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

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The Global Carbon Cycle

Biological Pump

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\(^{-1}\))
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?

NPP-VIIRS Annual Mean for 2014 (ocean color webpage)
What Are Our Present-day Capabilities?

MODIS Annual Mean Net Primary Production rate for 2007 (VGPM)
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 (Siegel et al. RSE 2013)
  – 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, …

NPP_S, NPP_L

AlgEZ = f_{Alg} * NPP_L

Grz_S, Grz_L

TotEZ

Small → Large

FecEZ

FecEZ = (f_{FecS} * Grz_S + f_{FecL} * Grz_L) * Z_{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 PhytoC & 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 (\(^{234}\)Th; \(r^2=0.75\))

Efficiency \((=\text{Export}/\text{NPP})\)
- 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, PSD, NPP, Export, etc.
  - Almost 20 years of satellite ocean ecology obs

- Couple satellite data & models
  - Predictive understanding of export & fate of NPP
  - Proposed EXPORTS Field Campaign

- Implement novel satellite sensing tools
  - PACE & ocean profiling lidars

- Realize that satellite data may not be enough
  - Profiling floats and the ARGO array
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 under review

http://cce.nasa.gov/cce/ocean_exports_intro.htm
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
Phytoplankton Functional Types

Different phytoplankton functional types have different pigments and absorption spectra

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

- SCHIAMACHY was an atmospheric chemistry mission with submicron resolution
- Spectral matching is used to discriminate cyanobacteria & diatoms
- Imagine if SCHIAMACHY was actually designed to do this…

SCHIAMACHY PhytoDOAS

Oct-Nov 2005

Cyanobacteria

Diatoms

Bracher et al. BGS [2009]
Global POC from CALIOP Lidar

CALIOP lidar
- Backscatter at 532 and 1064 nm
- Polarization at 532 nm

- Designed for cloud and aerosol measurements
- Retrievals do not need to be tied to a solar orbit
- Suboptimal for ocean profiling

CALIPSO website: www-calipso.larc.nasa.gov

Behrenfeld et al. GRL [2013]
Airborne HSRL Retrievals of Particulate Backscatter & Diffuse Attenuation

Preliminary field validation is very encouraging

High Spectral Resolution Lidar
Chris Hostetler – NASA Langley

NASA’s 2014 SABOR Experiment in Gulf of Maine
ARGO Array

- Temperature & salinity profiles of the ocean interior
- Some floats have $O_2$, $NO_3$ & bio-optics (growing rapidly)
- Work underway to develop particle imagers

[Map showing 3847 floats as of 18-Apr-2015]
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  – We have (almost) 20 years of satellite ocean ecology

• Couple satellite data & food-web models
  – Predictive understanding of export & fate of NPP
  – Proposed EXPORTS Field Campaign

• Dream up novel satellite sensing tools
  – PACE & ocean profiling lidars

• Realize that satellite data may not be enough
  – Profiling floats and the ARGO array