Observational approaches to the biologically driven carbon pumps (BCP)

Phoebe J. Lam
Dept of Ocean Sciences
University of California, Santa Cruz

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The EXPORTS “wiring diagram” of the BCP

- Squares represent living biota (phytoplankton, zooplankton and bacteria)
- Circles represent stocks of non-living matter (POC, aggregates, fecal pellets, etc.)
- Arrows indicate carbon flow and key processes
- Can approach this by measuring all stocks and all arrows

Particle Export Efficiency = $\text{PE}_{\text{eff}} = \text{EF}/\text{PP}$

Export Flux

Transfer Efficiency = $\text{TE}_{\text{eff}} = \text{SF}/\text{EF}$

Sequestration Flux

http://exports.oceancolor.ucsb.edu
A particle-centric view of the biological carbon pump (with apologies to the microbial C pumpers out there)

- Particle dynamics (aggregation, disaggregation, remineralization, sinking) determine the **strength and transfer efficiency** of the biological pump.

- Recall that Stokes sinking is *linearly* proportional to particle excess density, and proportional to the *square* of particle diameter.

- Greater **aggregation** and sinking should promote stronger and more efficient BCP.

- Greater **disaggregation** and **remineralization** should promote weaker and less efficient BCP.
To understand particle dynamics, we collect or image particles

<table>
<thead>
<tr>
<th>Method</th>
<th>Pro</th>
<th>Con</th>
</tr>
</thead>
<tbody>
<tr>
<td>Collecting</td>
<td>-Chemical measurements can be made: composition (POC, mineral content), biomarkers as indicators of fecal vs fresh algal matter, radionuclides (Th)</td>
<td>-Size distribution and morphologies of particles possible but very difficult (eg. Bishop et al. 1986 Prog Ocean; Dagg et al. 2014 DSR) -limited spatial and temporal resolution possible</td>
</tr>
<tr>
<td>Imaging</td>
<td>-Particle size distribution can be determined -can potentially go onto autonomous platform and sample at high temporal and spatial resolution!</td>
<td>No physical sample to measure, so particle composition (POC and mineral content) must be inferred optically</td>
</tr>
</tbody>
</table>
Collecting suspended particles


Marine snow catcher

MULVFS in-situ pump

Dual-flow McLane in-situ pump

Dual-flow McLane in-situ pump

Dual-flow McLane in-situ pump

>51um

0.8-51um Supor

1-51um QMA

Marine snow catcher

MULVFS in-situ pump >51um

55°S 134 m

1cm

56°S 136 m

1cm
Collecting sinking particles


**Bottom moored (BM)**
B. McLane time-series trap

**Surface Tethered (ST)**
A. PITS trap
C. Technicap PPS time-series trap
F. Optical Sediment Recorder

**Neutrally Buoyant (NB)**
D. NBST
E. PELAGRA

Particle dynamics from particle geochemistry

- Understanding the geochemistry of the sinking and suspended particle pools can give us qualitative (eg. biomarkers) and quantitative (eg. thorium isotopes) information about the degree of exchange between the two pools (and thus about the workings of the BCP)

- Two examples:
  - Organic biomarkers
  - Thorium isotopes
Geochemically linking suspended and sinking particles: organic biomarkers

- **Spring:** Suspended and sinking particles more different—less exchange; more fecal pellets in sinking particles; suspended particles have biomarkers of fresh pigment material: arrived through disaggregation of rare, rapidly sinking phytoplankton aggregates

- **Summer:** Suspended and sinking particles more similar, and show a shift from zooplankton-processed to microbially processed material.
Geochemically linking suspended and sinking particles: Thorium isotopes

Surface adsorbed, including radiogenic (eg. 230Th)
Biological (eg. POC or Cd)
Authigenic particles (eg. Ba in the form of barite)
Lithogenic particles (eg. Ti)
Observations—NW Pacific VERTIGO stn K2d1

$^{234}$Th—Total

$^{234}$Th—small part.

$^{234}$Th—large part.

POC Flux

$^{234}$Th from Buesseler et al. 2009; POC from Bishop and Wood 2008
Particle cycling rates in C units (C m\(^{-3}\) d\(^{-1}\))

- Rates decrease with depth, as we would expect
- Disaggregation rates are larger than remineralization
- This is a reflection of the fact that large POC concentrations decreases more quickly with depth than small POC

Giering et al. calculated respiration using leucine incorporation, CF and prokaryotic growth efficiency; zoop resp = \(f(\text{body mass, T, resp quotient})\)
Linking suspended and sinking particles—summary

• Chemical analyses of sinking and suspended particles show variability in the degree of exchange (aggregation and disaggregation) between the suspended and sinking particle fractions as a function of season and location that correlate with changing dominance of fecal pellets.

• Can invert observations of particle chemistry (e.g. POC, thorium isotopes) for some particle cycling rates that are of same order with direct estimates (e.g. respiration) and others that are impossible to measure directly (e.g. aggregation and disaggregation rates).
Imaging of suspended particles—fast!

<table>
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<tr>
<th>Size range</th>
<th>Name</th>
<th>Method</th>
</tr>
</thead>
<tbody>
<tr>
<td>&gt;100μm</td>
<td>UVP-Underwater Vision Profiler</td>
<td>Imaging</td>
</tr>
<tr>
<td></td>
<td>VPR-Video Plankton Recorder</td>
<td>Imaging</td>
</tr>
<tr>
<td></td>
<td>LOPC-Laser Optical Particle Counter</td>
<td>Laser absorbance</td>
</tr>
<tr>
<td>Micro, nano-</td>
<td>FlowCam</td>
<td>Flow cytometry plus imaging</td>
</tr>
<tr>
<td>plankton</td>
<td>Imaging Flow Cytobot</td>
<td></td>
</tr>
<tr>
<td></td>
<td>CytoSense</td>
<td></td>
</tr>
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</table>

Jackson et al. 2015 DSR1: LOPC on a solo float:
- High resolution sampling allows calculation of aggregate settling velocities
- Sedimentation was very episodic, with export occurring in ¼ of days
Imaging sinking particles: the C-Flux Explorer with Optical Sedimentation Recorder

3 Lighting modes
Dark Field
Transmitted light (POC)
Cross-polarized (PIC)

Transmission
POC
X polarized

5 Mpix Imaging (RGB)
Set f. no., shutter, & focal distance

Image resolution 15 µm

Figures from Jim Bishop
Clean, image @ Hour (0, 0.5, 1.0, … 3.0), Clean … repeat Surface every 17 Hrs, GPS, data in/out Dive to next depth

In animations: 1s ~ 3hrs; loops are ~1d
Open questions

1. What leads to high production, low export conditions?
2. What is the geographical distribution of flux? mismatch between geochemical methods and particle-based methods
3. Fecal pellets vs marine snow: important control on transfer efficiency?
Does High Surface Chlorophyll mean high carbon sedimentation?  
**NO:** flux was 20x higher under low chl conditions

**CFE001** various depths 250 to 750 m
Q1: what leads to high production, low export conditions?

- Has been observed elsewhere (eg. Maiti et al. 2013 GRL—Southern Ocean High productivity, low export)
- Some observations suggest this is a steady state condition
- Other regions may exhibit this condition transiently, and possibly not at all
- Need more time-series observations (hourly resolution? for months) of different kinds of ecosystems to monitor the initiation, peak, and decline (if present) of high productivity ecosystems that seem to have low export, and those that have high export (eg. NABE)
- Autonomous platforms are the way to answer this
Open questions

1. High production, low export: where is it a transient and where is it a steady state condition?

2. What is the geographical distribution of flux? mismatch between geochemical methods and particle-based methods

3. Fecal pellets vs marine snow: important control on transfer efficiency?
Comparing with other methods of estimating Export Flux

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<th>Timescale of integration</th>
<th>Conceptual basis</th>
</tr>
</thead>
<tbody>
<tr>
<td>Imaging/ filtration</td>
<td>Particle concentration</td>
<td>Seconds to hours</td>
<td>Must multiply by sinking rate to convert to flux; for imaging, must also convert # to POC; does not include DOC flux</td>
</tr>
<tr>
<td>Sediment traps</td>
<td>Particle flux</td>
<td>Days</td>
<td>Direct measurement of exported POC; Does not include DOC flux</td>
</tr>
<tr>
<td>$^{238}$U-$^{234}$Th disequilibrium</td>
<td>Particle/geochemical flux</td>
<td>Weeks</td>
<td>$^{234}$Th deficit due to particle scavenging; no DOC</td>
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<tr>
<td>$O_2$ mass balance ($O_2/x$, $x$=Ar, Ne, N$_2$)</td>
<td>Geochemical flux</td>
<td>Seasonal</td>
<td>Net $O_2$ production is net community production = export production. Use inert Ar, Ne, or N2 to correct for physics. Measure over seasonal cycle in mixed layer</td>
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- When particle-only flux methods add in estimate of DOC flux, they are similar (within factor of 2) to $O_2$ mass balance estimates (eg. Emerson et al. 1997, Emerson and Hedges 2008)
Q2: Mismatch between geochemical methods and satellite/model understanding of BCP distribution

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<th>Method</th>
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<td>O₂ mass balance (O₂/x, x=Ar, Ne, N₂)</td>
<td>Geochemical</td>
<td>Subtropical Pac (HOT) 2.7±1.7, 1.3±0.9, Subarctic Pac (Stn P) 2.0±1.0</td>
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O₂ mass balance over an annual cycle at HOT vs Stn P suggest similar export flux!

Compare to our satellite/model view of export flux...
Q2: Mismatch between geochemical methods and satellite/model understanding of BCP distribution

Satellite and model estimates of export and sequestration flux suggest low/high flux in subtropical (H)/subpolar (P) regions

Henson et al. 2012 GBC: satellite algorithms

Lima et al. 2014 BG: CCSM-BEC model

(c) POC flux at z₀ total = 6.04 Pg C y⁻¹
Methods for measuring Sequestration and Burial flux

- Sequestration flux is usually measured by bottom-moored time-series sediment traps
- Flux to seafloor has been estimated using benthic oxygen flux (oxygen consumption due to POC flux to seafloor)
Q2: Mismatch between geochemical methods and satellite/model understanding of BCP distribution

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O₂ mass balance over an annual cycle at HOT vs Stn P suggest similar export flux!

Benthic O₂ consumption map (~POC flux to seafloor) from Jahnke 1996 also suggests that HOT and Stn P could be fairly similar...if so, then this means that subtropical regions could be burying as much POC as parts of subpolar regions.
Q2: Mismatch between geochemical methods and satellite/model understanding of BCP distribution

*Satellite and model estimates of export and sequestration flux suggest low/high flux in subtropical (H)/subpolar (P) regions*

Henson et al. 2012 GBC: satellite algorithms
Lima et al. 2014 BG: CCSM-BEC model

(c) POC flux at $z_0$
(d) POC flux at 2000 m

- Total = 6.04 Pg C yr$^{-1}$
- Total = 0.21 Pg C yr$^{-1}$
Open questions

1. High production, low export: where is it a transient and where is it a steady state condition?
2. What is the geographical distribution of flux? mismatch between geochemical methods and particle-based methods
3. Fecal pellets vs marine snow: important control on transfer efficiency?
Q3: Fecal pellets vs marine snow: important control on transfer efficiency?

From organic biomarkers, Wakeham and Canuel 1988 postulate that marine snow has higher rates of disaggregation, and so would have lower transfer efficiency than fecal pellets. In contrast, huge sedimentation of marine snow aggregates also observed. Sinking particles may shift seasonally from being dominated by one to the other—does this affect transfer efficiency? Autonomous platforms with imaging capability could address this. Geochemical estimates of disaggregation rates in ecosystems dominated by one or the other could address this.
Open questions

1. High production, low export: where is it a transient and where is it a steady state condition?
2. What is the geographical distribution of flux? mismatch between geochemical methods and particle-based methods
3. Fecal pellets vs marine snow: what control on transfer efficiency?