The Life and Times of Marine Particles: the JGOFS story

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Marine Particles
“separate biogeochemistry from physical oceanography”
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How do we get from here?

C uptake in surface ocean
SeaWiFS global primary production
Behrenfeld & Falkowski, 1997

To here?

C flux to seafloor - benthic $O_2$ demand
Jahnke, 1996
Outline

• pre-JGOFS world

• Basic Facts - marine particles

• Particle Export vs. Primary Production
  
  Rates and controls measured during JGOFS studies

• Predictions of POC Flux - global & regional
  
  Southern Ocean example

• What does the future hold

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pre-JGOFS world: \( \text{Export} \approx \beta z \ast \text{Primary Production} \)

How well do we understand rates and controls on POC export?
- the “F” in JGOFS

- Important implications for export derived from satellite productivity
Marine Particles - basic facts

Methods classically define suspended vs. sinking particles
- filtration
- sediment traps

*Methods matter!*

Settling velocity proportional to $(\text{radius})^2$ & density difference
- size matters
- and so does density (ballast; sinking speed)
- and so does chemistry (degradation; surface properties)

Sources: biogenic material dominates surface open ocean vs. inorganic/detrital
Marine Particles- basic facts

- Sinking particles do not sink vertically
  - sinking velocity = 10’s - >500 m/day
  - horizontal velocity = few - 10’s cm/sec
  (avg. “sinking” particle- 2 m drop & 270m trajectory during 30 min talk)
Particle export vs. primary production

Bermuda Atlantic Time-Series (BATS)

No simple relationship between production and export

What controls

Particle Export: Primary Production ratio?

- Ecology/Community Structure is important
- Timing is important
  Decoupling of export:production
  blooms & episodic pulses
  Seasonal dynamics can be large
difficulties with sampling
Impact of community structure on particle flux

North Atlantic Bloom Study

Boyd & Newton, 1995

1989 vs. 1990

Chlorophyll similar
Prim. Production similar

Dominant phytoplankton
1989 Large >200 µm diatoms (Chaetoceros spp.)
1990 Small 3-4 µm diatoms (Nanoneis hasleae spp.) and autotrophic nanoflagellates

POC Flux at 3100m (mg m⁻² d⁻¹)

Conclusion:
Two fold change in deep POC flux due to different algal size distributions

Michaels & Silver, 1988
POC Export: Production - timing is important

- Primary Production
- POC Export
- export/production ratio
  - varies within bloom
  - varies between food webs

Time lag between onset of primary production and POC export

High C flux (low thorium-234) during SW Monsoon

Buesseler et al., 1998
High C flux (low thorium-234) during SW Monsoon associated with bloom of large diatoms

Buesseler et al., 1998
Garrison et al., 2000

Diatoms rule!
(the upper ocean POC flux)
- large
- rapidly sinking
- bSi ballast
- bioprotection
- mass aggregation
Diatom assoc. flux

Coccolithophorid assoc. POC flux

Why can’t diatoms control upper ocean export on regional or seasonal basis, while CaCO₃ materials show stronger association with deep flux?

Differences abound- in diatom types, sinking rates & bSi/C ratios

Variability in POC flux:production within mesoscale features

<table>
<thead>
<tr>
<th></th>
<th>In</th>
<th>Out</th>
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<tbody>
<tr>
<td>Primary Prod.</td>
<td>73</td>
<td>56</td>
</tr>
<tr>
<td>POC flux (mmol C m⁻² d⁻¹)</td>
<td>2.6</td>
<td>1.0</td>
</tr>
<tr>
<td>Export:Prod</td>
<td>3.6%</td>
<td>1.8%</td>
</tr>
</tbody>
</table>

Higher POC flux associated with larger >3µm phytoplankton

Bidigare et al., 2003
Variability in POC flux:production within mesoscale features

Bidigare et al., 2003

BATS 1993-1995
4 out of 6 high thorium-234 flux events associated with an eddy

Higher POC flux associated with larger >3um phytoplankton

Age of the eddy matters
i.e. state of the bloom

Sweeney et al., 2003 in press

POC export efficiency
JGOFS examples

POC flux/Primary Production
(100m thorium-234 & 14C methods)
North Atlantic bloom = <10-30%
Equatorial Pacific = 1-10%
Arabian Sea
  late SW monsoon = 15-30%
  intermonsoon = 1-10%
Southern Ocean = 25 - >50%
Hawaii = 4-10% (up to 22%)
Bermuda = <10% (up to 50%)

Primary Prod. | In | Out
---------------|----|----
POC flux       | 73 | 56
( mmol C m⁻² d⁻¹)
Export:Prod    | 3.6% | 1.8%

Higher POC flux associated with larger >3um phytoplankton

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BATS 1993-1995
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Sweeney et al., 2003 in press
post-JGOFS view: Life & Times of Marine Particles

No simple relationship between particle export & production
Regional differences- export efficiency <5% to >50%

Efficiency of biological pump tied to foodweb
Diatoms rule the upper ocean (bSi ballast, bioprotection)
What about other flux producers
coccolithophores- rule the deep sea flux?
salps- massive blooms & large pellets

Seasonal & episodic variability important
What controls end of bloom?
grazing, nutrient limits, light/temp.

So where does this leave us with respect to models and JGOFS synthesis?
How well can we predict global POC export?

SeaWiFS PProd from Behrenfeld and temperature dependent food web model
*Laws et al., 2000*

Inverse model used to calculate POC export flux
*Schlitzer, 2002, 2003*

Regional example: *Southern Ocean C cycle*
Regional example: Southern Ocean C cycle

SeaWiFS Chl. vs. time

Buesseler et al., 2003
Regional example: *Southern Ocean C cycle*

POC Flux/Prim. Production

- North of APF: 16-25%
- APF and S-APF: 35-40%
- S-ACC & N. Ross Sea: >50-65%

Seasonal Food Web & Biogeochemistry

- Si limits to diatom growth; small phyto & microzooc grazing
- early *Phaeocystis* blooms w/retreat ice; large diatoms & aggregation w/Si depletion
- *Phaeocystis* & small pennate diatoms; iron <0.2 nM; short growing season


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How well can we predict POC export?

*Southern Ocean 170°W comparisons*

Carbon Flux-field estimates

Upper Ocean C Flux mol C m⁻² yr⁻¹

<table>
<thead>
<tr>
<th>Latitude South</th>
<th>Upper Ocean C Flux</th>
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<tbody>
<tr>
<td>75</td>
<td>0</td>
</tr>
<tr>
<td>70</td>
<td>2</td>
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<tr>
<td>65</td>
<td>4</td>
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<td>60</td>
<td>6</td>
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<tr>
<td>55</td>
<td>8</td>
</tr>
<tr>
<td>50</td>
<td>10</td>
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APF

100m

Southern Ocean 170°W comparisons
How well can we predict POC export?

Southern Ocean 170° W comparisons

Carbon Flux-field estimates

Upper Ocean C Flux
mol C m⁻² yr⁻¹

Latitudes South

100m 1000m Seabed

1000 m Sediment Trap

0.10 0.15 0.20

Seabed Nelson et al. 2002

Carbon Flux-model estimates

Upper Ocean C flux
mol C m⁻² yr⁻¹

Temp. dependent food web model
w/AESOPS PProd

Latitudes South

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How well can we predict POC export?

Southern Ocean 170° W comparisons

Carbon Flux-field estimates

Upper Ocean C Flux
mol C m⁻² yr⁻¹

0 2 4 6
0 2 4 6

LATITUDE S

Seabed 1000 m
APF

100 m

Laws et al. 2000
Schlitzer, 2002

Carbon Flux-model estimates

Upper Ocean C flux
mol C m⁻² yr⁻¹

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LATITUDE S

Seabed 1000 m
APF

100 m

w/AESOPS
PProd

Inverse model

Temp. dependent
food web model

Nelson et al. 2002

Moore et al. 2002

Moore, Doney,
Lindsay, in prep.
Estimates of Shallow Export flux from Southern Ocean

Extrapolations to all waters >50° S

Measured AESOPS- 1.6 Gt C yr\(^{-1}\)
   one annual cycle along 170°W; peak at S. of APF
Laws- 0.6 Gt C yr\(^{-1}\)
   \(>2\)x higher with new AESOPS Primary Productivity
Schlitzer- 1.0 Gt C yr\(^{-1}\)
   no peak near Polar Front
Moore- ___
   1-D vs. 3-D physics important; Fe and multi-limitations

Estimates of Shallow Export flux from Southern Ocean

Extrapolations to all waters >550° S

Measured AESOPS- 1.6 Gt C yr\(^{-1}\)
   one annual cycle along 170°W; peak at S. of APF
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Model derived budgets of upper ocean C export are converging on global averages around 8-12 Gt C yr\(^{-1}\), however-

- Very few measurements on appropriate time/space scales
- Controls are poorly understood, so predictions with global change are unconstrained
- Models don’t include seasonal/episodic events
What does the future hold?

Methods Matter!

- New developments in sampling POC & particle flux
  - Instrumented floats
  - Neutrally buoyant sediment traps
  - Satellite products - POC; food web info

- Particle geochemistry important

- Process studies needed to elucidate particle flux controls
  - Lagrangian time-series w/ ecology & biogeochemistry

- Biogeochemical models with improved functional ecology

- Inverse models for global balances

- Look deeper in the mesopelagic - “Twilight Zone”
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Too many to thank & credit for ideas, inspiration, challenges…