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

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HAWAII OCEAN TIME-SERIES
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H.O.T.
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NSF
Thank you

- Craig Carlson (UCSB) and Ricardo Letelier (OSU)
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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.
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.
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
Carbon fixation and particulate carbon export

Annually averaged
$^{14}$C-PP: 
$\sim 15 \text{ mol C m}^{-2} \text{ yr}^{-1}$

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

PC$_{150 \text{ m}}$: $^{14}$C-PP = 0.04-0.12
The many faces of Station ALOHA

Ricardo Letelier and Angel White (OSU)
Variability in mixed layer inorganic carbon

- Seasonal variations in $pCO_2$ 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

Biological and physical processes controlling variability in carbon inventories and fluxes

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 $\approx$ NCP
- Vertical transport of organic matter export (POC, DOC, and migrant flux)
Estimates of NCP at ALOHA abound...


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*

Biogeochemical cycling in the oligotrophic ocean: Redfield and non-Redfield models

James Robert Christian


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

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

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

Kenneth S. Johnson¹, Stephen C. Riser² & David M. Karl³
## Estimates of net community production at ALOHA

<table>
<thead>
<tr>
<th>Method of Determination</th>
<th>Rate (± stdev) mol C m⁻² yr⁻¹</th>
<th>Period</th>
<th>References</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>O₂ based approaches</strong></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Mixed Layer O₂: Ar</td>
<td>1.4 - 3.7 (± 1.0)</td>
<td>1992–2008</td>
<td>Emerson et al. (1997); Hamme and Emerson (2006); Juranek and Quay (2005); Quay et al. (2010)</td>
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<tr>
<td>Mooring O₂</td>
<td>4.1 (± 1.8)</td>
<td>2005</td>
<td>Emerson et al. (2008)</td>
</tr>
<tr>
<td>Sub-mixed layer float profiles</td>
<td>1.1 - 1.7 (±0.2)</td>
<td>2003–2010</td>
<td>Riser and Johnson (2008)</td>
</tr>
<tr>
<td>Sub-mixed layer glider surveys</td>
<td>0.9 (± 0.1)</td>
<td>2005</td>
<td>Nicholson et al. (2008)</td>
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<tr>
<td><strong>C-based approaches</strong></td>
<td></td>
<td></td>
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</tr>
<tr>
<td>Mixed layer ¹³C/¹²C and DIC dynamics</td>
<td>1.6 ± 0.9</td>
<td>1990-1995</td>
<td>Emerson et al. (1997)</td>
</tr>
<tr>
<td></td>
<td>2.8 ± 0.8</td>
<td>1988-2002</td>
<td>Keeling et al. (2004)</td>
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<td><strong>Passive and active OM fluxes</strong></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Sediment traps (150 m)</td>
<td>0.9 (± 0.3)</td>
<td>1988-2012</td>
<td>HOT core data</td>
</tr>
<tr>
<td>²³⁴Th deficits</td>
<td>1.5 (± 0.8)</td>
<td>1999-2000</td>
<td>Benitez-Nelson et al. (2001)</td>
</tr>
<tr>
<td>DOC export</td>
<td>0.4</td>
<td>2002-2012</td>
<td>HOT core data</td>
</tr>
<tr>
<td>Zooplankton-mediated</td>
<td>0.1 (± 0.09)</td>
<td>1994-2005</td>
<td>Al-Mutairi and Landry (2001); Hannides et al. (2009)</td>
</tr>
</tbody>
</table>

**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.
  - $\text{NO}_3^-$ supported new production
- **Biological:**
  - $\text{N}_2$ fixation ($\text{N}_2 \rightarrow \text{NH}_3$)

Where do nutrients come from to support NCP? [Diagram]

- Physical:
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- Biological:
  - $\text{N}_2$ fixation ($\text{N}_2 \rightarrow \text{NH}_3$)
Nitrate supply from deep to near-surface waters of the North Pacific subtropical gyre

Kenneth S. Johnson¹, Stephen C. Riser² & David M. Karl³

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
Sub-euphotic zone waters have $\Delta C: \Delta N$ ratio of ~25:1 to >400:1

Sinking particles C:N ~7:1
Biological N supply to the ocean: N₂ fixation

- N₂ fixation estimated to fuel ~50% of particulate export in the subtropical N. Pacific
- Numerous taxa of N₂ fixing microorganisms
- N₂ fixation supported diatom-driven export estimated to contribute ~35% of the annual C-flux to the deep sea

The trouble with the bubble

ANGELIQUE E. WHITE

only 40% of the maximum rate measured in the incubations to which $^{15}\text{N}_2$-enriched seawater had been added. In other words, for the 12-h incubation period under the described experimental conditions, the $\text{N}_2$ fixation rate was underestimated by 60% when the $^{15}\text{N}_2$ was introduced as a gas bubble. In contrast, in both the isotopic equilibration and the culture experiments, the concentration of dissolved $^{15}\text{N}_2$ remained stable at the predicted value throughout the 24 h in incubations to which $^{15}\text{N}_2$-enriched water was added.

Doubling of marine dinitrogen-fixation rates based on direct measurements

Tobias Großkopf\textsuperscript{a}, Wiebke Mohr\textsuperscript{b}, Tina Baustian\textsuperscript{c}, Harald Schrumch\textsuperscript{d}, Diana Gill\textsuperscript{e}, Marcel M. M. Knappes\textsuperscript{e}, Gaute Lavik\textsuperscript{e*, Ruth A. Schmitz\textsuperscript{d}, Douglas W. R. Wallace\textsuperscript{d} & Julie LaRoche\textsuperscript{d,9}

Our data show that in areas dominated by Trichodesmium, the established method underestimates $\text{N}_2$-fixation rates by an average of 62%. We also find that the newly developed method yields $\text{N}_2$-fixation rates more than six times higher than those from the established method when unicellular, symbiotic cyanobacteria and $\gamma$-proteobacteria dominate the diazotrophic community. On the
• Annual (2005-2012) average N\textsubscript{2} fixation (bubble): 48 mmol N m\textsuperscript{-2} yr\textsuperscript{-1} (0.3 mol C m\textsuperscript{-2} yr\textsuperscript{-1})

• Annual (2012-2013) average N\textsubscript{2} fixation (no-bubble): 143 mmol N m\textsuperscript{-2} yr\textsuperscript{-1} (0.9 mol C m\textsuperscript{-2} yr\textsuperscript{-1})
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?
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.
\[^{14}\text{C}}\text{-primary production provides a highly sensitive means of quantifying daily rates of carbon fixation.}\]
- Requires confinement of samples
- DO\(^{14}\text{C}\)? At ALOHA \(~20\text{-}30\%\) of particulate carbon fixation
- Daytime only or 24 hours? \(~20\text{-}30\%\) loss overnight

\[^{14}\text{C}}\text{-primary production} \neq \text{gross primary production}\]

\[^{14}\text{C}}\text{-primary production} \neq \text{net community production}\]

Depending on how the method is employed, \(^{14}\text{C}}\text{-primary production} \approx \text{net primary production}?