BATS and HOT, 25 years of incredible productivity! CARIACO 18 years!

What should we focus on for the next 25 years?

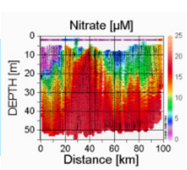
Ken Johnson

Monterey Bay Aquarium Research Institute

Net community production, carbon export and nutrient supply at ocean time series sites. Should we expect consensus? Should fluxes agree?

Ken Johnson

Monterey Bay Aquarium Research Institute



MBARI Chemical
Sensor Lab

Overarching goal – convince OCB community that we need a systematic assessment of major carbon fluxes (NCP, Export, …) at time series station (HOT, BATS, CARIACO, ESTOC, Papa).

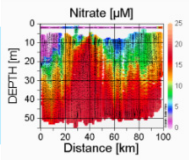
- Perhaps an OCB working group?
- How do methods compare?

I'll argue that time series stations need to make quantitative observations of major carbon fluxes over time.

- Are sediment traps at 150 m good enough?
- Methods should be intercomparable.
- Time series stations should serve as a benchmark for more expandable systems.

Ultimately we need global, carbon observing systems.

But first a little time series history!



HOT-1 Cruise Report
R/V Moana Wave
29 Oct. - 3 Nov. 1988

Narrative:

HOT-1 was the shakedown cruise of the HOT program, much of the equipment had never been used, and there were some equipment failures. One conductivity cell and the General Oceanics rosette pylon failed. In addition, there were problems with the winch level-wind mechanism, and with the slip-rings. The Kahe Point station was abandoned because of these problems.

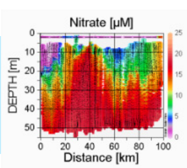
The sediment traps were tracked using ARGOS for two days after deployment, but we lost contact with them a few hours before they were due to be retrieved, and despite a 16-hour search, they were not found.

Bermuda Biological Station For Research, Inc.
U.S. JGOFS Bermuda Atlantic Time-series Study

Cruise Report, BATS 1

Cruise dates: October 20, 1988 - October 21, 1988
Personnel: A.H. Knap, R.L. Sherriff-Dow, P. Wassmann, R. Johnson.
R.V. Weatherbird

Cast 1 on deck at 0200.
Wire kinked. Decide not to put CTD back down.
Lat: 31.160 N; Long: 64.500 W
Nominal depths: 2000,2200,2400,2600,2800,3000,3200,3400,3600,3800,4000, 4200 m.

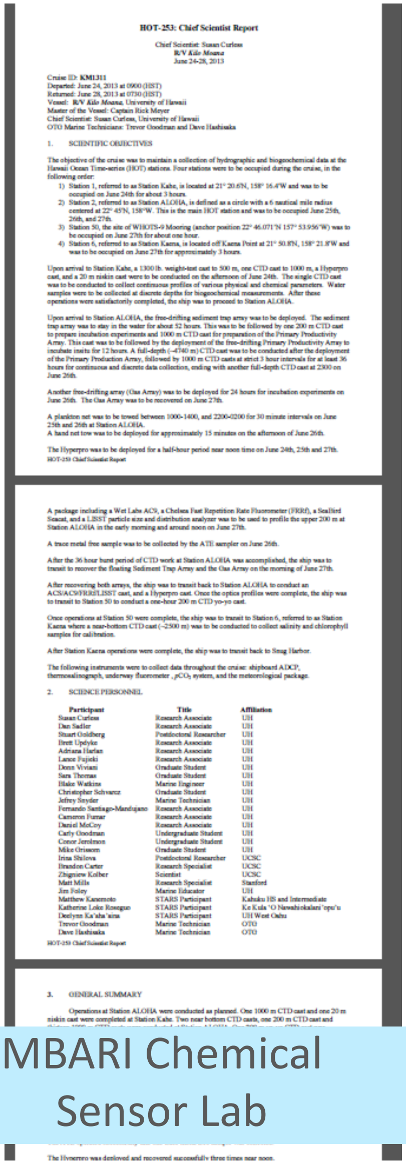


HOT-253: Chief Scientist Report

Chief Scientist: Susan Curless

R/V *Kilo Moana*

June 24-28, 2013

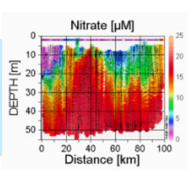

HOT-253: Chief Scientist Report

Chief Scientist: Susan Curless

R/V Kilo Moana

June 24-28, 2013

Investigator	Project	Institution
Matt Church Dave Karl Bob Bidigare	Core Biogeochemistry	UH
John Dore	Biogeochemistry QA/QC	MSU
Roger Lukas	Hydrography	UH
Mike Landry	Zooplankton dynamics	SIO
Ricardo Letelier	Optical measurements	OSU
Ancillary programs:		
Andrew Dickson	CO_2 dynamics and intercalibration	SIO
Paul Quay	$DI^{13}C$	UW
Matt Church & Ricardo Letelier	Diversity and activities of nitrogen-fixing microorganisms	UH
Sam Wilson	Reduced gases in the upper ocean: The cycling of methane, sulfide and nitrous oxide	UH
Donn Viviani	Bacterial production and EOC at Station ALOHA	UH
Sara Thomas	Chemolithoautotroph experiment	UH
Adina Paytan	O^{18} natural abundance	UCSC
Christopher Schvarcz	Viral Dynamics at Station ALOHA and surface water collection for virus and phytoplankton culturing	UH
Erica Goetze	Temporal stability of copepod populations at Station ALOHA	UH
Irina Shilova, Brandon Carter, Matt Mills, and Zbigniew Kolber	Phytoplankton responses to different nitrogen sources in the North Pacific Subtropical Gyre	UCSC Stanford
Scott Turn	Storage Stability of Next Generation Biofuels	HNEI/UH
Stu Goldberg	Nutrient and DOC cycling experiment	UH



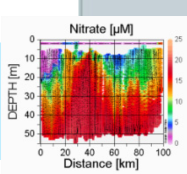
MBARI Chemical Sensor Lab

Matt Church presentation, OCB Time Series Workshop

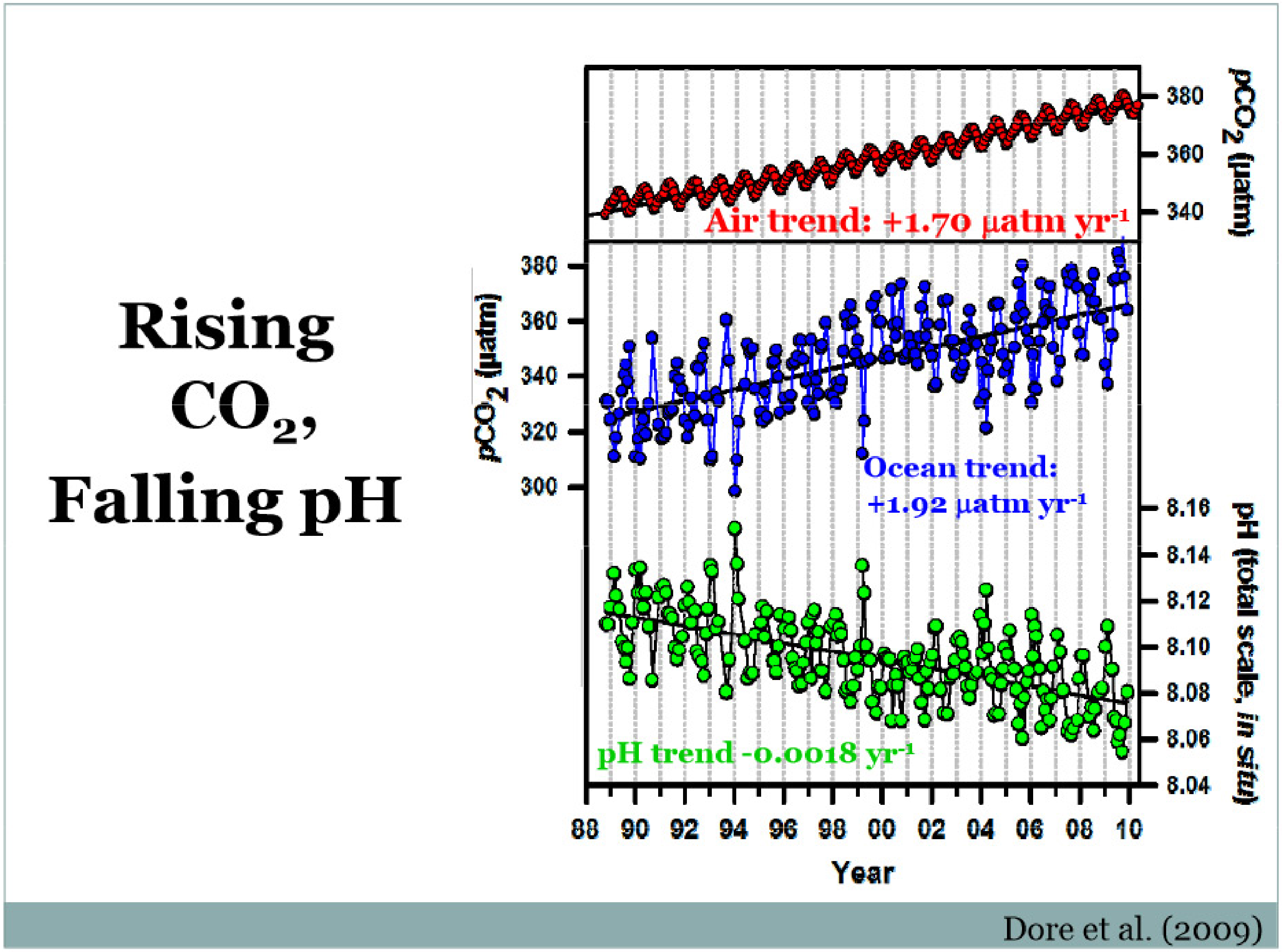
What's HOT?

Program objectives:

- Quantify time-dependent variability in key physical, biogeochemical, and ecological properties and processes
- Define relationships between plankton community structure and biogeochemical dynamics
- Quantify physical and biological processes controlling oceanic carbon uptake, transformation, and sequestration



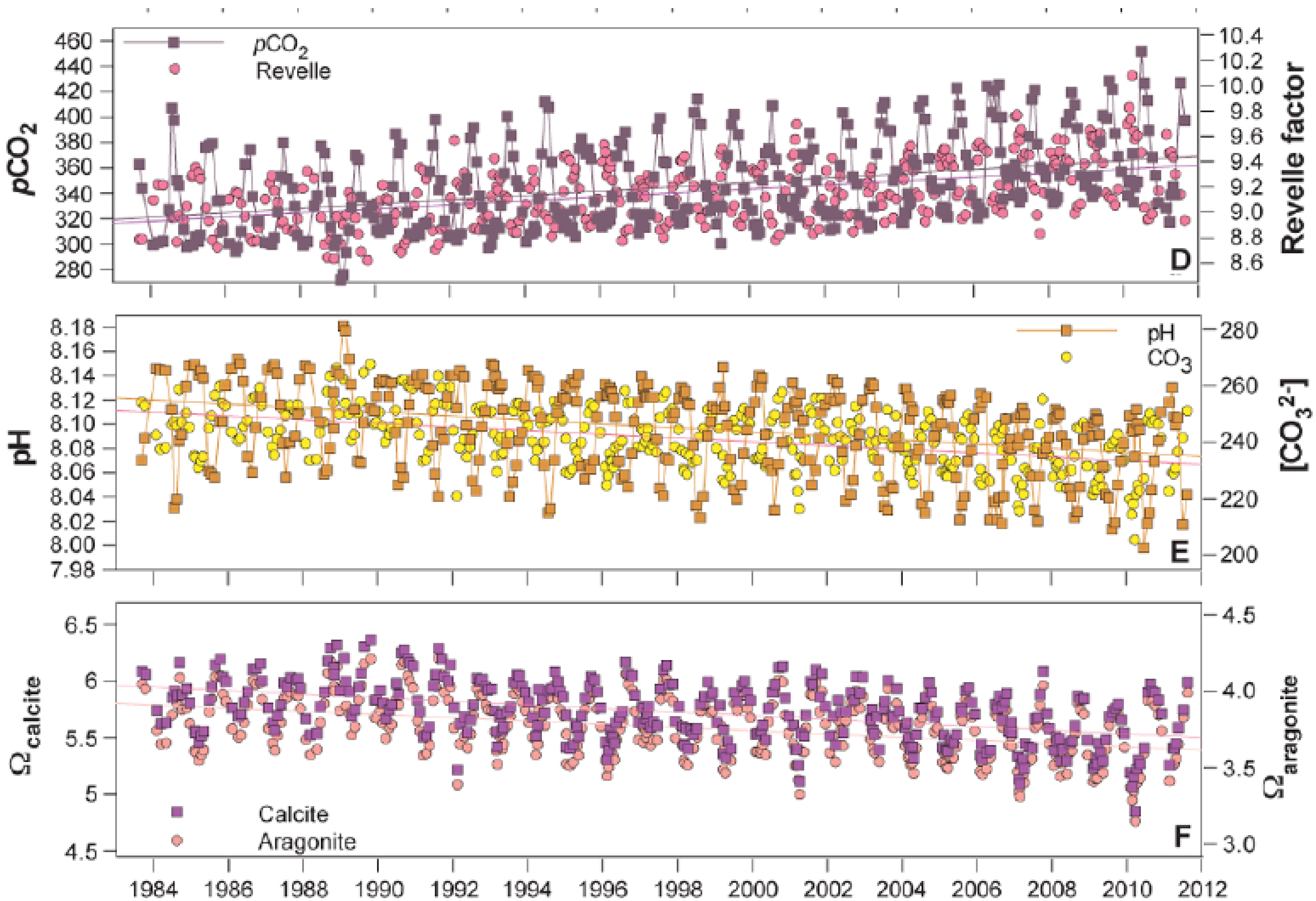
HOT –Dore et al., PNAS 2009

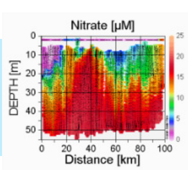


BATS

Biogeosciences, 9, 2509–2522, 2012 www.biogeosciences.net/9/2509/2012/

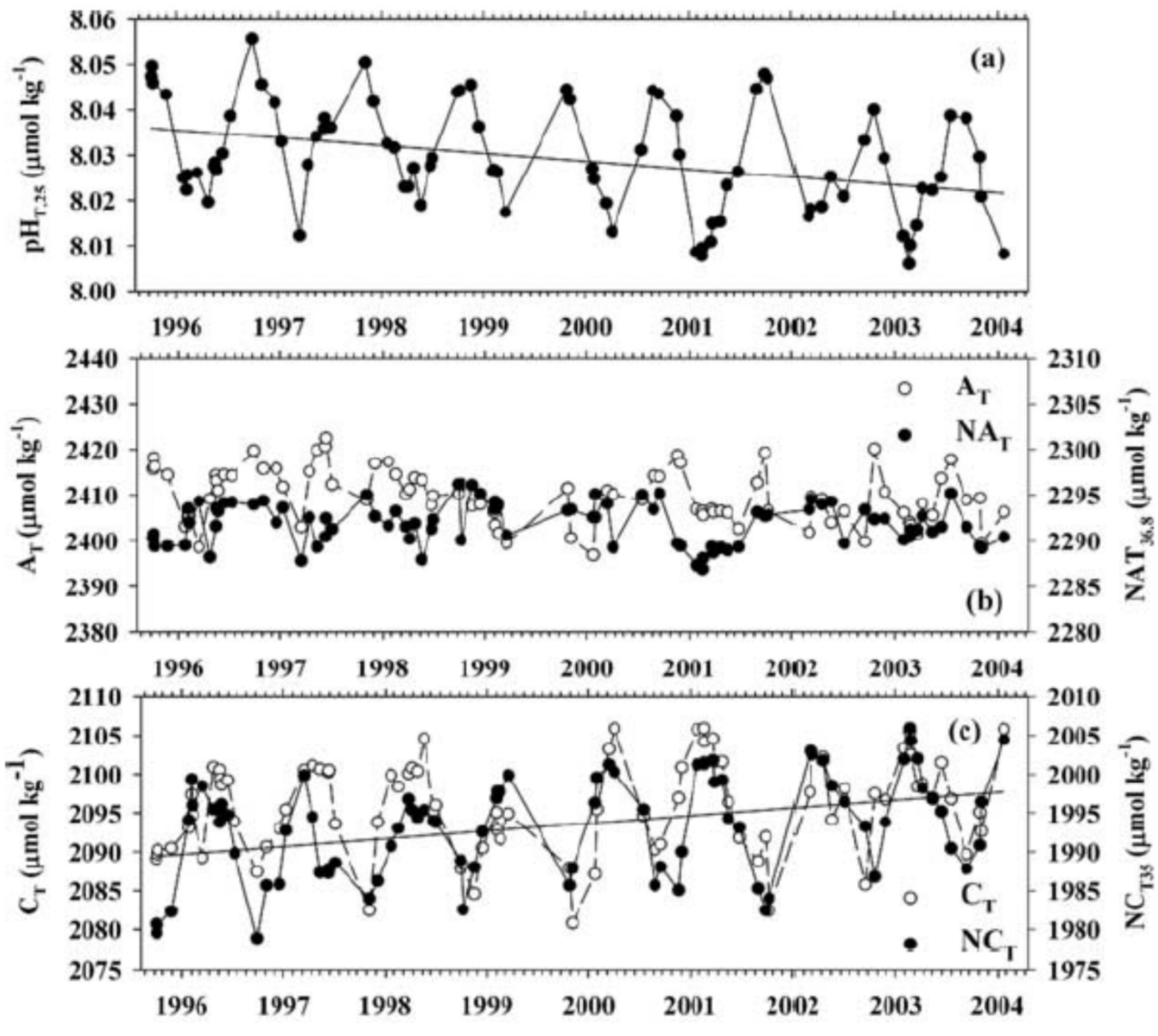
Bates et al.

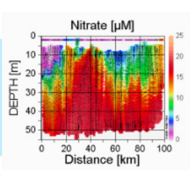




MBARI Chemical Sensor Lab

SANTANA-CASIANO ET AL.: CO_2 VARIABILITY AT THE ESTOC SITE





MBARI Chemical
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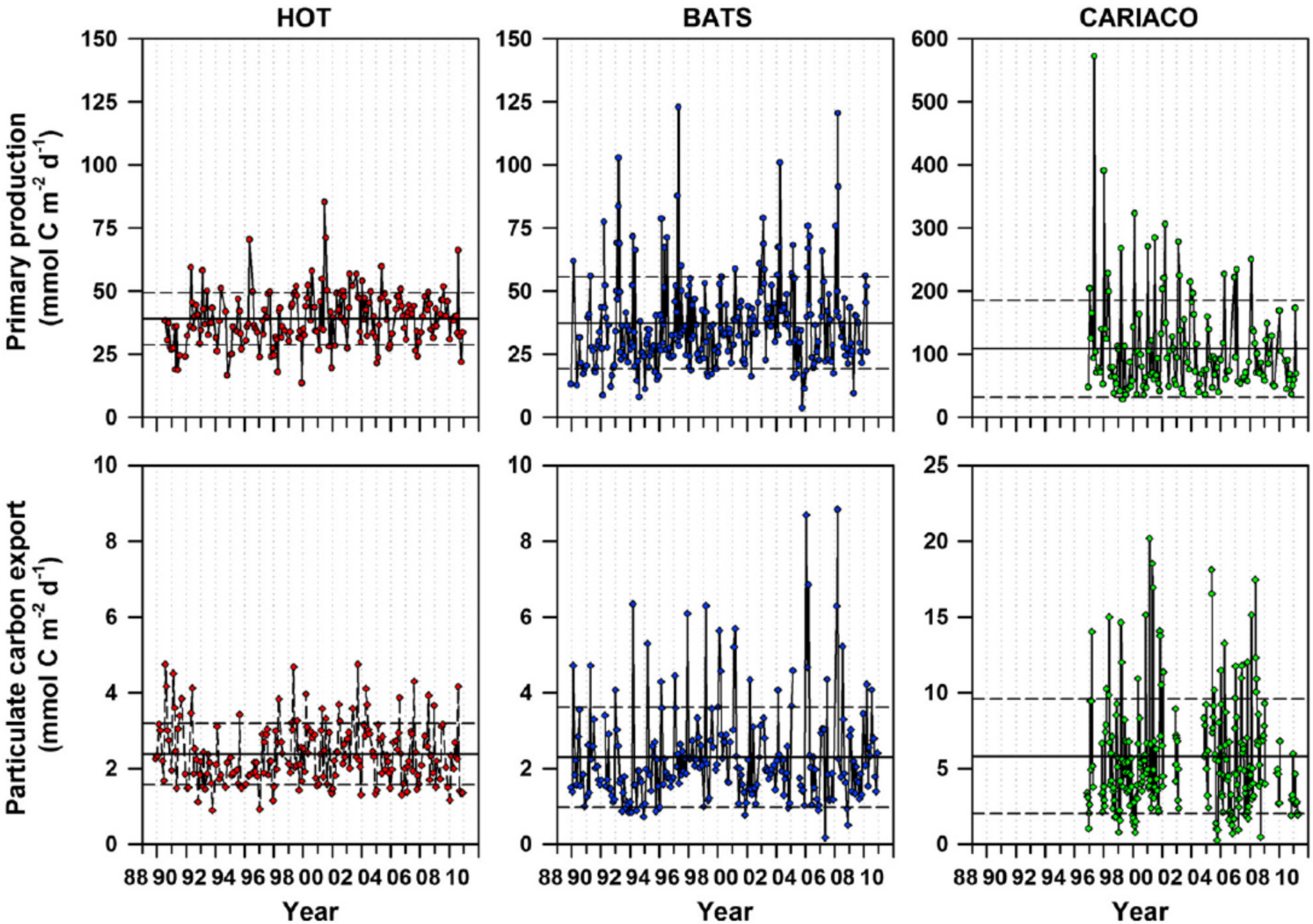
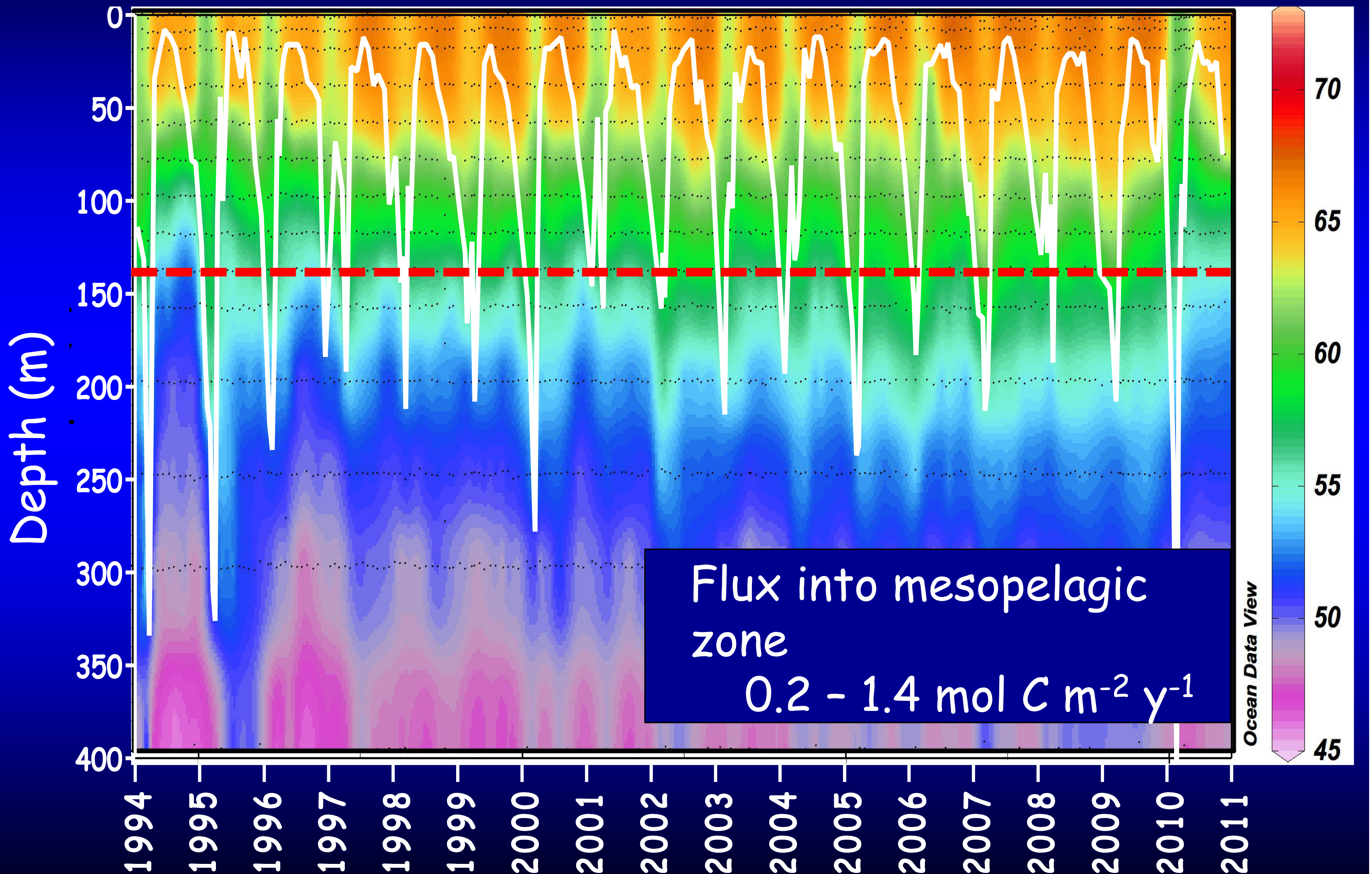
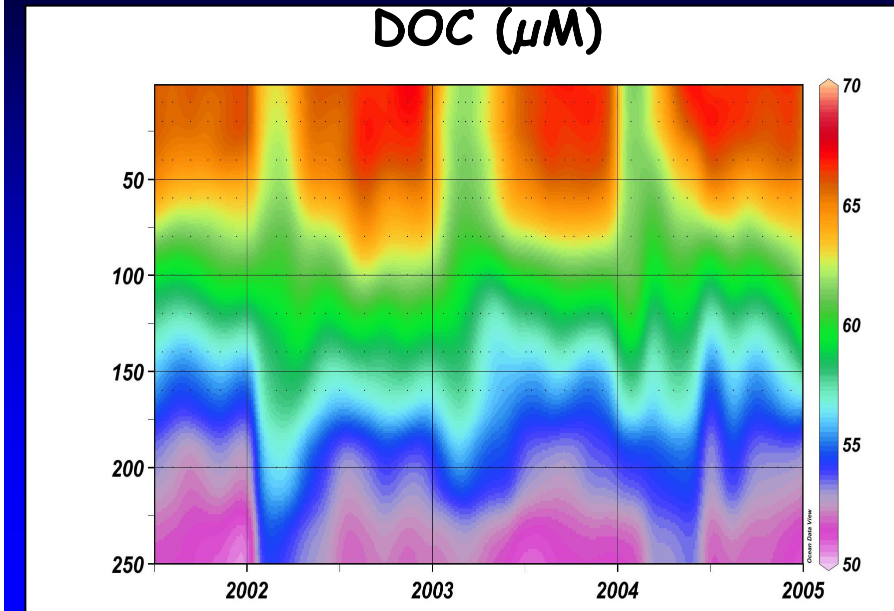
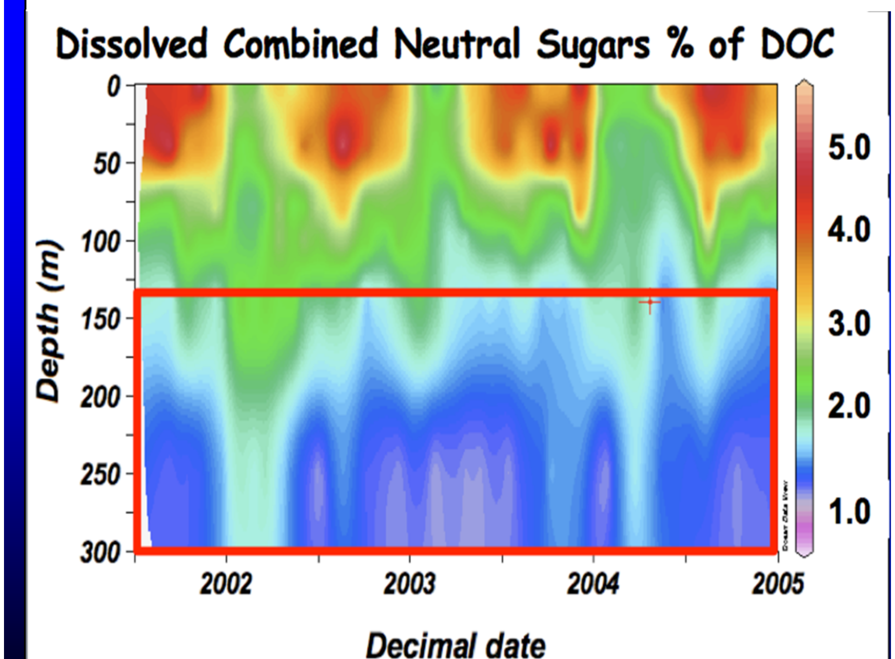

HOT
BATS
CARIACO
Primary production (mmol C m-2 d-1)
Particulate carbon export (mmol C m-2 d-1)
Year
88 90 92 94 96 98 00 02 04 06 08 10

DOC (μmol kg^{-1}) dynamics at BATS (Carlson & Hansell)



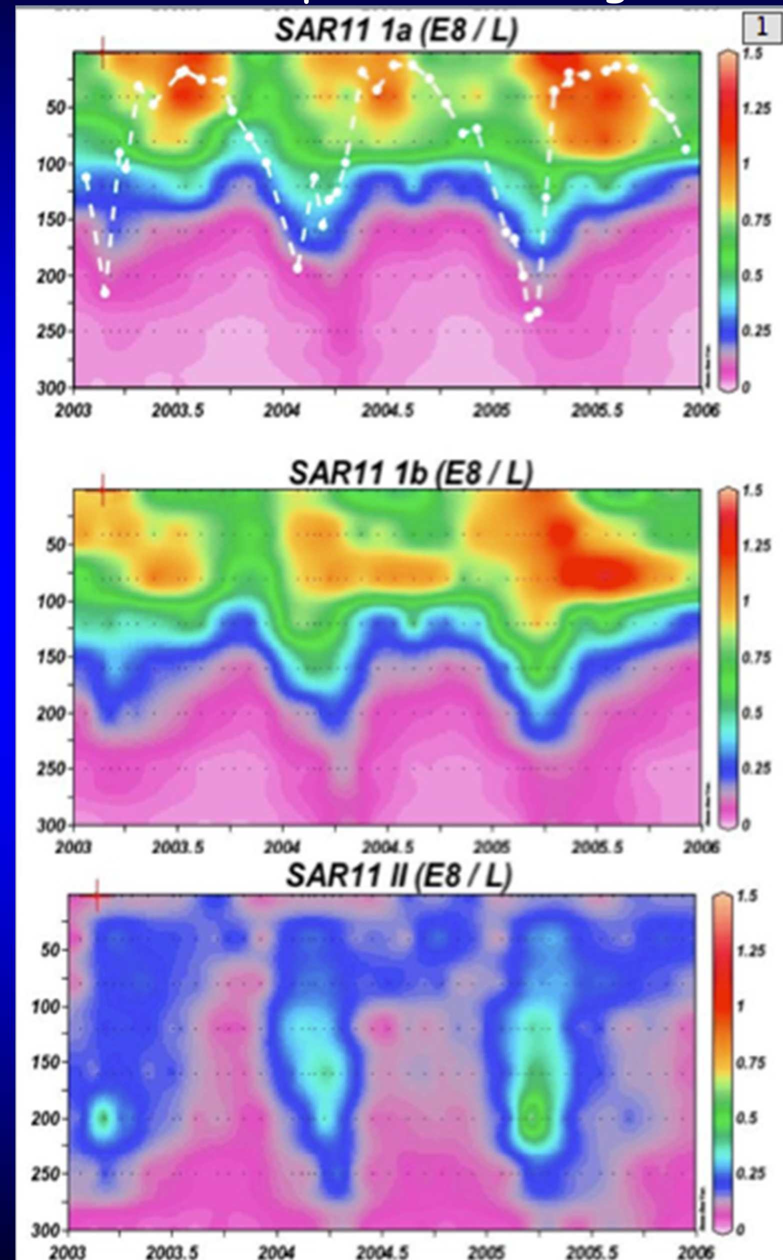
DOC Dynamics at BATS





Goldberg et al. 2009

Response of specific bacterioplankton lineages



Carlson et al. 2009

BATS/ Original Motivation and Objectives/

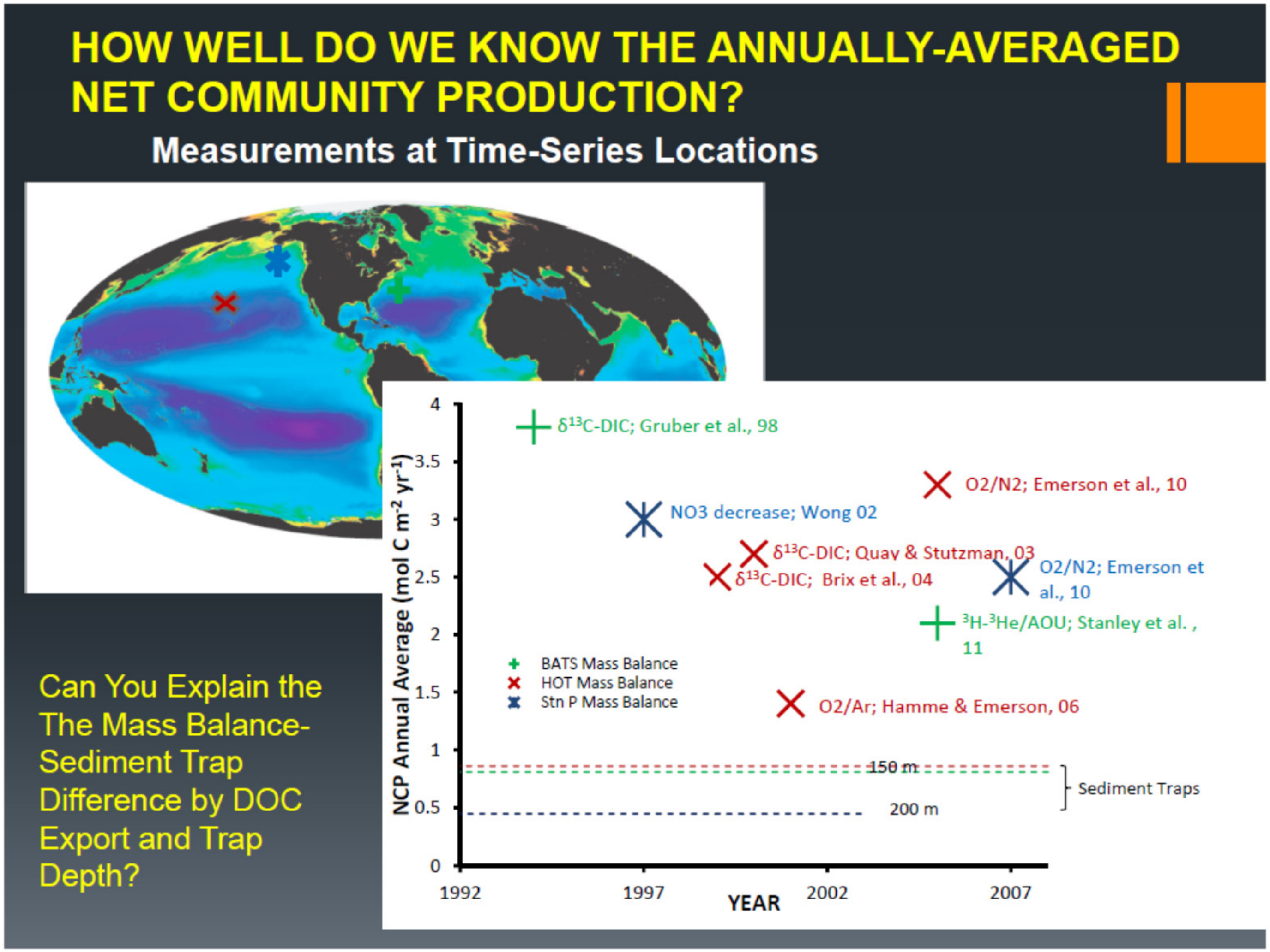
The Bermuda Atlantic Time-series Study (BATS) was initiated under the JGOFS umbrella with the overall motivation…

" *To determine and understand the **time-varying fluxes** of carbon and associated biogenic elements in the ocean and to evaluate the related **exchanges with the atmosphere, sea floor** and continental boundaries* ." (SCOR, 1987)

Original Objectives:

- **To understand the seasonal and interannual variations in ocean physics, chemistry and biology**
- **To understand the processes that control surface pCO_2**
- **To understand the physical controls on biological rate processes**
- **To provide a test-bed for the validation of new methods and technologies**

Steve Emerson, 2012 OCB Summer Workshop



Net Community Production (NCP) = Primary Prod. – Respiration at all trophic levels (Net production of C = C export on an annual basis)

NCP estimates near HOT to base of euphotic zone

Method	NCP (mol C m^{-2} y^{-1})	Ref.
POC Flux	1.1±0.3	Karl et al. 1995
$DI^{13}C$ mass balance	1.6±0.9	Emerson et al. 1997
Sum of C fluxes	2.0±0.9	Emerson et al. 1997
O_2 utilization rates	2.2±0.5	Sonnerup et al. 1999
O_2, Ar, N_2 mass balance	2.7±1.7	Emerson et al. 1997
^{234}Th C flux	2.7±0.9	Benitez-Nelson et al. 1995
DIC, $DI^{13}C$ & model	2.7±1.3	Quay & Stutsman 2003
DIC & model	2.8±0.8	Keeling et al., 2004
Moored O_2 sensor	4.0±2.0	Emerson et al., 2008
O_2/Ar	5.0±1.0	Quay et al., 2010
MEAN	**2.7±0.6 (90% CI)**	
19 Years of Prof. Float O_2	**3.4±0.4 (90% CI)**	

Matt Church, OCB Time Series Workshop

Net Community Production at Station ALOHA

Method	Rate mol C m^{-2} yr^{-1}	Period of measurements	References
Mixed Layer O_2 + Ar budgets	1.4 - 3.7 (± 1.0)	1992–2008	Emerson et al. (1997); Hamme and Emerson (2006); Juanek and Quay (2005); Quay et al. (2010)
DIC + $DI^{13}C$ budgets	2.7 - 2.8 (± 1.4)	1988–2002	Quay and Stutsman (2003); Keeling et al. (2004)
Mooring O_2	4.1 (± 1.8)	2005	Emerson et al. (2008)
Sub-mixed layer float profiles	1.1 - 1.7 (±0.2)	2003-2010	Riser and Johnson (2008)
Sub-mixed layer glider surveys	0.9 (± 0.1)	2005	Nicholson et al. (2008)
Sediment traps	0.9 (± 0.3)	1989–2009	HOT core data
In vitro O_2 incubations	-6.1 (± 4.6)	2001, 2005-2007	Williams et al. (2004)

NCP appears constrained to ~2-fold variability
GPP estimated ~20-fold greater than NCP

What Is the Metabolic State of the Oligotrophic Ocean? A Debate

Annu. Rev. Mar. Sci. 2013. 5

Hugh W. Ducklow[1] and Scott C. Doney[2]

[1]The Ecosystems Center, M
email: hducklow@mbl.edu

[2]Department of Marine Ch
Woods Hole, Massachusett

The Oligotrophic Ocean Is Autotrophic*

Peter J. le B. Williams,[1] Paul D. Quay,[2]
Toby K. Westberry,[3] and Michael J. Behrenfeld[3]

[1]School of Ocean Sciences, Bangor University, Menai
United Kingdom; email: pjlw@bangor.ac.uk

[2]School of Oceanography, University of Washington,

[3]Department of Botany and Plant Pathology, Oregon
Oregon 97331-2902

The Oligotrophic Ocean Is Heterotrophic*

Carlos M. Duarte,[1,2] Aurore Regaudie-de-Gioux,[1,4]
Jesús M. Arrieta,[1] Antonio Delgado-Huertas,[5]
and Susana Agustí[1,2,3]

[1]Department of Global Change Research, Mediterranean Institute of Advanced Studies, CSIC-UIB, 07190 Esporles, Spain; email: carlosduarte@imedea.uib-csic.es

[2]Oceans Institute and [3]School of Plant Biology, University of Western Australia, Crawley 6009, Australia

[4]Spanish Oceanographic Institute, 33213 Gijón, Spain

[5]Instituto Andaluz de Ciencias de la Tierra, CSIC-UGR, 18100 Armilla, Spain

IMPLICATIONS AND UNRESOLVED ISSUES

There are two key implications of our conclusions.

- A bias toward net heterotrophy in the *in vitro* O_2-based measurements calls into question whether the same issues exist for other *in vitro* measurements (i.e., ^{14}C and ^{15}N measurements)

- Net autotrophy….raises issues regarding sources of nutrients supporting positive NCP.

The Oligotrophic Ocean Is Autotrophic*

Peter J. le B. Williams,[1] Paul D. Quay,[2] Toby K. Westberry,[3] and Michael J. Behrenfeld[3]

GLOBAL BIOGEOCHEMICAL CYCLES, VOL. 14, NO. 4, PAGES 1231-1246, DECEMBER 2000

Temperature effects on export production in the open ocean

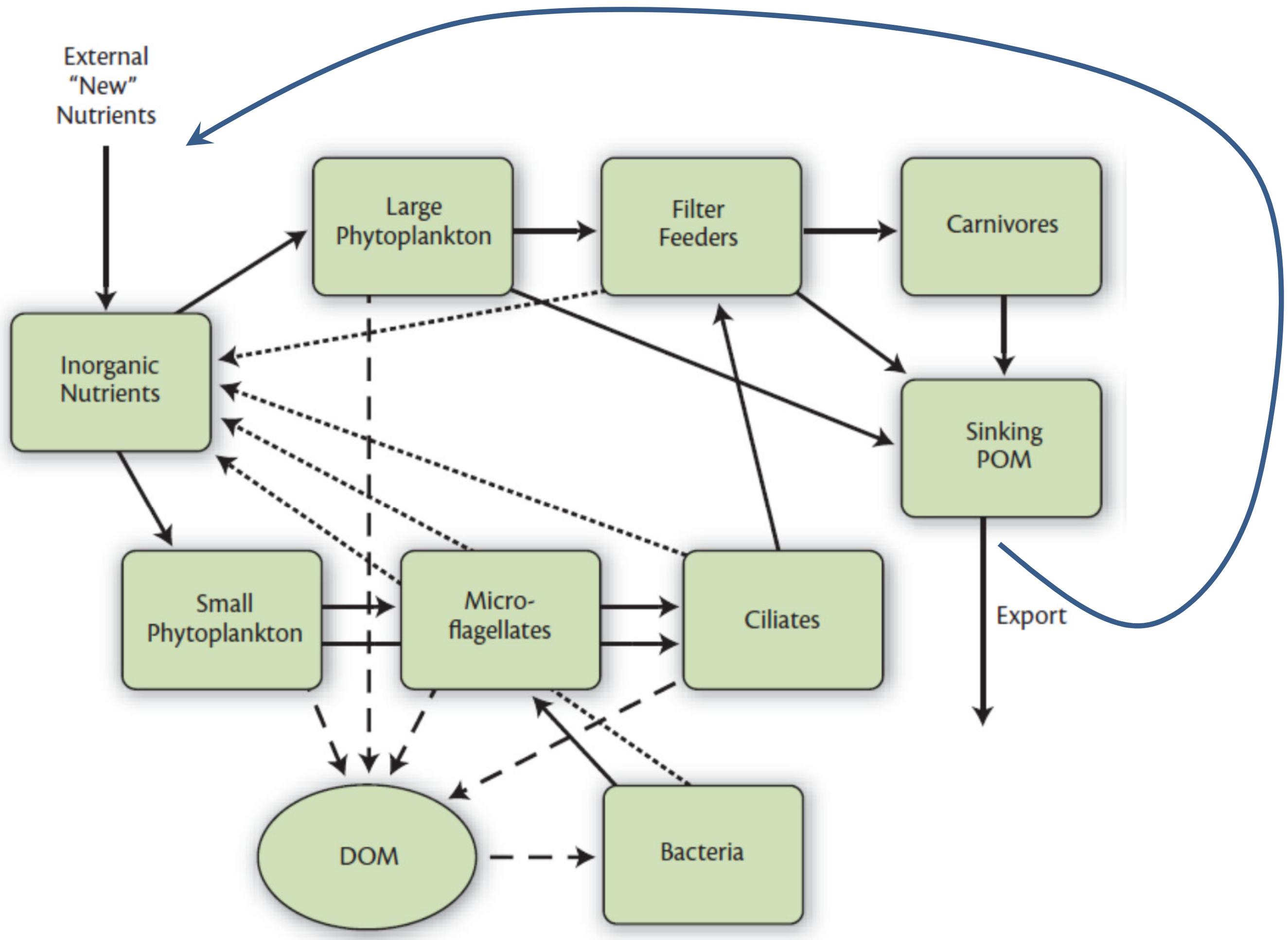
Edward A. Laws,[1] Paul G. Falkowski,[2] Walker O. Smith Jr.,[3] Hugh Ducklow,[3]
and James J. McCarthy[4]

New nutrient input =

Net Community Production =

Export =

New nutrient input



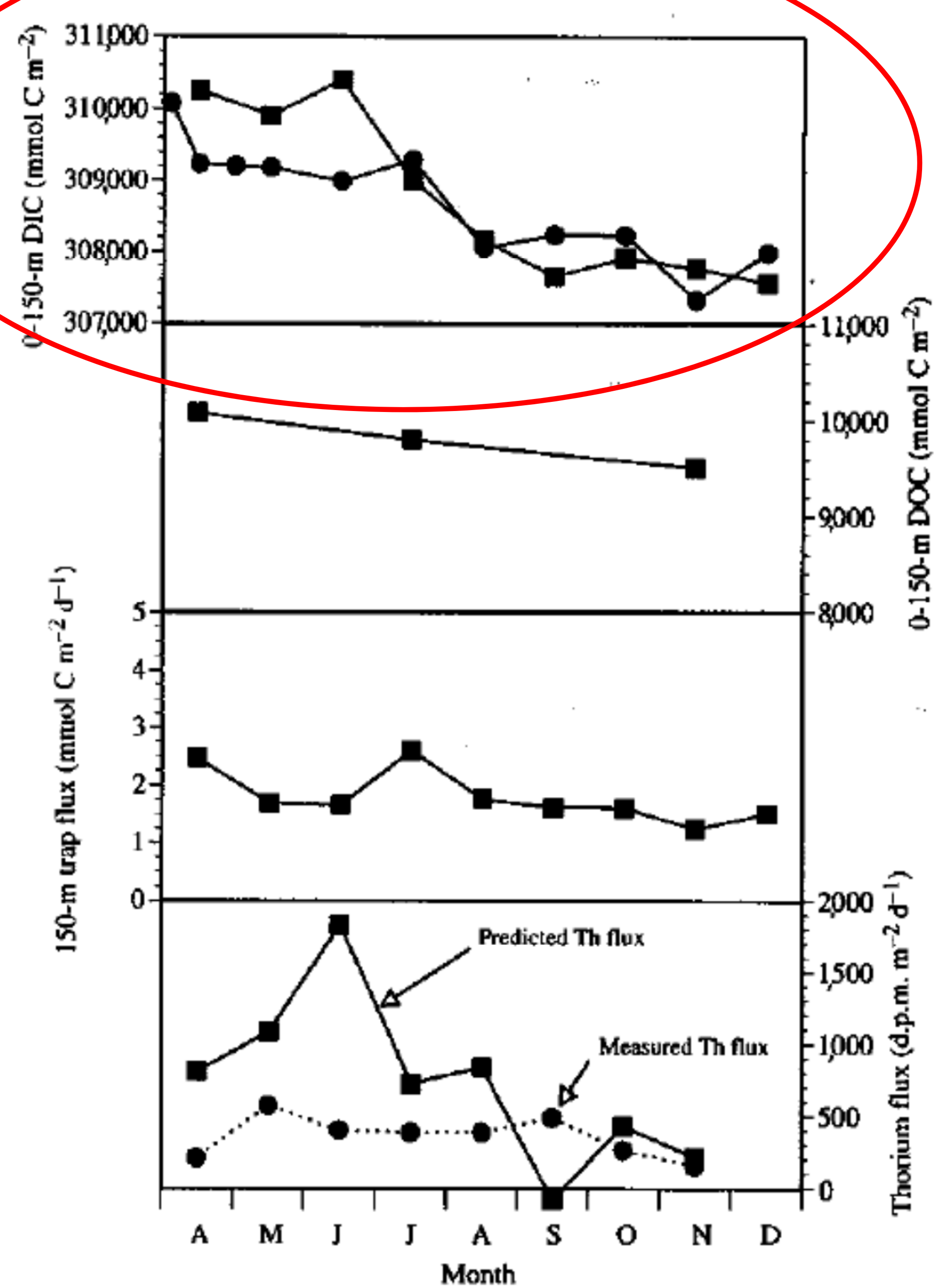
NATURE · VOL 372 · 8 DECEMBER 1994

Carbon-cycle imbalances in the Sargasso Sea

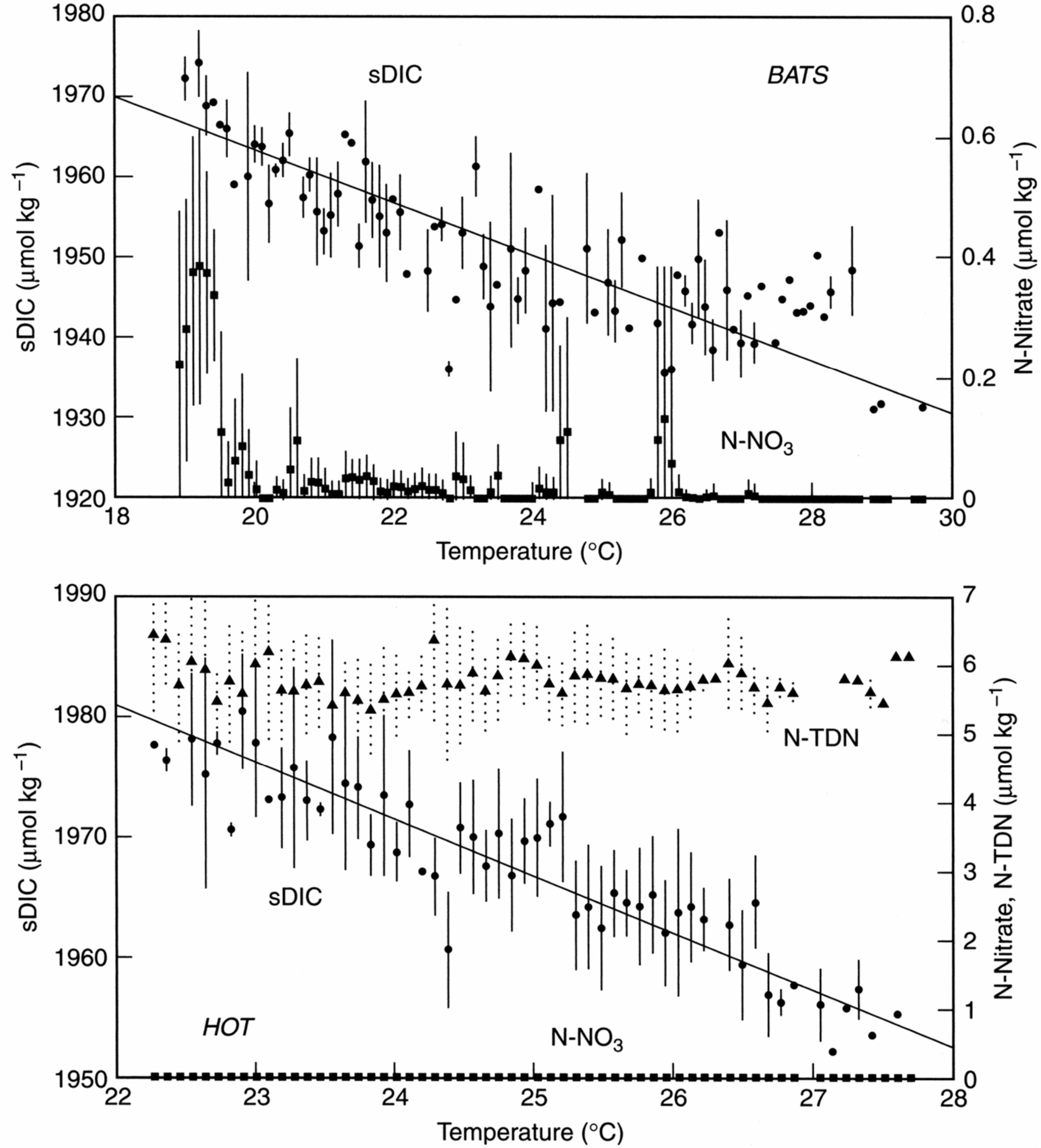
Anthony F. Michaels*, Nicholas R. Bates*, Ken O. Buesseler†, Craig A. Carlson‡ & Anthony H. Knap*

* Bermuda Biological Station for Research, Ferry Reach GE01, Bermuda
† Woods Hole Oceanographic Institution, Woods Hole, Massachusetts 02543, USA
‡ Horn Point Environmental Laboratory, University of Maryland, Cambridge, Maryland 21613, USA

DIC decreases each year, but there is no nitrate present!



from Karl et al. Chap. 10 in Fasham, “Ocean Biogeochemistry”



10.5.2 Case Study 2: A 'Bermuda Triangle' Carbon Mystery with Global Implications

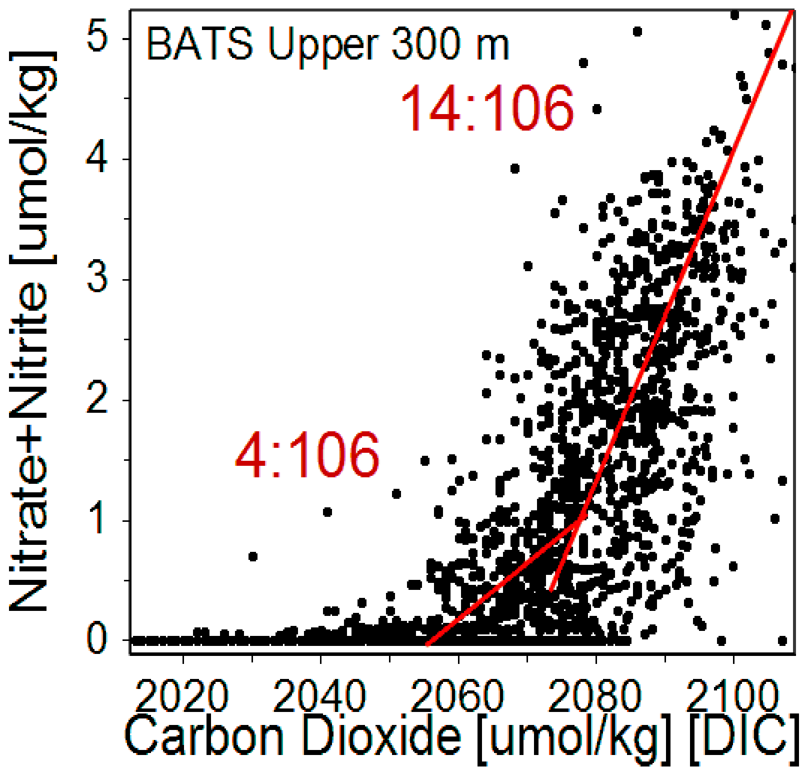
The continued disappearance of salinity normalized dissolved inorganic carbon (N-DIC) in the absence of nitrate was first reported by Michaels et al. (1994). They reasoned that if nitrate was added by episodic wind mixing or mesoscale eddy motions, the nitrate would be delivered along with DIC, so simple enhancements of nitrate-supported new and export production could not be responsible for the repeatable summertime N-DIC

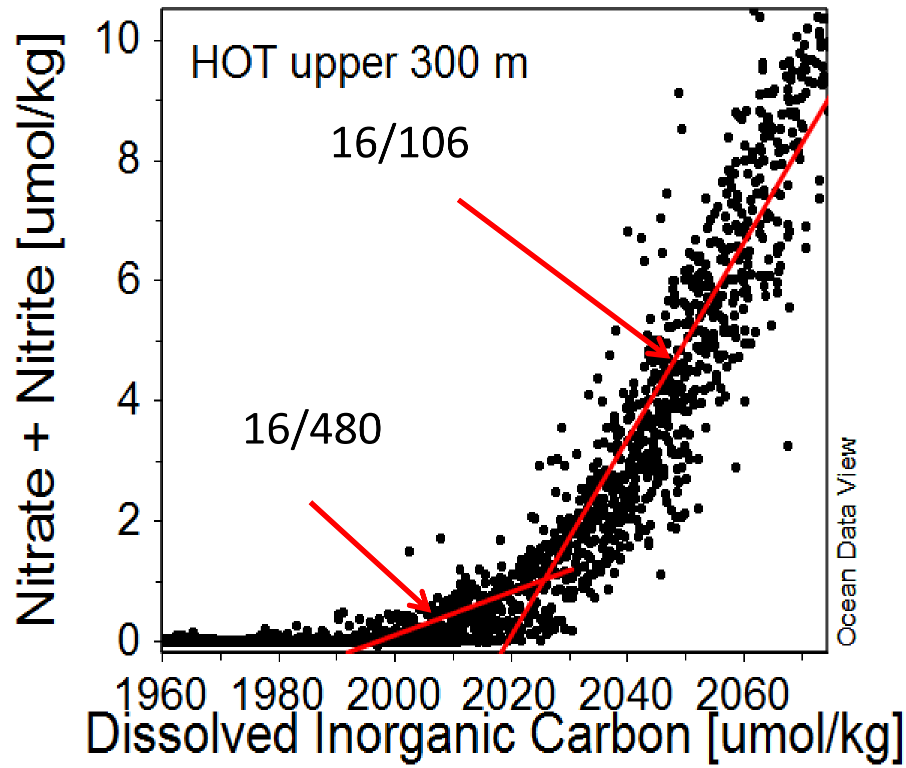
- from Karl et al. Chap. 10 in Fasham, "Ocean Biogeochemistry"

Siegel et al., JGR 104, 1999

	Annual Flux mol N m-2 y-1	Annual Flux mol C m-2 y-1
NCP	0.50	3.3
Total N Flux	0.51	3.4
Eddy pumping	0.18	1.2
Winter Convection	0.17	1.1
Isopycnal Diffusion	0.03	0.2
Large-scale Ekman pumping	0.03	0.2
Atmospheric Dep.	0.03	0.2
Diapycnal Diffusion	0.015	0.1

Carbon is at or above Redfield, relative to nitrate, at the base of the euphotic zone. Upward transport of sufficient nitrate also brings carbon and there is no annual drawdown





Why do we care about getting C and nutrient fluxes right???

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

- Trend detection based primarily on remote sensing and results can be opposite to in situ time series observations

- Need bio-chemical sensors to directly sense change in carbon cycle.

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 Hydrospheric 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. 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]

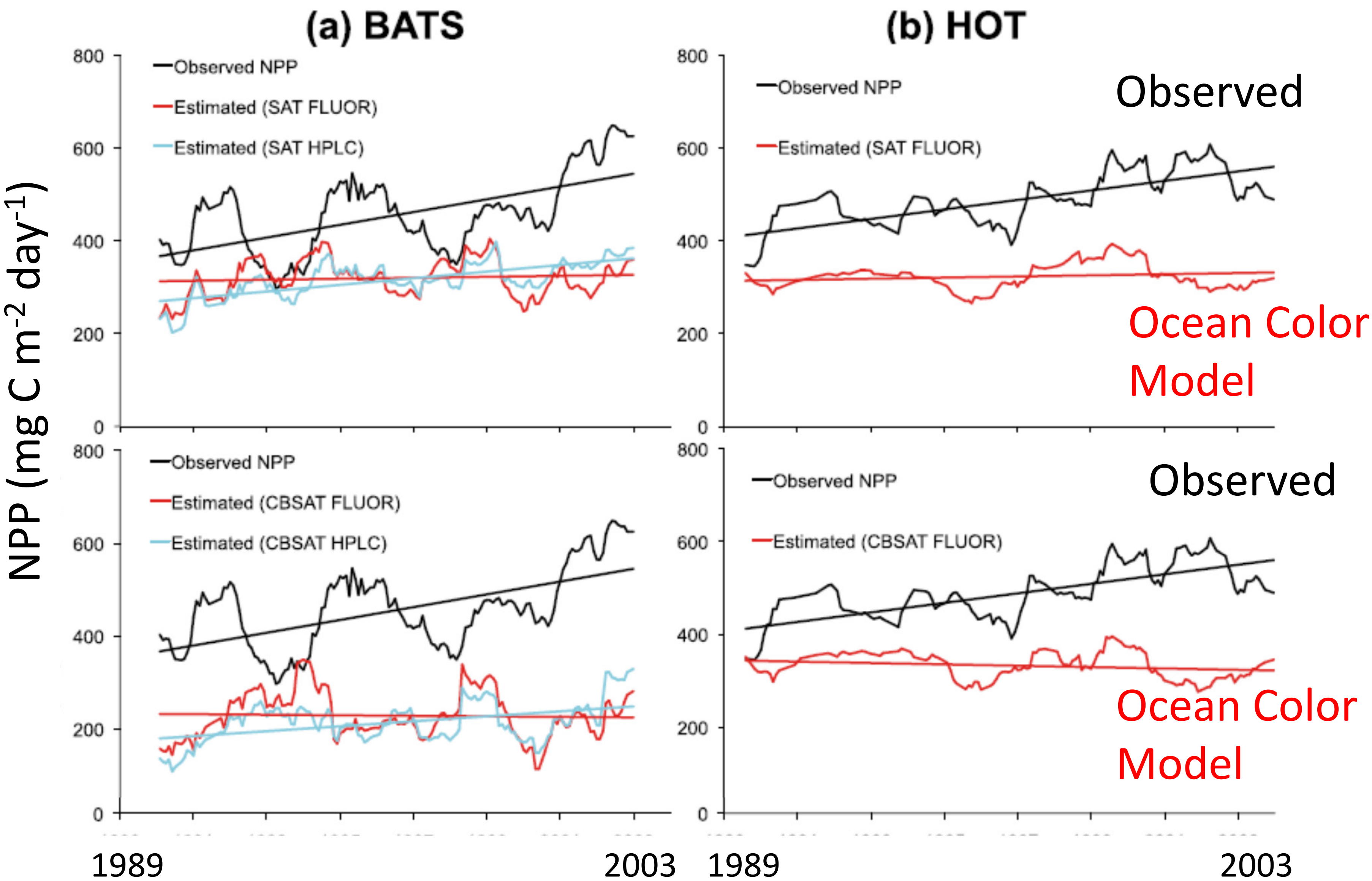
Vol 466|29 July 2010|doi:10.1038/nature09268 nature

ARTICLES

Global phytoplankton decline over the past century

Daniel G. Boyce[1], Marlon R. Lewis[2] & Boris Worm[1]

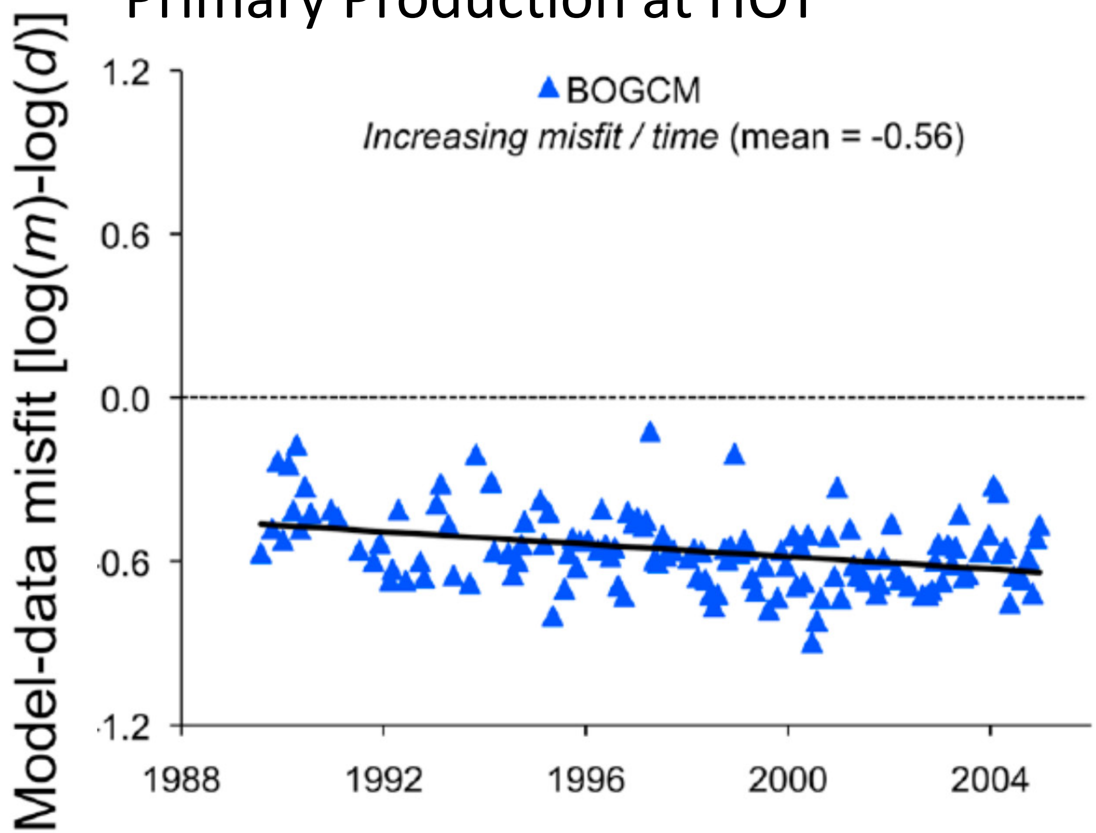
In the oceans, ubiquitous microscopic phototrophs (phytoplankton) account for approximately half the production of organic matter on Earth. Analyses of satellite-derived phytoplankton concentration (available since 1979) have suggested decadal-scale fluctuations linked to climate forcing, but the length 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


(a) BATS
(b) HOT
NPP (mg C m-2 day-1)
Observed NPP
Estimated (SAT FLUOR)
Estimated (SAT HPLC)
Estimated (CBSAT FLUOR)
Estimated (CBSAT HPLC)
Observed
Ocean Color Model
800
600
400
200
0
1989
2003

Mean 3D Biogeochemical model error for estimates of Net Primary Production at HOT

= log (Model NPP/Obsd. NPP)

$10^{-0.56} = 0.27$

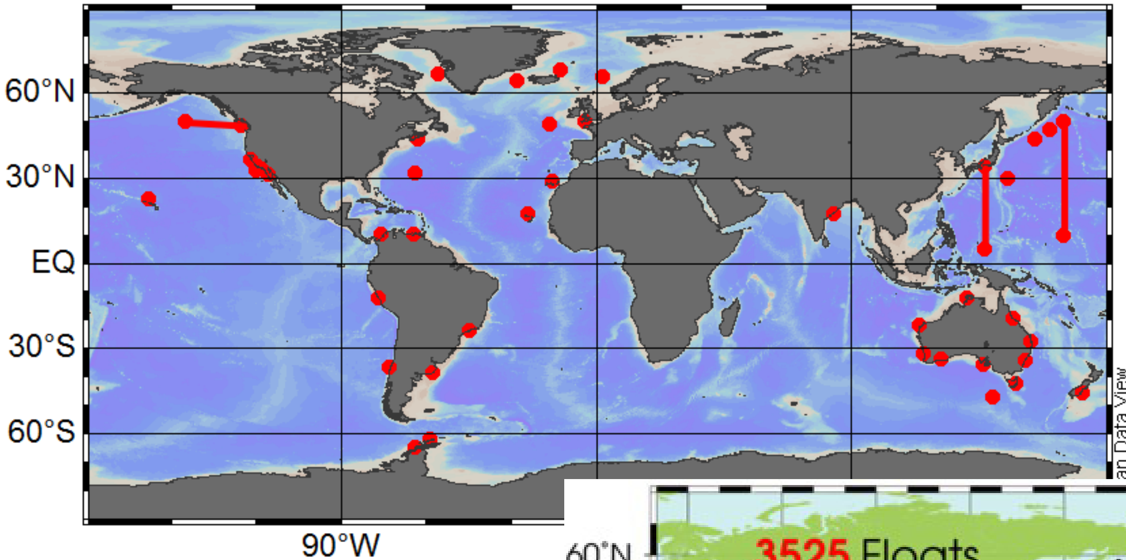


GLOBAL BIOGEOCHEMICAL CYCLES, VOL. 24, GB3020, doi:10.1029/2009GB003655, 2010

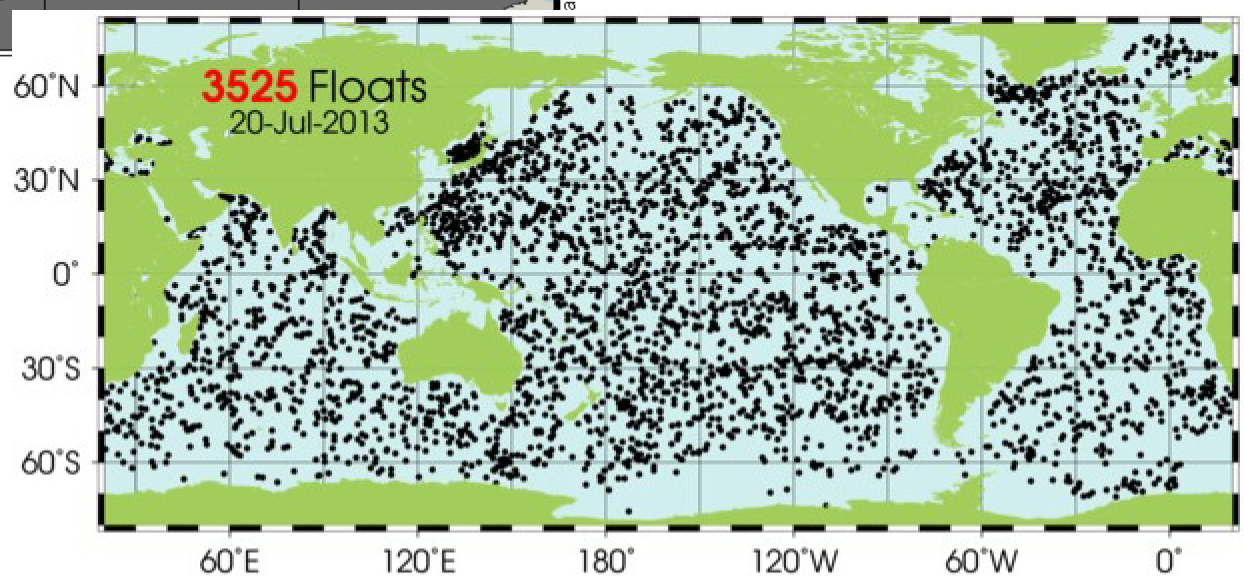
Challenges of modeling depth-integrated marine primary productivity over multiple decades: A case study at BATS and HOT

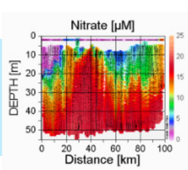
Vincent S. Saba,[1,2] Marjorie A. M. Friedrichs,[1] Mary-Elena Carr,[3] David Antoine,[4] & 39 others

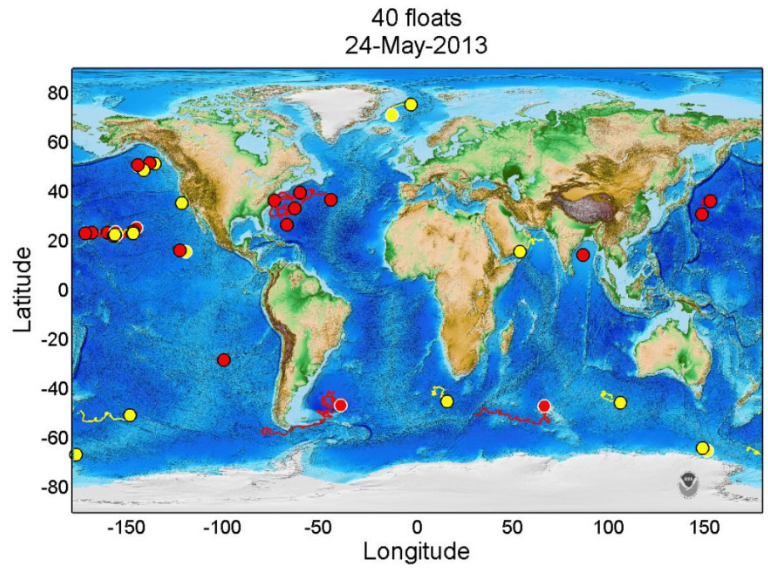
Time Series Represented at OCB Time Series Workshop Nov. 2012



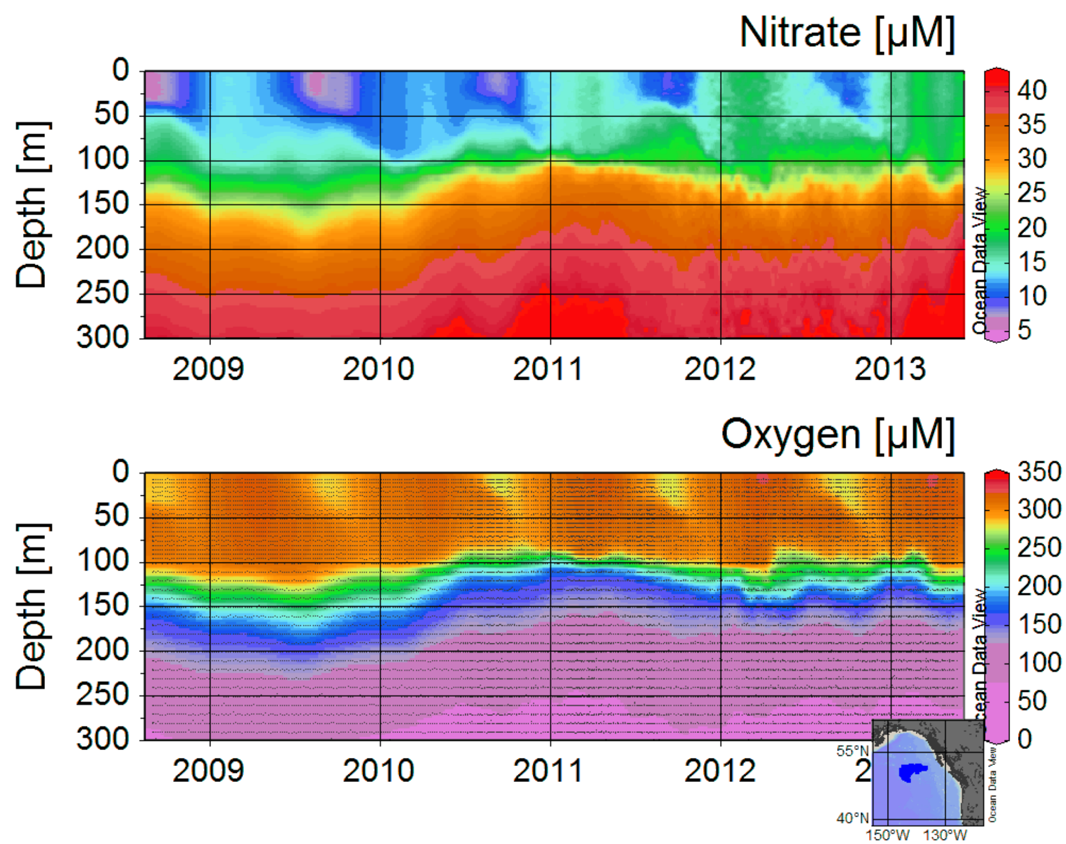
Observing system needed to get heat content



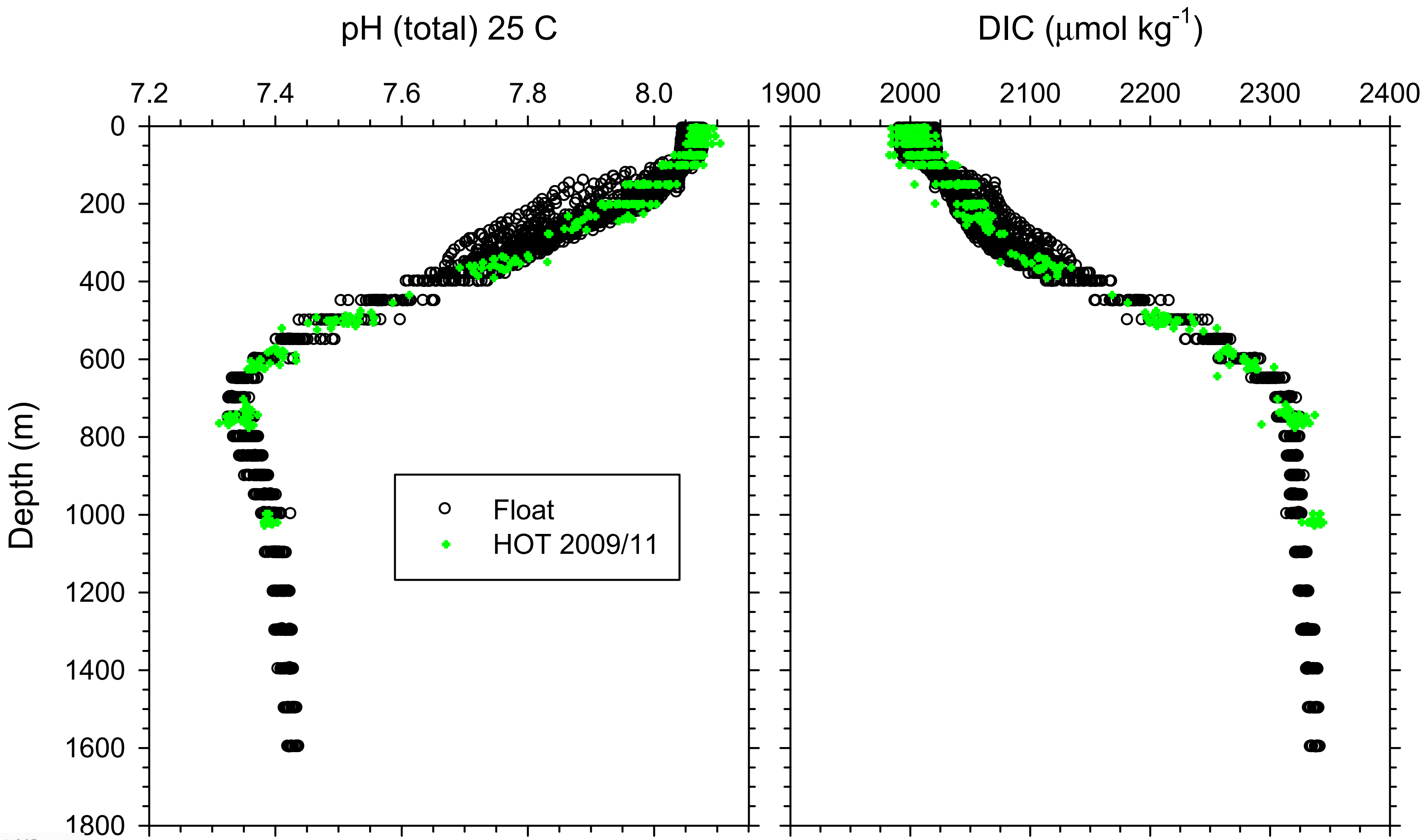


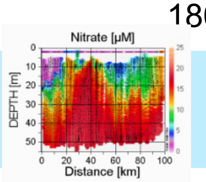


Nitrate
Oxygen
pH
Chl. Fluorescence
Optical Backscatter
60 obs. from 1000 m
300 profiles (4.5 y at 5 d/cycle)



pH can be measured robustly using Ion Sensitive Field Effect Transistors (Martz et al., L&O Methods, 2010). If you have pH, Dissolved Inorganic Carbon can be estimated to about 8 µmol/kg





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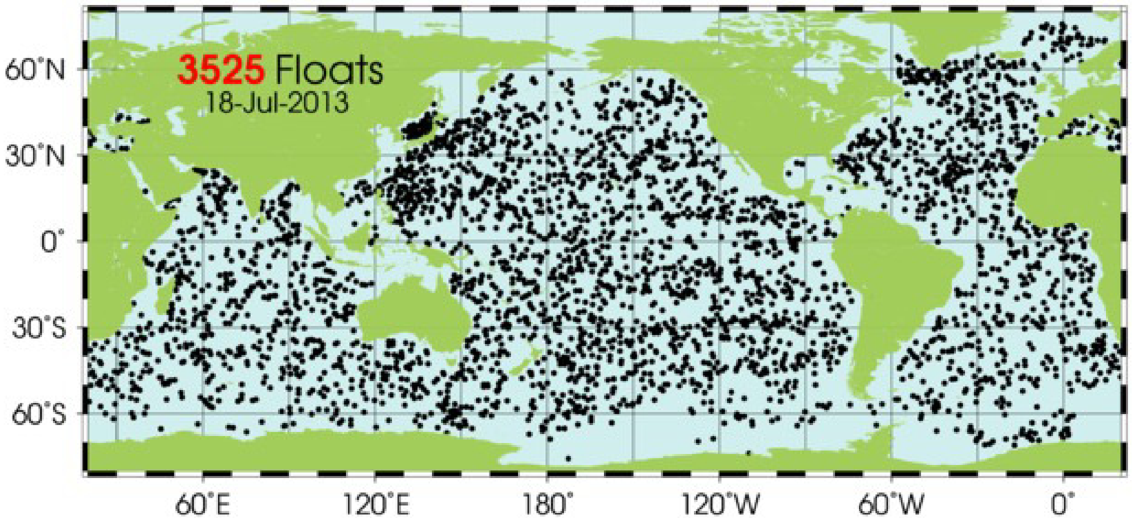
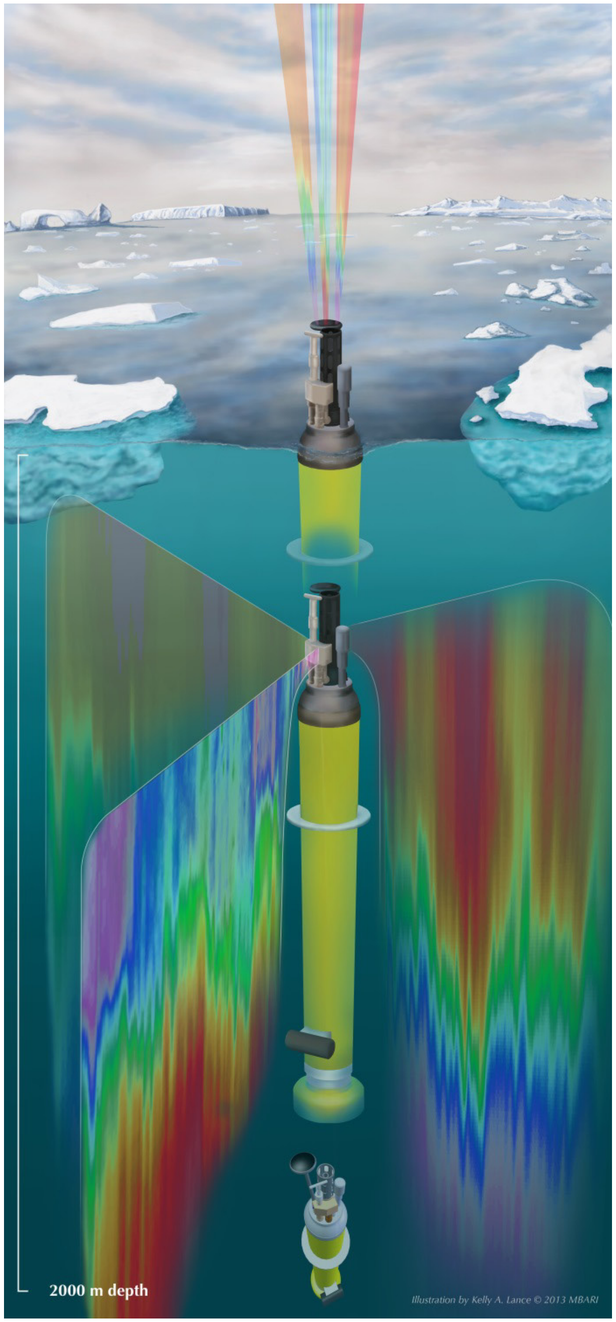
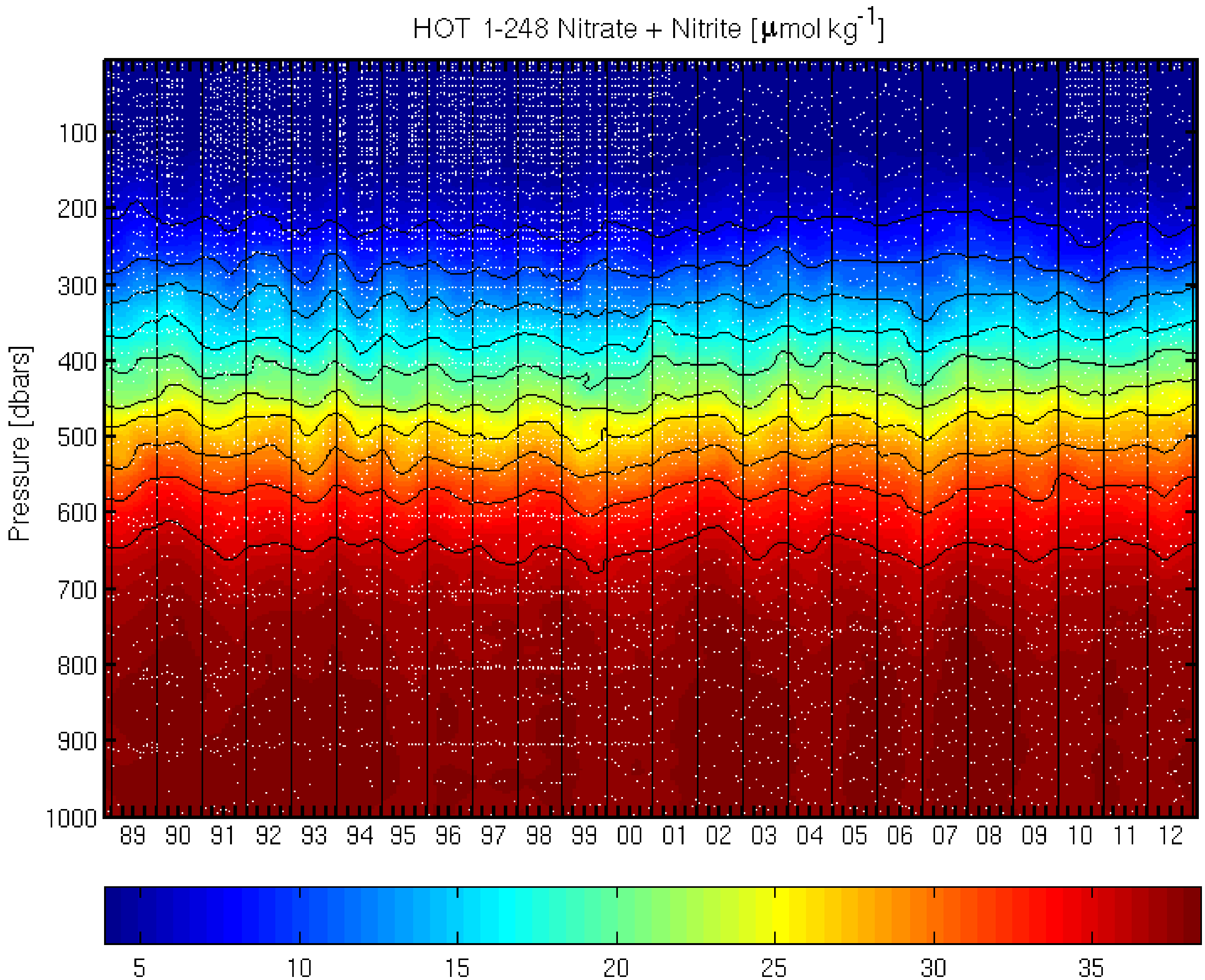
1. We need global scale, quantitative, autonomous observing systems for carbon.
2. We need to know time varying carbon flux at Time Series sites to ensure calibration of a global system carbon observing system.






HOT 1-248 Nitrate + Nitrite [μmol kg-1]
Pressure [dbars]
100
200
300
400
500
600
700
800
900
1000
89 90 91 92 93 94 95 96 97 98 99 00 01 02 03 04 05 06 07 08 09 10 11 12
5 10 15 20 25 30 35

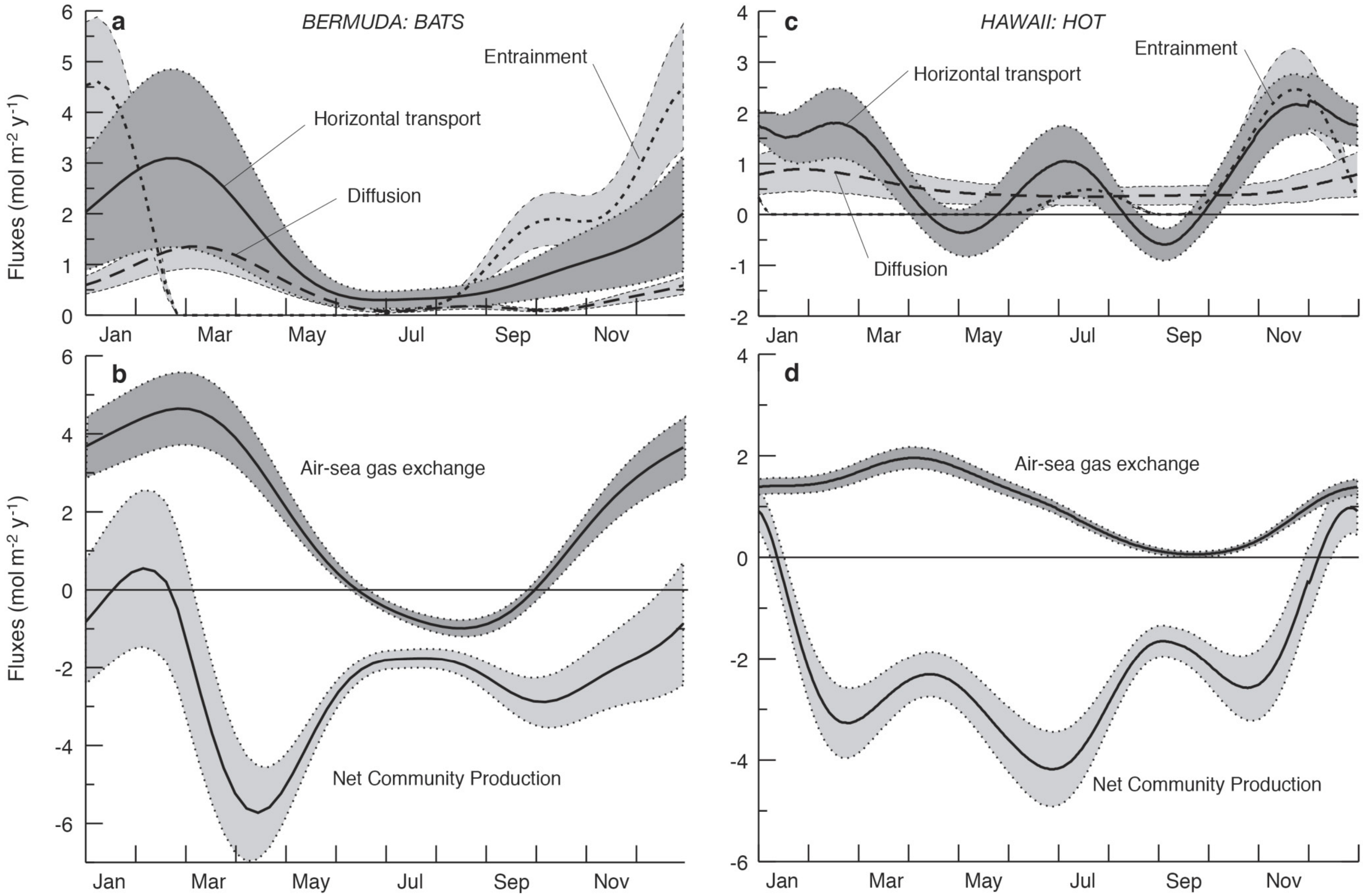
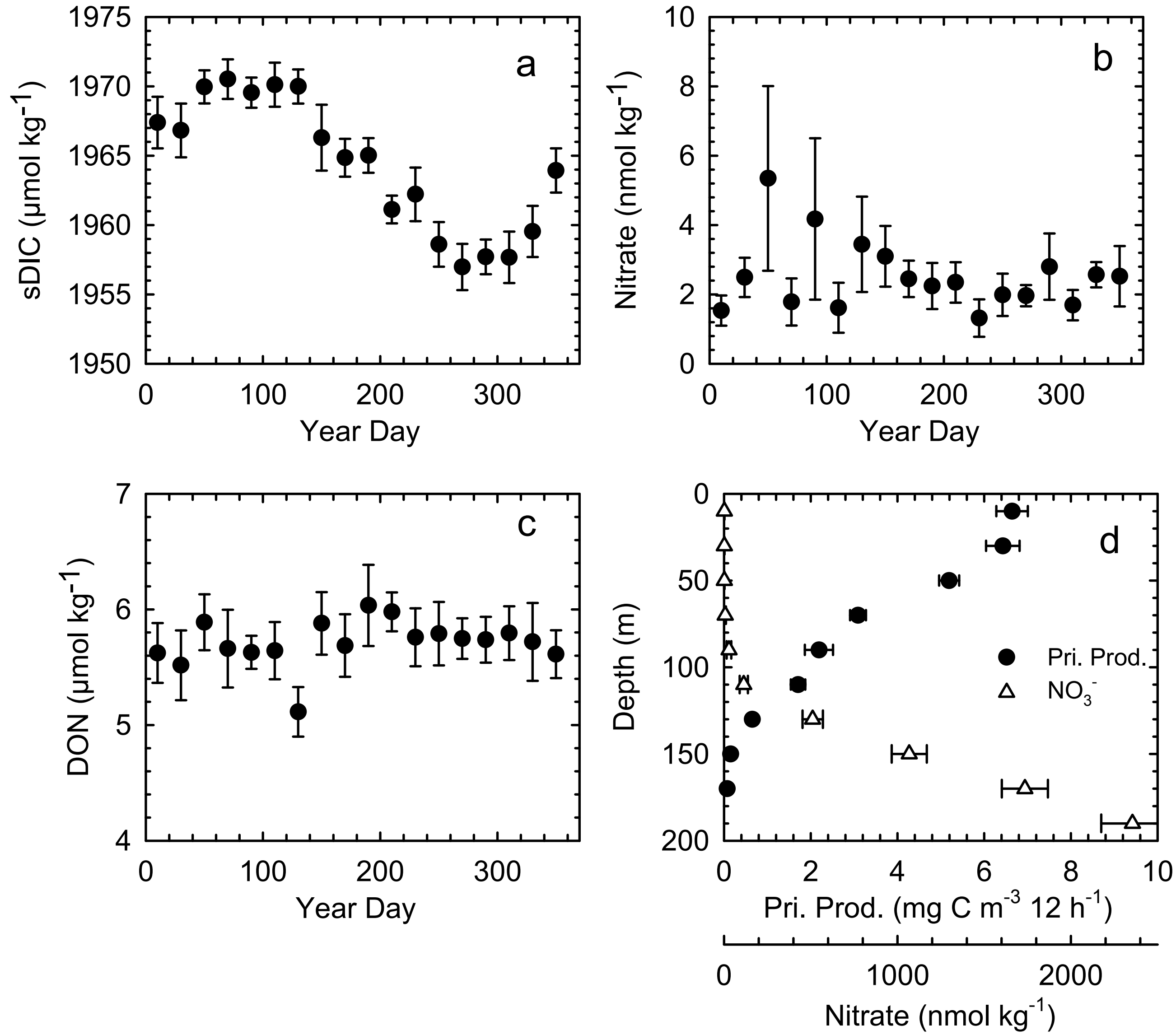


Fig. 8.3.11 Sarmiento & Gruber

The real question is, how do phytoplankton manage positive net growth with no apparent N in the system. Redfield requires C/N of 106/16 =6.6



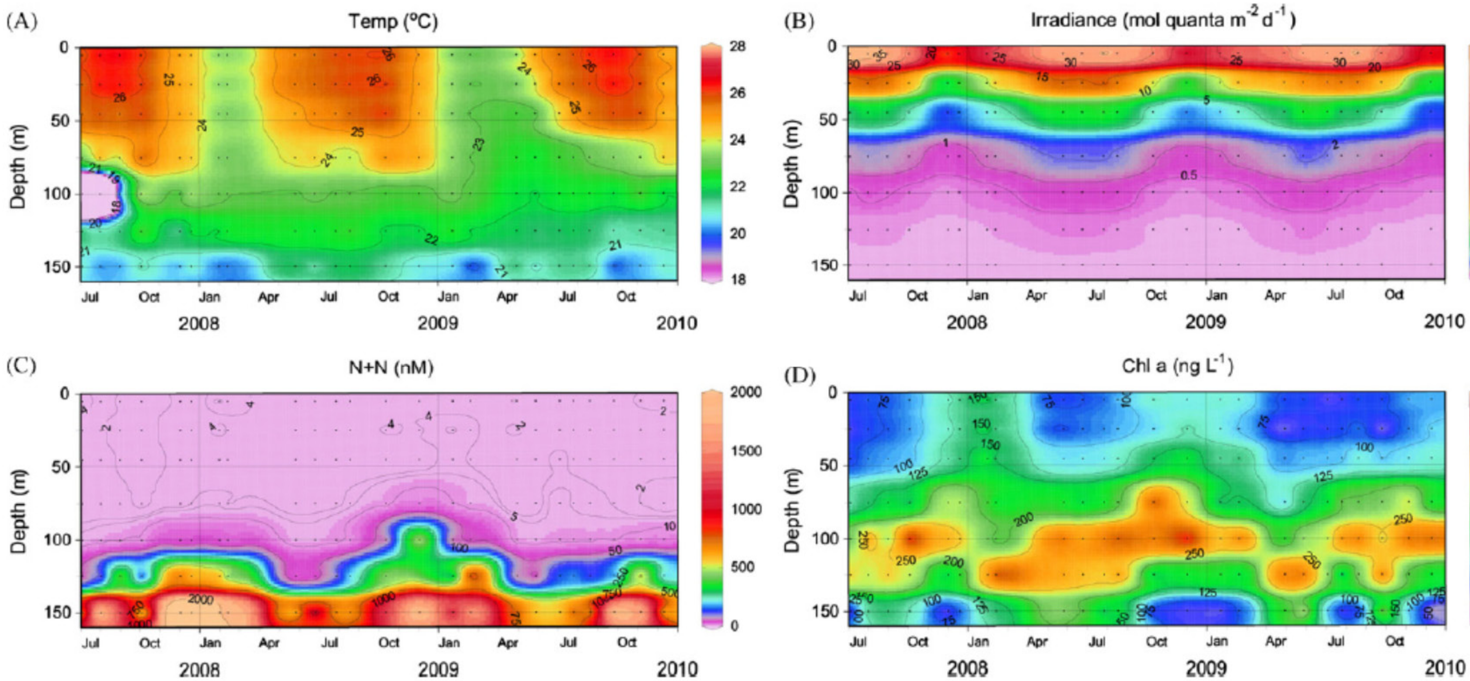


Fig. 2. Contour plots of temperature (A), photosynthetically active radiation (PAR) (B), nitrate+nitrite (N+N) concentrations (C), and Chl *a* (D) in the upper 150 m at Station ALOHA during this study (October 2007–December 2009).

Variability of chromophytic phytoplankton in the North Pacific Subtropical Gyre

Binglin Li [a], David M. Karl [a], Ricardo M. Letelier [b], Robert R. Bidigare [c], Matthew J. Church [a,*]

HOT – nutrient supply Church

BATS – C drawdown mechamisms – Lomas

Bats – DOC/link to microbiology…..

The objectives of HOT specific to the JGOFS program are to:

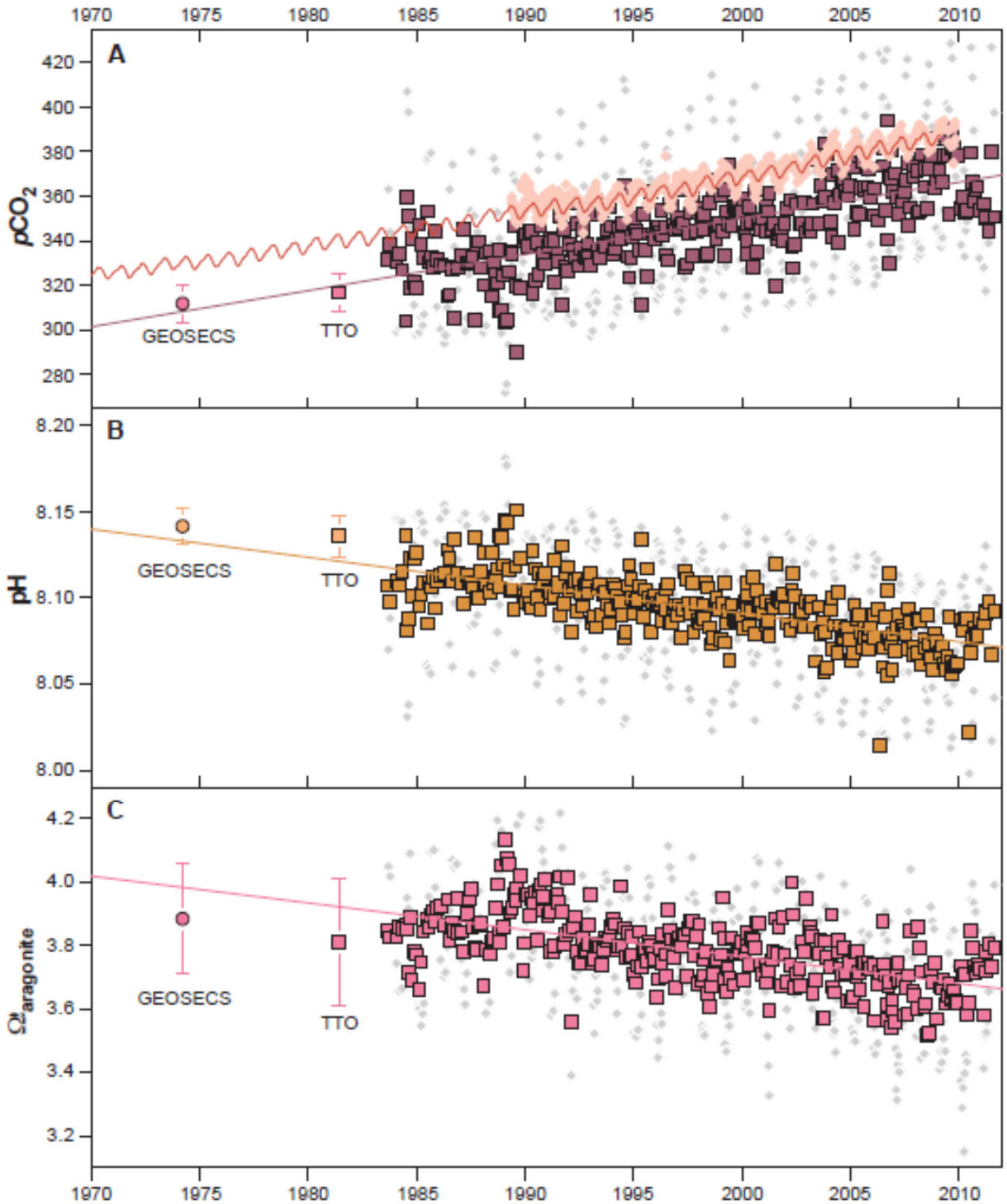
— document and understand seasonal and interannual variability in the rates of primary production, new production and particle export from the surface ocean;
— determine the mechanisms and rates of nutrient input and recycling, especially for N and P in the upper 200 m of the water column;
— measure the time-varying concentrations of carbon dioxide in the upper water column and estimate the annual air-to-sea gas flux.

Lomas et al (2013)

- Document the seasonal, interannual and decadal scale variability in carbon and macronutrient cycle parameters and processes.

- Including,for example, an understanding of the controls on the coupling/decoupling (relative to the Redfield ratio) of elemental cycles.

- Document variability in planktonic community structure and function, and its impact on the ocean's carbon cycle (including new and export production) and coupling with other macronutrient cycles.



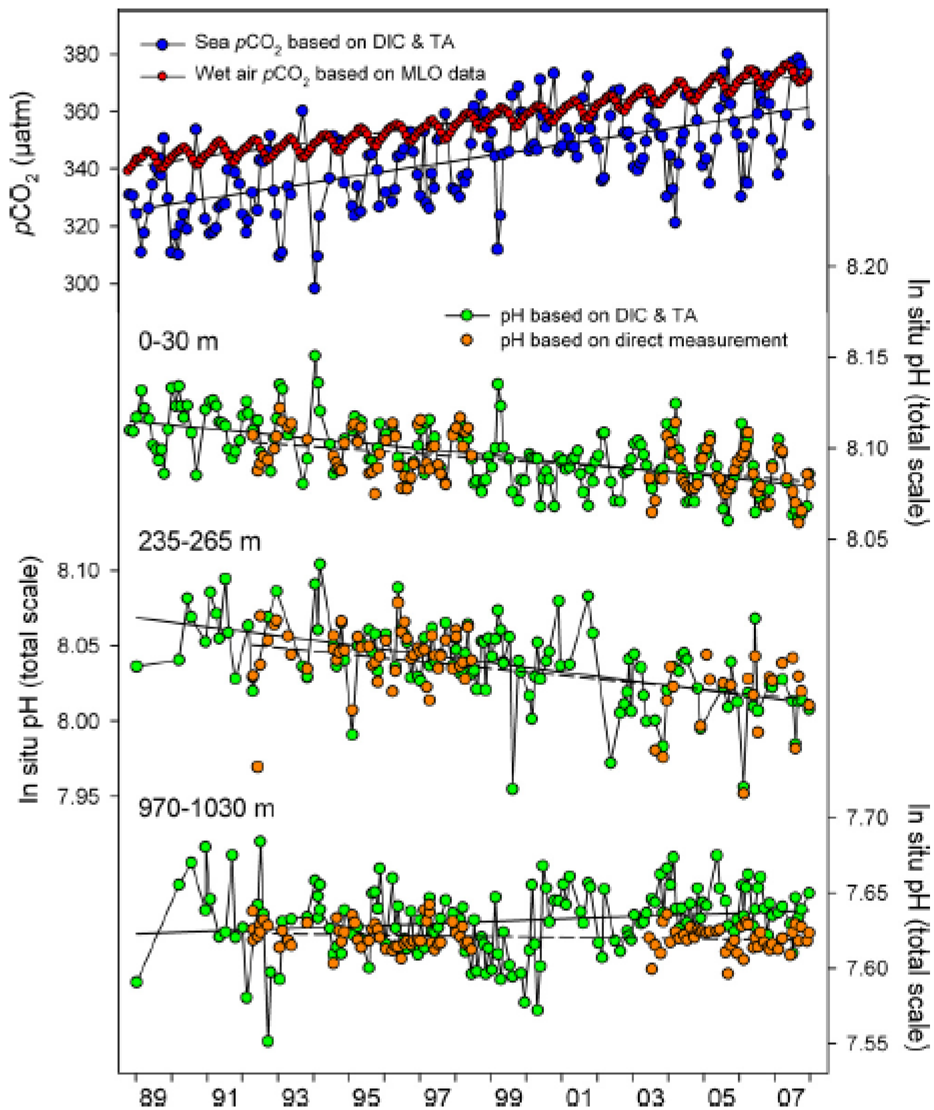
A
B
C
pCO2
pH
Ωaragonite
GEOSECS
TTO
1970
1975
1980
1985
1990
1995
2000
2005
2010
420
400
380
360
340
320
300
280
8.20
8.15
8.10
8.05
8.00
4.2
4.0
3.8
3.6
3.4
3.2

Physical and biogeochemical modulation of ocean acidification in the central North Pacific

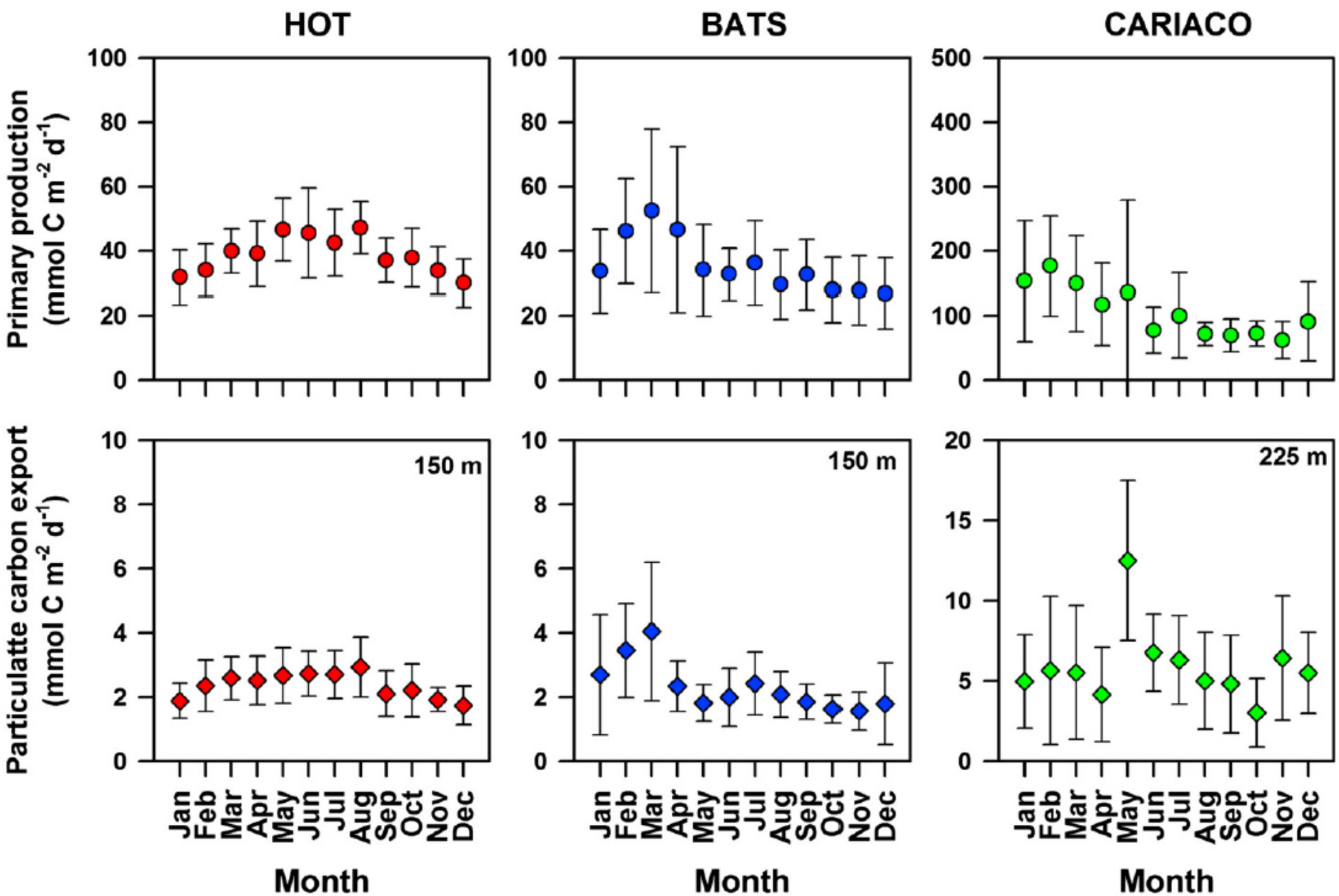
John E. Dore[a,1], Roger Lukas[b], Daniel W. Sadler[b], Matthew J. Church[b], and David M. Karl[b,1]

Acidification signal = -0.0017 pH/year

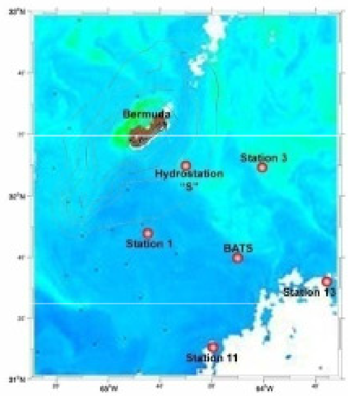
Production/Respiration signal = 0.03 pH/year

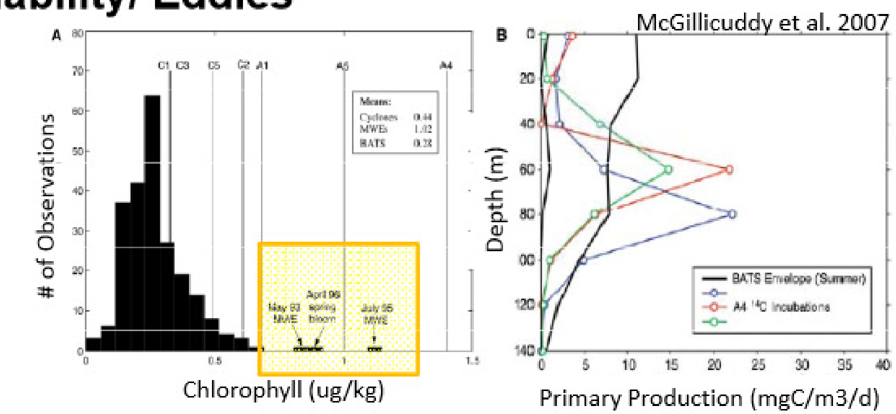


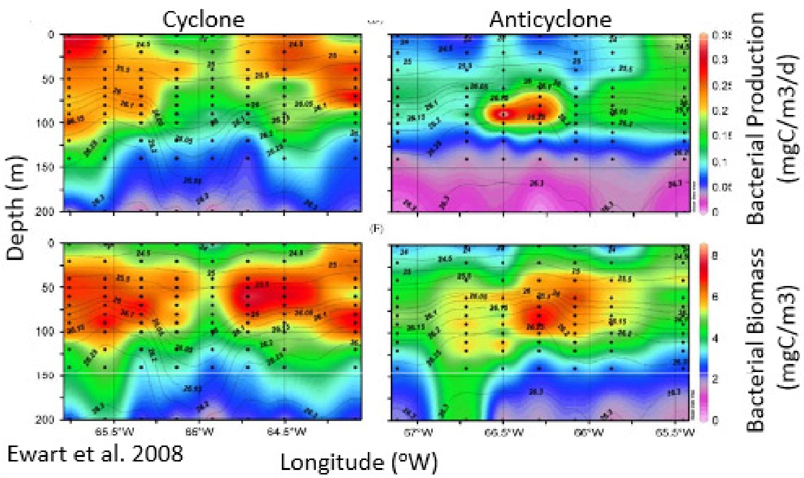
PNAS | July 28, 2009 | vol. 106 | no. 30 | 12235–12240

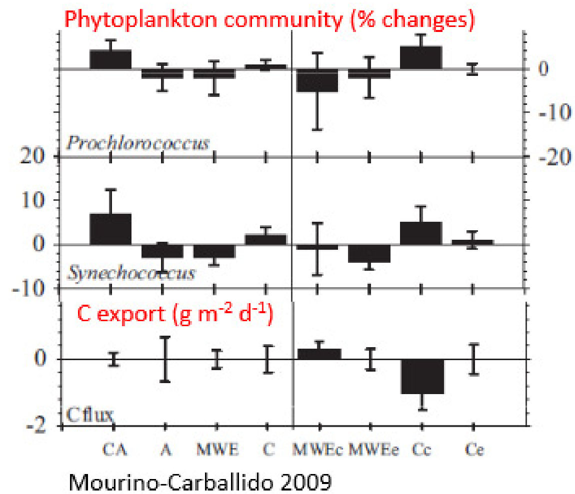

HOT
BATS
CARIACO
Primary production
(mmol C m-2 d-1)
Particulatte carbon export
(mmol C m-2 d-1)
150 m
150 m
225 m
0
20
40
60
80
100
0
100
200
300
400
500
0
2
4
6
8
10
0
5
10
15
20
Jan
Feb
Mar
Apr
May
Jun
Jul
Aug
Sep
Oct
Nov
Dec
Month

BATS/ Mesoscale variability/ Eddies



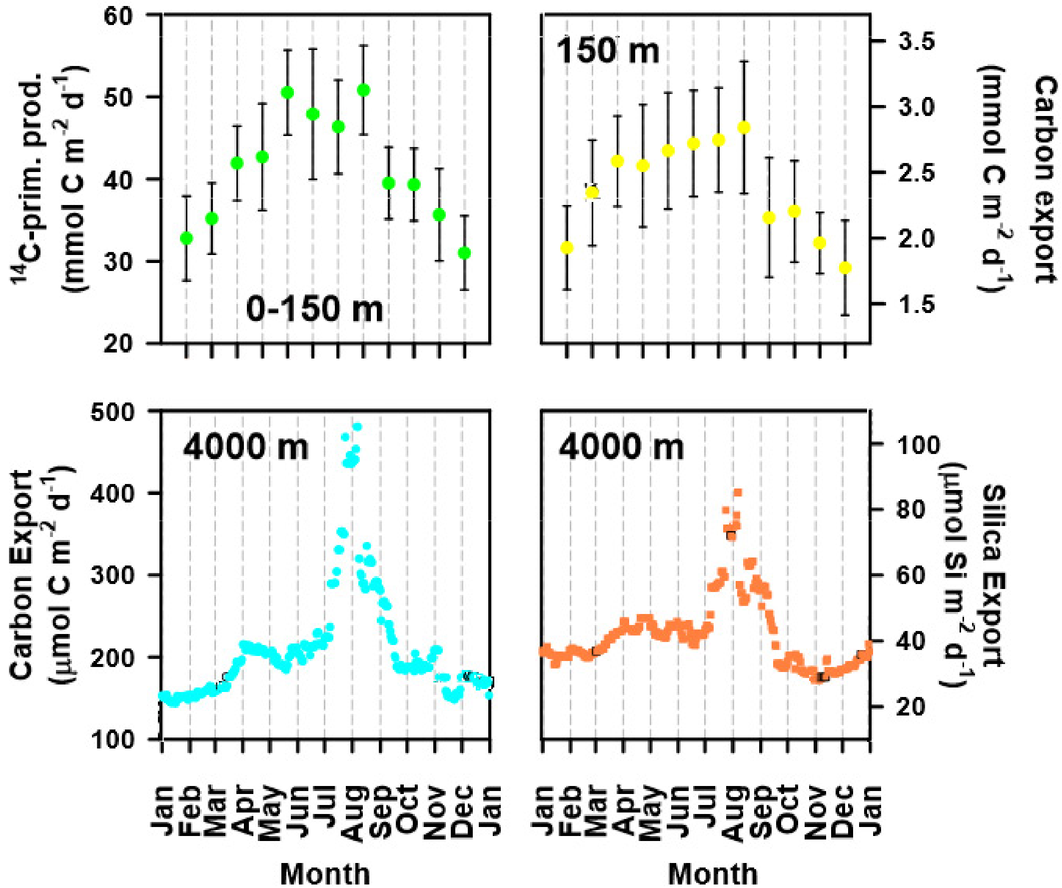




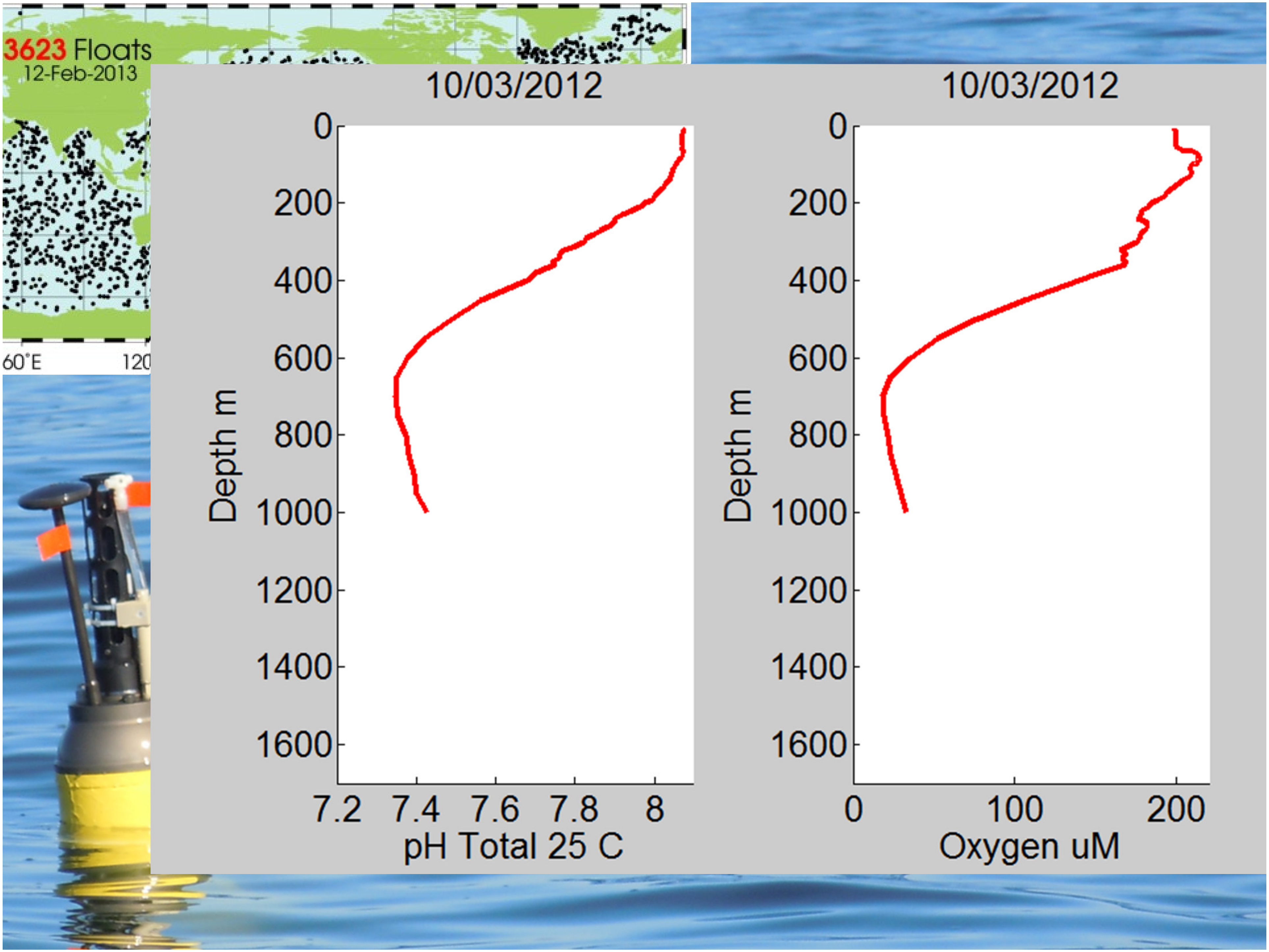


On an annual scale, eddies appear to ‘average out’ their impact on biogeochemistry.

Annual cycle of productivity and export



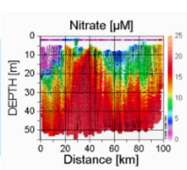
Plankton community structure plays a key role in carbon flux to the deep sea


3623 Floats
12-Feb-2013
60°E
120
10/03/2012
0
200
400
600
800
1000
1200
1400
1600
Depth m
7.2
7.4
7.6
7.8
8
pH Total 25 C
10/03/2012
0
200
400
600
800
1000
1200
1400
1600
Depth m
0
100
200
Oxygen uM

OCB time series success is a reflection of open data access policy

Time Series	Publ. Interval	Number
HOT	1990-2012	549
BATS	1988-2012	480
CARIACO	1996-2012	89*
Total		1118

*Publications by CARIACO PI's only.



Matt Church, OCB Time Series Workshop

Net Community Production at Station ALOHA

Method	Rate mol C m^{-2} yr^{-1}	Period of measurements	References
Mixed Layer O_2 + Ar budgets	1.4 - 3.7 (± 1.0)	1992–2008	Emerson et al. (1997); Hamme and Emerson (2006); Juanek and Quay (2005); Quay et al. (2010)
DIC + $DI^{13}C$ budgets	2.7 - 2.8 (± 1.4)	1988–2002	Quay and Stutsman (2003); Keeling et al. (2004)
Mooring O_2	4.1 (± 1.8)	2005	Emerson et al. (2008)
Sub-mixed layer float profiles	1.1 - 1.7 (±0.2)	2003-2010	Riser and Johnson (2008)
Sub-mixed layer glider surveys	0.9 (± 0.1)	2005	Nicholson et al. (2008)
Sediment traps	0.9 (± 0.3)	1989–2009	HOT core data
In vitro O_2 incubations	-6.1 (± 4.6)	2001, 2005-2007	Williams et al. (2004)

NCP appears constrained to ~2-fold variability
GPP estimated ~20-fold greater than NCP