Phytoplankton to the Ocean's Biological Pump: How Far Have We Come & How Far Do We Have To Go?

Dave Siegel – UC Santa Barbara

Help from …
Mike Behrenfeld – Oregon State
Ken Buesseler & Scott Doney – WHOI
Emmanuel Boss - UMaine
Sevrine Sailley – Plymouth Marine Lab
Phil Boyd – Univ. Tasmania
Stéphane Maritorena, Norm Nelson & Erik Fields – UCSB
EXPORTS Science Plan Writing Team

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The Global Carbon Cycle

IPCC AR5 [2013]
The Global Carbon Cycle

- Marine biota are 3 PgC, yet net primary production is 50 PgC y^-1 (rapid turnover - weeks)
- Biological pump exports 13 PgC y^-1 from surface ocean to depth
- Nearly all exported C is remineralized to DIC or retained at depth as DOC
  Sequestration times range from months to millennia
The Biological Pump is Complicated
Need to understand, quantify & predict ecosystem processes that transfers C to depth
Need to improve estimates of carbon export from the euphotic zone (4 to 13 Pg C y\(^{-1}\))

Physical Transport
0.5 - 2.5 Pg C y\(^{-1}\)

Sinking Flux
4 - 8 Pg C y\(^{-1}\)

Migration Flux
0.5 - 1.5 Pg C y\(^{-1}\)
Need to quantify attenuation of the export flux within the twilight zone which controls long-term C sequestration.
Biological Pump

- Food web processes export organic matter from the surface ocean to depth
  *Pathway for rapid C transport against a gradient of increasing inorganic C with depth*

- This export is rapidly attenuated beneath the surface ocean where it is remineralized
  *Vertical attenuation scale is important for quantifying ocean C sequestration*

- Global C export estimates range from 4 to 13 PgC y\(^{-1}\) (predicting sequestration depths is worse…)
  *We must do better*
What Are Our Present-day Capabilities?

Annual Chl-a Concentration

NPP-VIIRS
Year = 2014

Annual Net Primary Production

VGPM MODIS/Aqua
Year = 2007
Present-day Capabilities

- Present ocean color satellite data provide long-term, consistent estimates Chl & NPP
- Chl & NPP do not describe carbon export or its vertical attenuation with depth
- Chlorophyll is often a poor index for phytoplankton C biomass
  - Colored DOM interference
  - Chl:C is f(light, nutrients, species, …)
- Most NPP models are empirical (& not very good…)
  - Recent models are mechanistic (& hopefully better…)
The Pelagic Food Web & C Export

Sigman & Hain [2012] Nature Education
Pelagic Food Webs & C Export

- Size is important
- Two sinking pathways: fecal & algal
- NPP by large phyto leads to algal export
- Grazing leads to fecal export
A Mechanistic Approach…

Observational Requirements:
NPP, phytoplankton size, grazing, …

\[ \text{AlgEZ} = f_{\text{Alg}} \times NPP_L \]

\[ \text{FecEZ} = (f_{\text{FecS}} \times \text{Grz}_S + f_{\text{FecL}} \times \text{Grz}_L) \times Z_{\text{eu}} \]

Following Michaels & Silver (1988), Boyd & Stevens (2002) & many more...
Remote Sensing of Particle Size Distribution

- PSD modeled as a function of the particle backscatter spectrum using Mie theory
- Enables partitioning of Phyto C & NPP into size classes
- Patterns follow expectations
  - Pico’s dominate oligotrophic regions
  - Micro’s are found only in high latitudes & upwelling regions

Loisel et al. [2007] *JGR-Oceans*
Kostadinov et al. [2009] *JGR-Oceans*
Kostadinov et al. [2010] *Biogeosciences*
Remote Sensing of Phytoplankton Carbon

• Phytoplankton carbon modeled using satellite optical backscatter
• Satellite obs Illustrate importance of photo-acclimation on Chl:C
• Validated by flow cytometer observations of phytoplankton C

Diagnosing Grazing Rates

- Upper layer ($Z_{ML}$) phytoplankton biomass budget

\[
\frac{dP_i}{dt} = \frac{NPP_i}{Z_{eu}} - Grz_i - m_i P_i - \frac{AlgEZ_i}{Z_{eu}} - Detrn(Z_{ml}, P_i)
\]

- Solve for $Grz_S$ & $Grz_L$ by measuring or modeling terms in Phyto C budget

- Dominant balance is between NPP & Grazing
A Mechanistic Approach…

Siegel et al. GBC [2014]
Global Mean Sinking Carbon Export

Export Flux
- Global: 5.9 PgC y\(^{-1}\)
- Robust to changes in parameters or input data
- Validated using regional export values \((^{234}\text{Th}; r^2=0.75)\)

Efficiency \(=\) Export / NPP
- Global: 10%
- Oceanographically sensible patterns...

Siegel et al. GBC [2014]
But, there Are Other Export Pathways...

Physical Transport of POC & DOC

Sinking Particle Flux

Vertical C Transport by Diel Migrating Zooplankton
Need to Know Ultimate Fate of Exported C

- Twilight zone ecology is poorly quantified
  Only recently were C budgets closed (Giering et al. 2014)
- Evidence that biomineralization is important
  Opal, carbonate & mineral dust ballasting of sinking material is thought to be important
  Links processes in the twilight zone with the upper ocean
Steps Forward…

• Improve, maintain & extend satellite data obs
  – PhytoC, NPP, PSD, NCP / Export, etc.

• Couple satellite data & models
  – Predictive understanding of export & fate of NPP
  – Planned NASA EXPORTS Field Campaign

• Implement novel satellite sensing tools
  – PACE & global hyperspectral ocean color observations
  – Advance models that retrieve both PSD & PFTs!
EXports

EXport Processes in the Ocean from RemoTe Sensing
What is EXPORTS?

A community-vetted science plan for a NASA field campaign

**Goal**: Predict the export & fate of ocean NPP from satellite & other observations

**Hypothesis**: Fate of ocean NPP is regulated by the state of the surface ecosystem

**EXPORTS Science Plan is presently under consideration for implementation by NASA**
PACE will improve our understanding of ocean ecosystems and carbon cycling through its...

- **Spectral Resolution** – 5 nm resolution to separate constituents, characterize phytoplankton communities & nutrient stressors
- **Spectral Range** – Ultraviolet to Near Infrared covers key ocean spectral features
- **Atmospheric Corrections** – UV bands allow ‘spectral anchoring’, SWIR for turbid coastal systems, polarimeter option for advanced aerosol characterization
- **Strict Data Quality Requirements** – Reliable detection of temporal trends and assessments of ecological rates on global scales
Advancing PSD Retrievals

• Mie calculations of \( a_p(\lambda) \) and \( b_{bp}(\lambda) \) for different linear PSD slopes (normalized to 490 nm)

\[
\frac{a_p(\lambda)}{a_p(490)} \quad \text{and} \quad \frac{b_{bp}(\lambda)}{b_{bp}(490)}
\]

• Use both \( \Delta \)'s in \( b_{bp}(\lambda) \) slope & \( a_p(\lambda) \) shape to constrain PSD slope & retrieve (maybe) more…

• Need hyperspectral data to do this!!!
Phytoplankton Functional Types

Different phytoplankton functional types have different pigments and absorption spectra.

Dierssen et al. L&amp;O [2006]
Phytoplankton Functional Types

- SCHIAMACHY was an atmospheric chemistry mission with submicron resolution
- Spectral matching is used to discriminate cyanobacteria & diatoms (need good spectral resolution)
- Imagine if a satellite (PACE!!) was actually designed to do this...

- PFT’s will provide info on the composition of export flux
- First step for quantifying export flux attenuation from satellite obs

Bracher et al. BGS [2009]
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