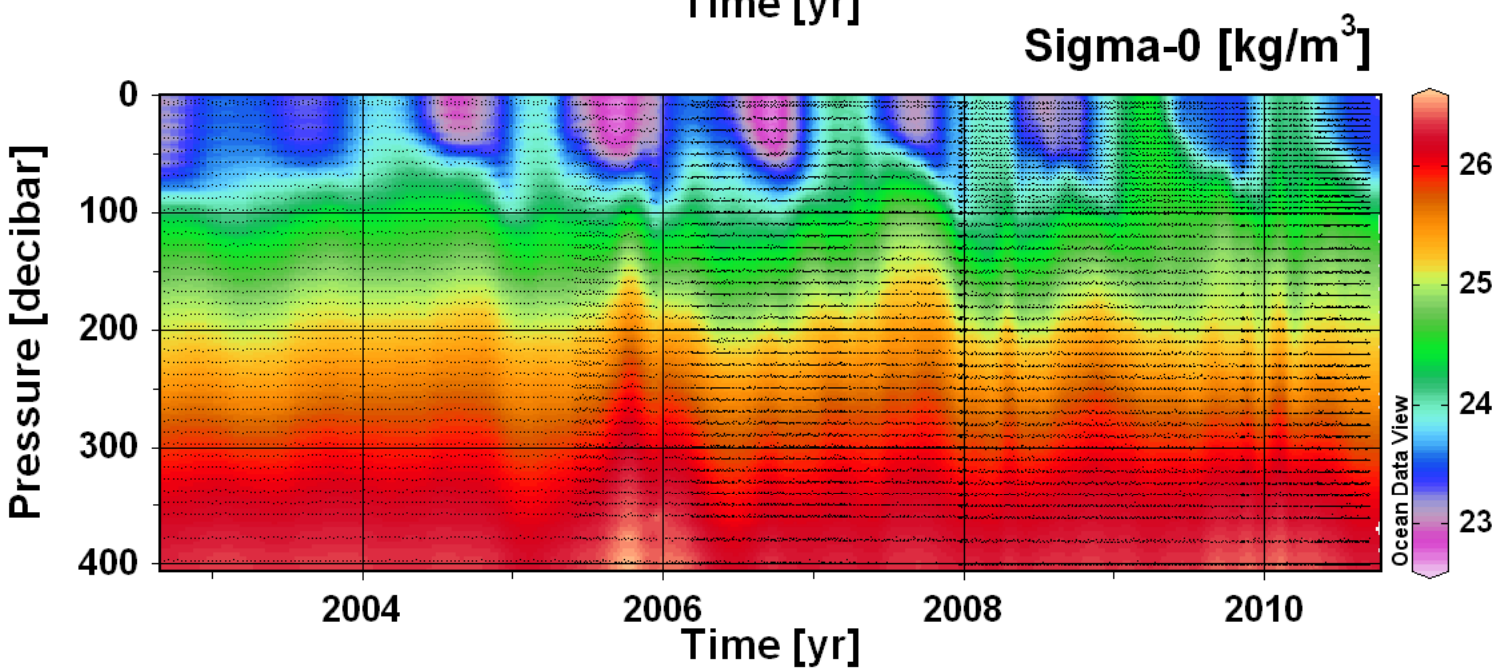
National Oceanographic Partnership Program

Promoting Partnerships for the Future of Oceanography

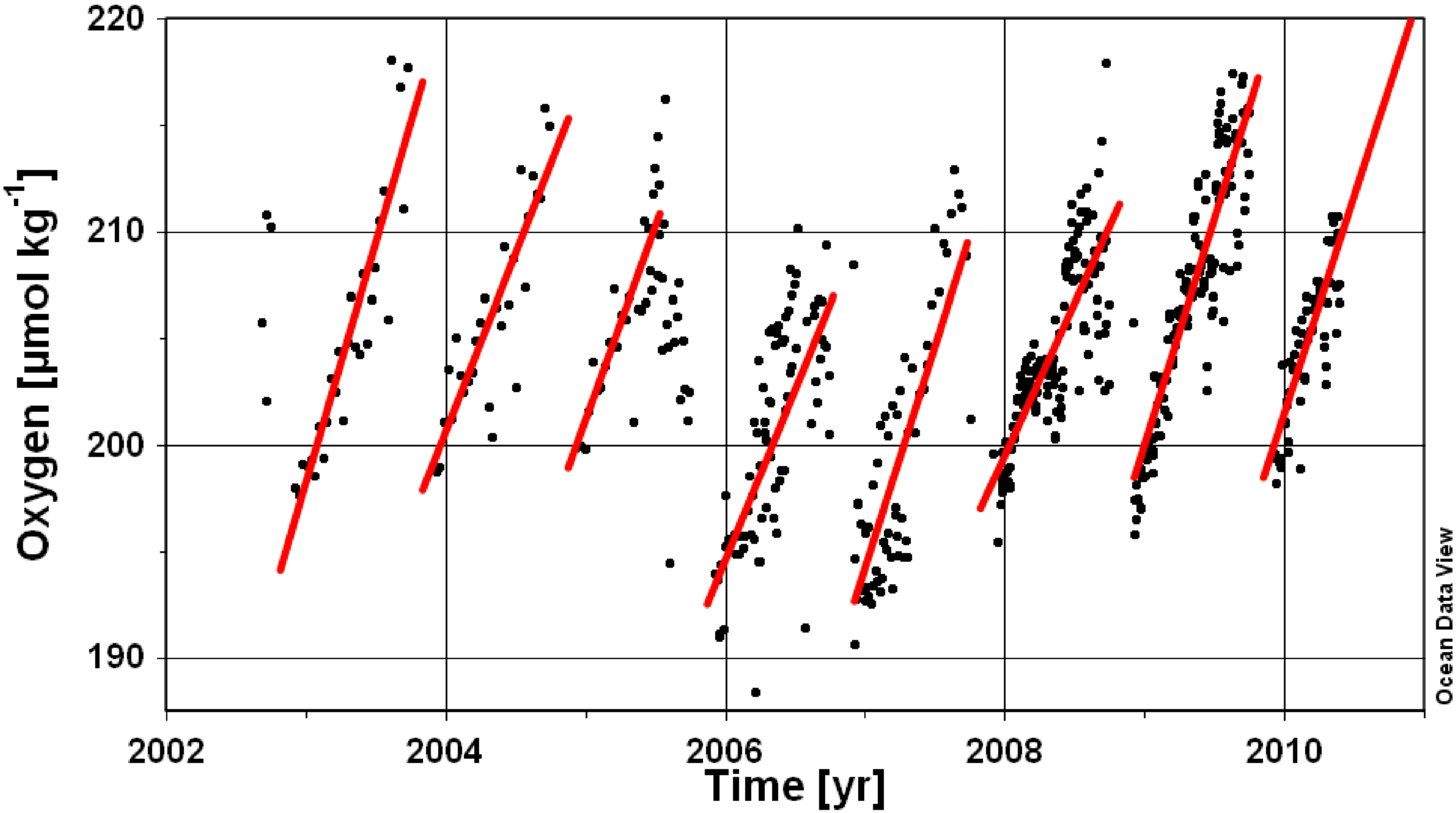
Eight years, nine floats. Some years have 3 floats operating simultaneously.



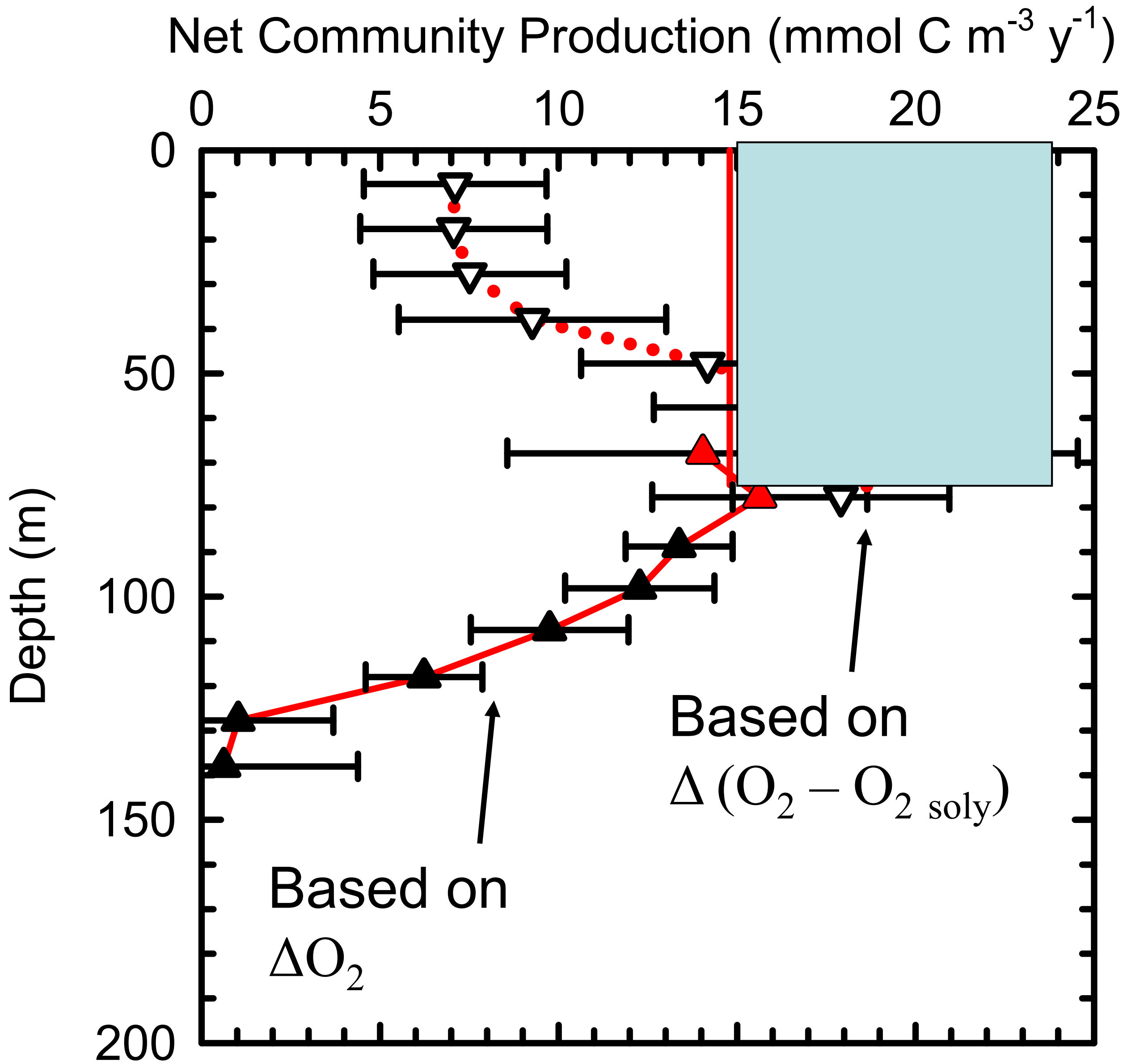




8 years of oxygen data at 75 m depth (below seasonal mixed layer) from floats near HOT.



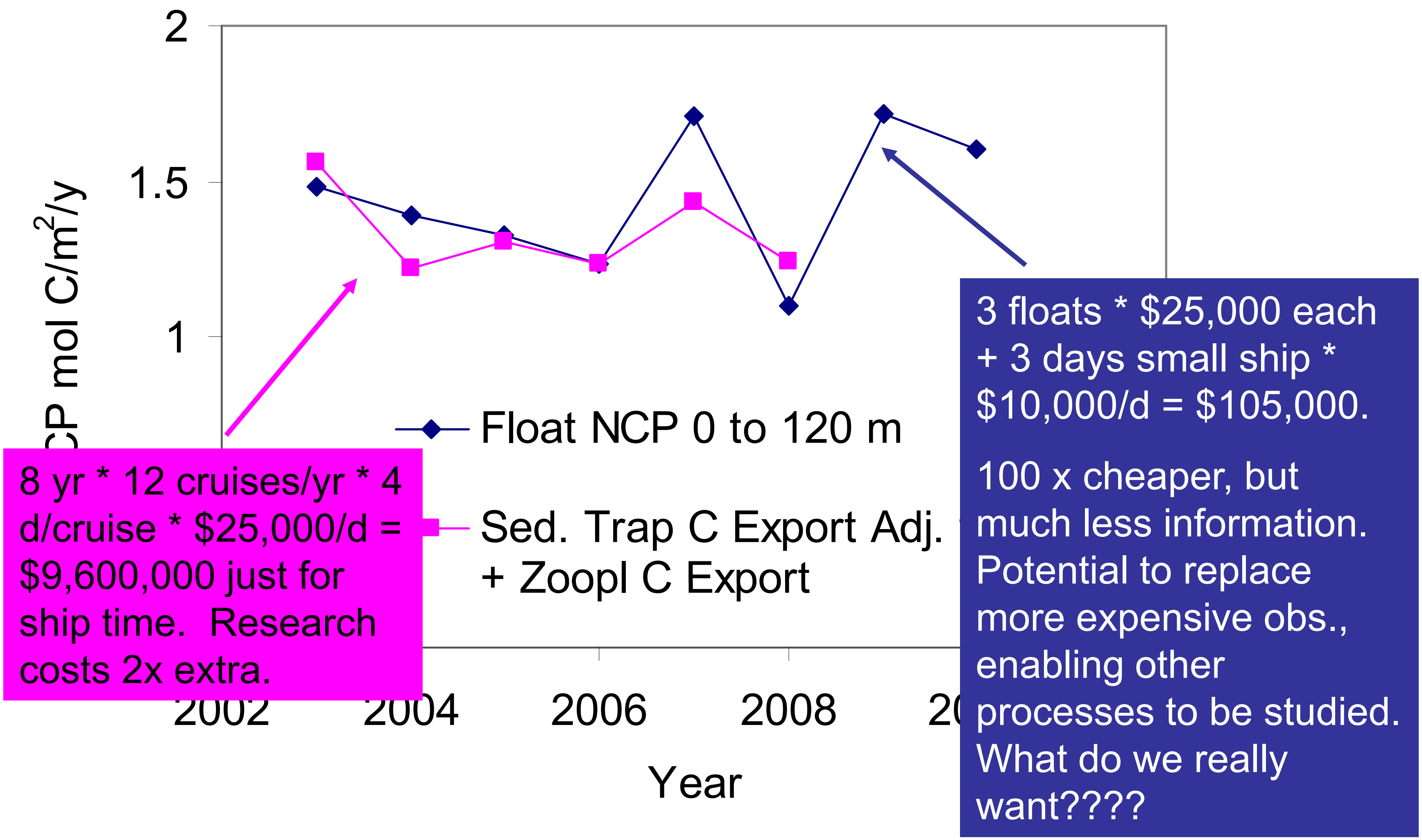
But NCP can't be measured in the mixed layer due to oxygen outgassing – better sensors required.

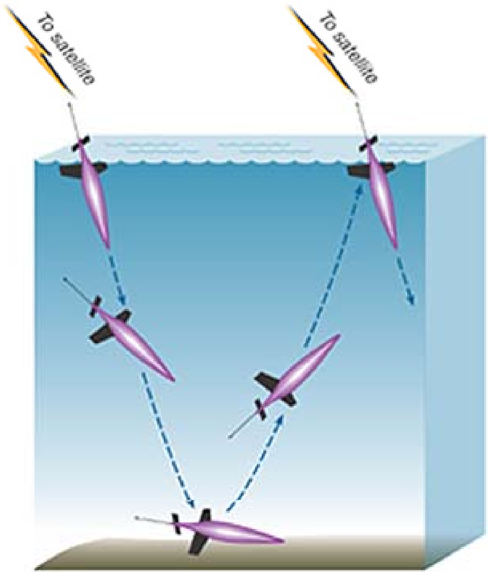


Vertically integrated Net Community Production at HOT = 1.6±0.2 mol C/m²/y.

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

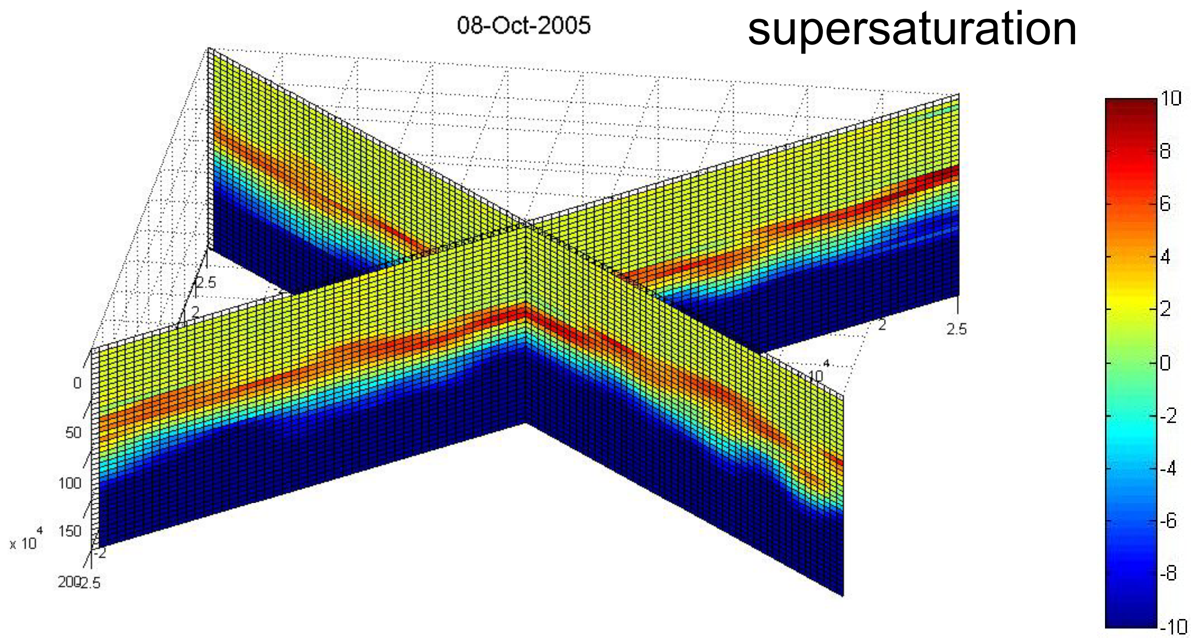
Net community production (NCP = primary production – respiration) over 8 years computed from annual increase in oxygen measured by floats (after converting O_2 to C using Redfield Ratio). Compared to C export at the nearby Hawaii Ocean Time-series (HOT) . They should be ~ equal.





Nicholson et al., 2008, Net community production in the deep euphotic zone of the subtropical North Pacific gyre from glider surveys. Limnol. Ocean

O_2 % supersaturation



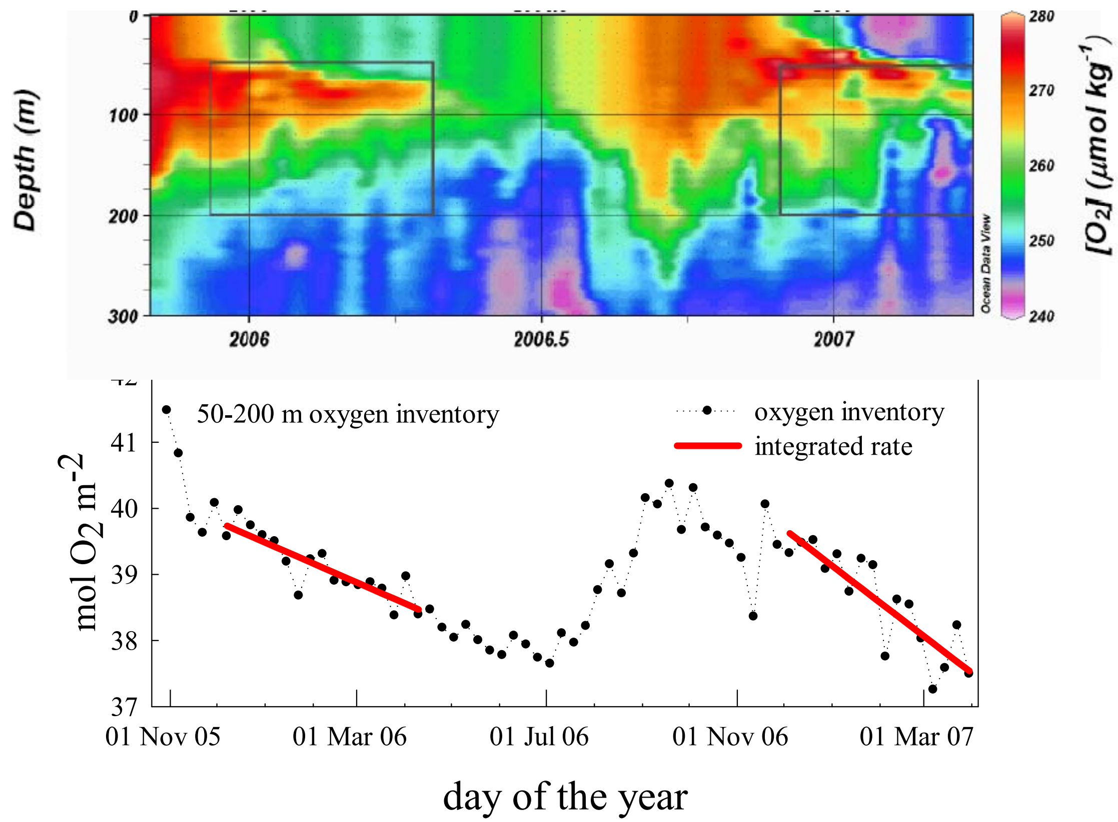
Respiration-Ventilation at 43°S

Martz et al., Limnol. Oceanogr. 2008

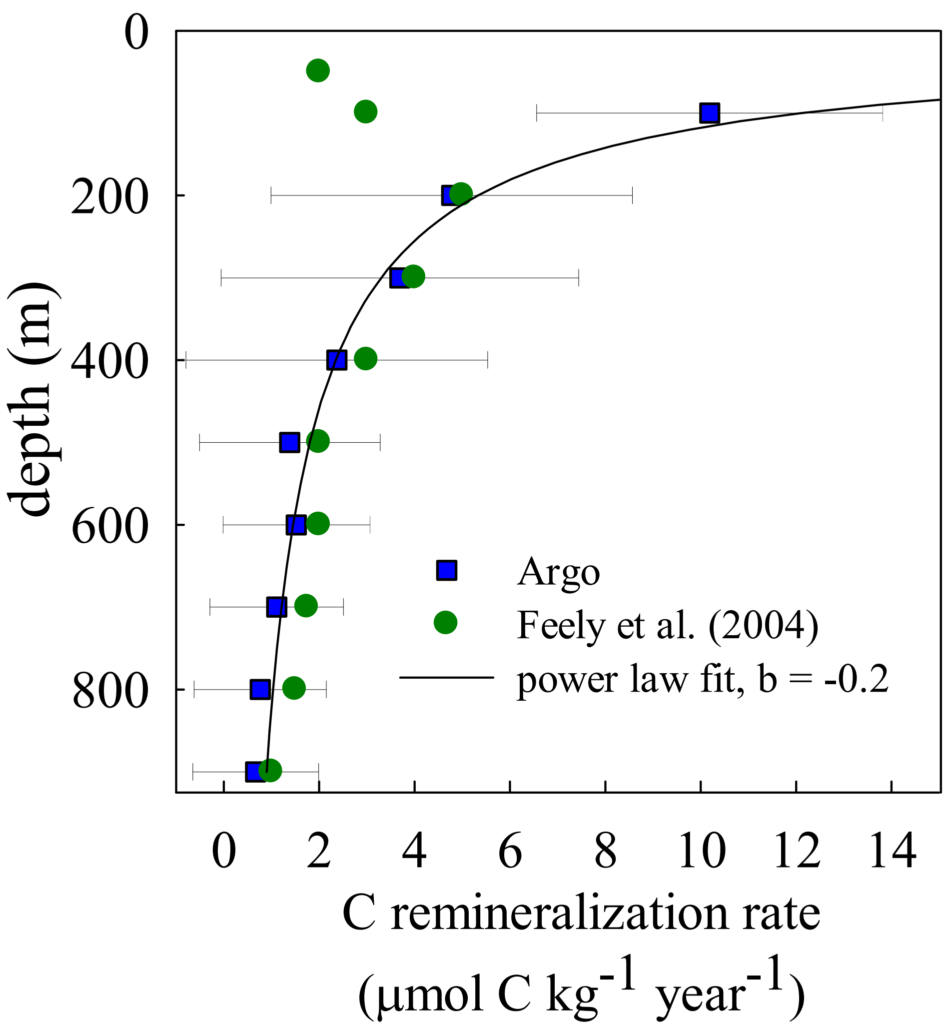
At 43°S there is not a clear production signal because mixed layer spans most of the euphotic zone and outgassing removes O_2.

Integrated oxygen utilization rate = Export Production

Integrated 50-200m rates for the 18 floats at 40-45°S.



Remineralization rates at 43ºS



Derivative of the particle flux attenuation function

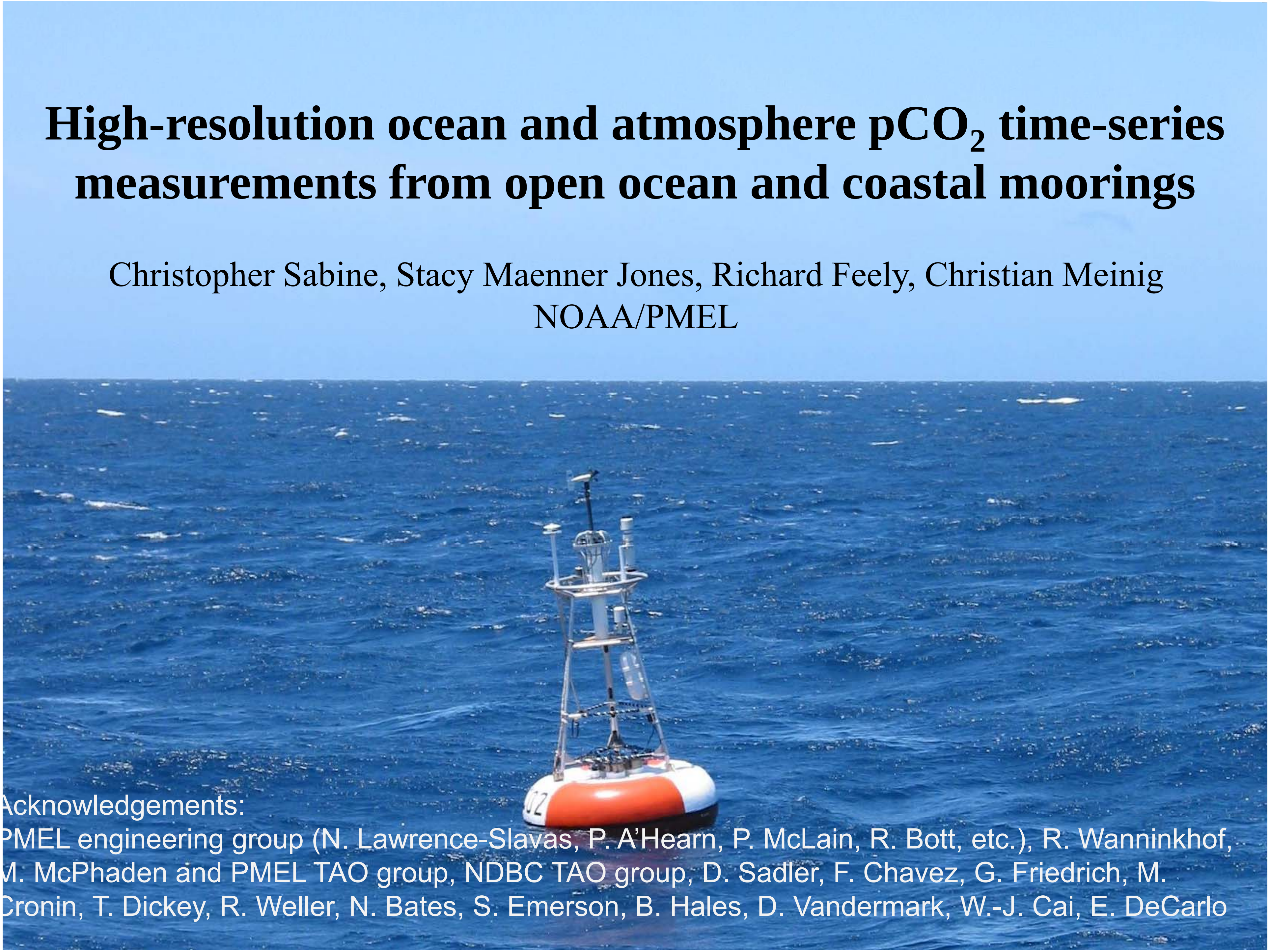
$$R_z \approx \frac{\partial F}{\partial z} = R_{100}\left(\frac{z}{100}\right)^{b-1}$$

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 zooplankton consumption of POC at shallow depth and respiration of POC deeper in water column.

pCO_2/pH

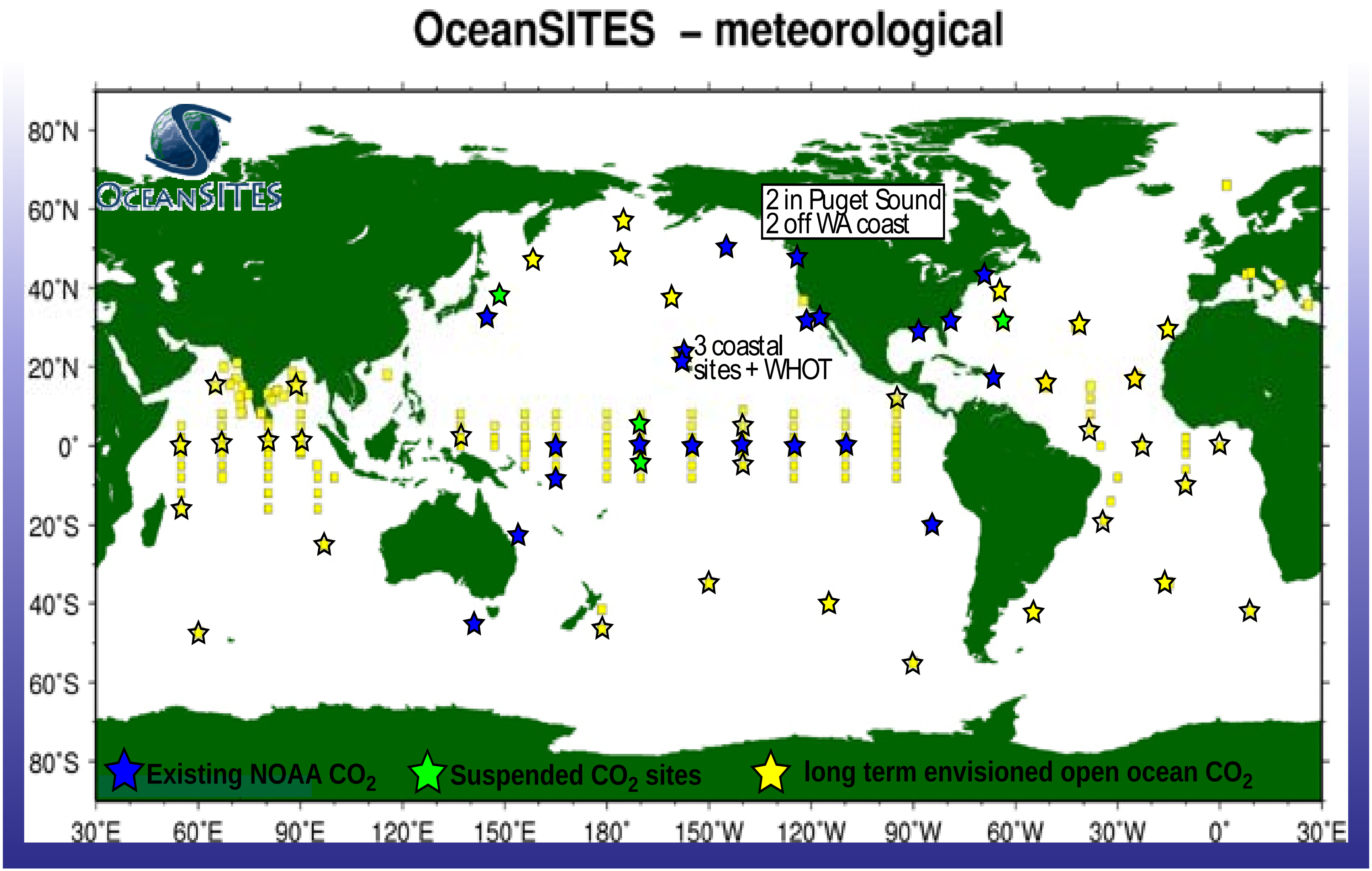


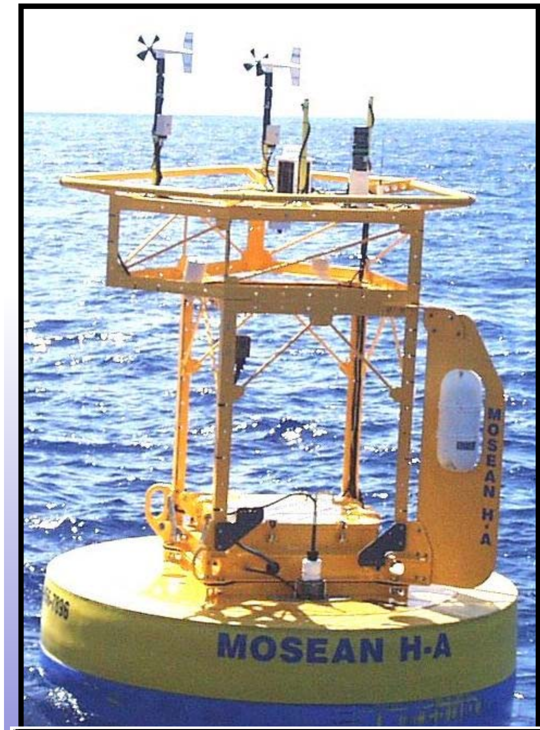
High-resolution ocean and atmosphere pCO_2 time-series measurements from open ocean and coastal moorings

Christopher Sabine, Stacy Maenner Jones, Richard Feely, Christian Meinig
NOAA/PMEL

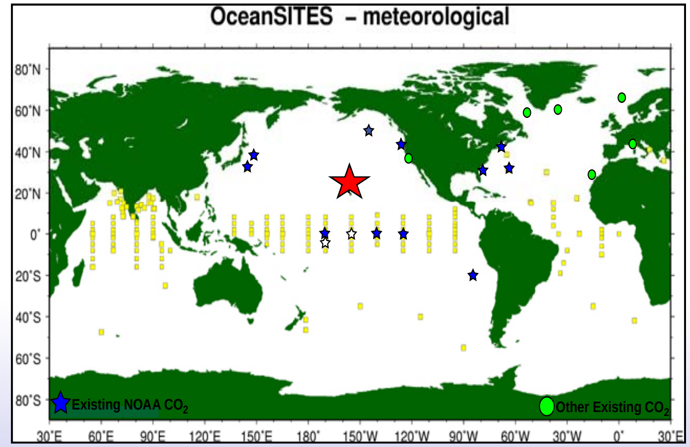
Acknowledgements:
PMEL engineering group (N. Lawrence-Slavas, P. A'Hearn, P. McLain, R. Bott, etc.), R. Wanninkhof, M. McPhaden and PMEL TAO group, NDBC TAO group, D. Sadler, F. Chavez, G. Friedrich, M. Cronin, T. Dickey, R. Weller, N. Bates, S. Emerson, B. Hales, D. Vandermark, W.-J. Cai, E. DeCarlo

As of 2009 NOAA/PMEL was maintaining 23 CO_2 time series sites and plans to add 3-5 sites/yr over the next few years



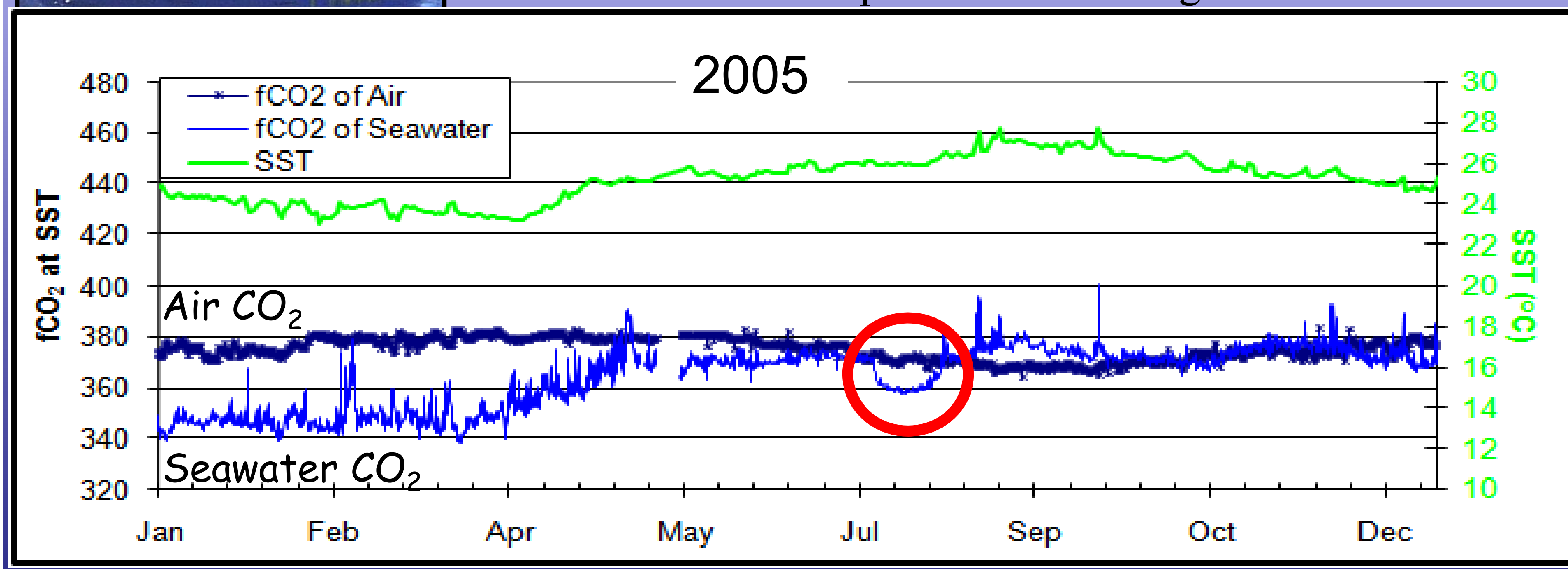


MOSEAN/WHOT mooring near Hawaii

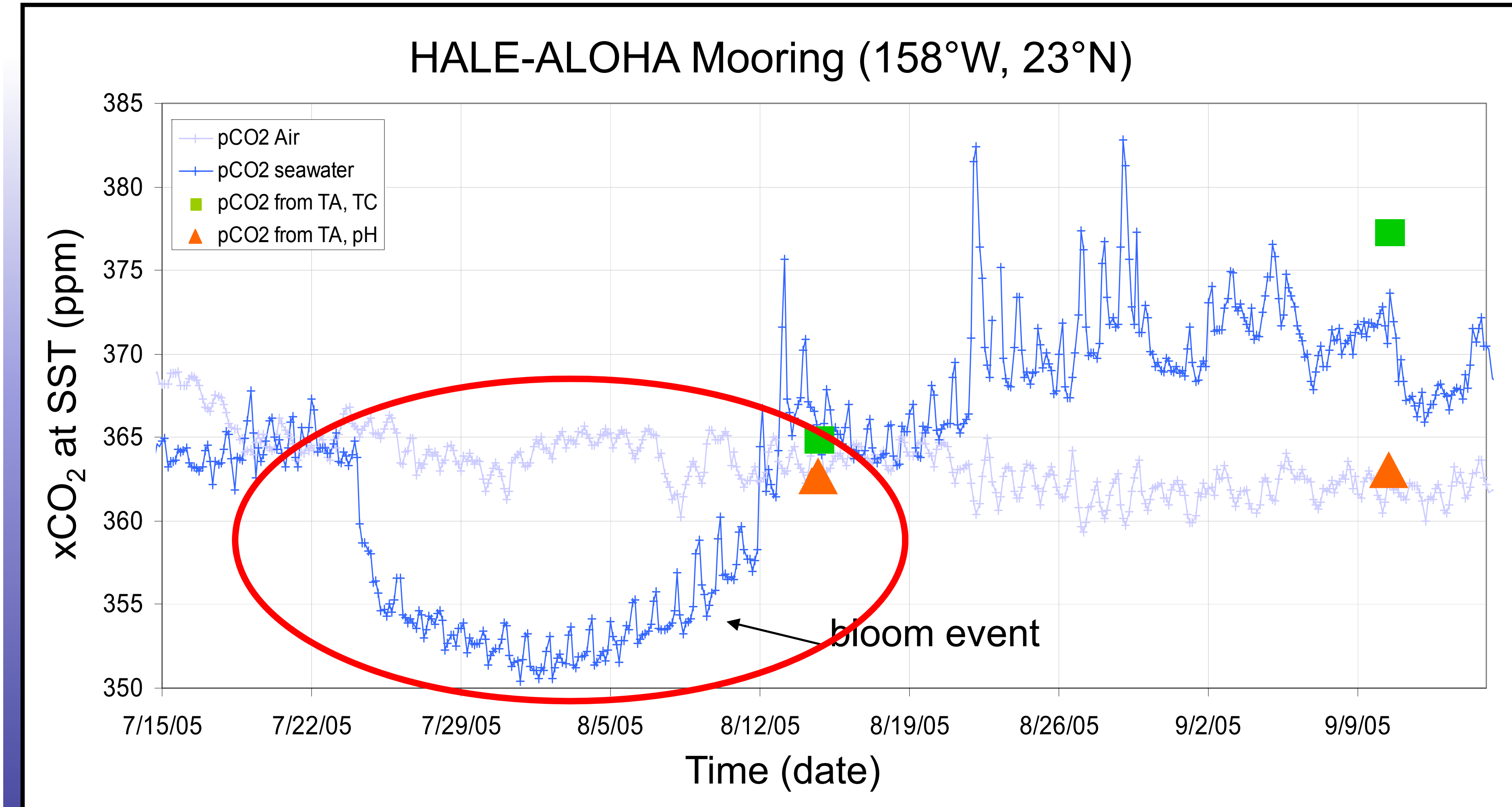


Seasonal amp.: ~50 ppm
Sub-seasonal variations: ~15 ppm
Diurnal cycle: 3-8 ppm

Combined temperature and biological control

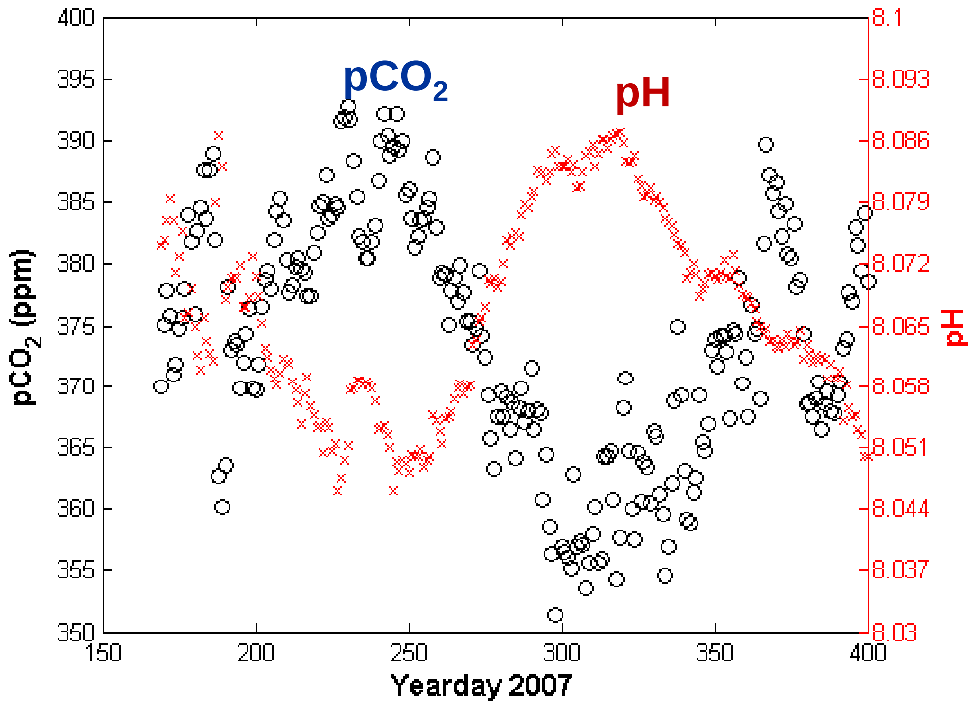


moorings can capture variability missed between ship visits

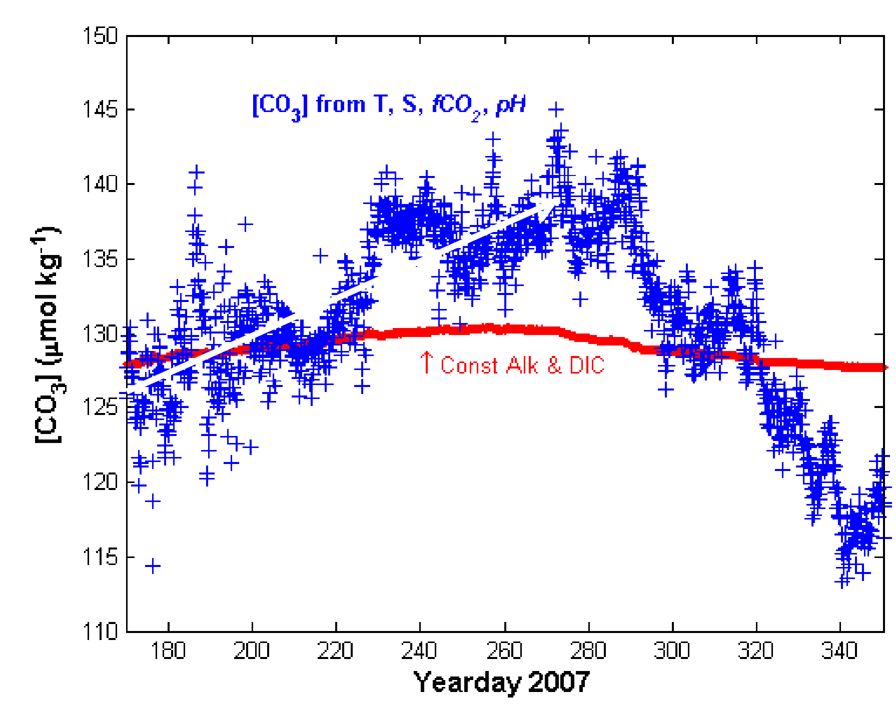


THE ROLES of $CaCO_3$ and ORGANIC MATTER in the BIOLOGICAL PUMP

pH and pCO_2 at Stn P



$[CO_3^{2-}]$ calculated

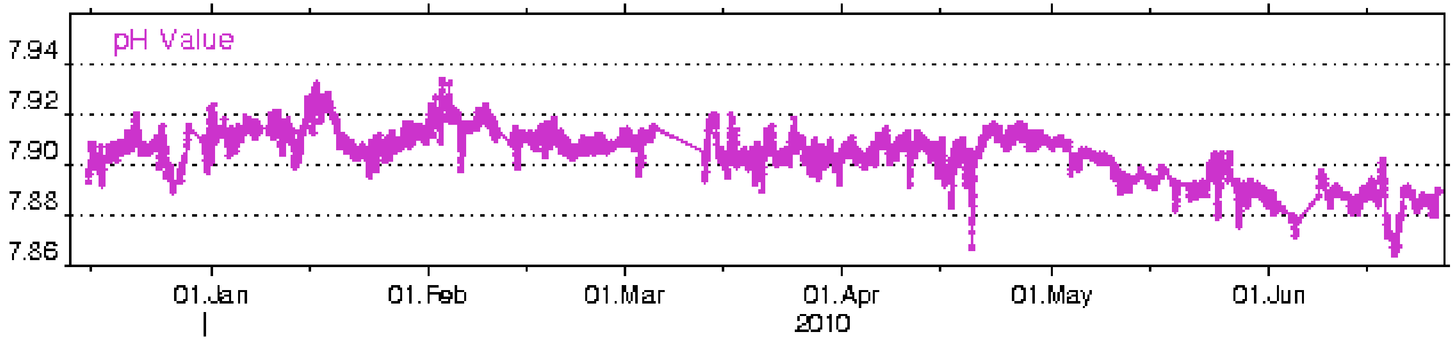


fCO_2 Chris Sabine

pH Steve Emerson and Mike DeGrandpre

$$K_1 K_2 K_H = \frac{[CO_3^{2-}][H^+]^2}{fCO_2}$$

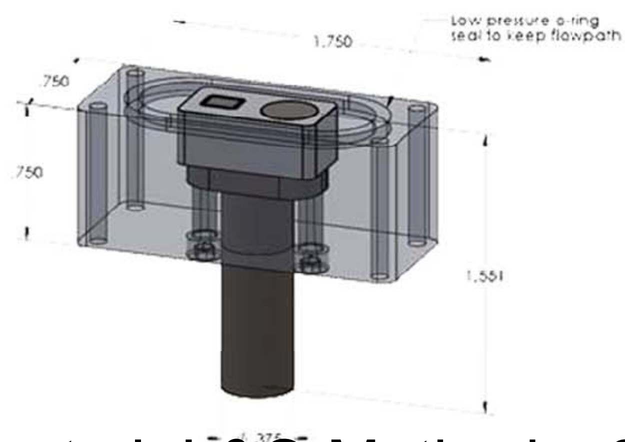
Opportunities to adapt industrial process control technology.

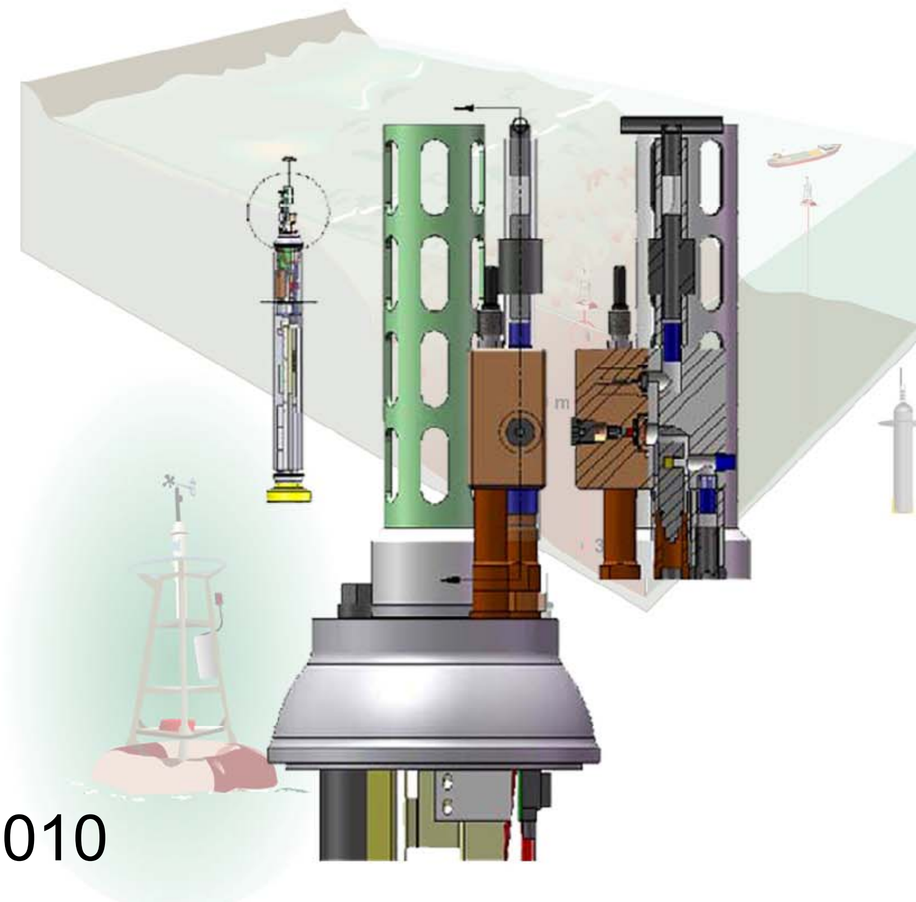


Honeywell pH sensor on Scripps mooring 200 km offshore

http://mooring.ucsd.edu

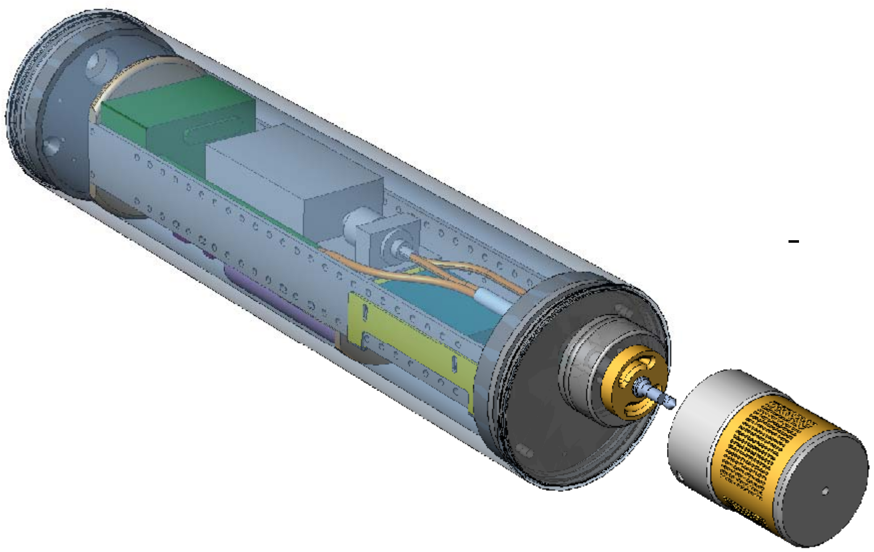
Novel solid state pH sensor adapted for use on profiling floats at MBARI/Scripps/UW in partnership with Honeywell.

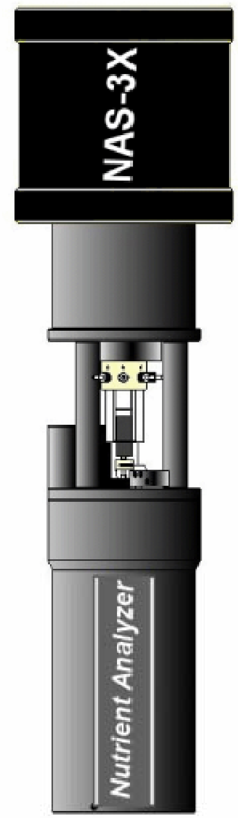




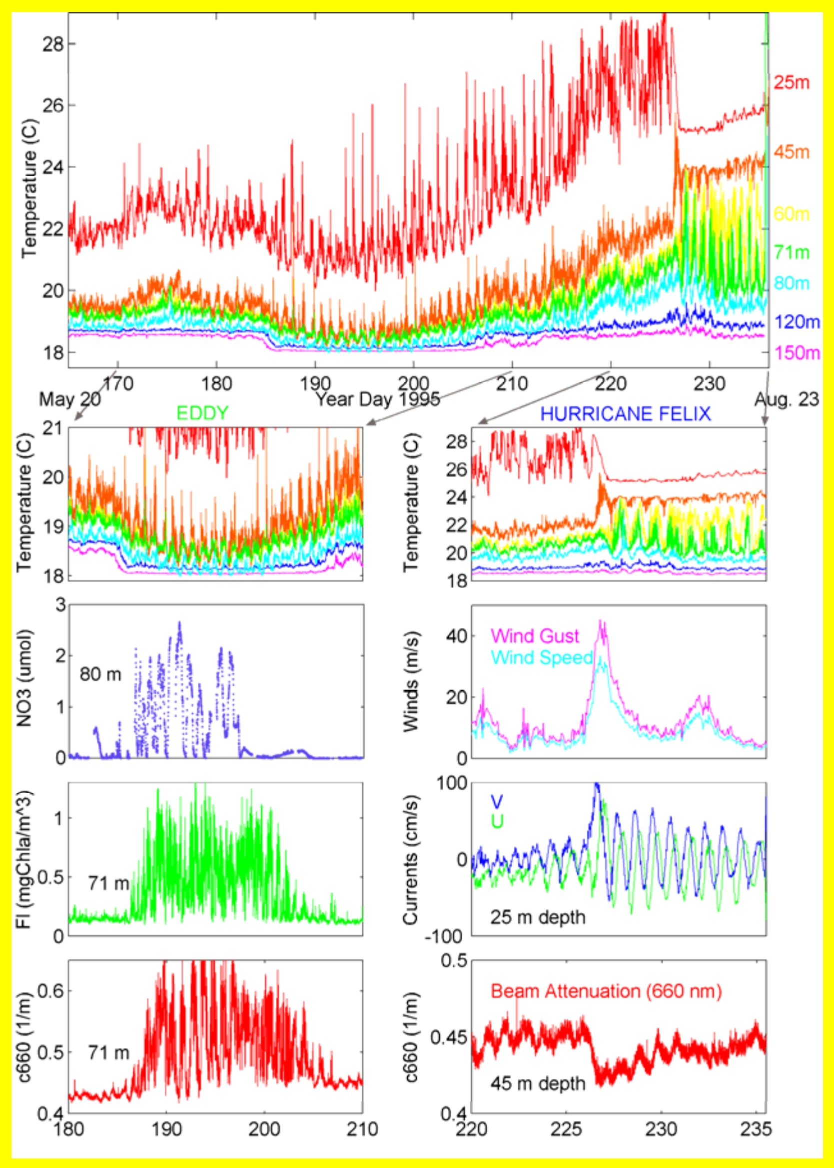
Martz et al. L&O Methods, 2010

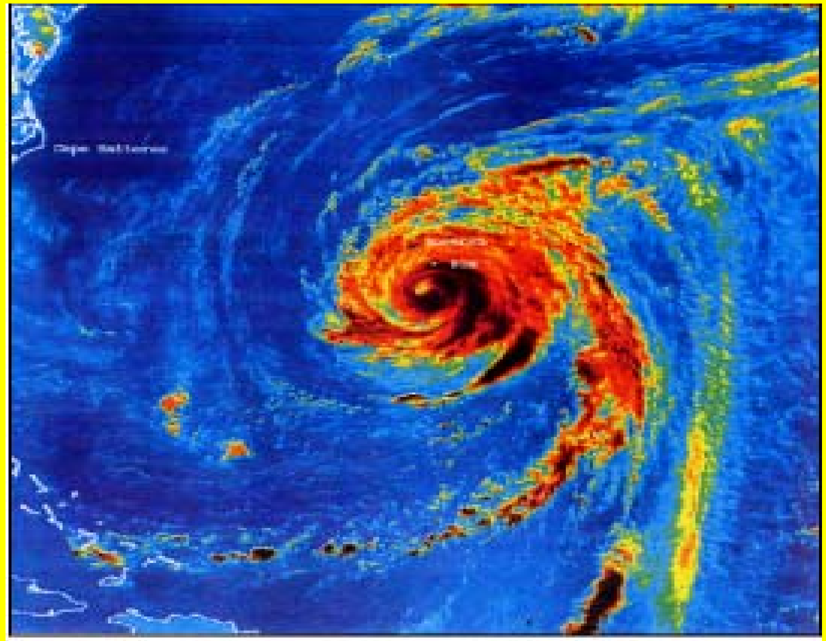
nitrate

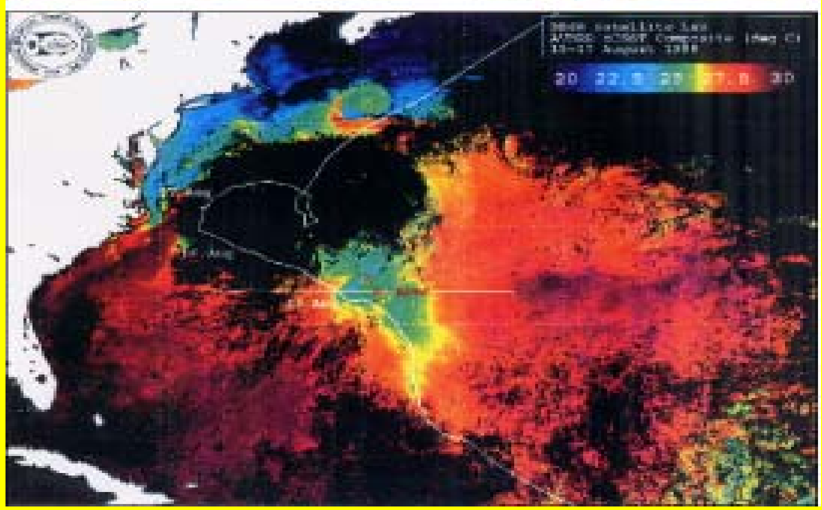




Events at the Bermuda Testbed Mooring Site





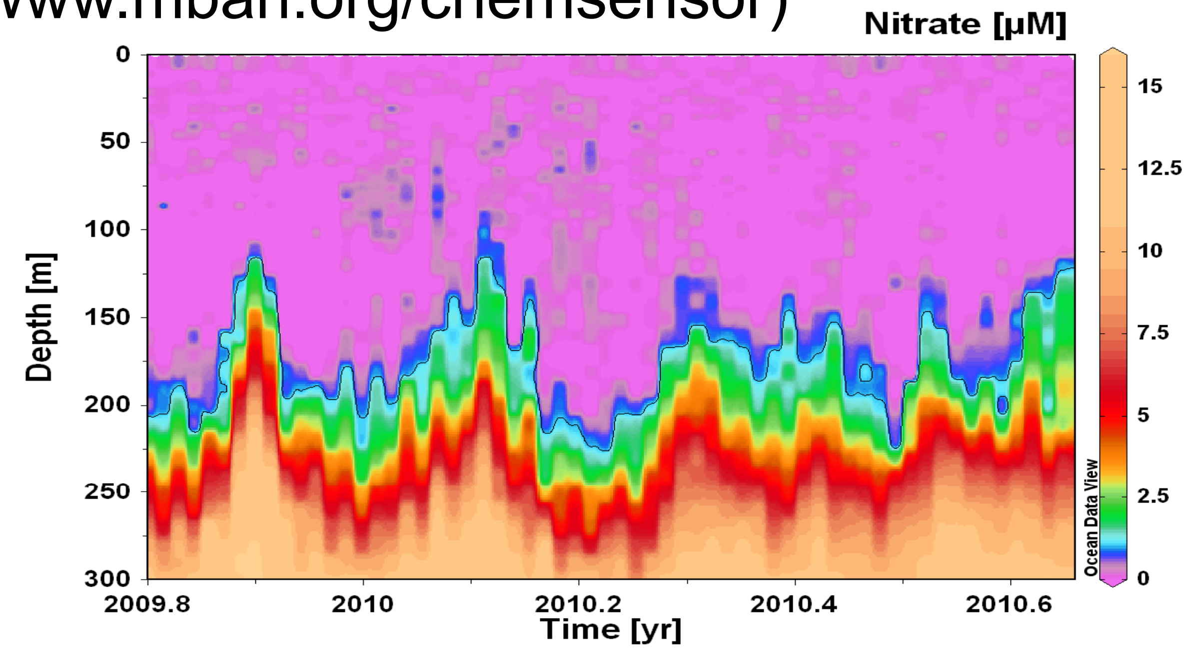


Dickey et al., 1998a,b, 2001a; McGillicuddy et al., 1998; McNeil et al., 1999; Zedler et al. 2002

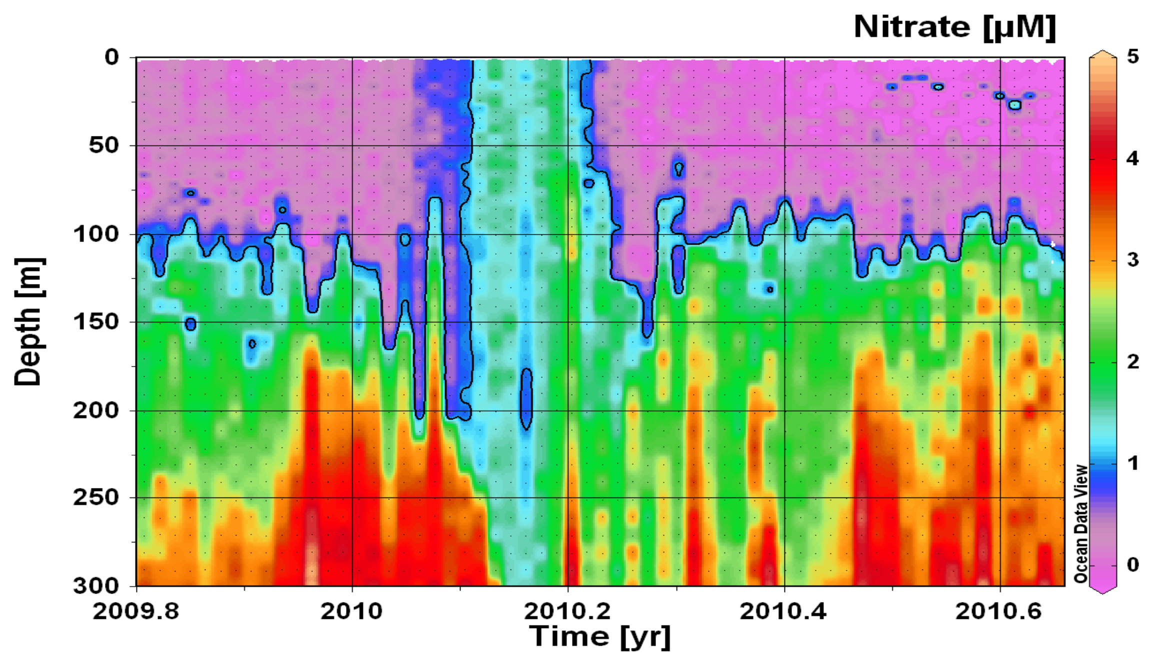
ISUS nitrate sensors on profiling floats at HOT and BATS (data at www.mbari.org/chemsensor)

HOT

(corrected for 2 offsets of ~1 µM as in Johnson et al 2010)



BATS

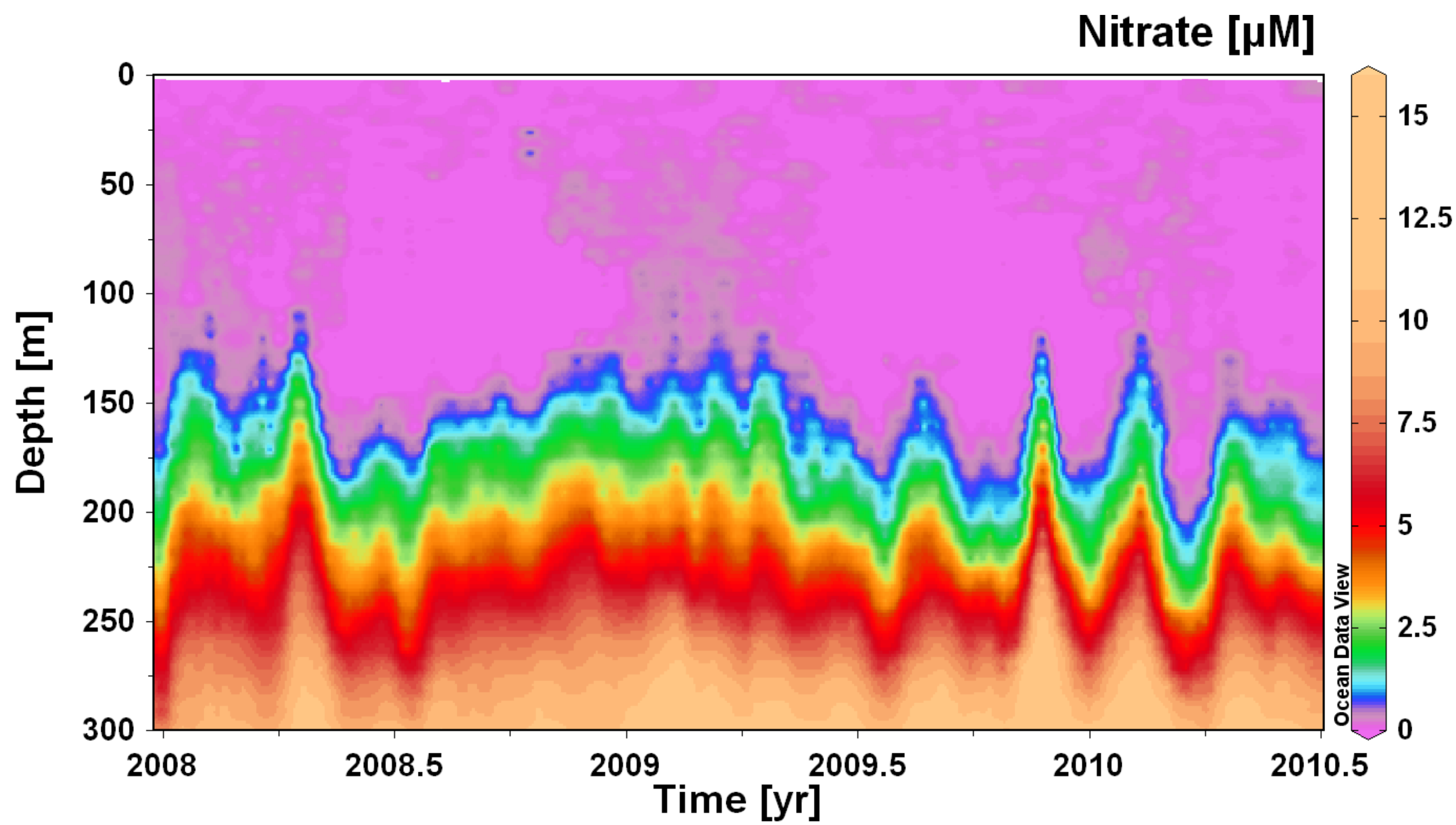


nature Vol 465|24 June 2010|doi:10.1038/nature09170

LETTERS

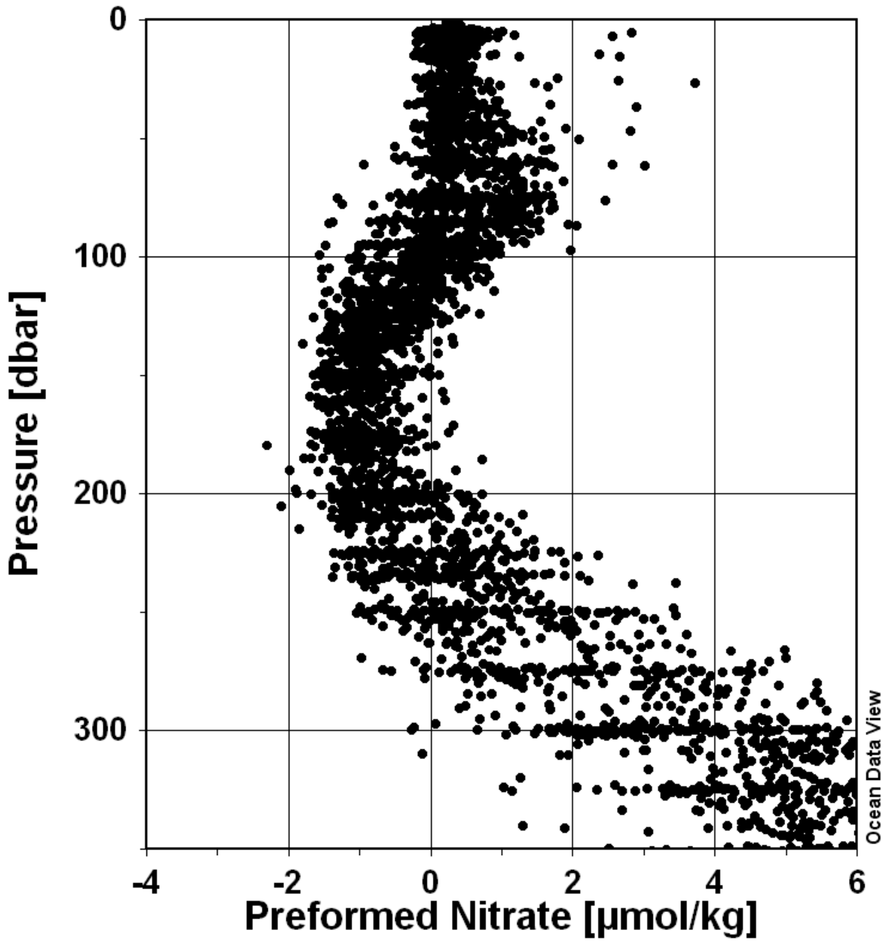
Nitrate supply from deep to near-surface waters of the North Pacific subtropical gyre

Kenneth S. Johnson[1], Stephen C. Riser[2] & David M. Karl[3]

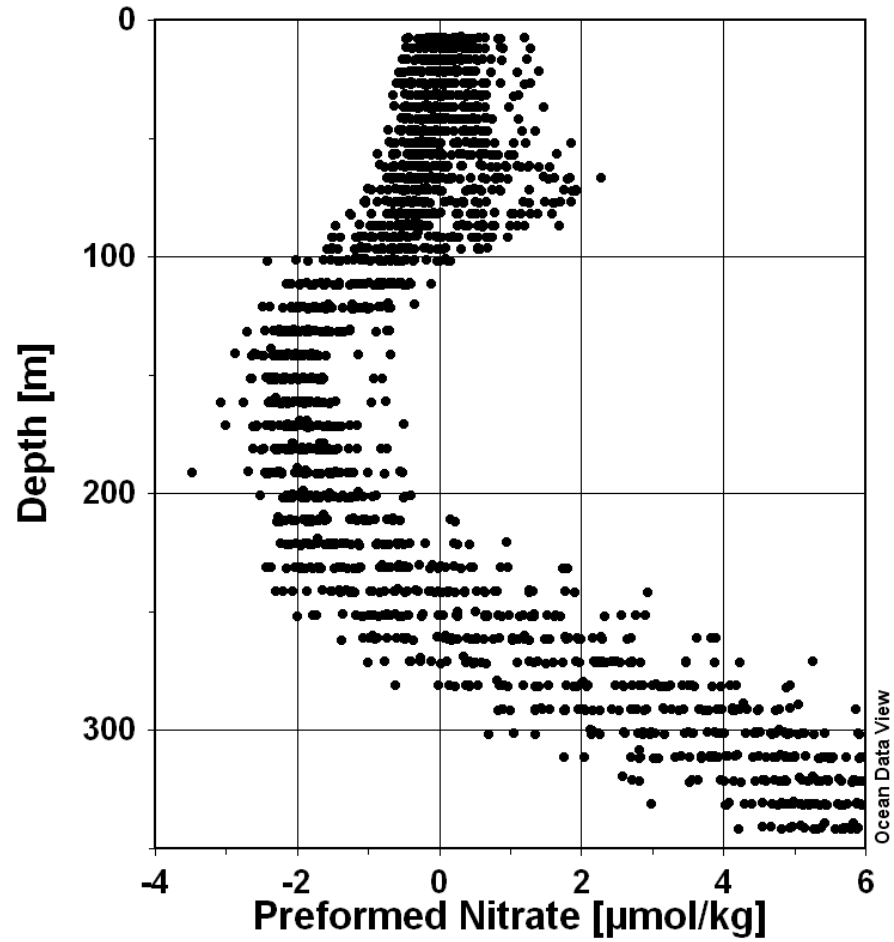


Preformed Nitrate = amount of nitrate in seawater when it left the surface
PreNO3- = (NO3-) observed + AOU / Redfield Ratio (O2/N)

HOT Bottle Data



Profiling Float Data



Journal of Marine Research, 53, 499–513, 1995

Chemical tracers of biological processes in shallow waters of North Pacific: Preformed nitrate distributions

by Steven Emerson[1] and Thomas L. Hayward[2]

Preformed Nitrate < 0 if,

- Nitrate consumed, and oxygen not produced

or

- Oxygen consumed to remineralize particulate matter, but nitrate is not produced.

$O_2 - O_2$ solubility

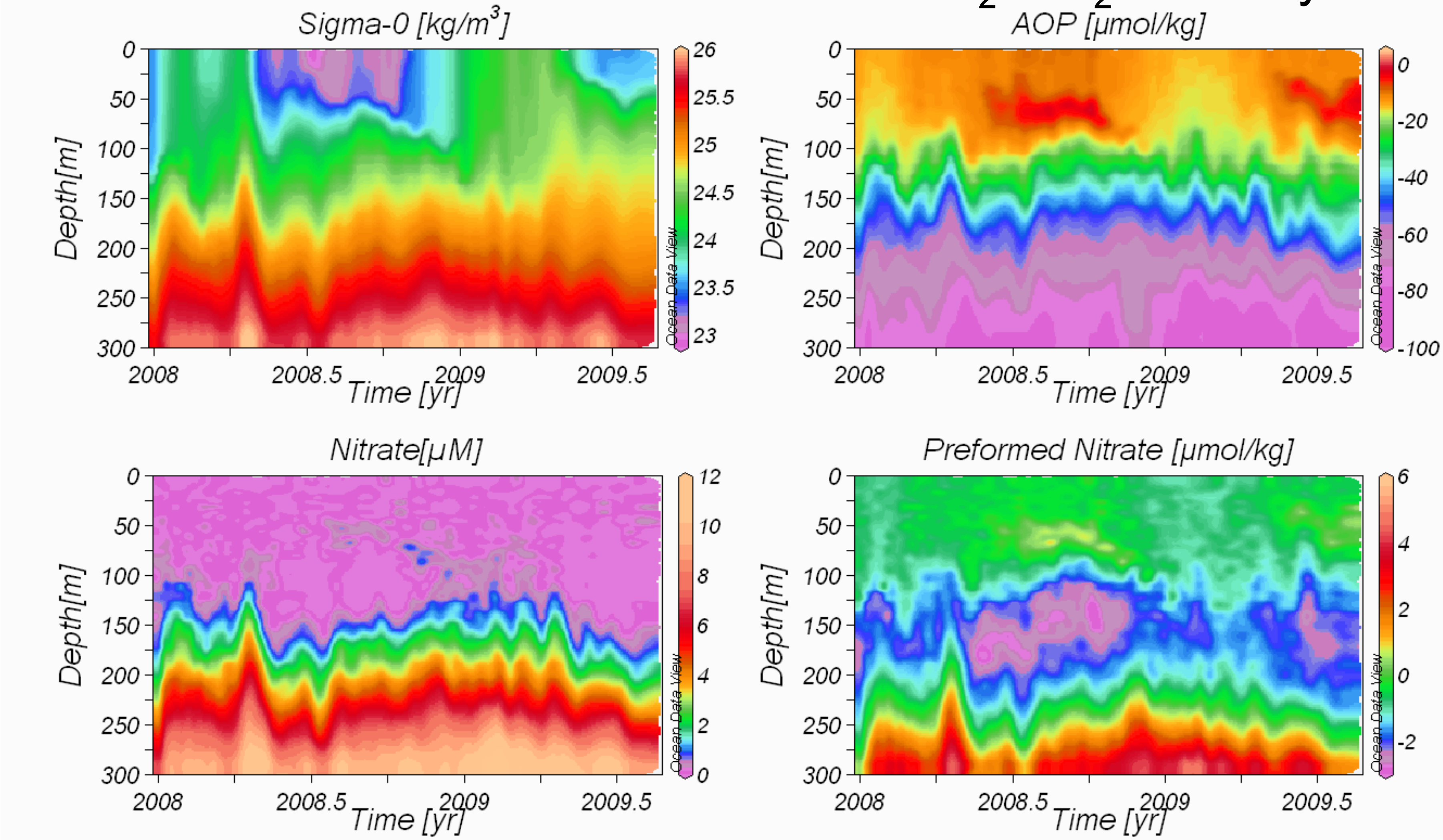


Table 1 | Organic and inorganic fixed nitrogen flux summary

Process	Flux ± 95% CI (mmol m^{-2} yr^{-1})	Reference
NCP N requirement*	287 ± 100	10
Particulate organic N export at 150 m	105 ± 7	12
Zooplankton organic N export	38 ± 4	12
Total organic N loss	143 ± 11	—
Nitrogen fixation†	41 ± 8	15
Integrated NO_3^- deficit‡	160 ± 78	This work
Integrated $PreNO_3^-$ deficit‡	103 ± 39	This work
Total inorganic N supply	144 ± 47 to 201 ± 86	—
HOT integrated NO_3^- deficit§	94 ± 66	This work
Event-driven vertical NO_3^- transport‖	>88	This work

How do we go from nitrate concentration to rates?

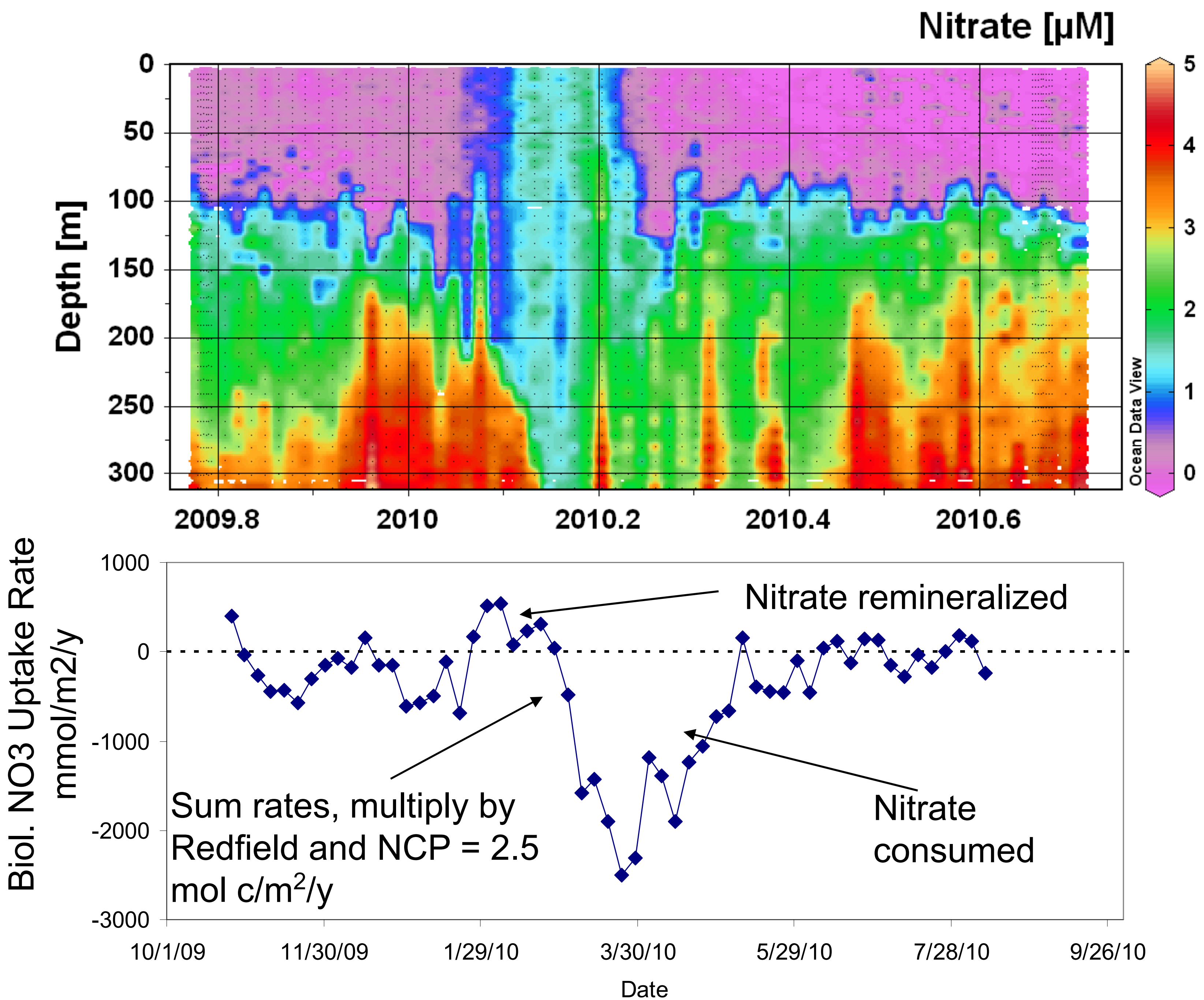
Use a 1-D Price/Weller/Pinkel type mixed layer model to separate impact of ocean physics and biology on nitrate rate of change.

Nitrate is treated as a passive tracer.

- For each float profile at time t, initialize model with T/S/NO_3^- observed by float.
- Run model forward 5 days to next float profile at t+1.
- Rate of biological source/sink (& un-modeled physics) at each depth is:

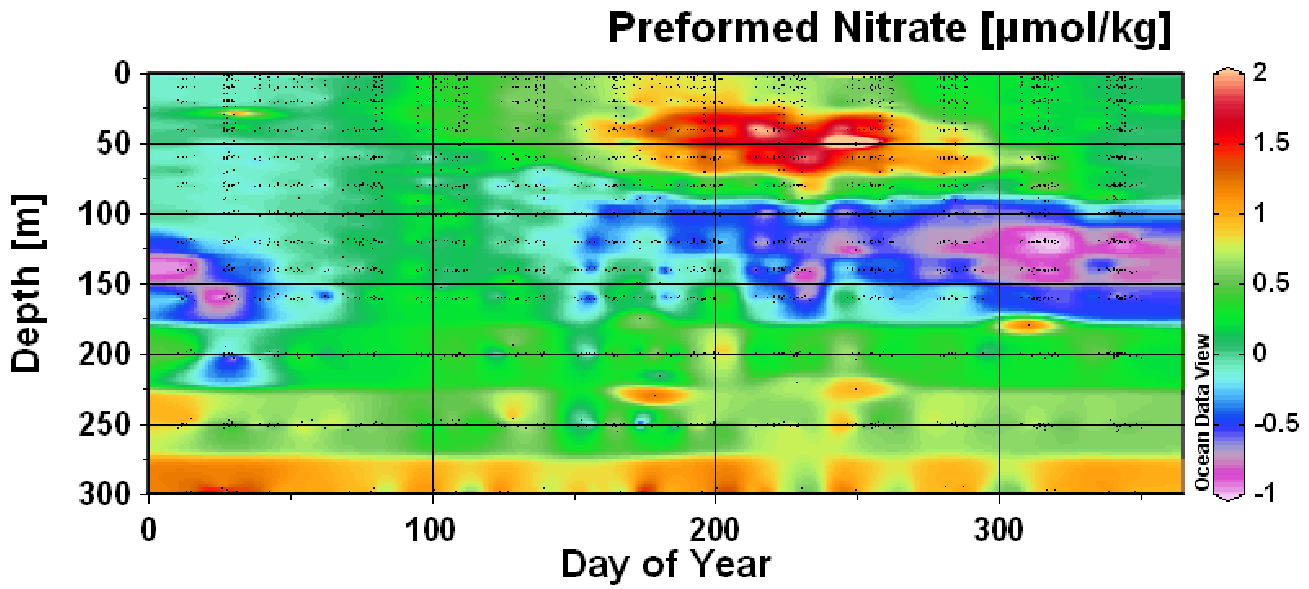
$$R_{Biology} = [\text{Observed } NO_3^-{}_{(t+1,\,Z)} - \text{Modeled } NO_3^-{}_{(t+1,\,Z)}] / \Delta t$$

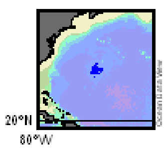
Uptake is negative, remineralization is positive.

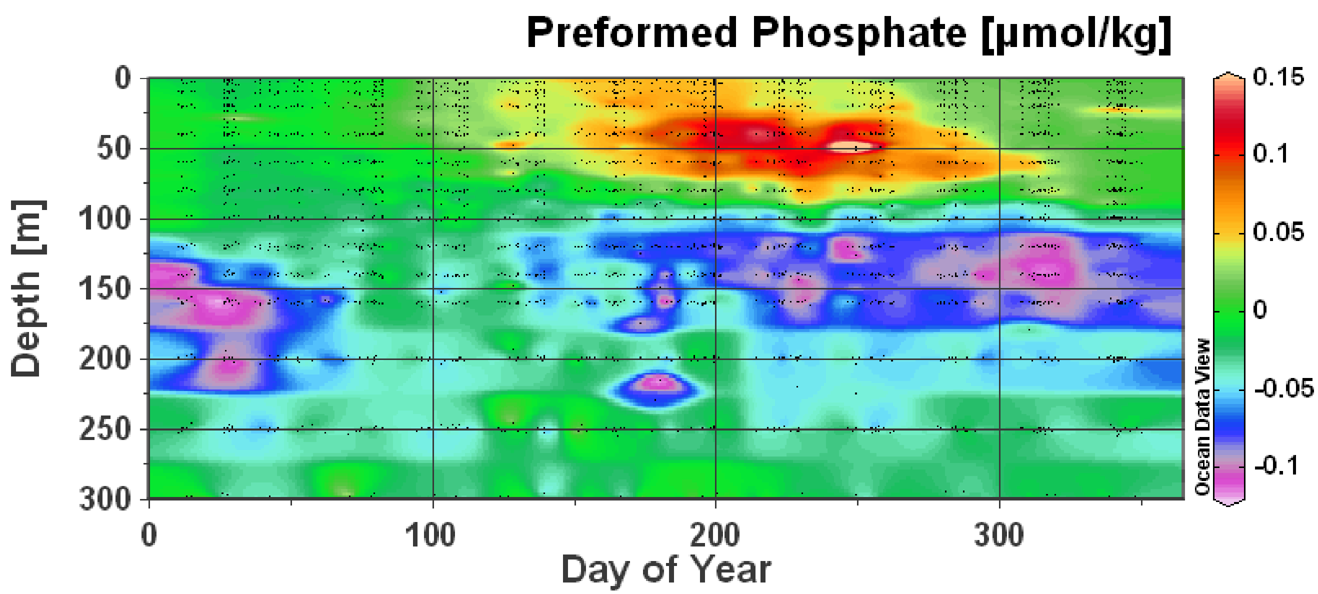


Nitrate [μM]
Depth [m]
0
50
100
150
200
250
300
2009.8
2010
2010.2
2010.4
2010.6
5
4
3
2
1
0
Ocean Data View
Biol. NO3 Uptake Rate
mmol/m2/y
1000
0
-1000
-2000
-3000
Nitrate remineralized
Sum rates, multiply by Redfield and NCP = 2.5 mol c/m2/y
Nitrate consumed
10/1/09
11/30/09
1/29/10
3/30/10
5/29/10
7/28/10
9/26/10
Date

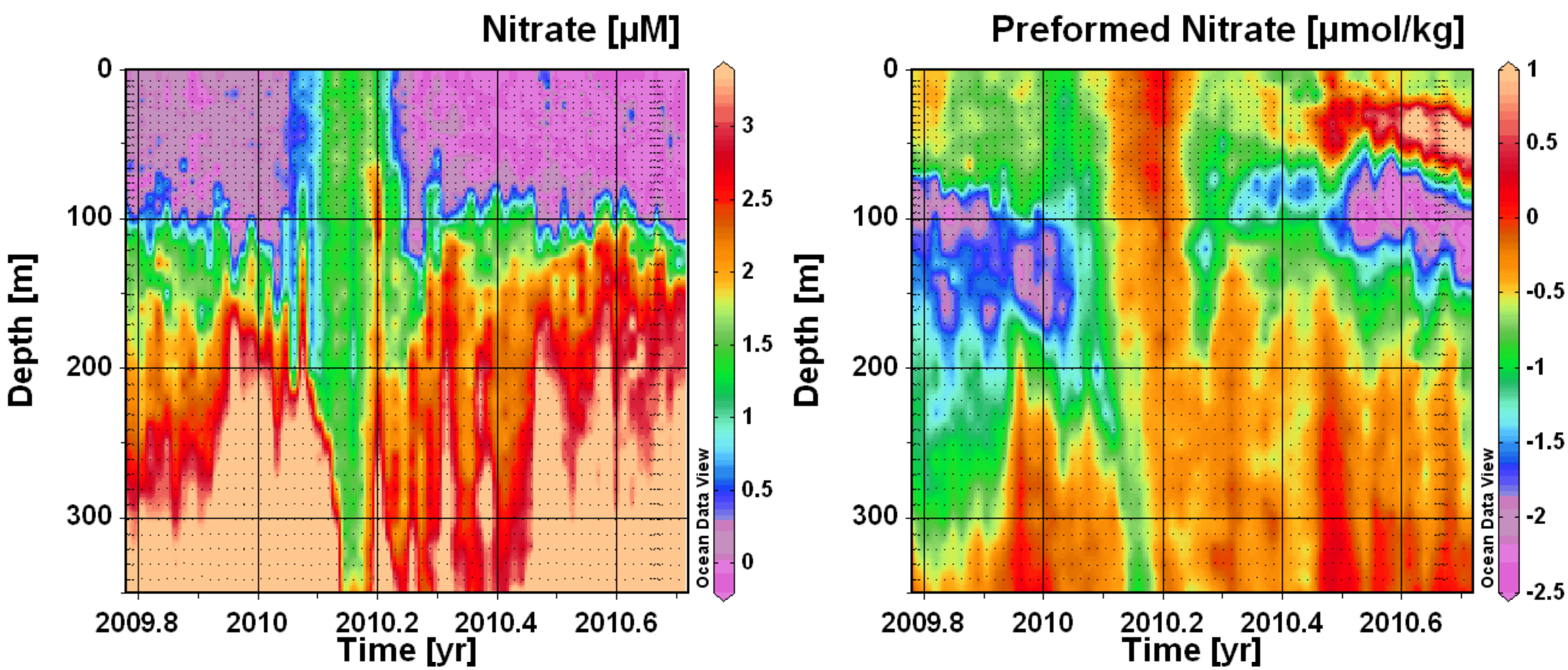
Composite annual cycle at BATS using time series hydrographic data.







Acquisition of nitrate (and phosphate) from below euphotic zone also occurs at BATS. Missing nitrate equivalent to 0.8 mmol C/m^2/y. Total NCP at BATS = 2.5 + 0.8 = 3.3 mol C/m^2/y based on float nitrate observations.



Biooptics/acoustics

Jiang, Dickey et al., 2007 Zooplankton biomass at BTM estimated from ADCP backscatter intensity.

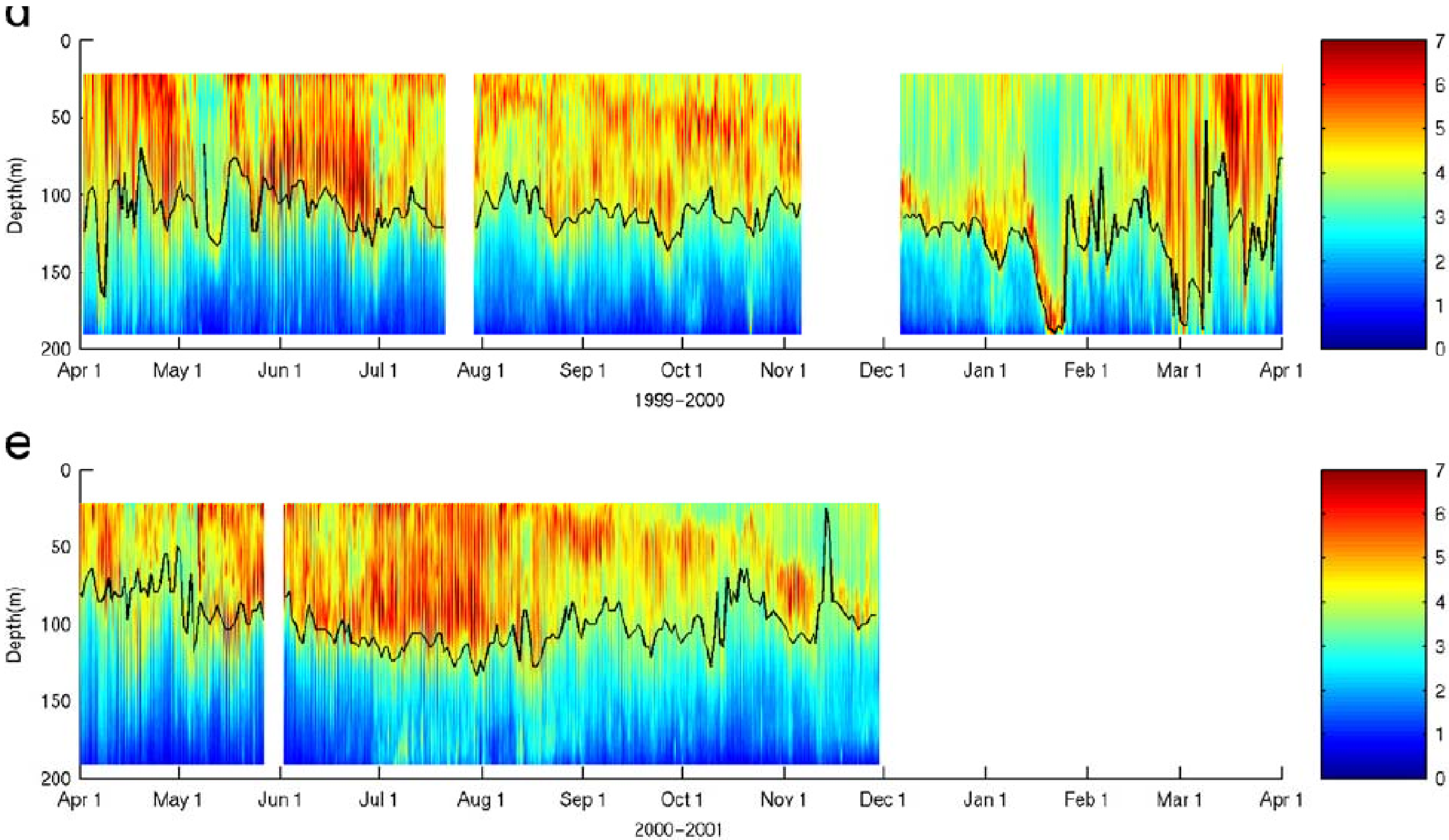
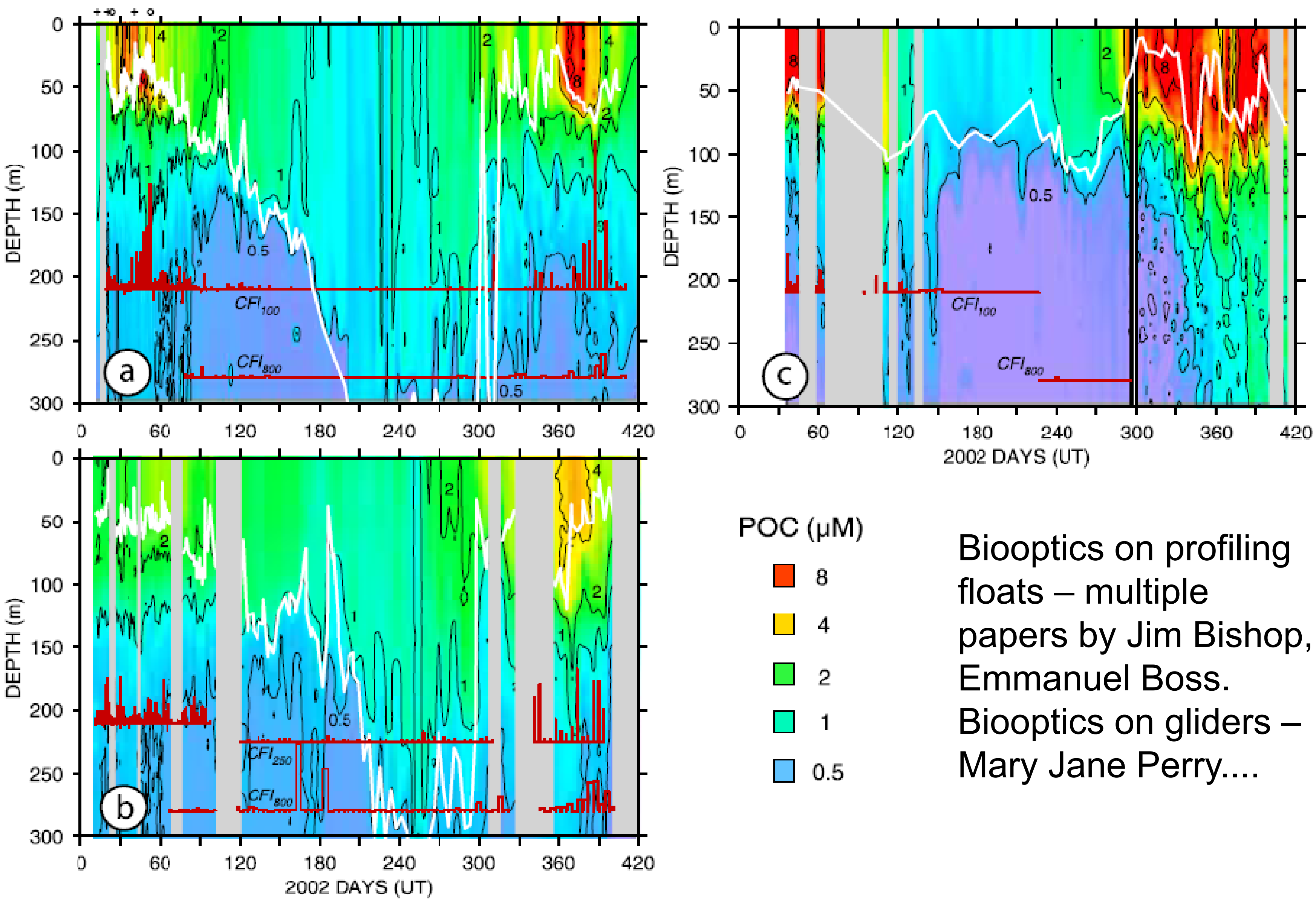


Fig. 3. Contours of zooplankton biomass estimated from ADCP backscatter intensity (using 1-h averaged data) during Deploym

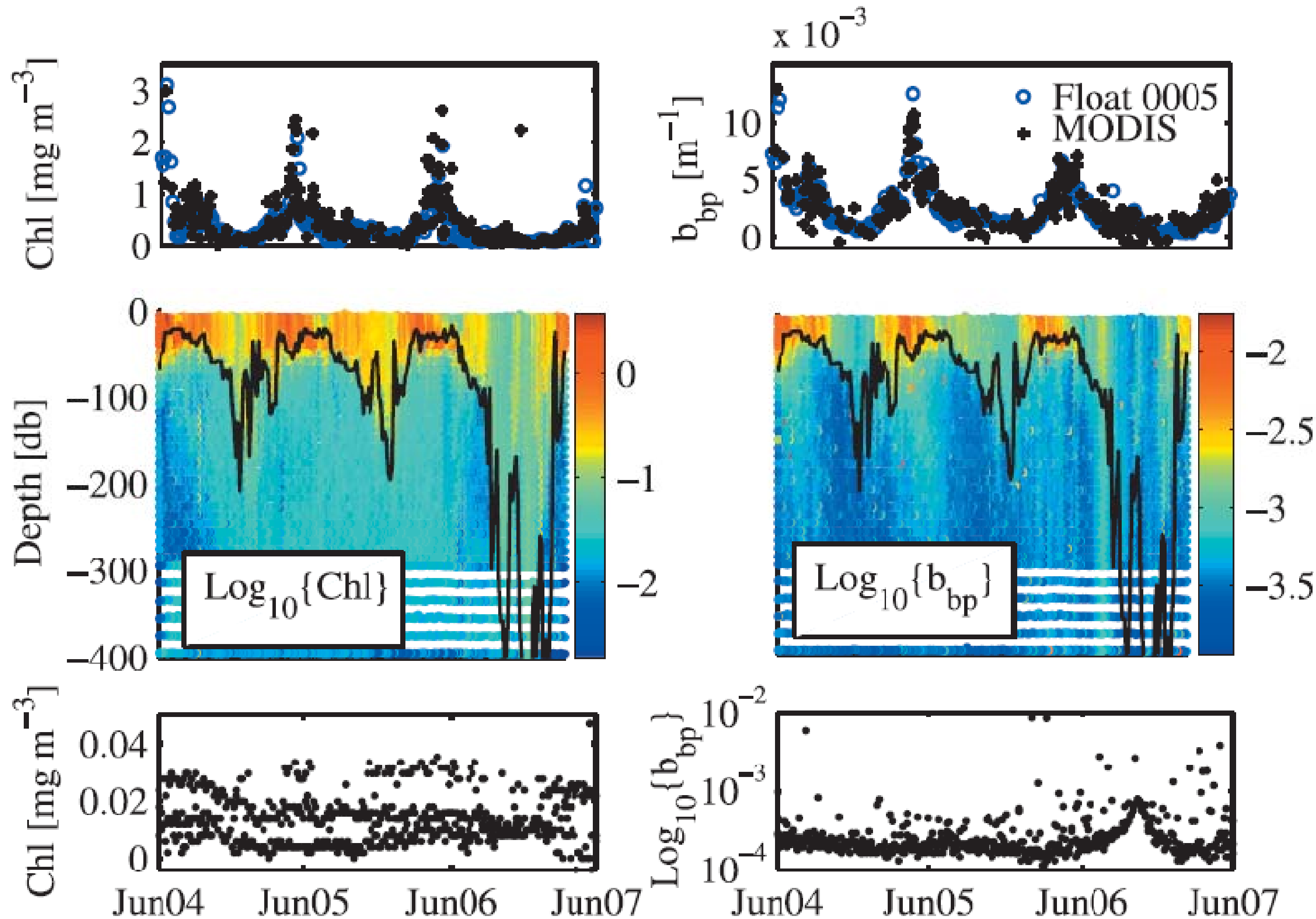


Biooptics on profiling floats – multiple papers by Jim Bishop, Emmanuel Boss.
Biooptics on gliders – Mary Jane Perry....

Figure 7. POC and carbon flux index time series for (a) CE 55A, (b) CE 55C, and (c) CE 66A. POC concentrations of 1, 2, 4, and 8 μM are contoured with heavy black lines; 0.5 μM is contoured by the thin black line. CFI is shown as red bars. Relative vertical placement denotes CFI readings at 100, 250, and

Surface time-series

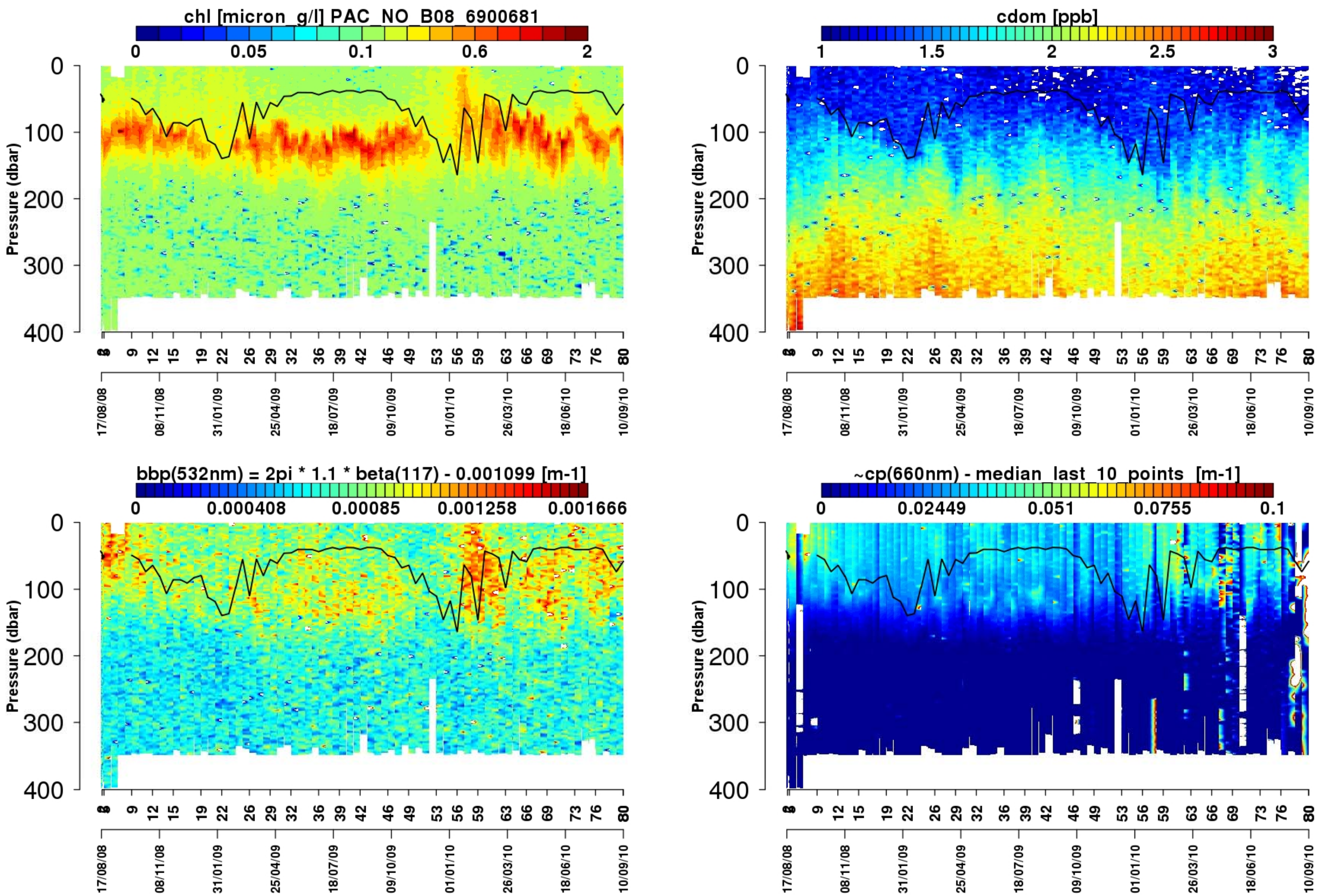
1000 m time-series



E. Boss et al., 2008 (EOS and L&O). Three yrs of data for a fluorometer on a profiling float in the Labrador Sea. No sensor drift.

Herve Claustre Biooptical float near HOT

http://www.obs-vlfr.fr/OAO/provbio/summary.html

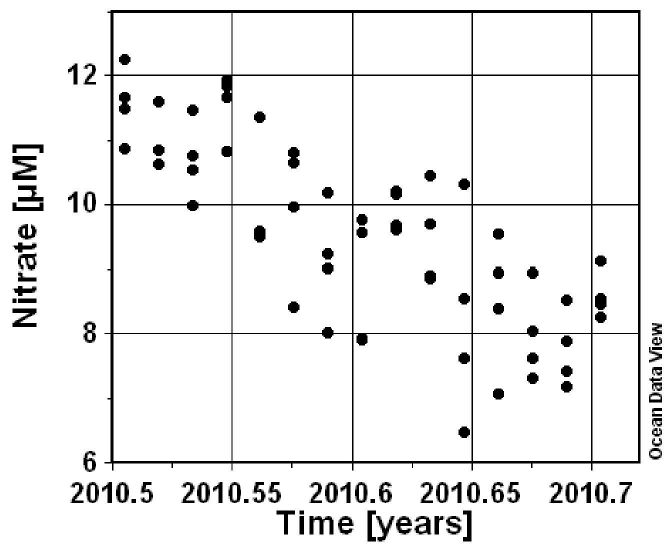


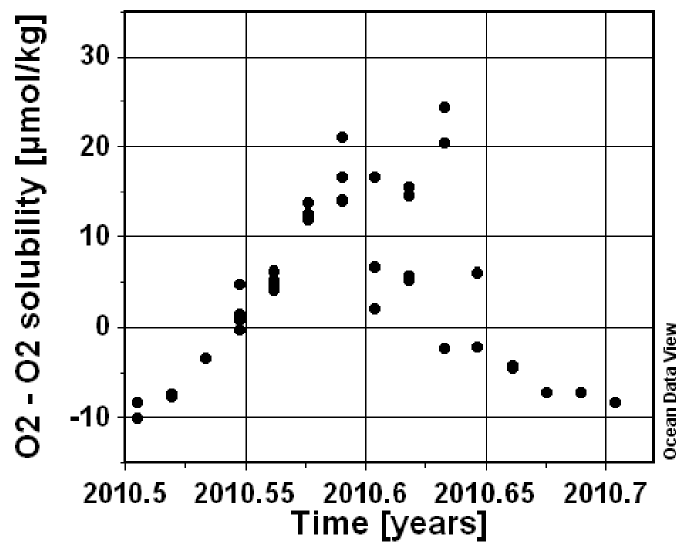
NO_3^- drops by ~3 µM O_2 up by ~30 µM (about Redfield = 3x10 O_2/NO_3)

Ocean Station Papa

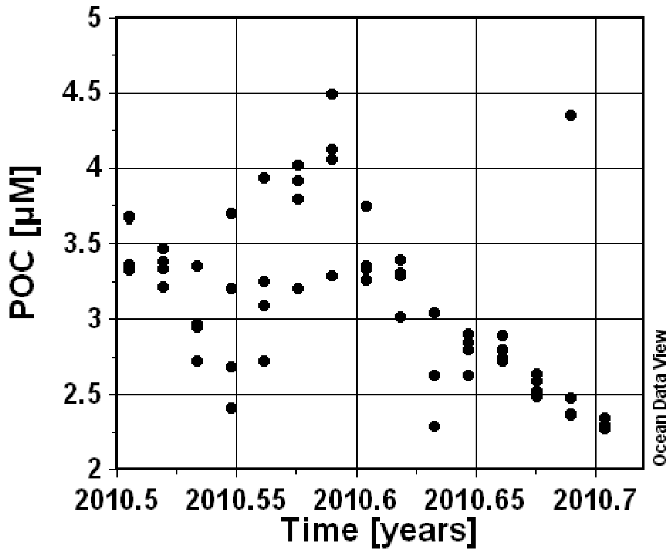
Gulf of Alaska

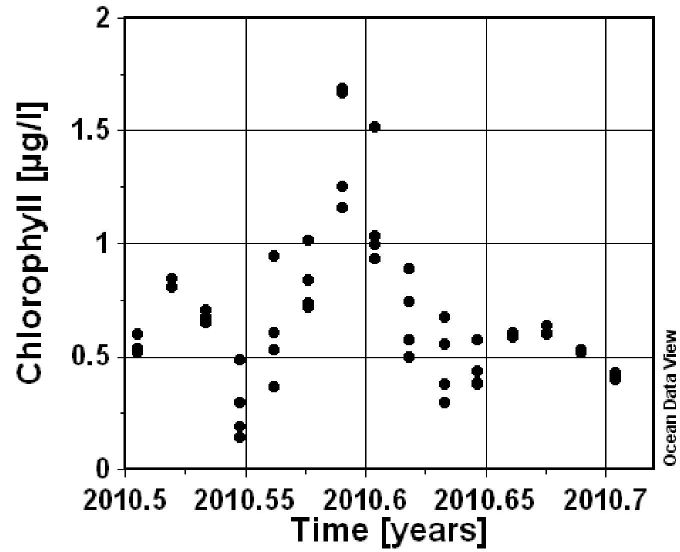
Data in upper 25 m collected by profiling float 6400.





POC up by ~1 µM (<<Redfield = 3x6.6).   Is difference C export???





A vision for the future: the Riley (or NPZ) float

Boss et al., 2008, *EOS*

N: ISUS

P: FL-NTU

Z: LOPC/Gorsky/novel cheap acoutic b_b

+PAR & O_2

Minimum sensor-suite to constrain ecosystem models.

Our current vision is constrained to be 'bottom-up' by the lack of cheap zooplankton sensors

The age of exploration is not over!

Floats or Gliders (and/or Moorings kj)?

1. **Gliders provide spatial structure (slowly) and simplify recovery**
2. **Glider measurements can (to some extent) be positioned**
3. **Floats provide (very approximate) Lagrangian time series**
4. **Floats are less expensive (purchase 15K$ vs 90K$)**
5. **Floats are much easier to adapt (more batteries, big sensors)**
6. **Floats are relatively immune to fouling – better for long duration**

Map with L/T (of signal) > 25 cm/s: array of floats

Map with L/T < 25 cm/s: glider(s)

Quasi-Lagrangian time series: floats

Many big co-located sensors: floats

Russ Davis, SIO

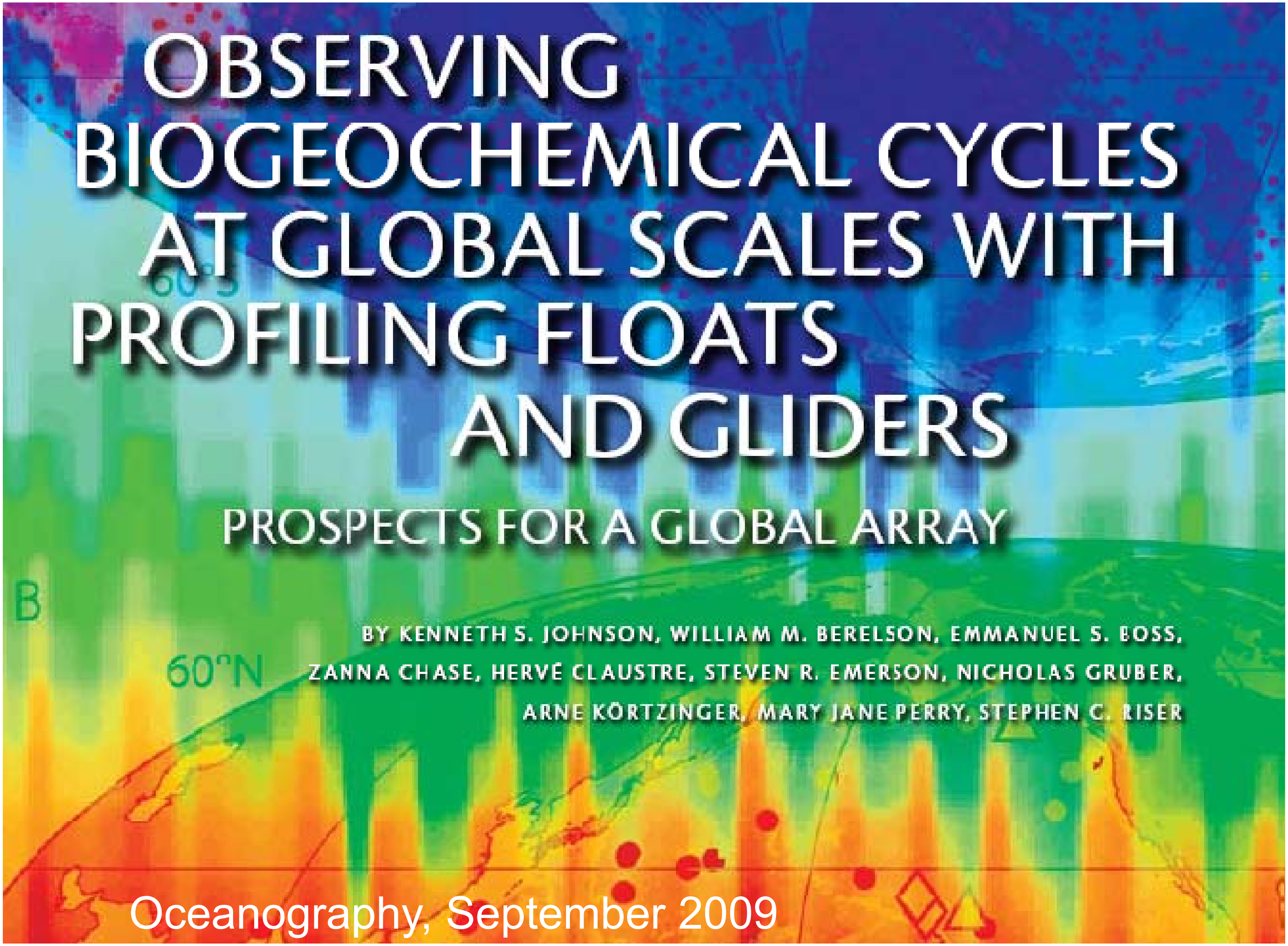
Conclusions:

- A limited set of chemical/biological sensors are available for long-term deployments.

- These sensors can be used to quantify some, but not all, biogeochemical rates.

- Can we reinvent OCB time series? Autonomous observations of a few, key rates at much higher resolution, combined with intensive, annual process studies?

- The footprint of time-series sites can be greatly expanded with autonomous obs.



OBSERVING BIOGEOCHEMICAL CYCLES AT GLOBAL SCALES WITH PROFILING FLOATS AND GLIDERS

PROSPECTS FOR A GLOBAL ARRAY

BY KENNETH S. JOHNSON, WILLIAM M. BERELSON, EMMANUEL S. BOSS, ZANNA CHASE, HERVÉ CLAUSTRE, STEVEN R. EMERSON, NICHOLAS GRUBER, ARNE KÖRTZINGER, MARY JANE PERRY, STEPHEN C. RISER

Oceanography, September 2009