25 years of Hawaii Ocean Time-series carbon flux determinations: Insights into productivity, export, and nutrient supply in the oligotrophic ocean

MATTHEW CHURCH, ROBERT BIDIGARE, JOHN DORE, DAVID KARL,
MICHAEL LANDRY, RICARDO LETELIER, ROGER LUKAS

OCEAN CARBON BIOGEOCHEMISTRY SUMMER WORKSHOP

JULY 2013

HAWAII OCEAN TIME-SERIES
SCHOOL OF OCEAN AND EARTH SCIENCE AND TECHNOLOGY

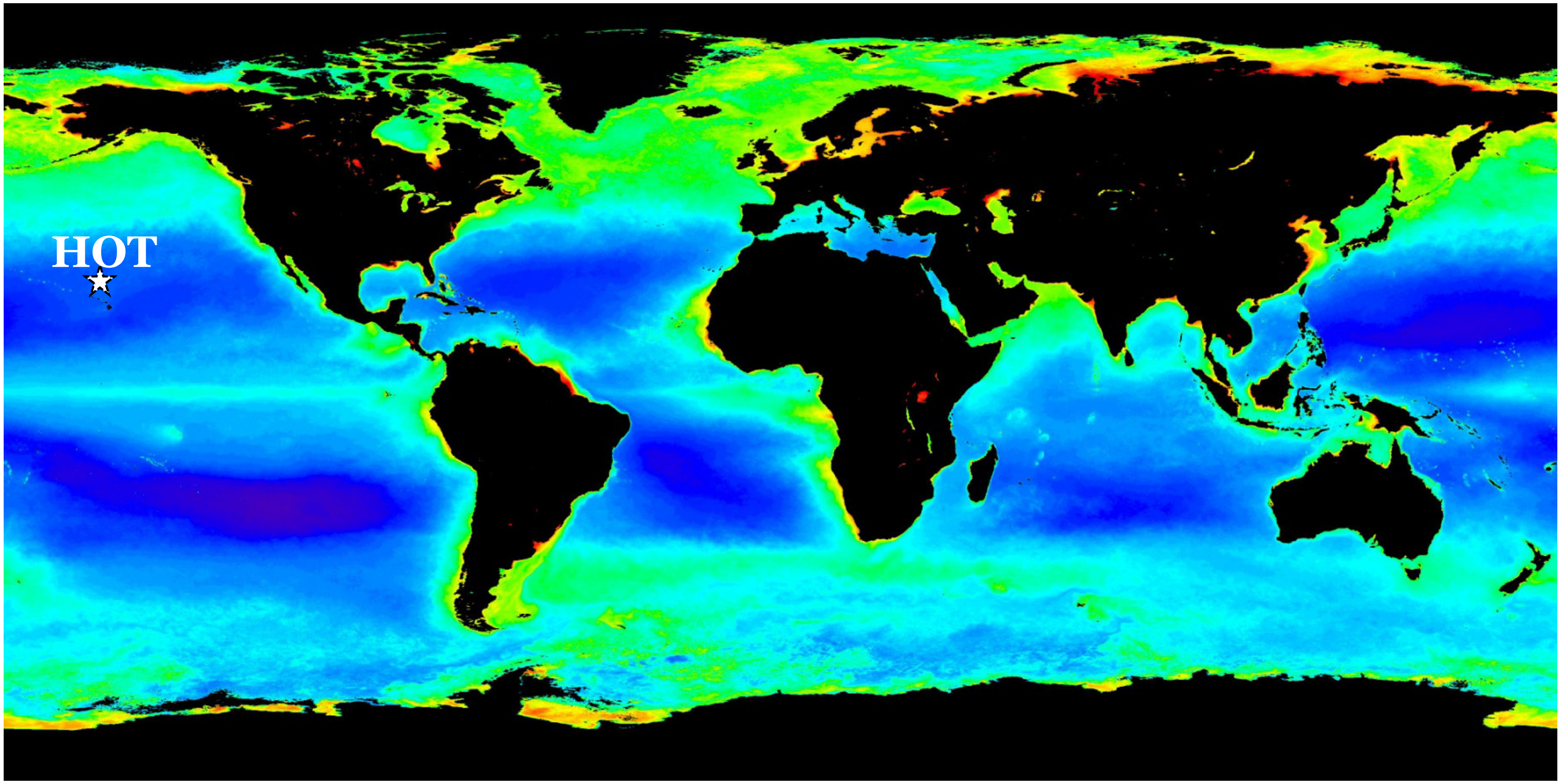
H.O.T.
UNIVERSITY OF HAWAII

Thank you

- Craig Carlson (UCSB) and Ricardo Letelier (OSU)
- Ken Johnson (MBARI)
- Heather Benway (WHOI)
- Mary Z. (WHOI)
- The National Science Foundation

NSF

A Dedicated HOT Team



- Subtropical gyres comprise some the largest habitats on this planet

- Constraining carbon production and sequestration in these regions is critical to global carbon budgets

- Time series programs afford unique opportunities to define the magnitude and pathways of carbon fluxes in the open sea

Time, water, and change

- **The complexity of ecosystem dynamics, even in "stable" systems, demands multi-disciplinary, sustained observations.**

- **Implementation and leveraging of remote and autonomous sampling platforms at ocean time series sites is providing new insights into bioelemental cycling in these ecosystems.**

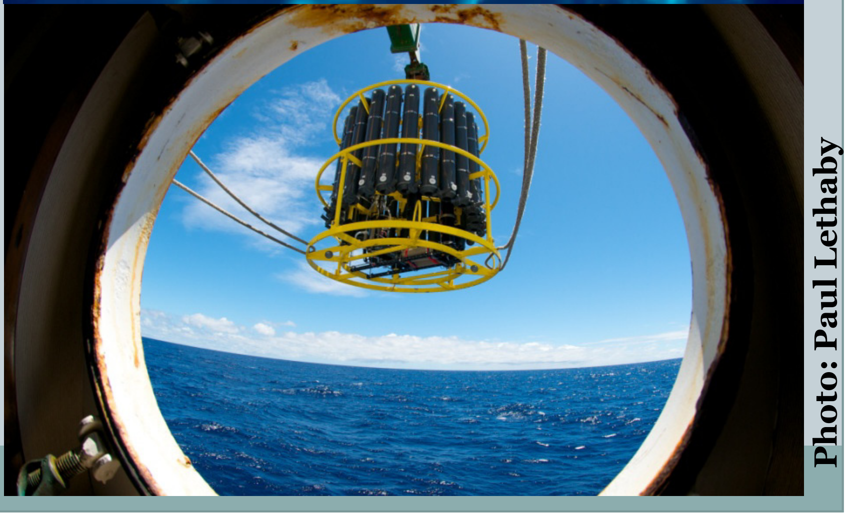
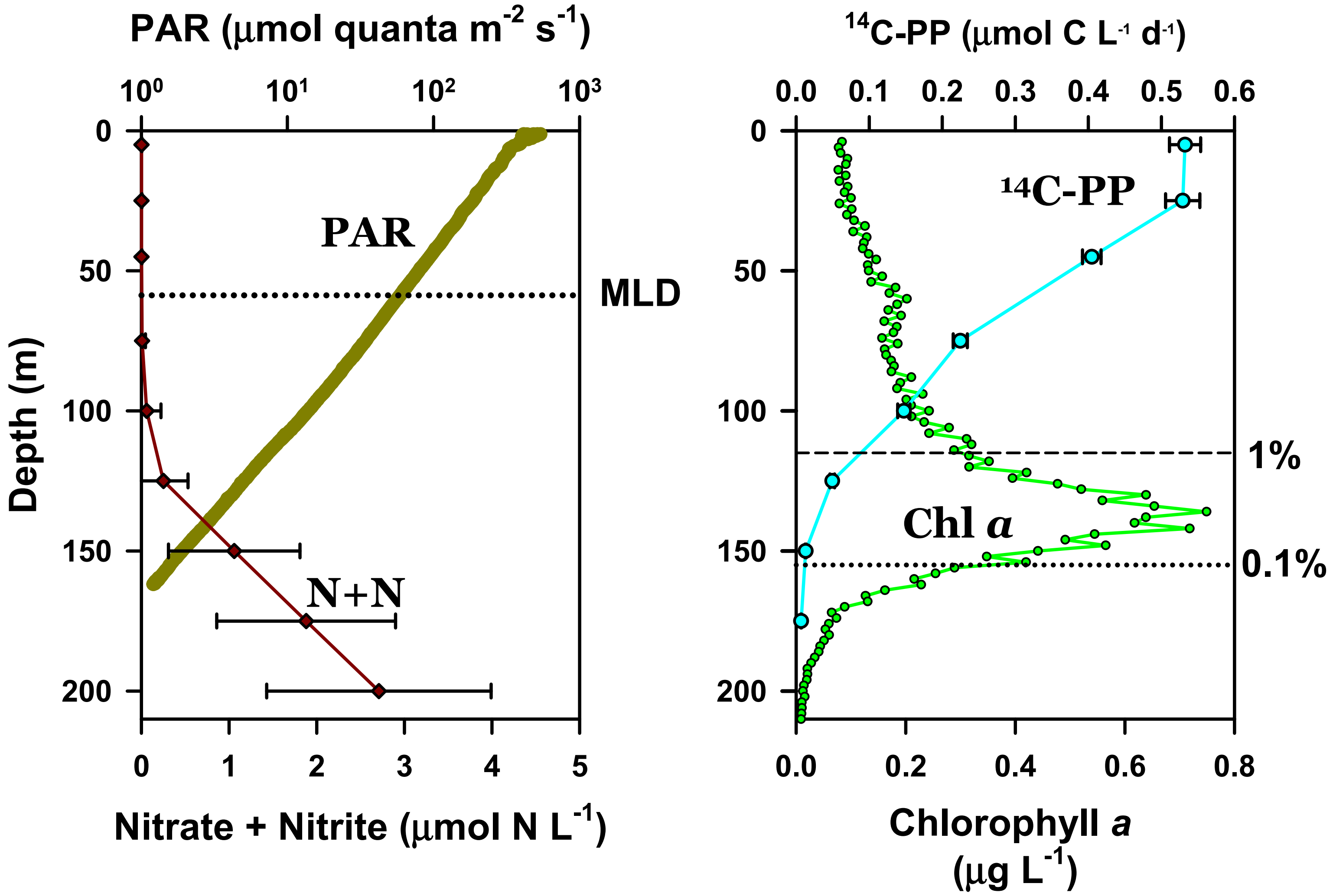


Photo: Paul Lethaby

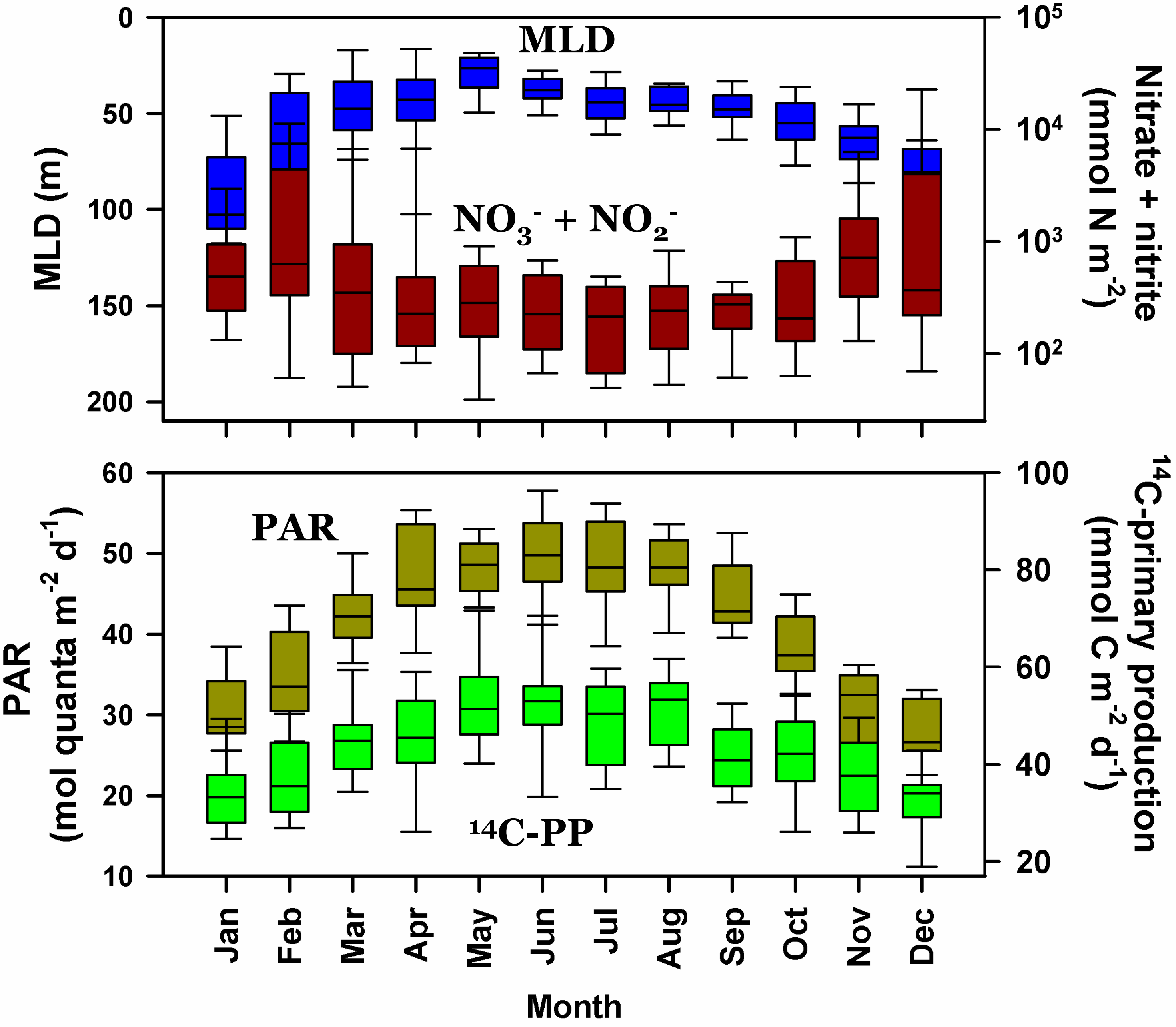
The Hawaii Ocean Time-series (HOT)

- Near monthly cruises to Station ALOHA since October 1988
- ALOHA is a deep, open ocean (~4800 m) site
- Shipboard and remote (moorings, gliders, floats, and satellites) measurements of ocean biogeochemistry, physics, and plankton ecology
- 4-day cruises, intensive sampling to 1000 m

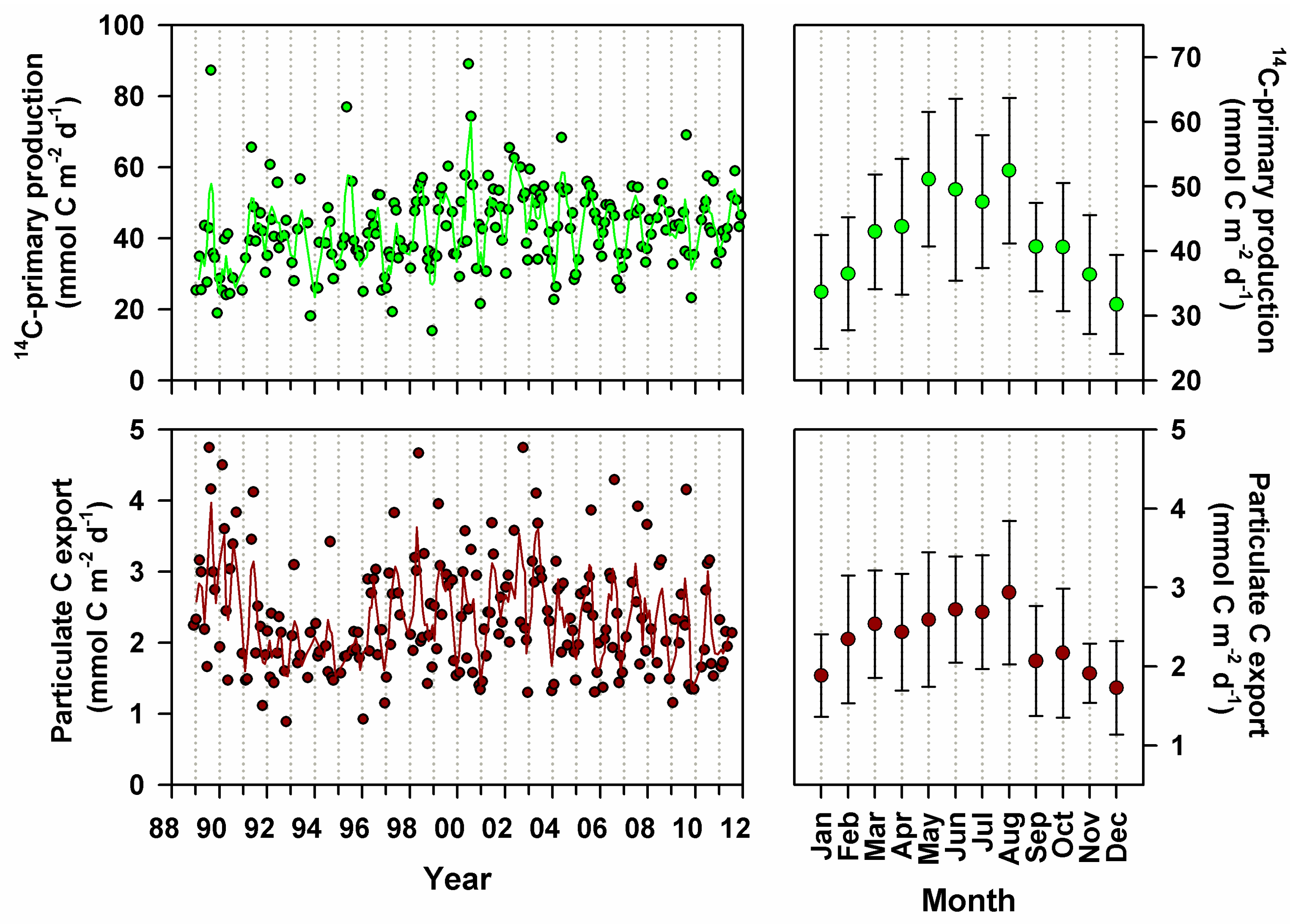
The upper ocean habitat



- Mixed layer ~30-100 m, euphotic zone ~100-125 m
- >65% of the daily carbon fixation occurs in the nutrient-deplete mixed layer


MLD
NO$_3^-$ + NO$_2^-$
MLD (m)
0
50
100
150
200
Nitrate + nitrite (mmol N m^{-2})
10^5
10^4
10^3
10^2
PAR
^{14}C-PP
PAR (mol quanta m^{-2} d^{-1})
60
50
40
30
20
10
^{14}C-primary production (mmol C m^{-2} d^{-1})
100
80
60
40
20
Jan
Feb
Mar
Apr
May
Jun
Jul
Aug
Sep
Oct
Nov
Dec
Month

Carbon fixation and particulate carbon export

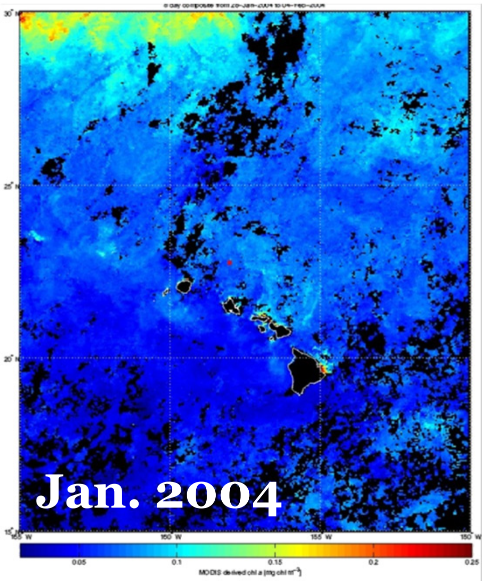


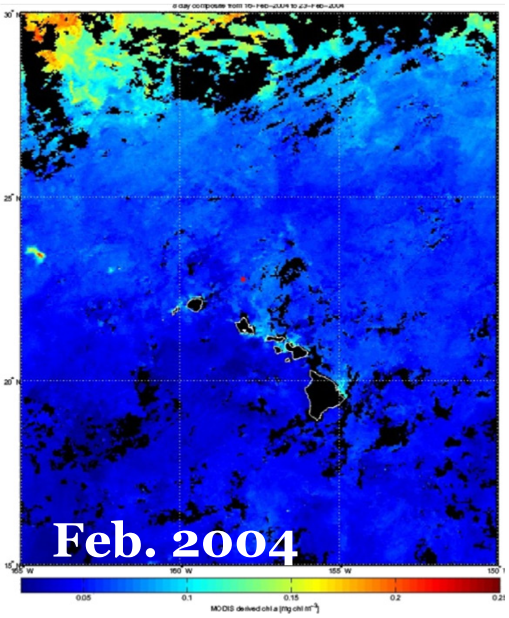
Annually averaged ^{14}C-PP: ~15 mol C m^{-2} yr^{-1}

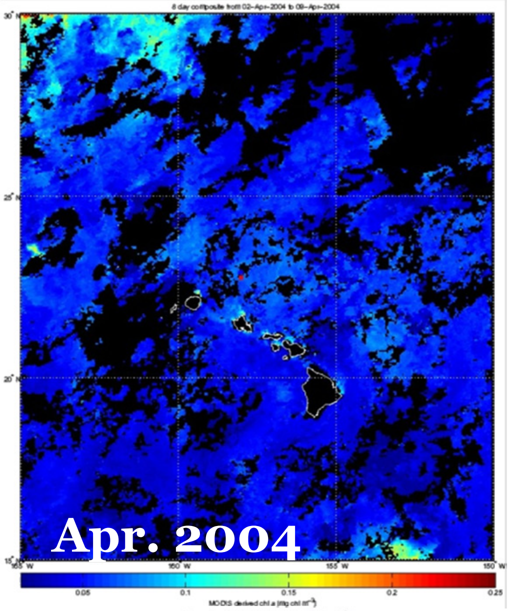
Annually averaged PC$_{150m}$ export: ~0.9 mol C m^{-2} yr^{-1}

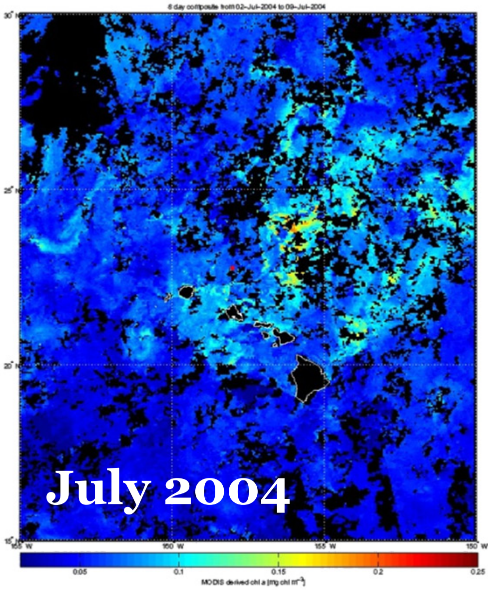
PC$_{150\ m}$: ^{14}C-PP = 0.04-0.12

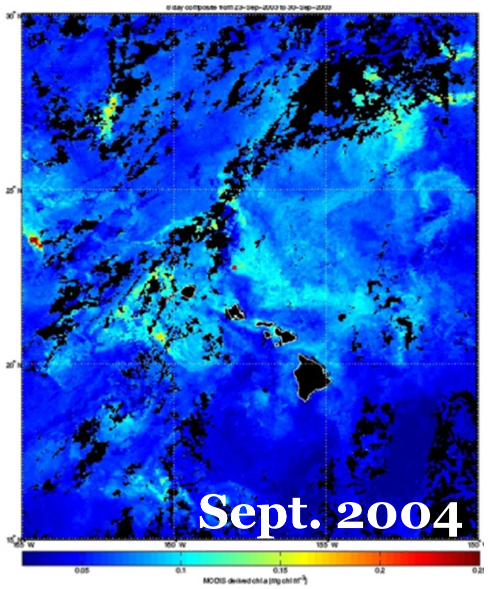
The many faces of Station ALOHA

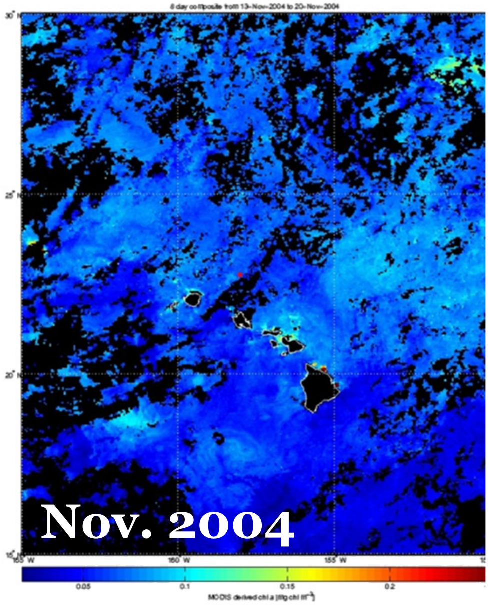

Jan. 2004


Feb. 2004


Apr. 2004

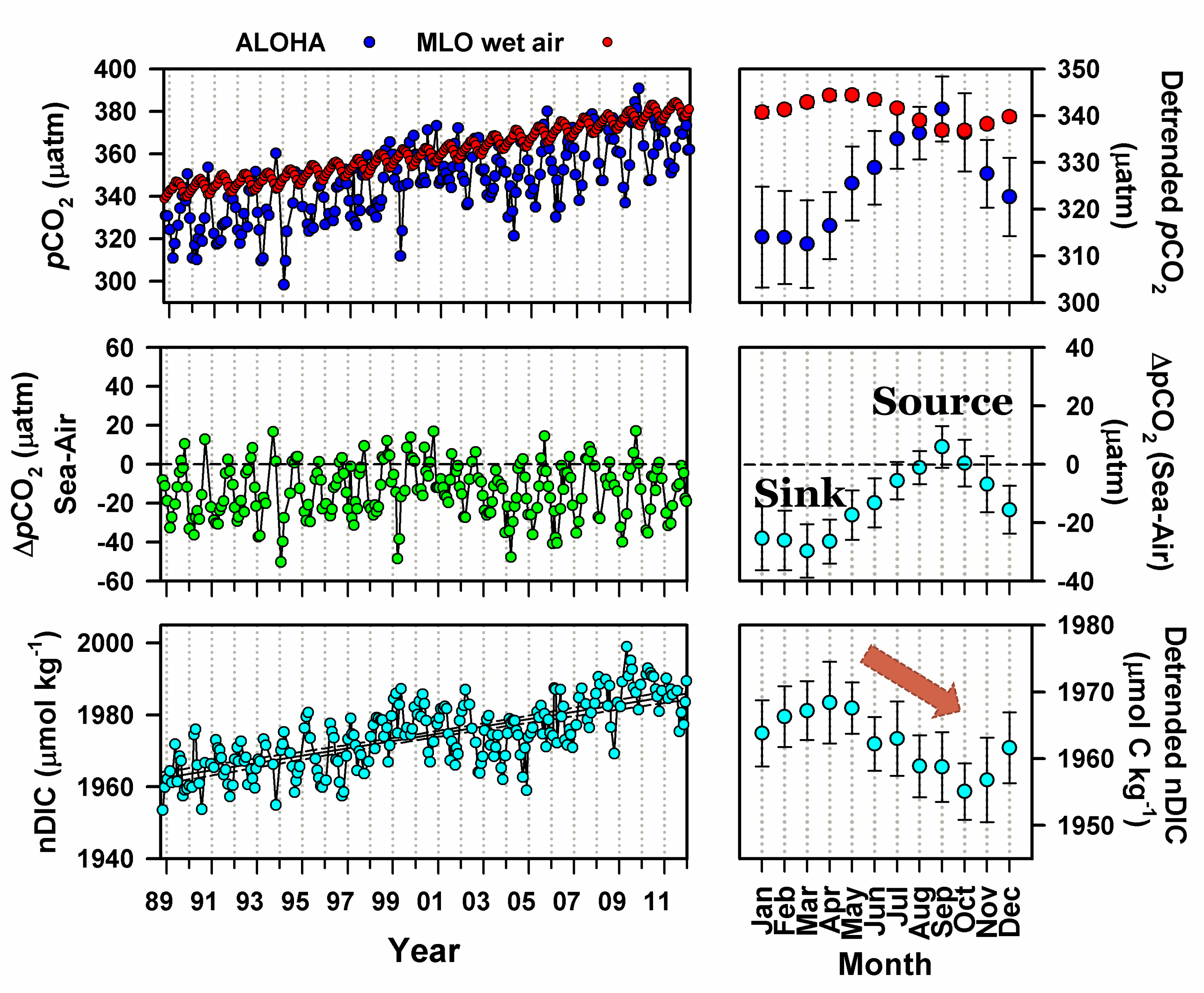

July 2004


Sept. 2004


Nov. 2004

Ricardo Letelier and Angel White (OSU)

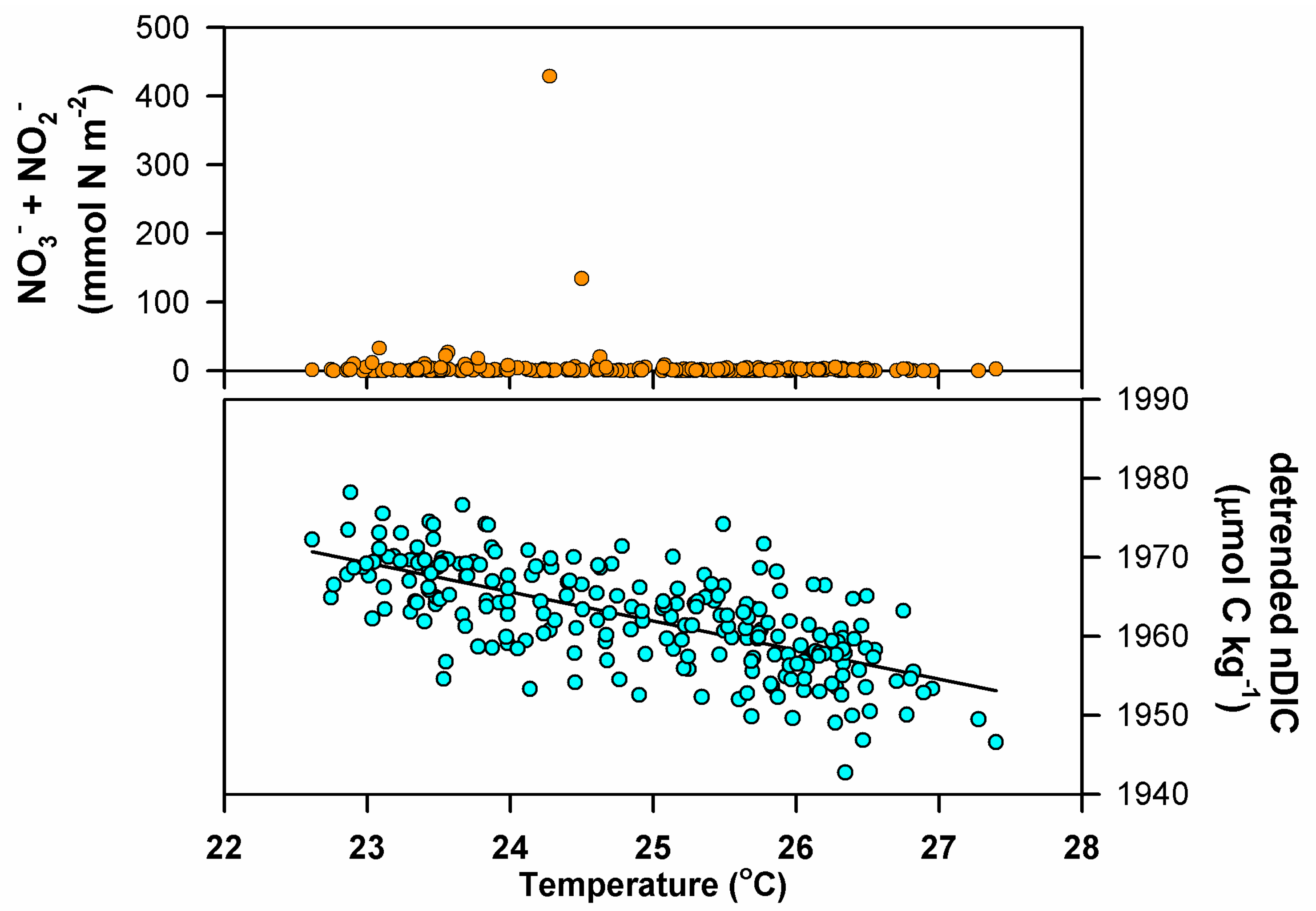
Variability in mixed layer inorganic carbon



- **Seasonal variations in *p*CO_2 largely a function of temperature.**
- **Most of the year mixed layer CO_2 is undersaturated (~13 µatm), becoming a weak source of CO_2 in the late summer.**
- **Salinity normalized DIC decreases from winter-spring into summer-fall.**

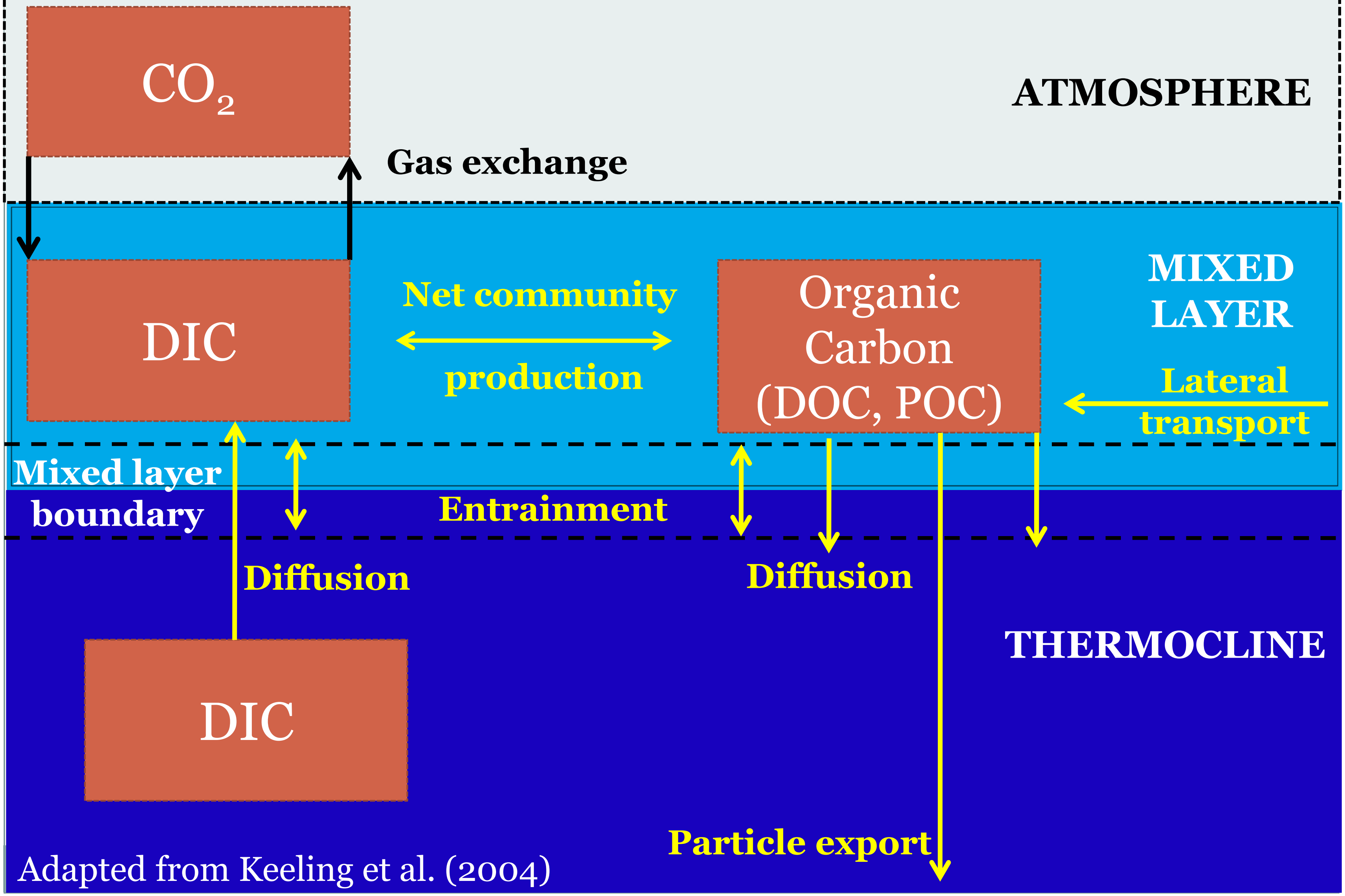
What processes control the summertime drawdown of DIC at Station ALOHA?

Spring-fall drawdown of DIC in the absence of nitrate is a common feature of the subtropical gyres



(Michaels et al. 1994, Bates et al. 1996, 1998, Gruber et al. 1998, Lee et al. 2000, Karl et al. 2003, etc.)

Biological and physical processes controlling variability in carbon inventories and fluxes



CO_2

ATMOSPHERE

Gas exchange

DIC

Net community production

Organic Carbon (DOC, POC)

MIXED LAYER

Lateral transport

Mixed layer boundary

Entrainment

Diffusion

Diffusion

THERMOCLINE

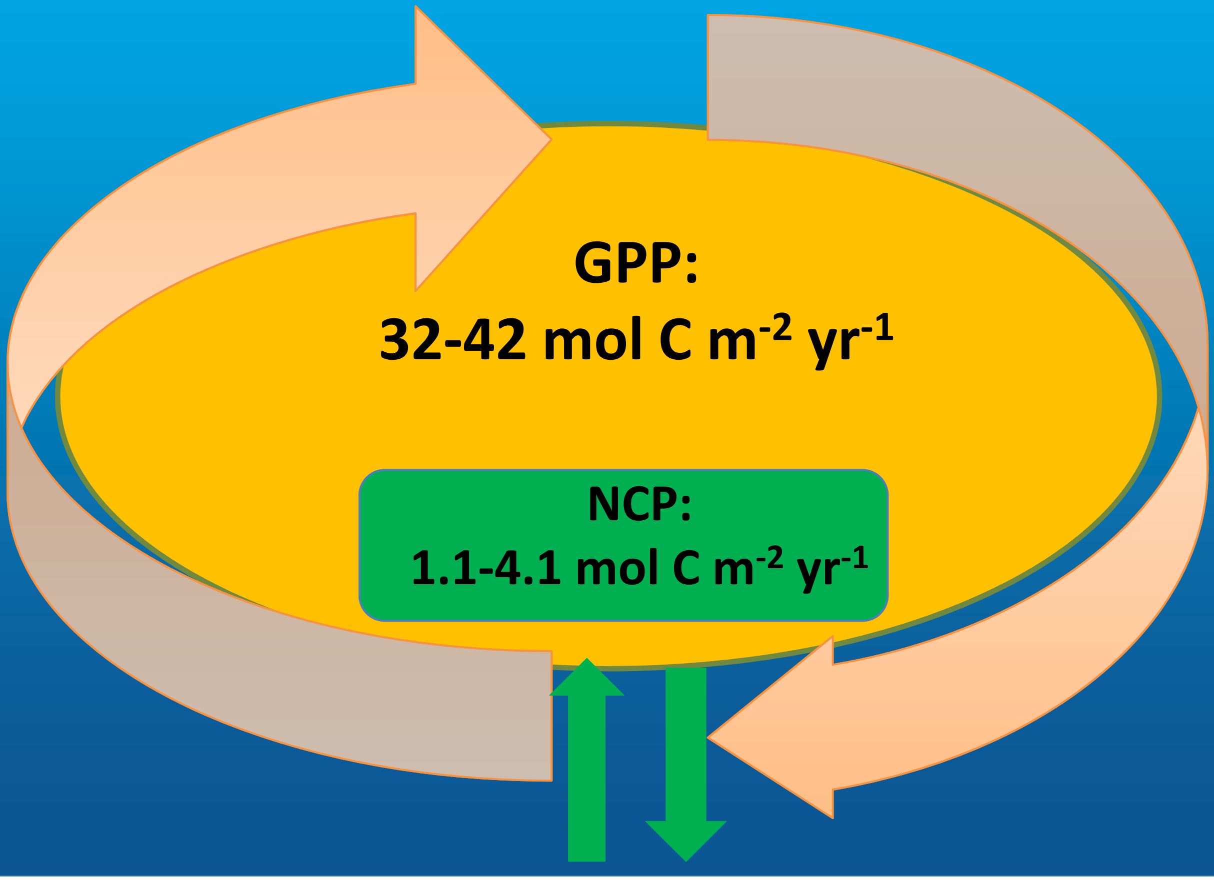
DIC

Particle export

Adapted from Keeling et al. (2004)

Quantifying net community production in the open sea is difficult

1. Small net changes superimposed on large background pools and fluxes
2. Need to accurately quantify impacts of biology (production and respiration) and physics (vertical and lateral transport, air-sea exchange)
3. Ecology matters – nutrient fluxes and growth efficiencies



GPP:

32-42 mol C m^{-2} yr^{-1}

NCP:

1.1-4.1 mol C m^{-2} yr^{-1}

GPP - R = NCP

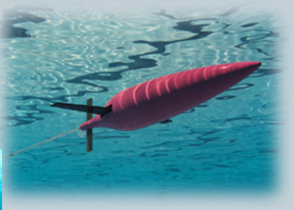
Station ALOHA

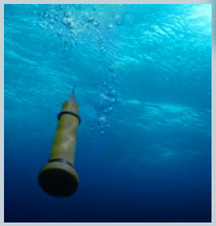
NCP : GPP =

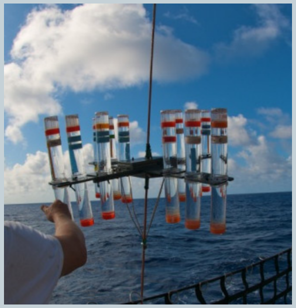
0.03-0.13

Measurements of net community production at Station ALOHA

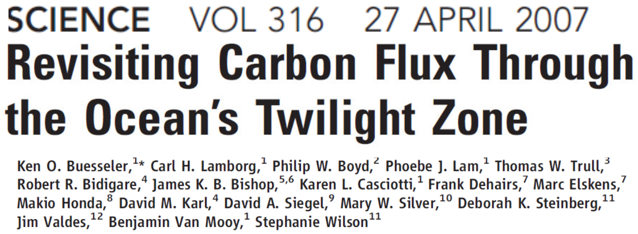
- Mixed layer DIC and $^{13}C/^{12}C$
- Seasonal evolution of dissolved oxygen, O_2:inert gas ratios, and oxygen isotopes
- Nitrogen-based determinations of new production; over annual scales ≈ NCP
- Vertical transport of organic matter export (POC, DOC, and migrant flux)





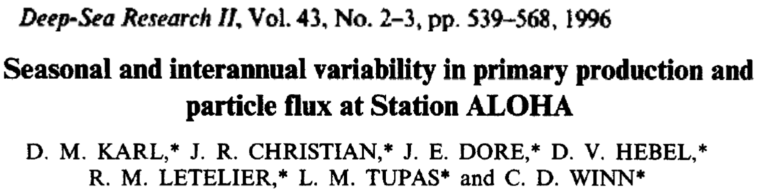


Estimates of NCP at ALOHA abound…


SCIENCE VOL 316 27 APRIL 2007

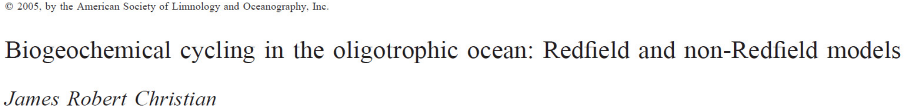
Revisiting Carbon Flux Through the Ocean's Twilight Zone

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]


Deep-Sea Research II, Vol. 43, No. 2–3, pp. 539–568, 1996

Seasonal and interannual variability in primary production and particle flux at Station ALOHA

D. M. KARL,* J. R. CHRISTIAN,* J. E. DORE,* D. V. HEBEL,* R. M. LETELIER,* L. M. TUPAS* and C. D. WINN*


Limnol. Oceanogr., 50(2), 2005, 646–657
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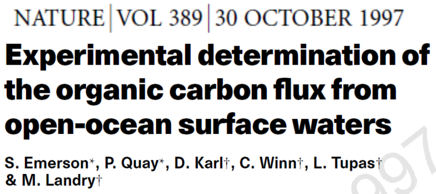
Biogeochemical cycling in the oligotrophic ocean: Redfield and non-Redfield models

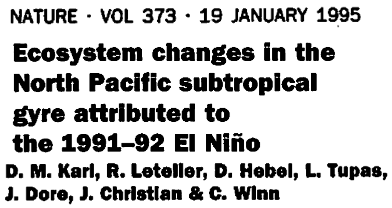
James Robert Christian


NATURE | VOL 389 | 30 OCTOBER 1997

Experimental determination of the organic carbon flux from open-ocean surface waters

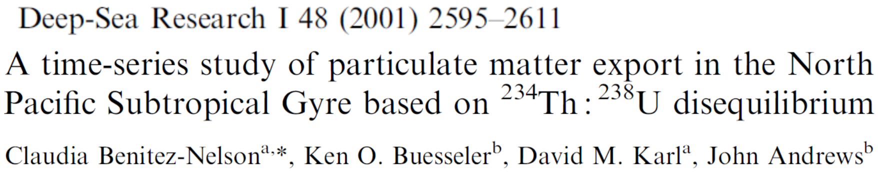
S. Emerson*, P. Quay*, D. Karl†, C. Winn†, L. Tupas† & M. Landry†

…nutrient mass balances and carbon export


NATURE · VOL 373 · 19 JANUARY 1995

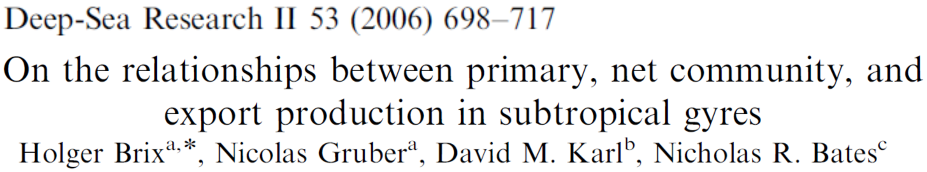
Ecosystem changes in the North Pacific subtropical gyre attributed to the 1991–92 El Niño

D. M. Karl, R. Letelier, D. Hebel, L. Tupas, J. Dore, J. Christian & C. Winn


Deep-Sea Research I 48 (2001) 2595–2611

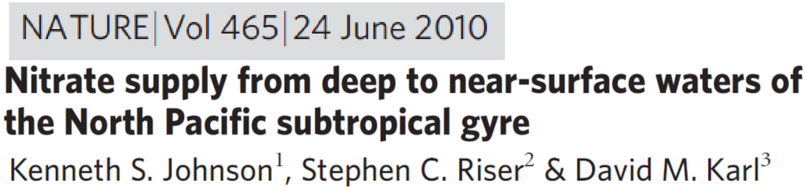
A time-series study of particulate matter export in the North Pacific Subtropical Gyre based on ^{234}Th : ^{238}U disequilibrium

Claudia Benitez-Nelson[a,*], Ken O. Buesseler[b], David M. Karl[a], John Andrews[b]


Deep-Sea Research II 53 (2006) 698–717

On the relationships between primary, net community, and export production in subtropical gyres

Holger Brix[a,*], Nicolas Gruber[a], David M. Karl[b], Nicholas R. Bates[c]


NATURE | Vol 465 | 24 June 2010

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]

Estimates of net community production at ALOHA

	Method of Determination	Rate (± stdev) mol C m^{-2} yr^{-1}	Period	References
O_2 based approaches	Mixed Layer O_2: Ar	**1.4 - 3.7 (± 1.0)**	1992–2008	Emerson et al. (1997); Hamme and Emerson (2006); Juranek and Quay (2005); Quay et al. (2010)
	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)
C-based approaches	Mixed layer $^{13}C/^{12}C$ and DIC dynamics	**1.6 ± 0.9**	1990-1995	Emerson et al. (1997)
		2.7 ± 1.4	1994-1999	Quay and Stutsman (2003)
		2.8 ± 0.8	1988-2002	Keeling et al. (2004)
Passive and active OM fluxes	Sediment traps (150 m)	**0.9 (± 0.3)**	1988-2012	HOT core data
	^{234}Th deficits	**1.5 (± 0.8)**	1999-2000	Benitez-Nelson et al. (2001)
	DOC export	**0.4**	2002-2012	HOT core data
	Zooplankton-mediated	**0.1 (± 0.09)**	1994-2005	Al-Mutairi and Landry (2001) Hannides et al. (2009)

NCP ranges 1.1-4.1 mol C m^{-2} yr^{-1}, averaging ~2 mol C m^{-2} yr^{-1}
Many of these estimates have uncertainties of ~30-60%

The devil is in the details…

- **Diagnostic models depend on accuracy of :**
  - **Air-sea flux (±30%) - limited by gas exchange parameterization**
  - **Lateral transport (±50-70%) – limited by horizontal velocities**
  - **Vertical entrainment/diffusion (±50%) - poor constraint on K_z**

- **Some estimates based on mixed layer dynamics (*i.e.* O_2: Ar or $^{13}C/^{12}C$) while others based on sub-mixed layer (seasonal evolution of O_2)**

- **O_2 based approaches require appropriate PQ and RQ**

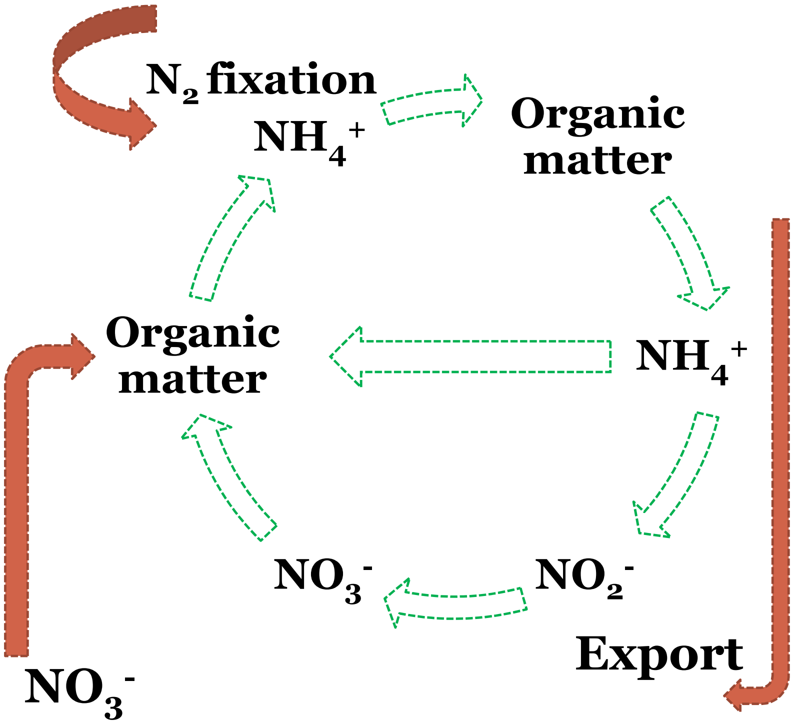
- **Sediment trap biases**

- **Particles and DOC**

- **Nutrient sources supporting NCP**

Where do nutrients come from to support NCP?

- ○ **Physical :**
  - ❖ **Mixing, upwelling, diffusion, advection, etc.**
  - ❖ **NO_3^- supported new production**
- ○ **Biological:**
  - ❖ **N_2 fixation ($N_2 \rightarrow NH_3$)**



N_2 fixation

NH_4^+

Organic matter

Organic matter

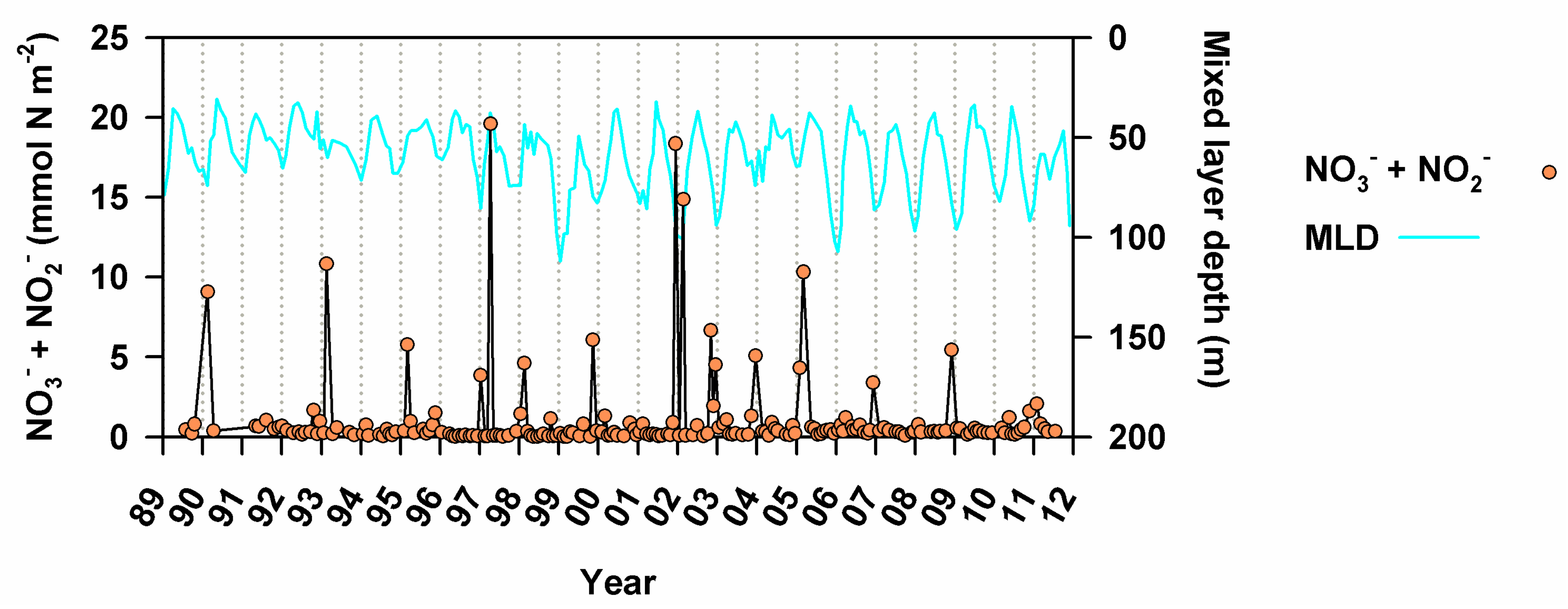
NH_4^+

NO_3^-

NO_2^-

Export

NO_3^-



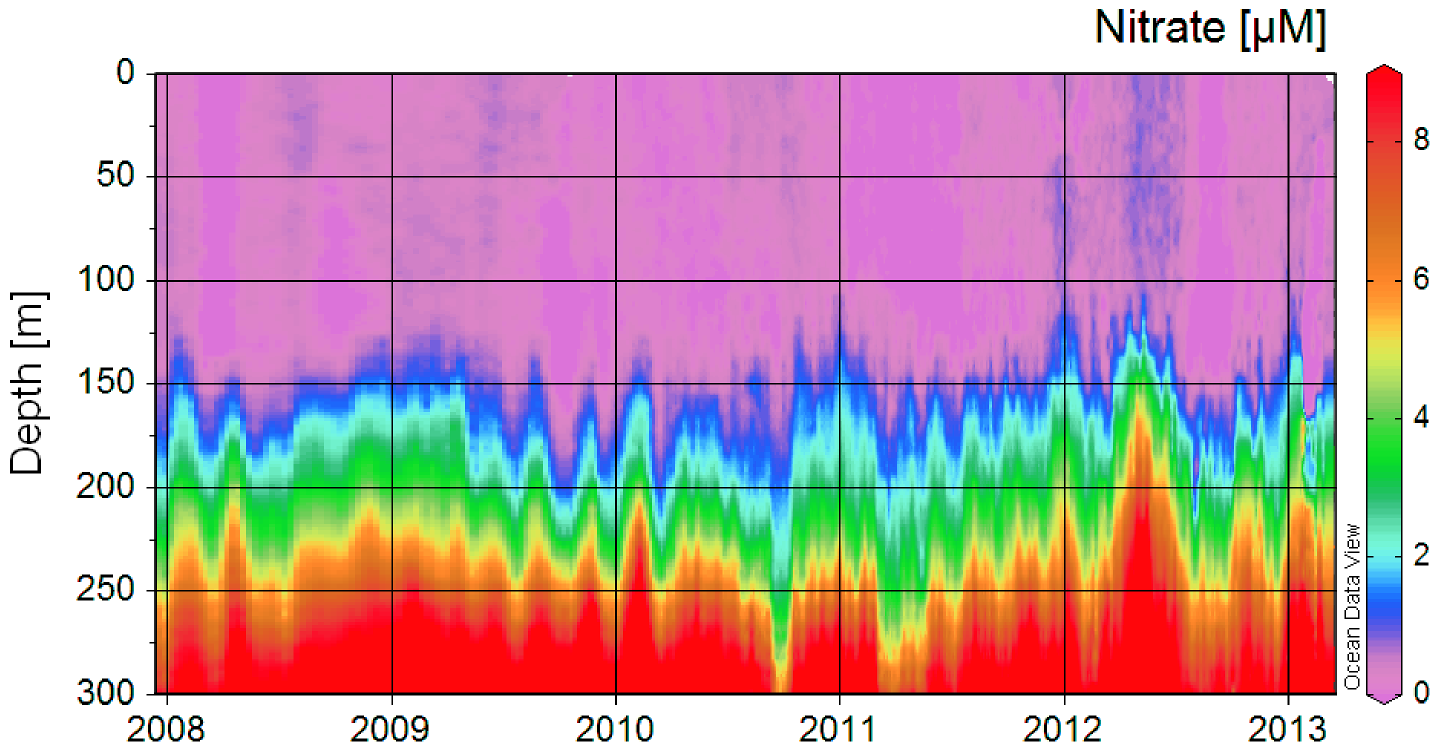
nature

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

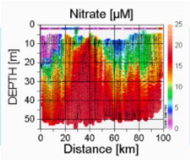
LETTERS

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]

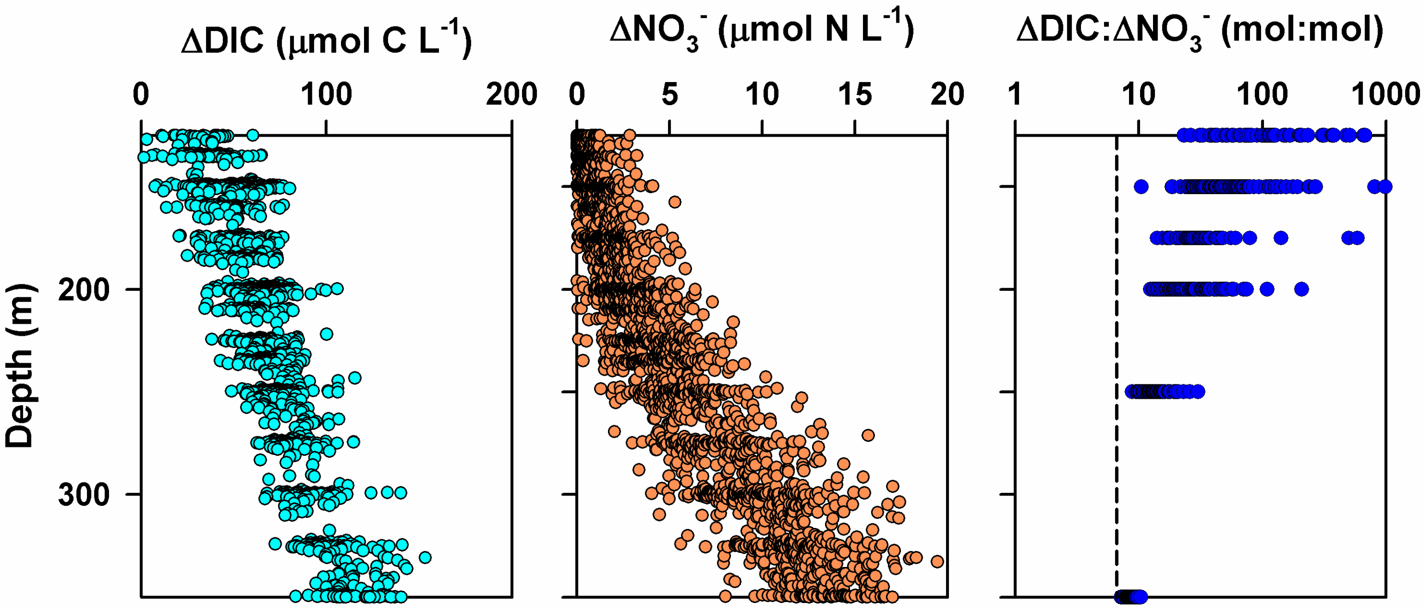


Annual N supply: >88 mmol N m^{-2} yr^{-1} (0.6 mol C m^{-2} yr^{-1})

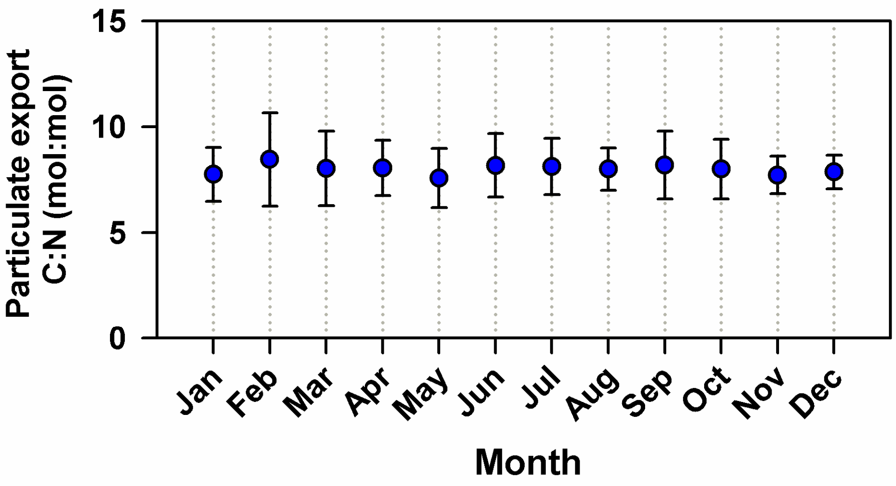


Courtesy of Ken Johnson, MBARI Chemical Sensor Lab

Vertical transport of nutrients by physical processes introduces C-enriched waters



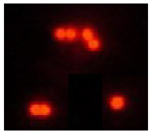
Sub-euphotic zone waters have ΔC:ΔN ratio of ~25:1 to >400:1

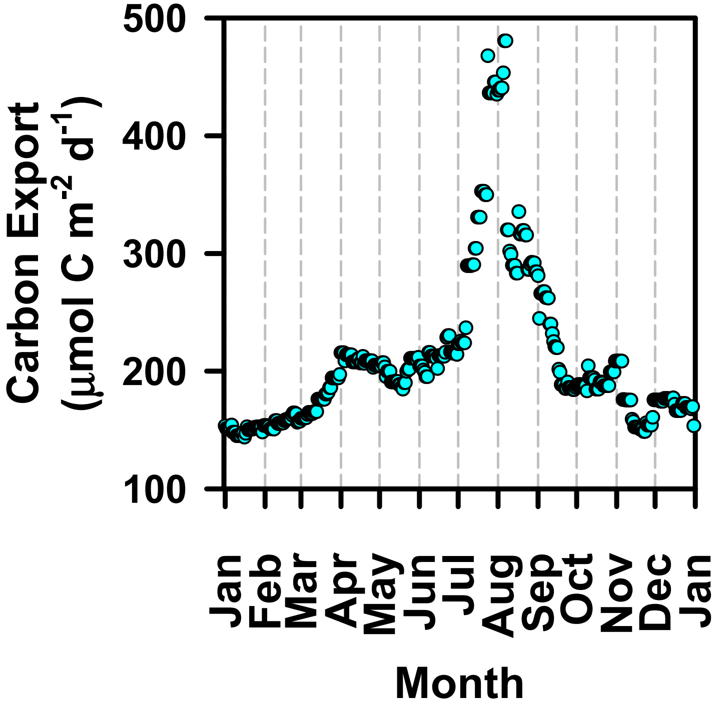


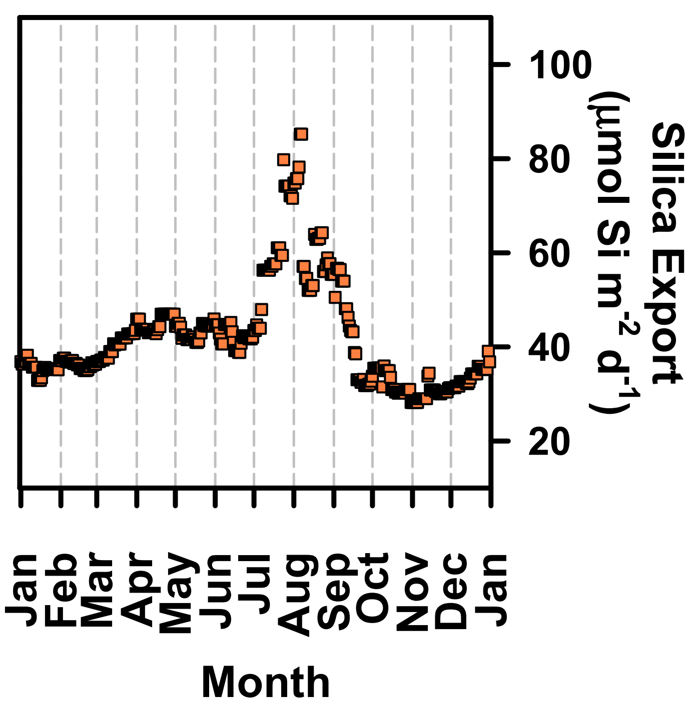
Sinking particles C:N ~7:1

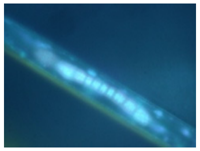
Biological N supply to the ocean: N_2 fixation

- N_2 fixation estimated to fuel ~50% of particulate export in the subtropical N. Pacific
- Numerous taxa of N_2 fixing microorganisms
- N_2 fixation supported diatom-driven export estimated to contribute ~35% of the annual C-flux to the deep sea







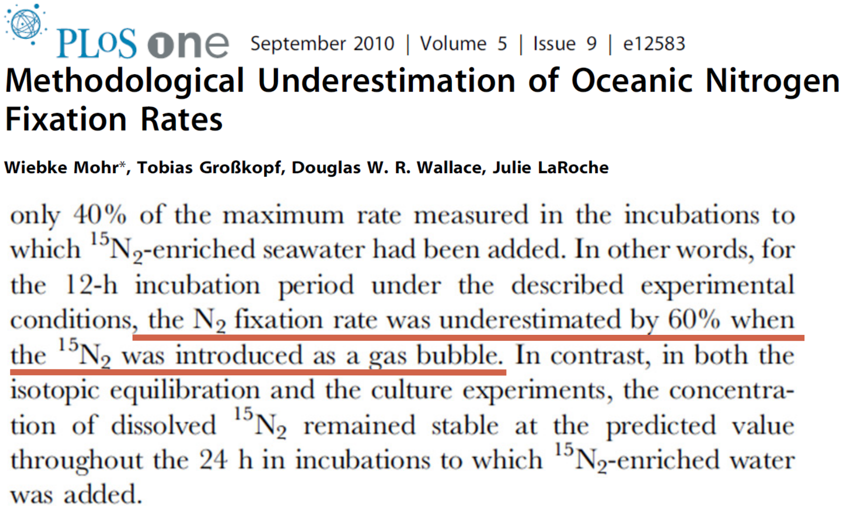


Karl et al. (2012) PNAS 109: 1842-1849

290 | NATURE | VOL 488 | 16 AUGUST 2012

The trouble with the bubble

ANGELICQUE E. WHITE

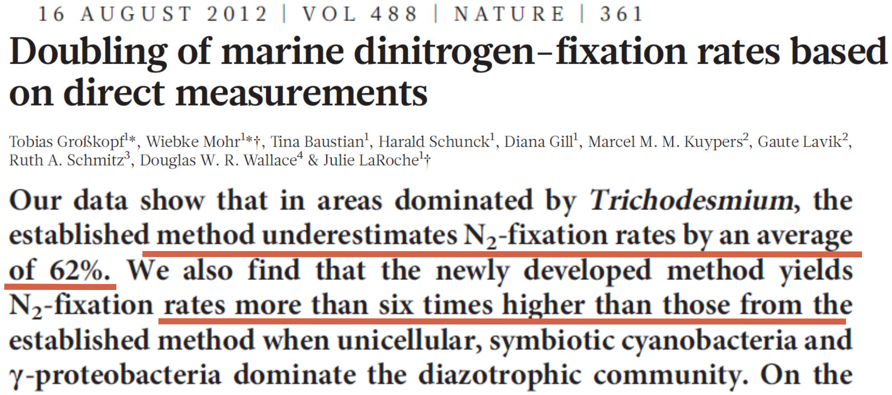


PLoS one September 2010 | Volume 5 | Issue 9 | e12583

Methodological Underestimation of Oceanic Nitrogen Fixation Rates

Wiebke Mohr*, Tobias Großkopf, Douglas W. R. Wallace, Julie LaRoche

only 40% of the maximum rate measured in the incubations to which $^{15}N_2$-enriched seawater had been added. In other words, for the 12-h incubation period under the described experimental conditions, the N_2 fixation rate was underestimated by 60% when the $^{15}N_2$ was introduced as a gas bubble. In contrast, in both the isotopic equilibration and the culture experiments, the concentration of dissolved $^{15}N_2$ remained stable at the predicted value throughout the 24 h in incubations to which $^{15}N_2$-enriched water was added.



16 AUGUST 2012 | VOL 488 | NATURE | 361

Doubling of marine dinitrogen-fixation rates based on direct measurements

Tobias Großkopf[1]*, Wiebke Mohr[1]*†, Tina Baustian[1], Harald Schunck[1], Diana Gill[1], Marcel M. M. Kuypers[2], Gaute Lavik[2], Ruth A. Schmitz[3], Douglas W. R. Wallace[4] & Julie LaRoche[1]†

Our data show that in areas dominated by *Trichodesmium*, the established method underestimates N_2-fixation rates by an average of 62%. We also find that the newly developed method yields N_2-fixation rates more than six times higher than those from the established method when unicellular, symbiotic cyanobacteria and γ-proteobacteria dominate the diazotrophic community. On the

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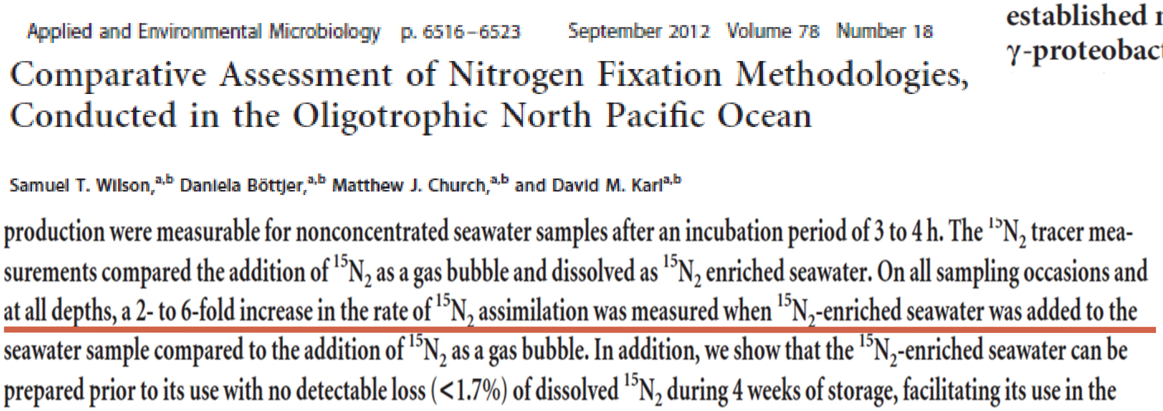


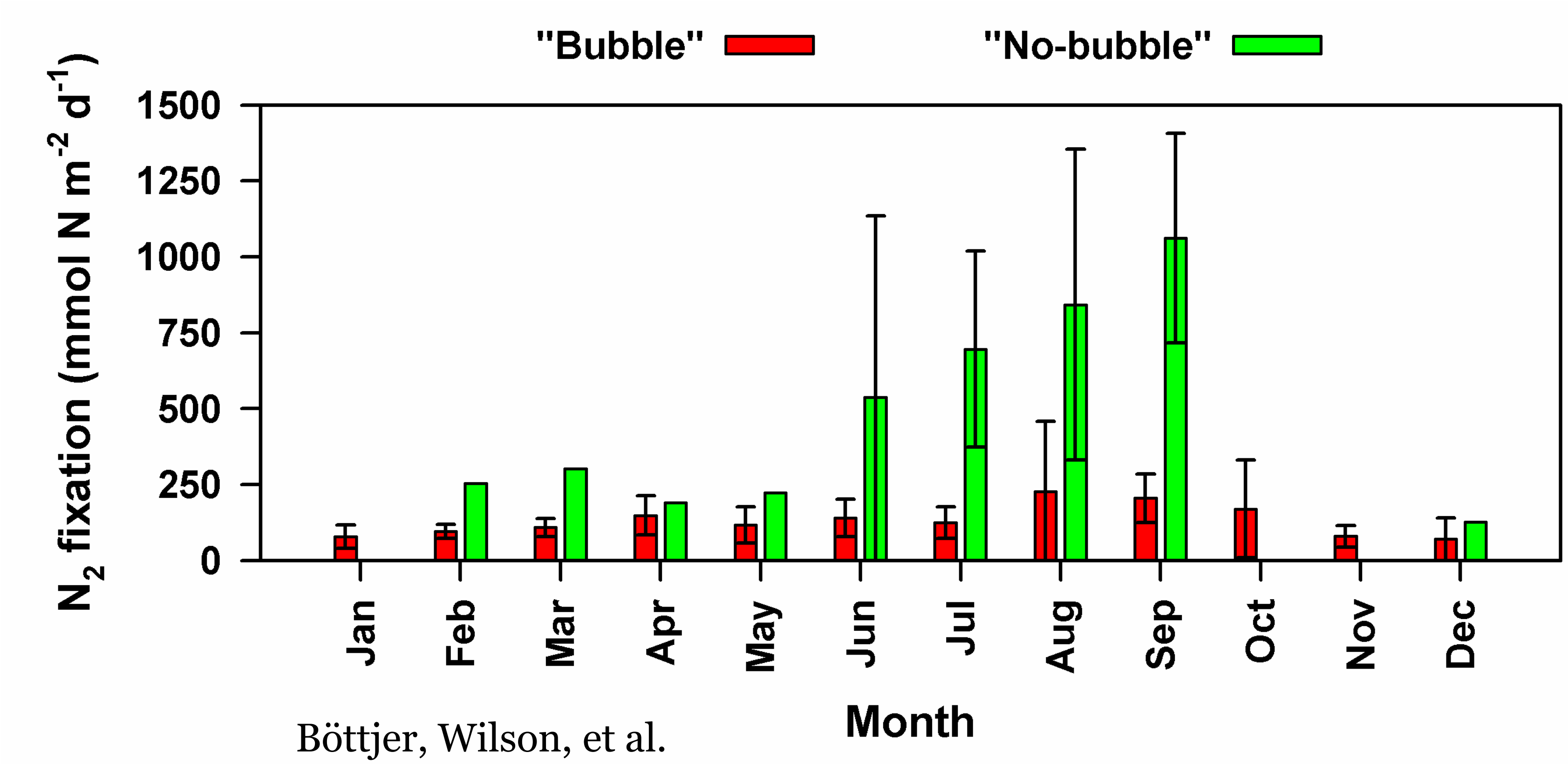
Applied and Environmental Microbiology p. 6516–6523 September 2012 Volume 78 Number 18

Comparative Assessment of Nitrogen Fixation Methodologies, Conducted in the Oligotrophic North Pacific Ocean

Samuel T. Wilson,[a,b] Daniela Böttjer,[a,b] Matthew J. Church,[a,b] and David M. Karl[a,b]

production were measurable for nonconcentrated seawater samples after an incubation period of 3 to 4 h. The $^{15}N_2$ tracer measurements compared the addition of $^{15}N_2$ as a gas bubble and dissolved as $^{15}N_2$ enriched seawater. On all sampling occasions and at all depths, a 2- to 6-fold increase in the rate of $^{15}N_2$ assimilation was measured when $^{15}N_2$-enriched seawater was added to the seawater sample compared to the addition of $^{15}N_2$ as a gas bubble. In addition, we show that the $^{15}N_2$-enriched seawater can be prepared prior to its use with no detectable loss (<1.7%) of dissolved $^{15}N_2$ during 4 weeks of storage, facilitating its use in the

Annual climatology of N_2 fixation at Station ALOHA



Böttjer, Wilson, et al.

- **Annual (2005-2012) average N_2 fixation (bubble):**

48 mmol N m^{-2} yr^{-1} (0.3 mol C m^{-2} yr^{-1})

- **Annual (2012-2013) average N_2 fixation (no-bubble):**

143 mmol N m^{-2} yr^{-1} (0.9 mol C m^{-2} yr^{-1})

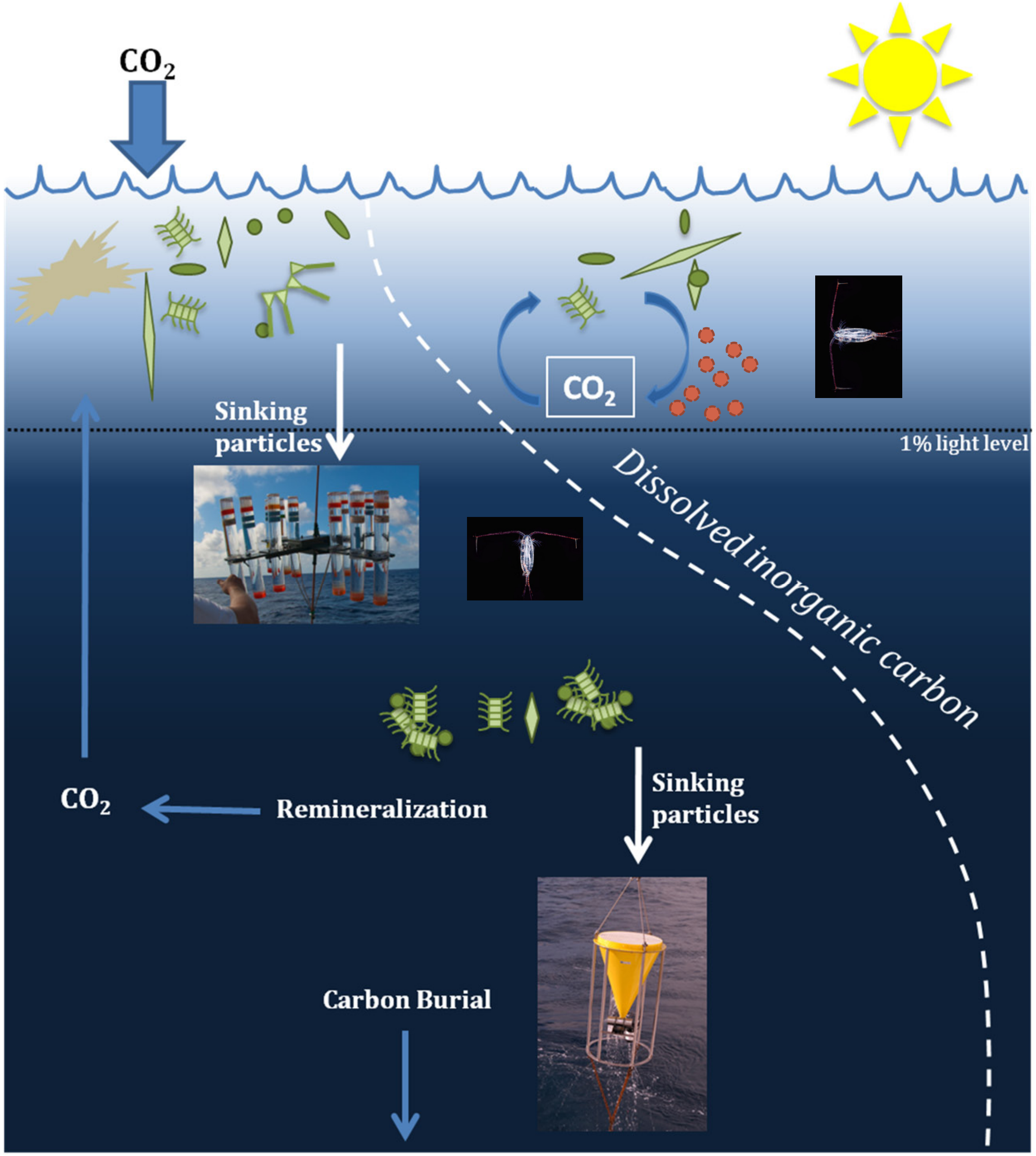
Summary

- NCP at ALOHA averages ~2 mol C m^{-2} yr^{-1}, with an uncertainty of ~±50%.
- Uncertainties in NCP derive from poor constraint on both physical (lateral advection, vertical entrainment, air-sea exchange) and biological processes (DOC flux, sediment traps, vertical migrators).
- The processes supplying nutrients supporting NCP remain unclear.
- Time series programs (augmented by autonomous technologies) continue to improve our ability to constrain the magnitude and variability in carbon fluxes in the open sea.

THANK YOU

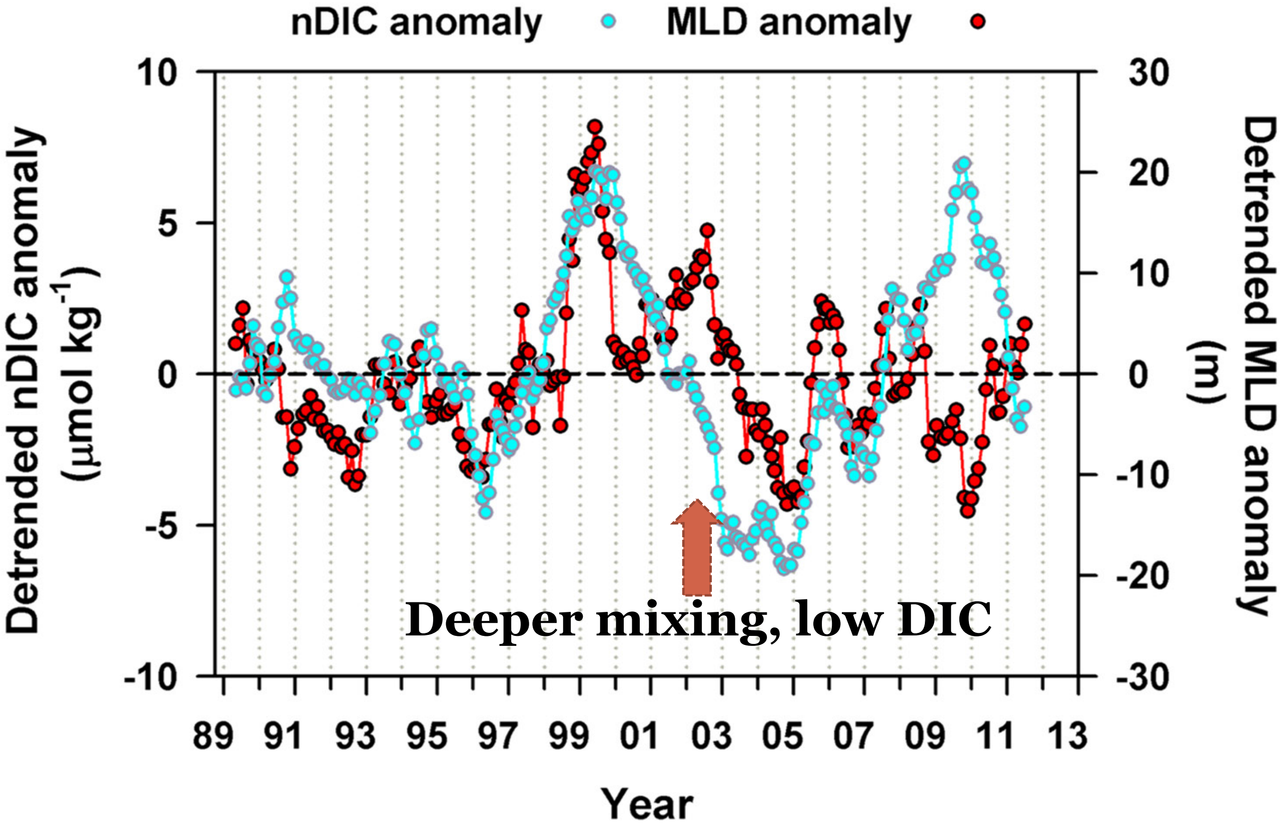
EXTRA SLIDES

Station ALOHA is one of the few places on Earth where time series measurements enable mass balance constraint on ocean NCP



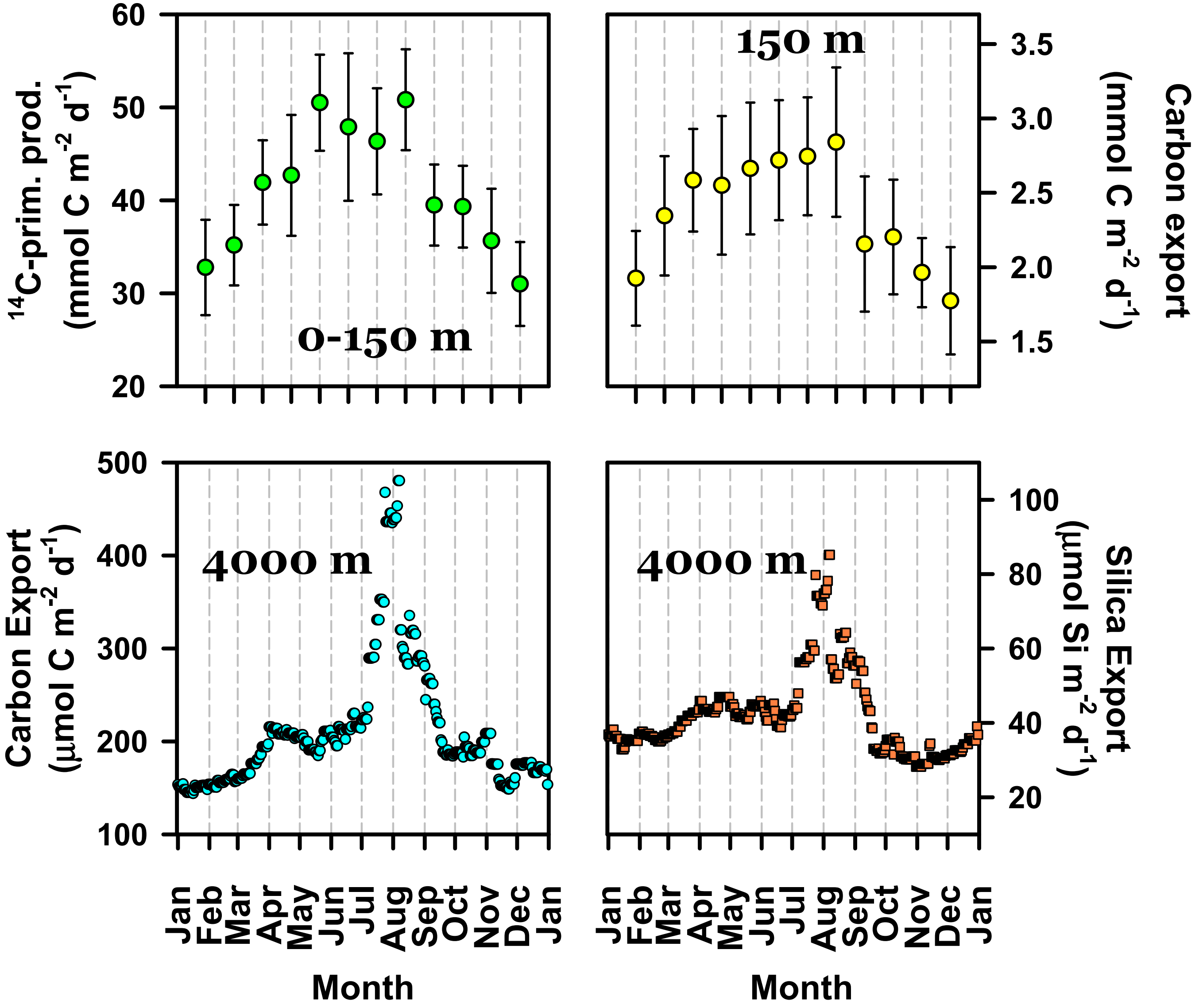
- ➢How temporally variable are rates of production and export in the central North Pacific?
- ➢What processes control this variability?
- ➢What is the fate of biologically fixed carbon?

Interannual to subdecadal scale variability in mixing and mixed layer DIC



What role do biological and physical processes play in controlling the magnitude and variability in seasonal- to decadal-scale ocean carbon fluxes?

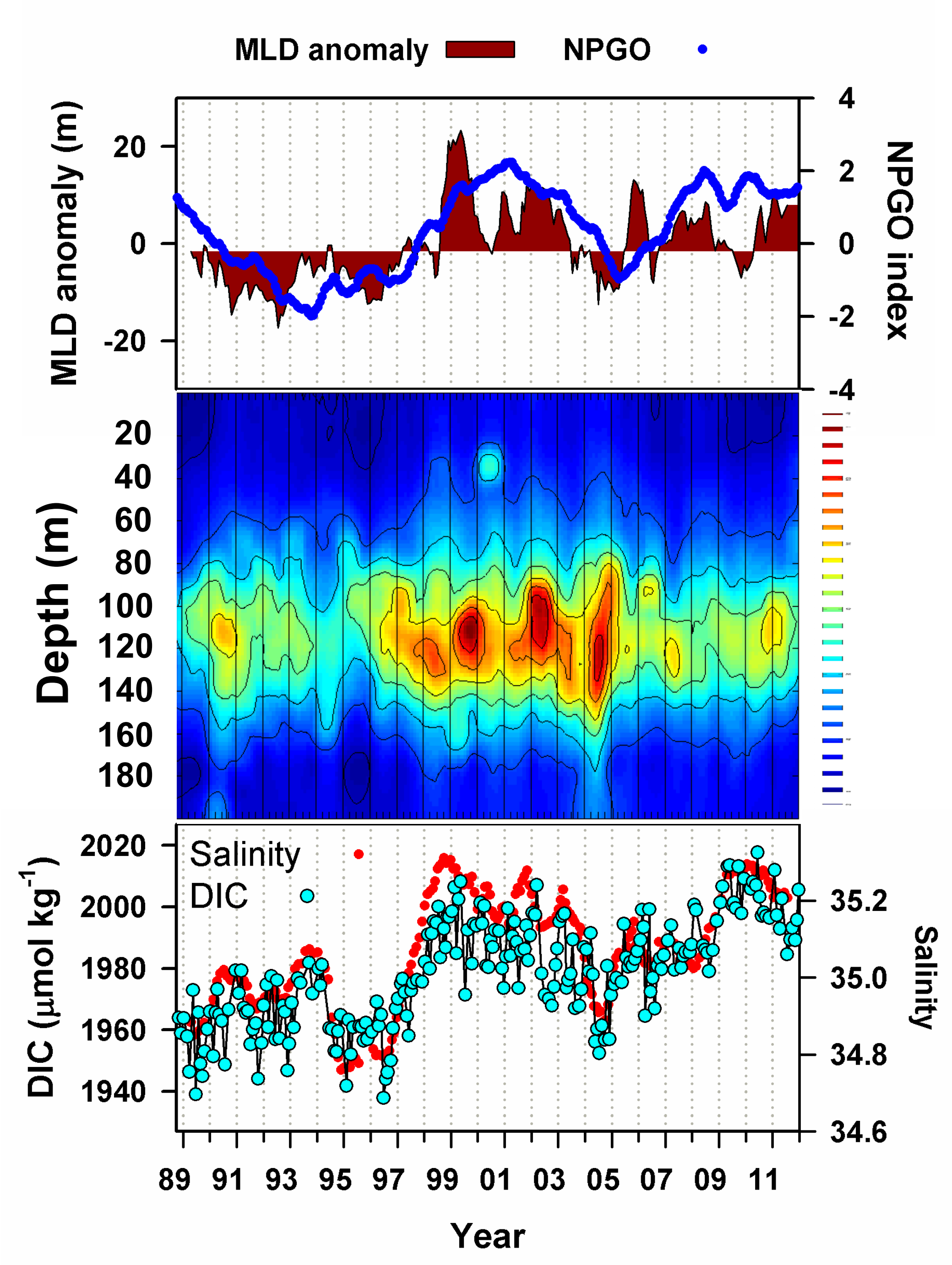
Annual cycle of productivity and export



Plankton community structure plays a key role in controlling carbon export

Climate modulated changes in the NPSG ecosystem

- Interannual to subdecadal variability in upper ocean mixing appears linked to basin-scale climate fluctuations.
- Changes in nutrient and light availability alters biological productivity and biomass.
- Variability in inorganic carbon inventories, ocean pH, and air-sea CO_2 flux appear correlated to variations in salinity.



- ^{14}C-primary production provides a highly sensitive means of quantifying daily rates of carbon fixation.
  - Requires confinement of samples
  - DO^{14}C? At ALOHA ~20-30% of particulate carbon fixation
  - Daytime only or 24 hours? ~20-30% loss overnight

- ^{14}C-primary production ≠ gross primary production
- ^{14}C-primary production ≠ net community production
- Depending on how the method is employed, ^{14}C-primary production ≈ net primary production?