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

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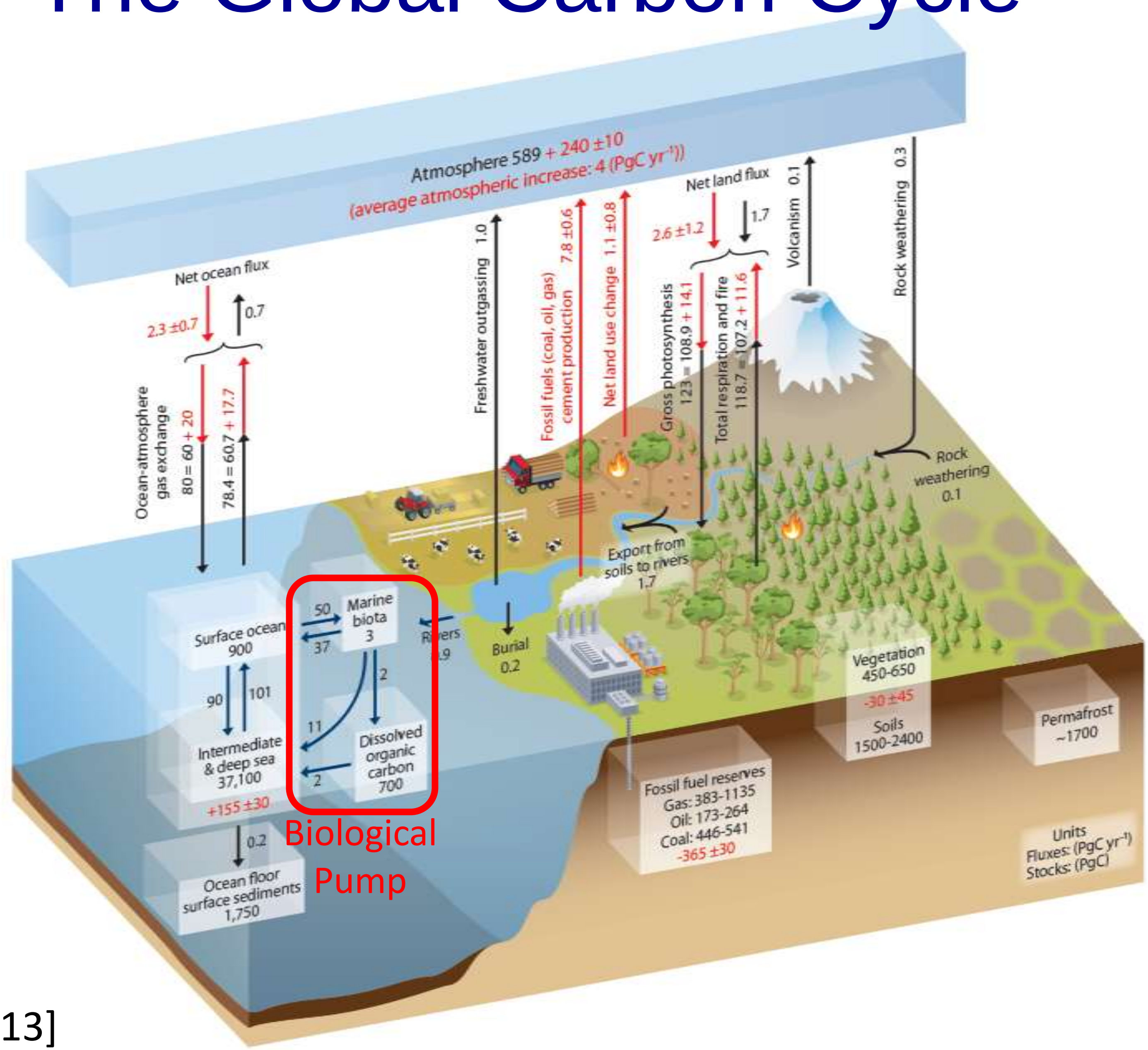
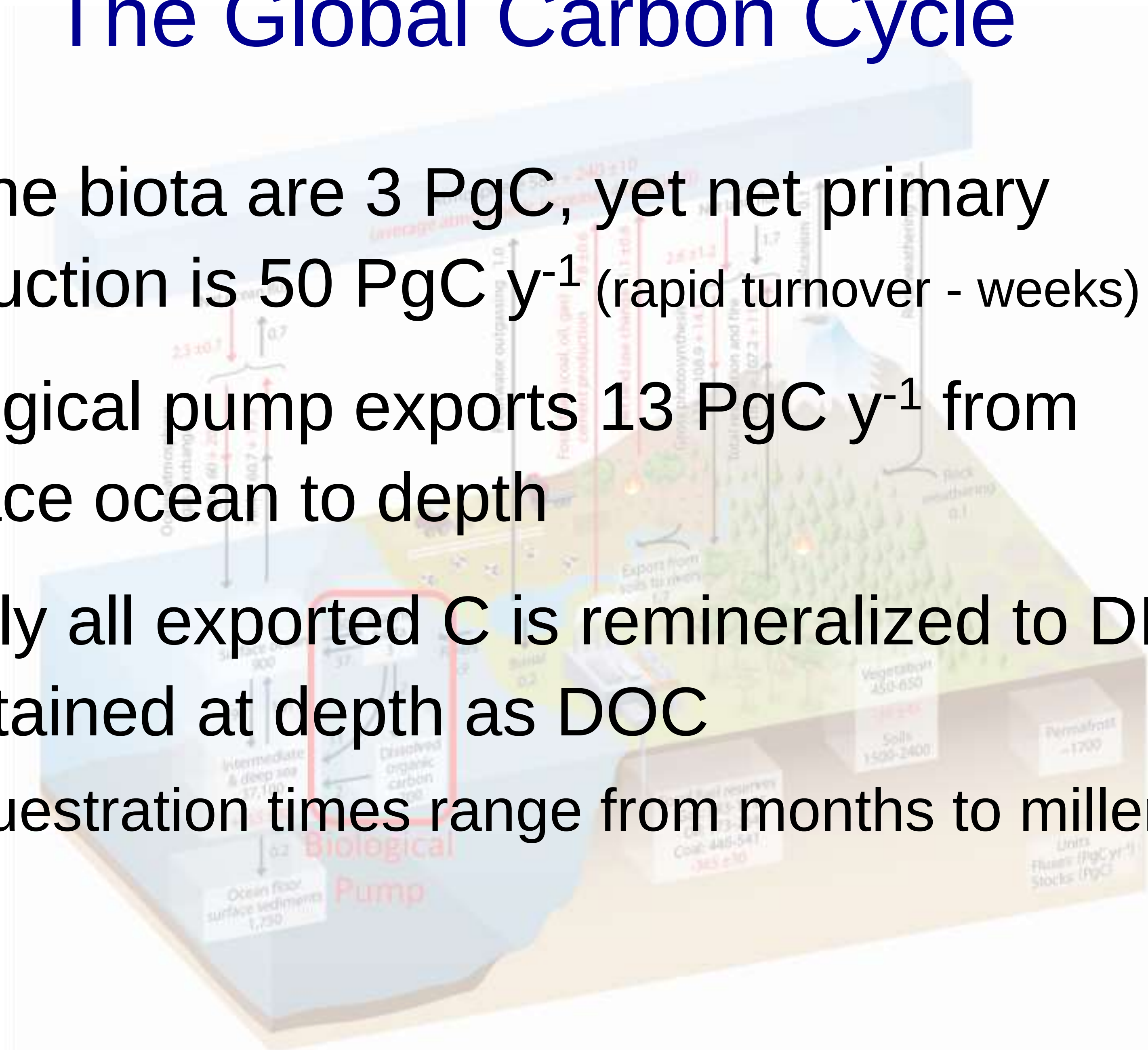
Support from NASA Ocean Biology & Biogeochemistry Program

The Global Carbon Cycle



IPCC AR5 [2013]

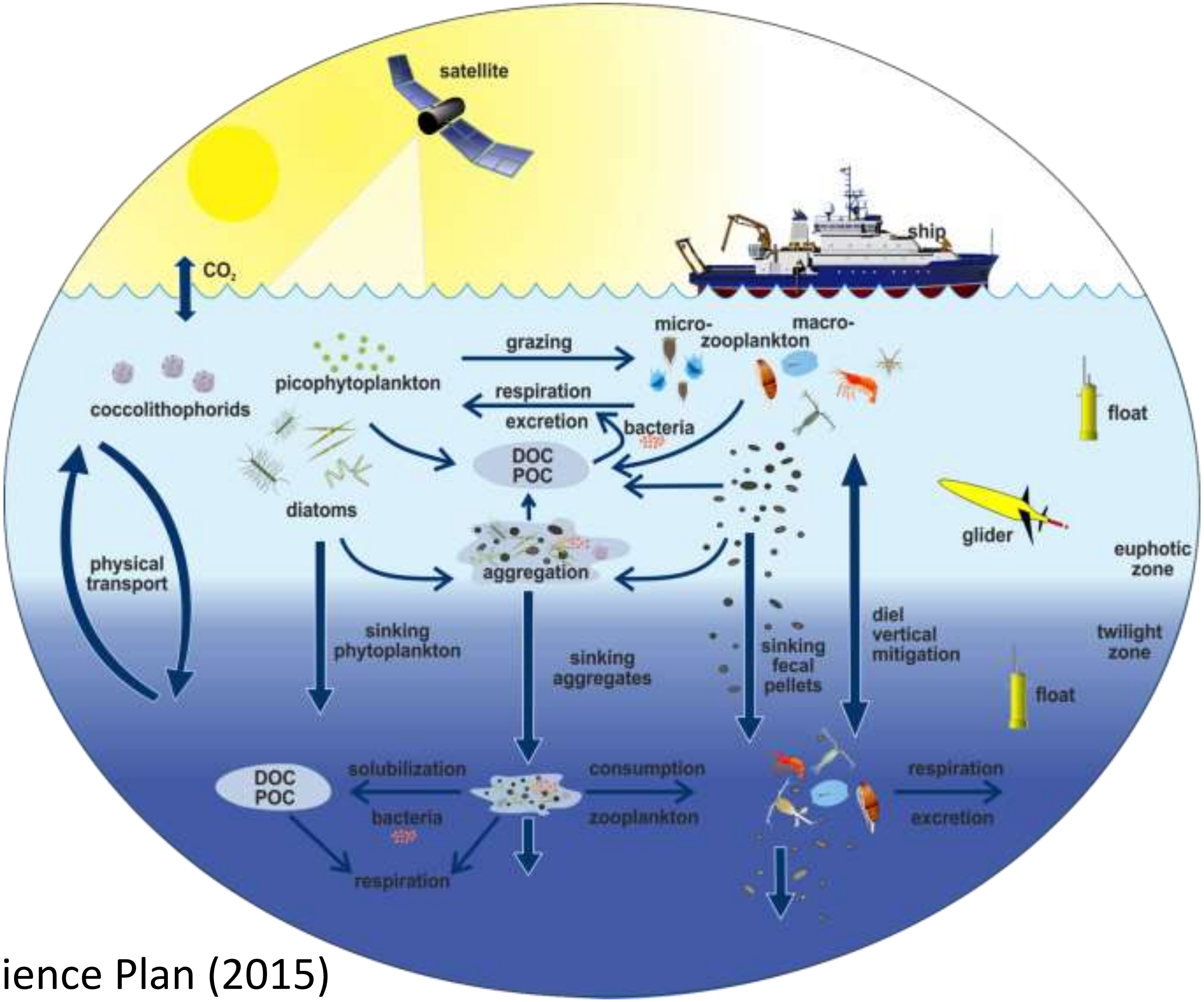
The Global Carbon Cycle



- 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

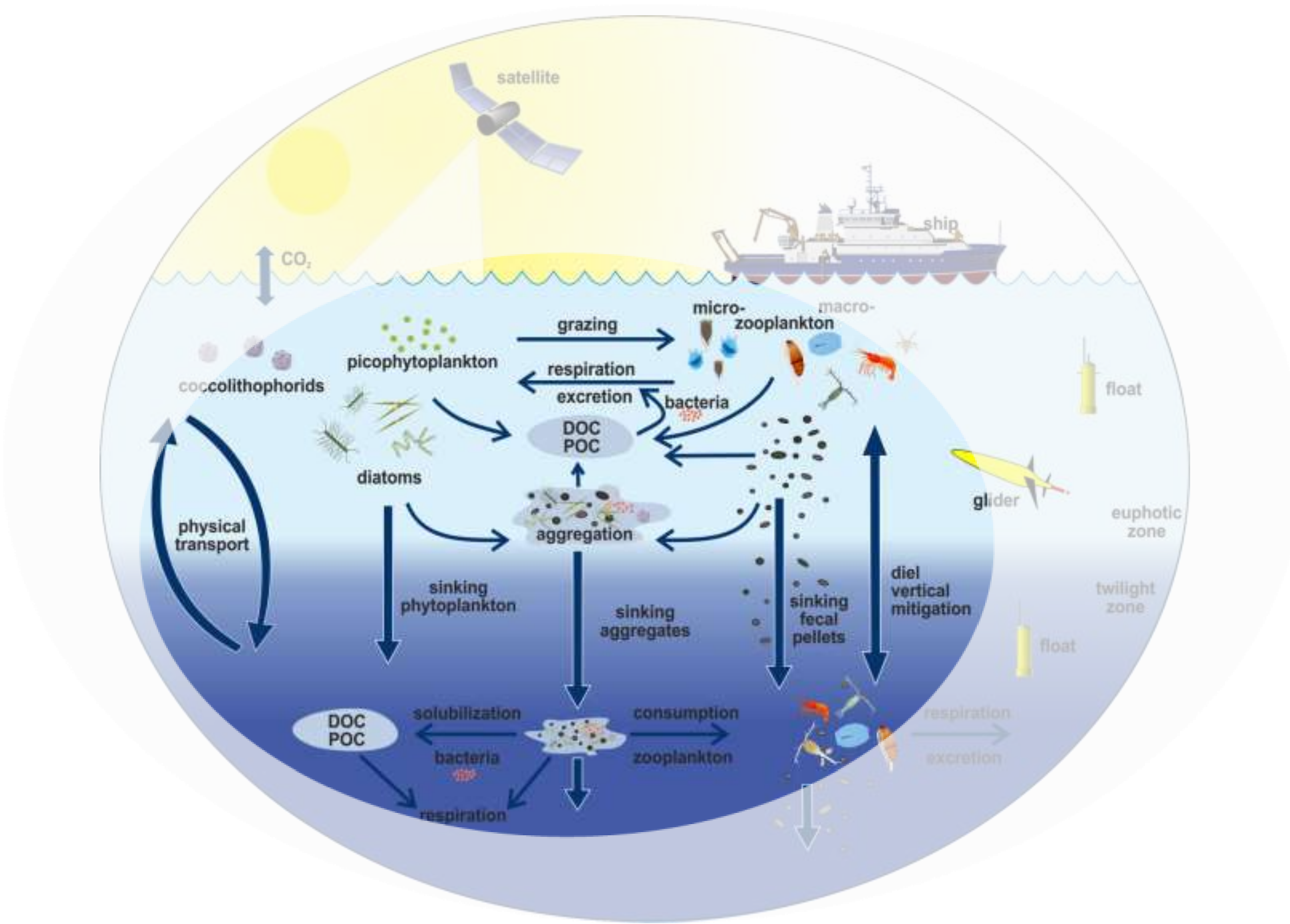
  Sequestration times range from months to millennia

The Biological Pump is Complicated



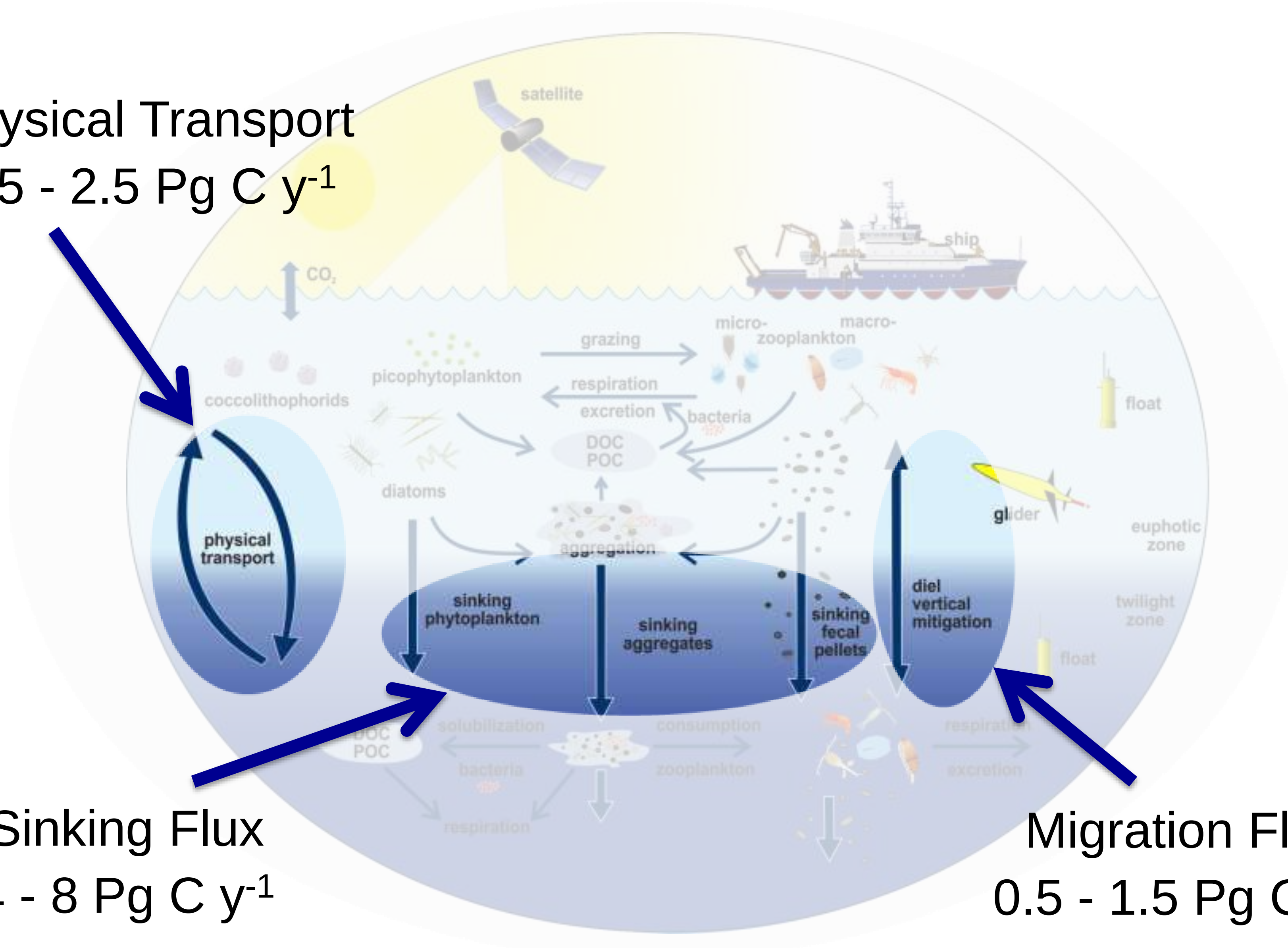
EXPORTS Science Plan (2015)

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})

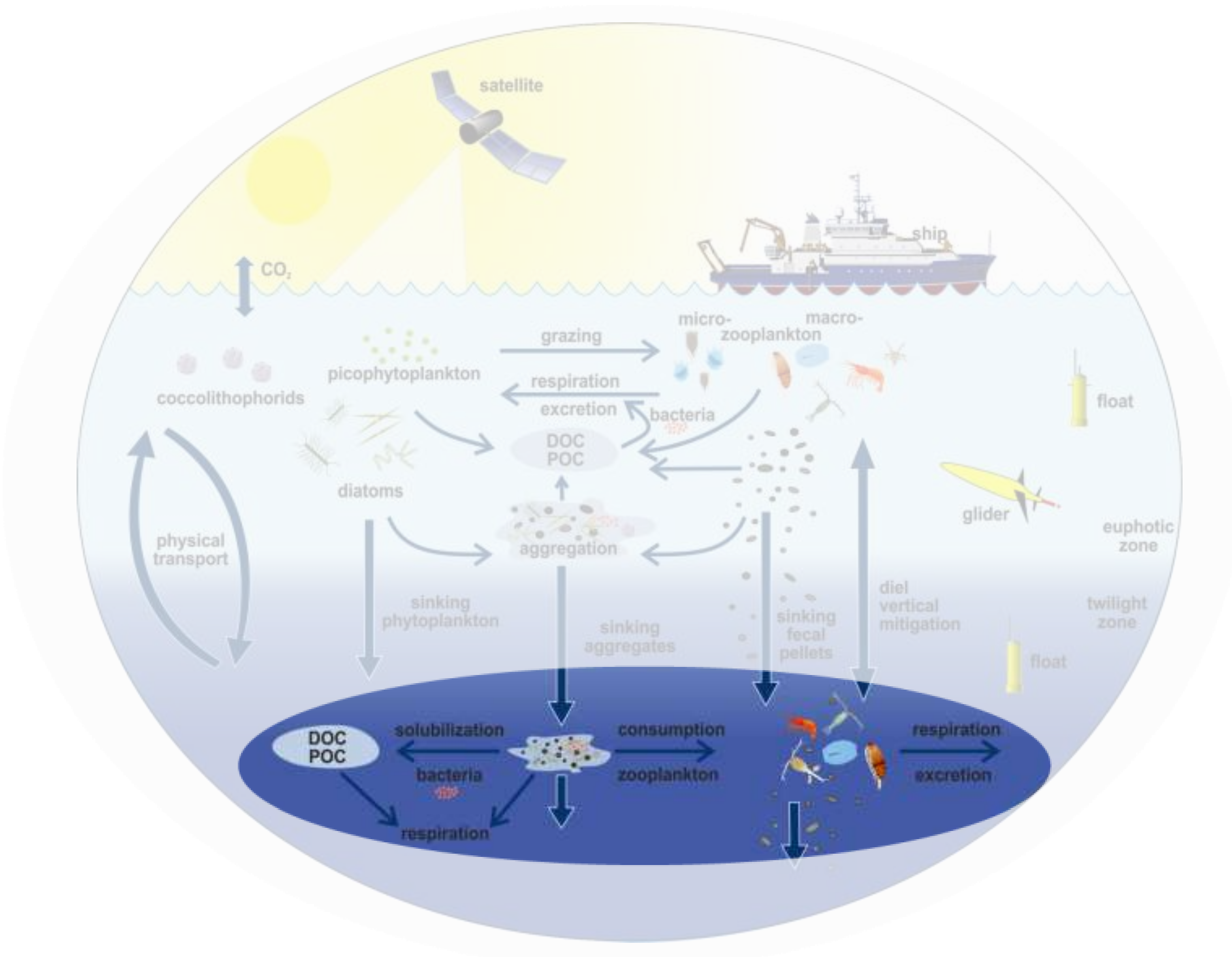
Physical Transport
0.5 - 2.5 Pg C y^{-1}



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

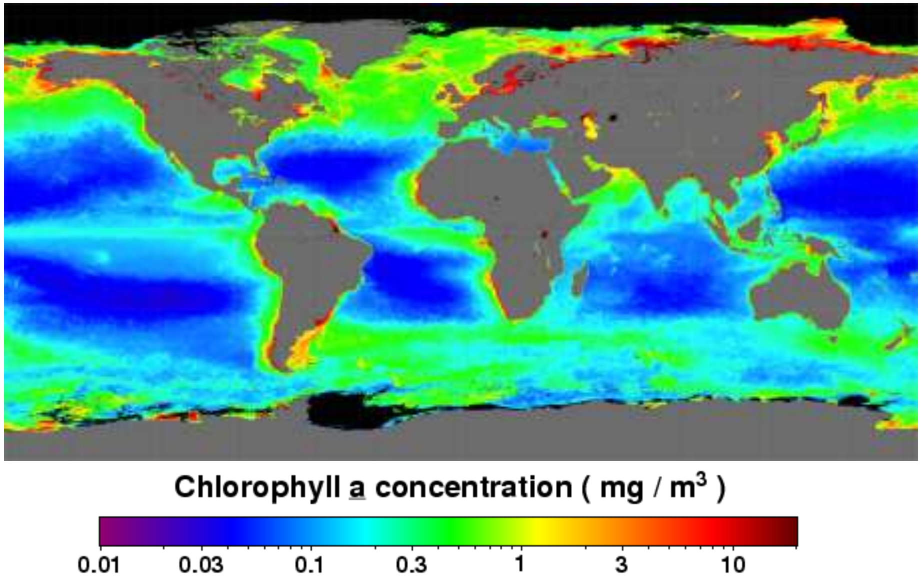
- This export is rapidly attenuated beneath the surface ocean where it is remineralized

  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…)

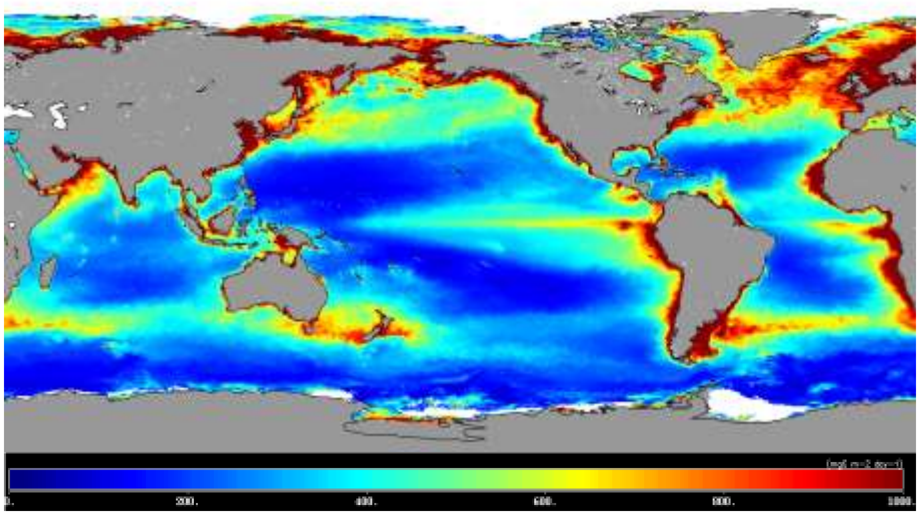
  We must do better

What Are Our Present-day Capabilities?



Annual Chl-a Concentration

NPP-VIIRS
Year = 2014



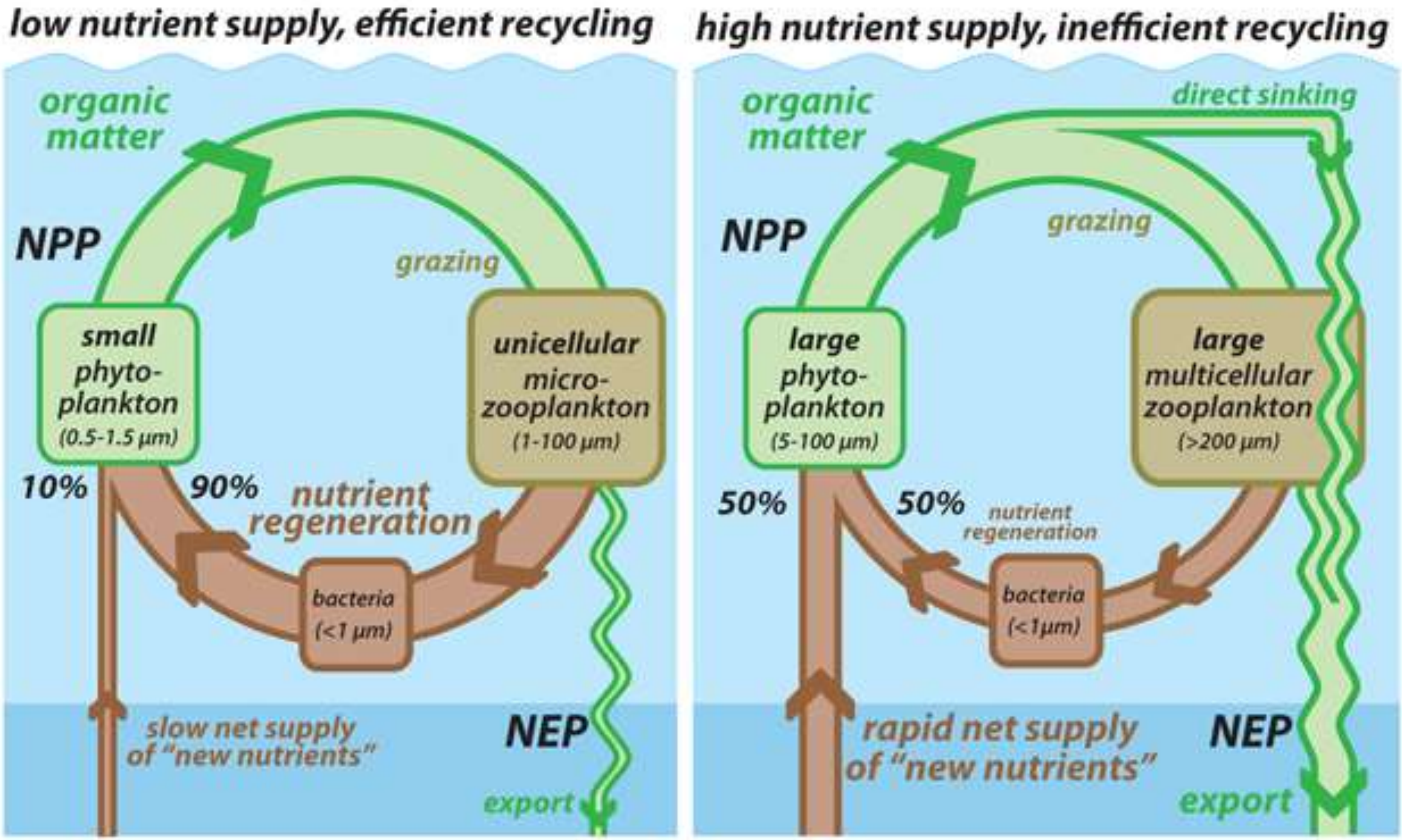
Annual Net Primary Production

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…)

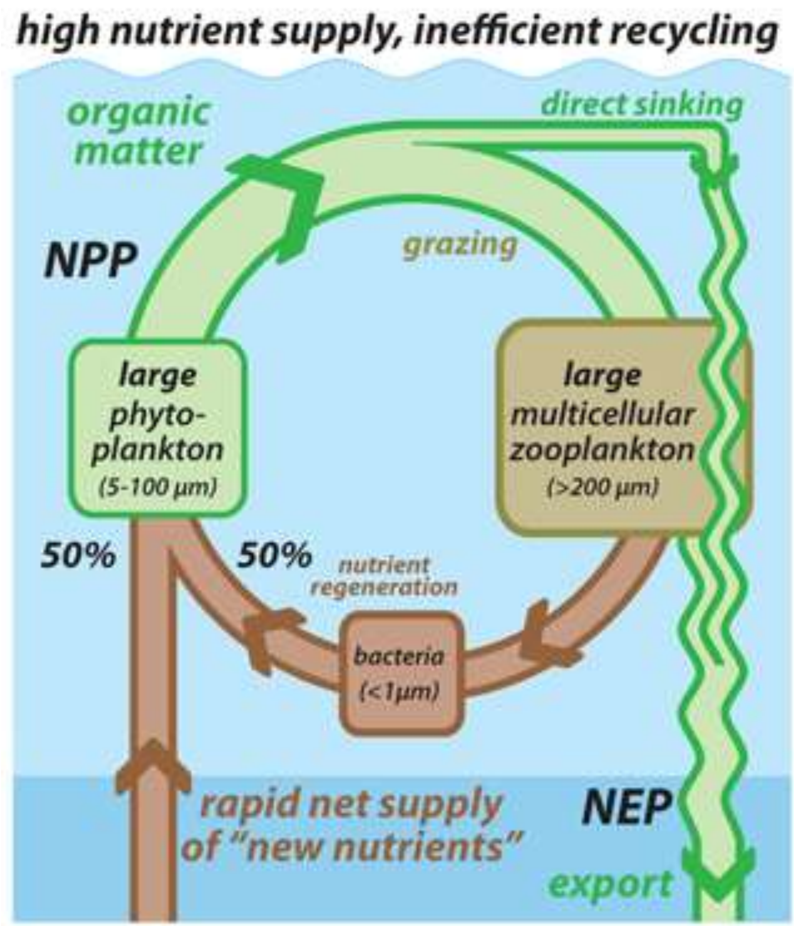
The Pelagic Food Web & C Export



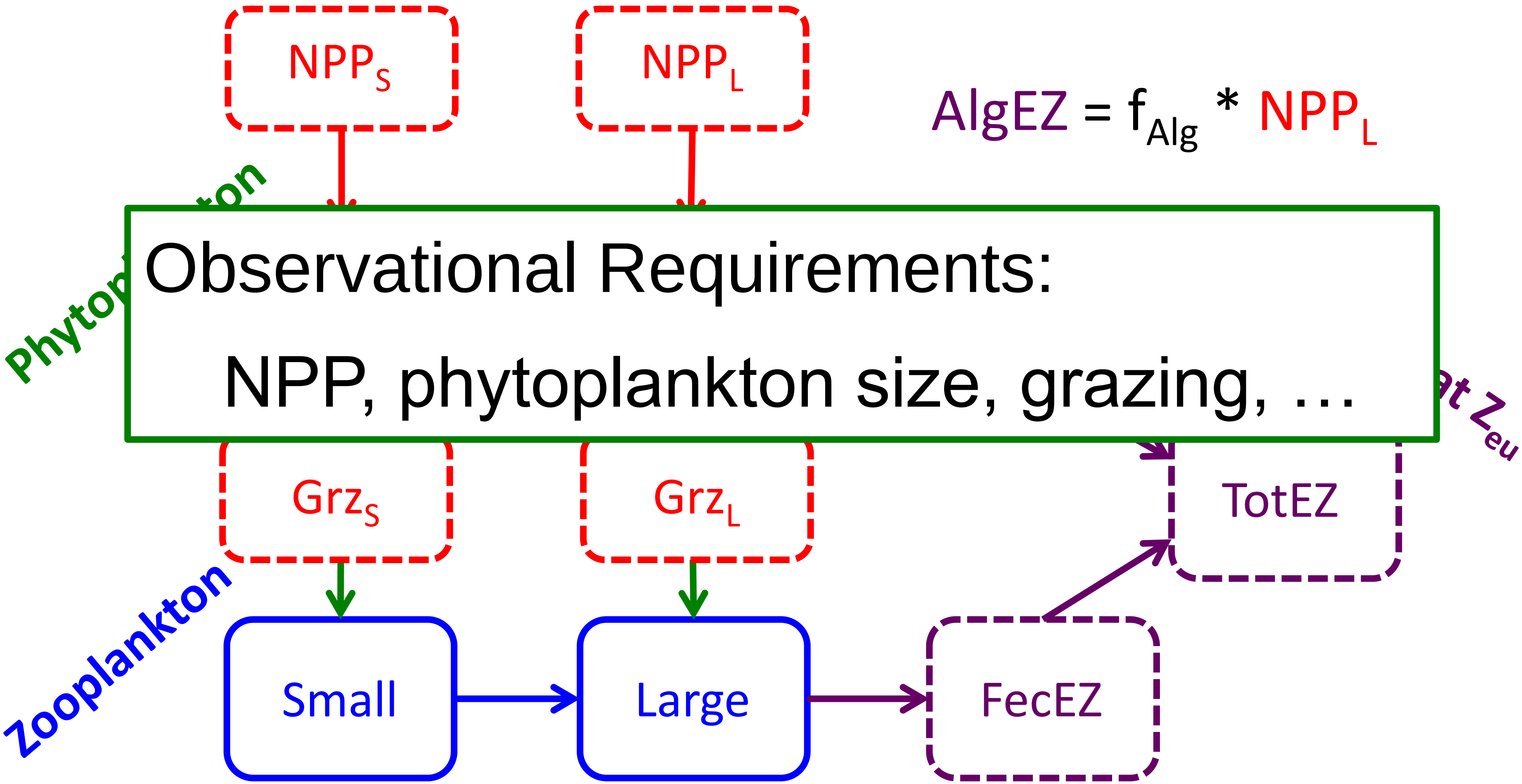
Sigman & Hain [2012] *Nature Education*

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…



$$AlgEZ = f_{Alg} * NPP_L$$

Observational Requirements:

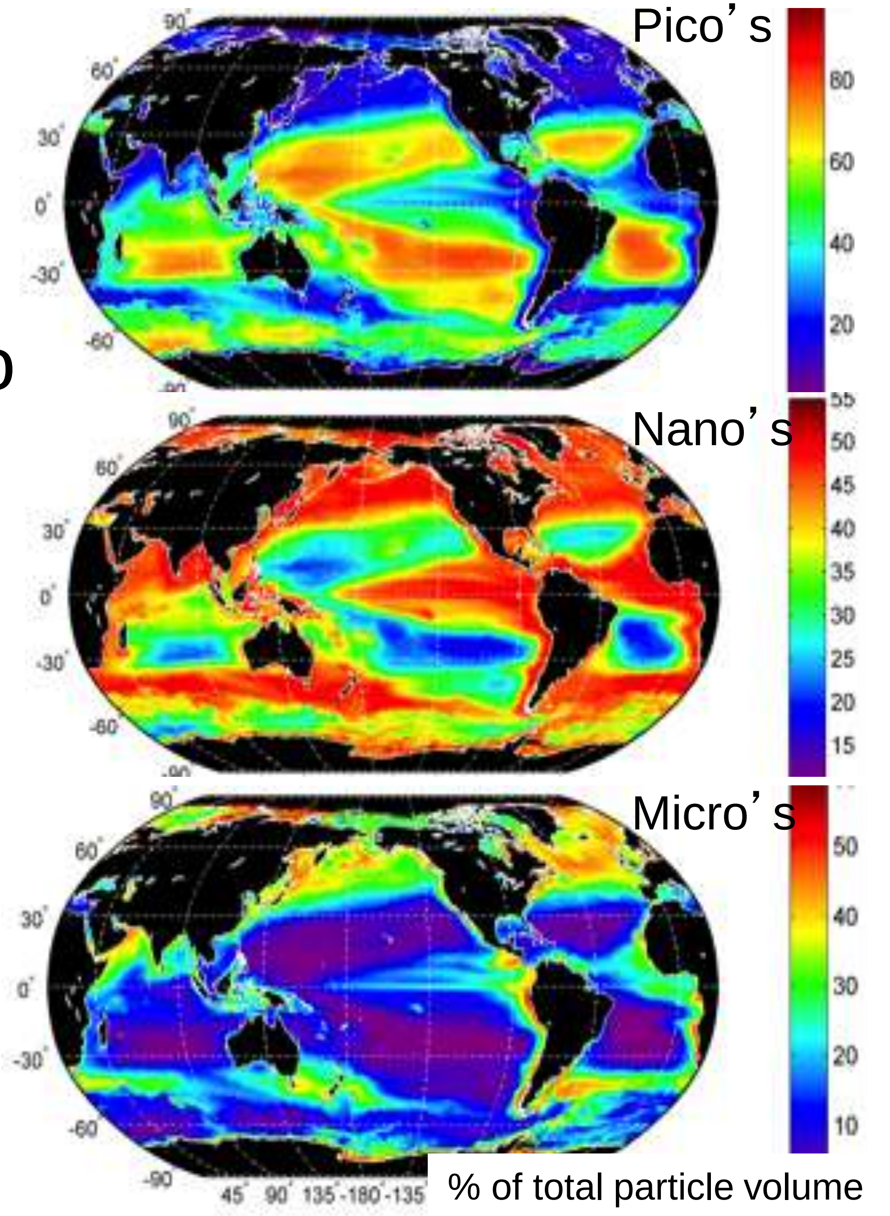
NPP, phytoplankton size, grazing, …

$$FecEZ = (f_{FecS} * Grz_S + f_{FecL} * Grz_L) * Z_{eu}$$

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 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*

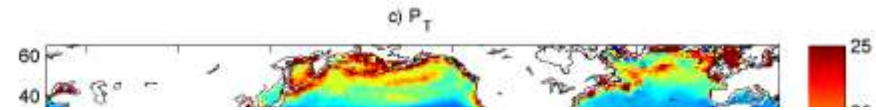
Remote Sensing of Phytoplankton Carbon

- 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

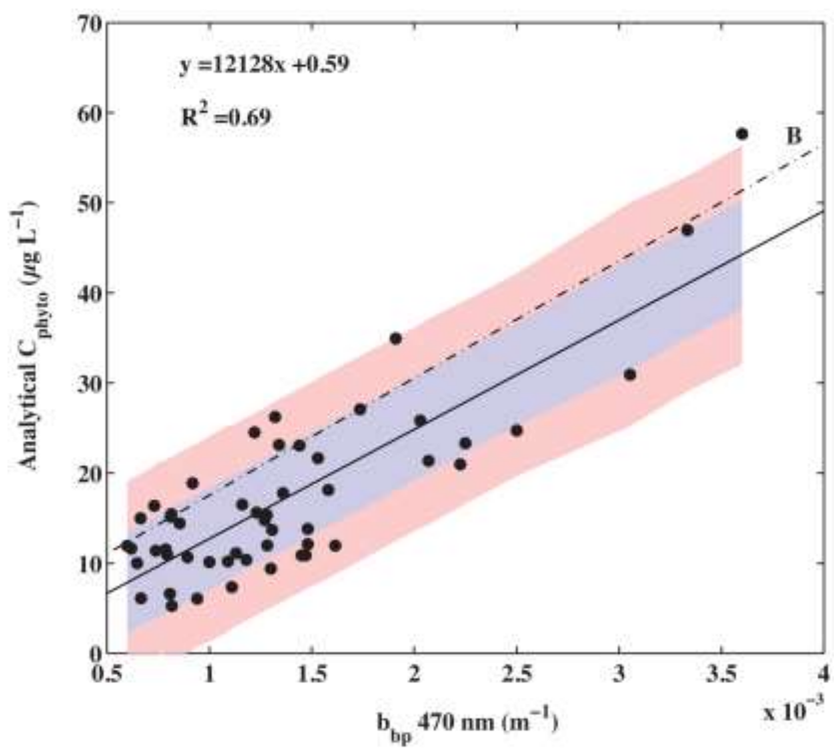
Phyto C

Latitude (ºN)

(mg C m⁻³)



Longitude (º)



Behrenfeld et al. [2005] *Global Biogeochem, Cyc.*
Siegel et al. [2013] *Rem. Sens. Environ.*
Graff et al. [2015] *Deep-Sea Research, Part I*

Diagnosing Grazing Rates

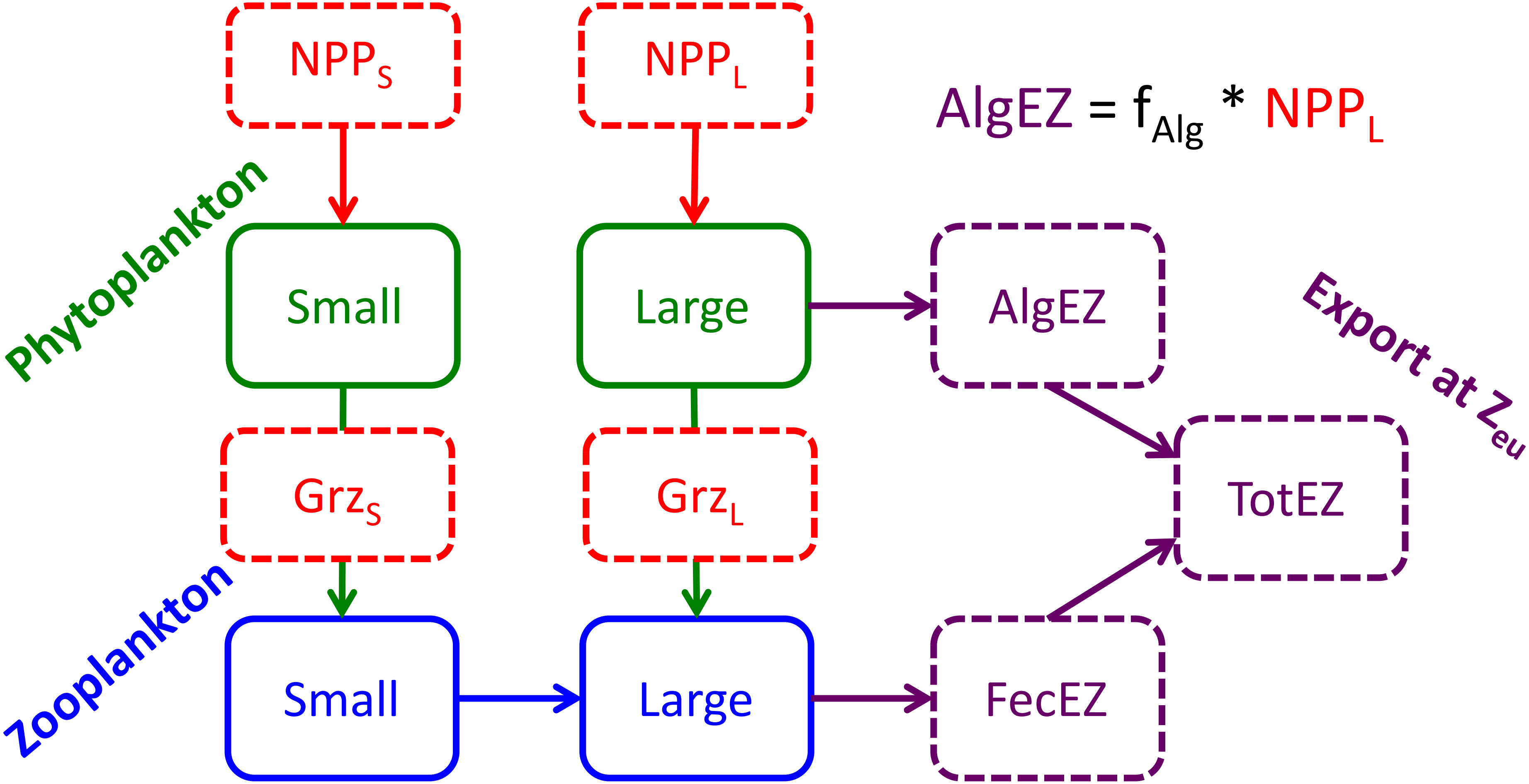
- Upper layer (Z_{ML}) phytoplankton biomass budget

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

unsteady | NPP/vol | grazing | mortality | direct sinking loss | detrainment

- Solve for Grz_S & Grz_L by measuring or modeling terms in Phyto C budget
- Dominant balance is between NPP & Grazing

A Mechanistic Approach…

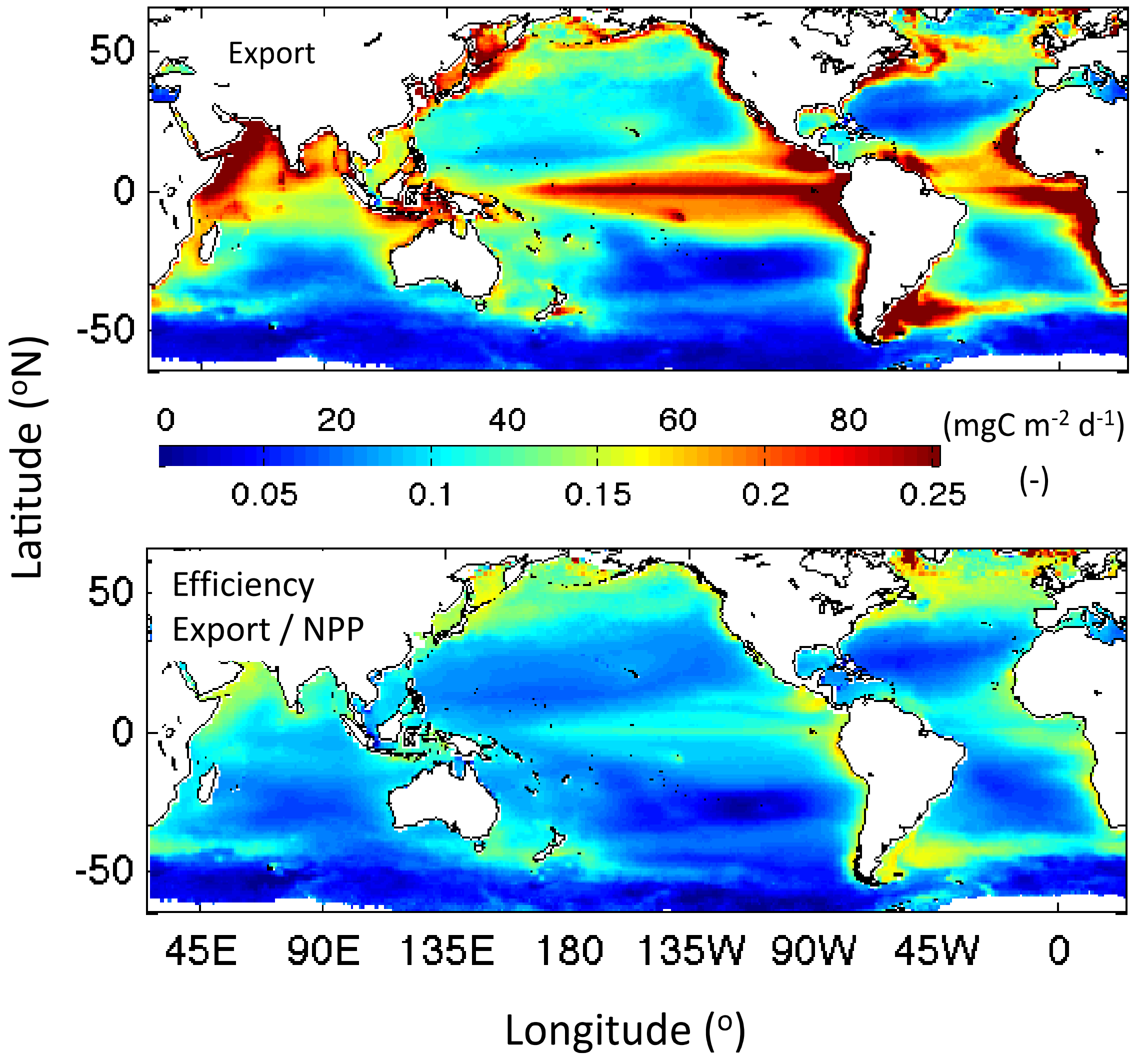


$$AlgEZ = f_{Alg} * NPP_L$$

$$FecEZ = (f_{FecS} * Grz_S + f_{FecL} * Grz_L) * Z_{eu}$$

Siegel et al. GBC [2014]

Global Mean Sinking Carbon Export



Siegel et al. GBC [2014]

Export Flux

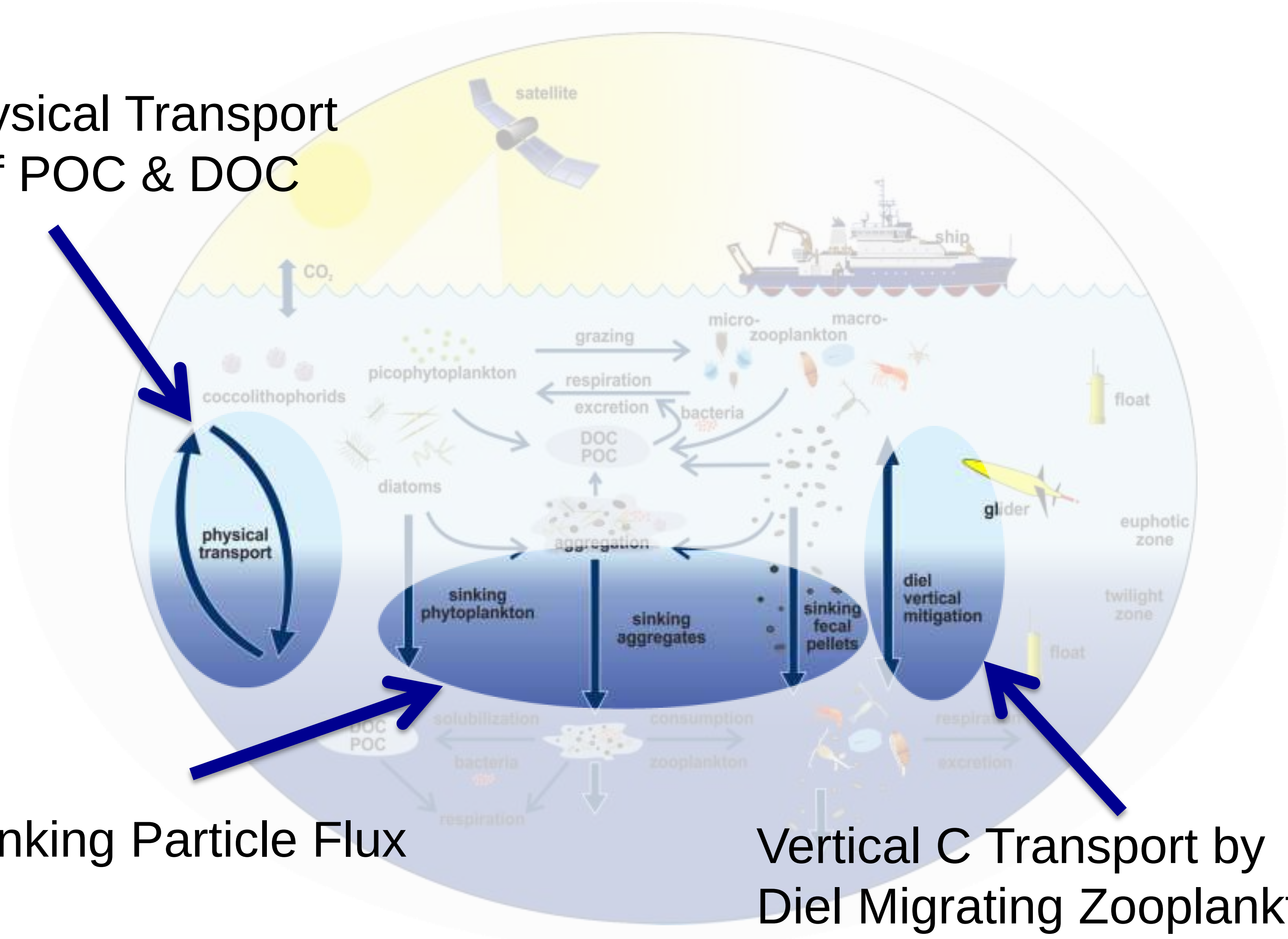
- Global: 5.9 PgC y^{-1}
- Robust to changes in parameters or input data
- Validated using regional export values (^{234}Th; r^2=0.75)

Efficiency (= Export / NPP)

- Global: 10%
- Oceanographically sensible patterns…

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

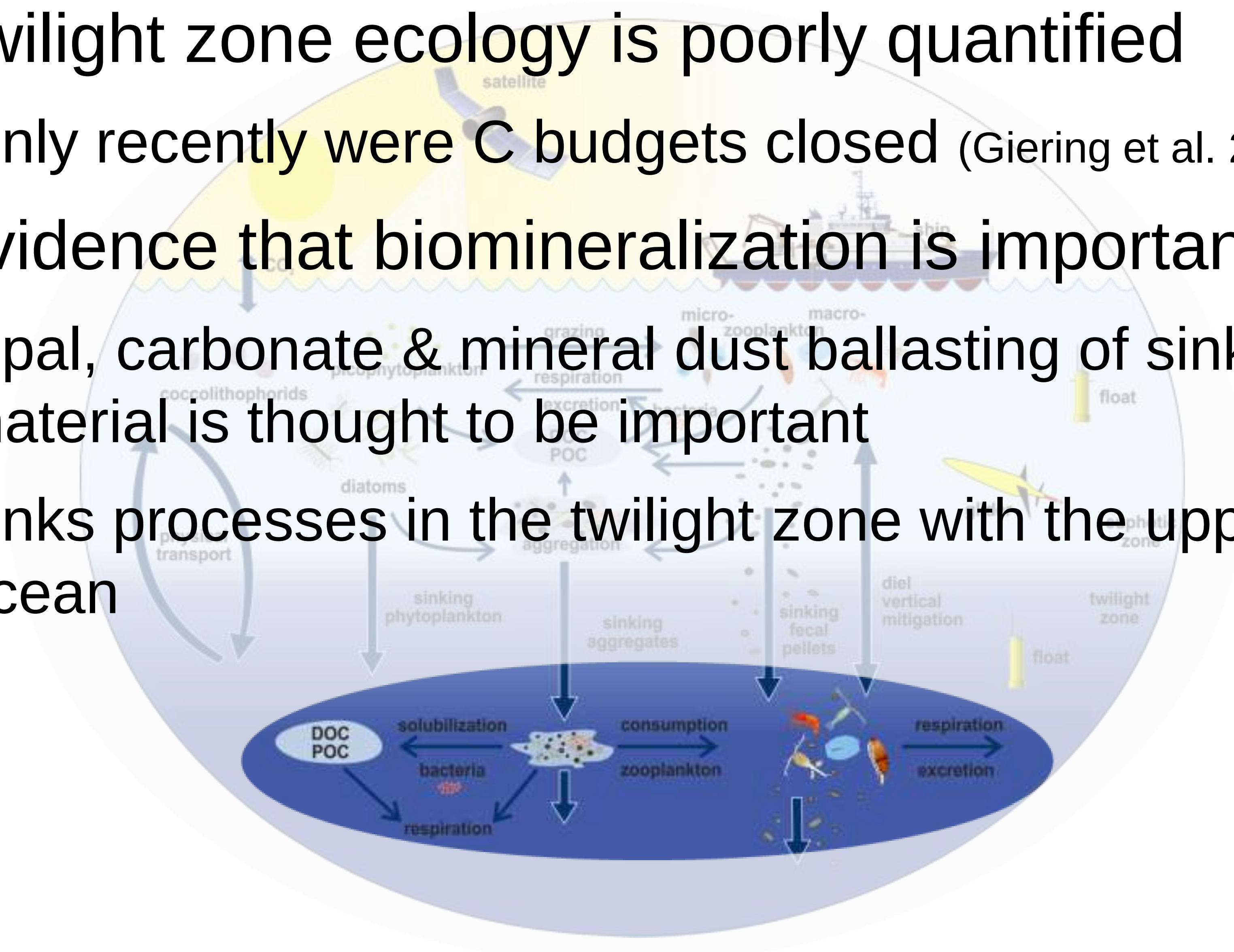
- Twilight zone ecology is poorly quantified

  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

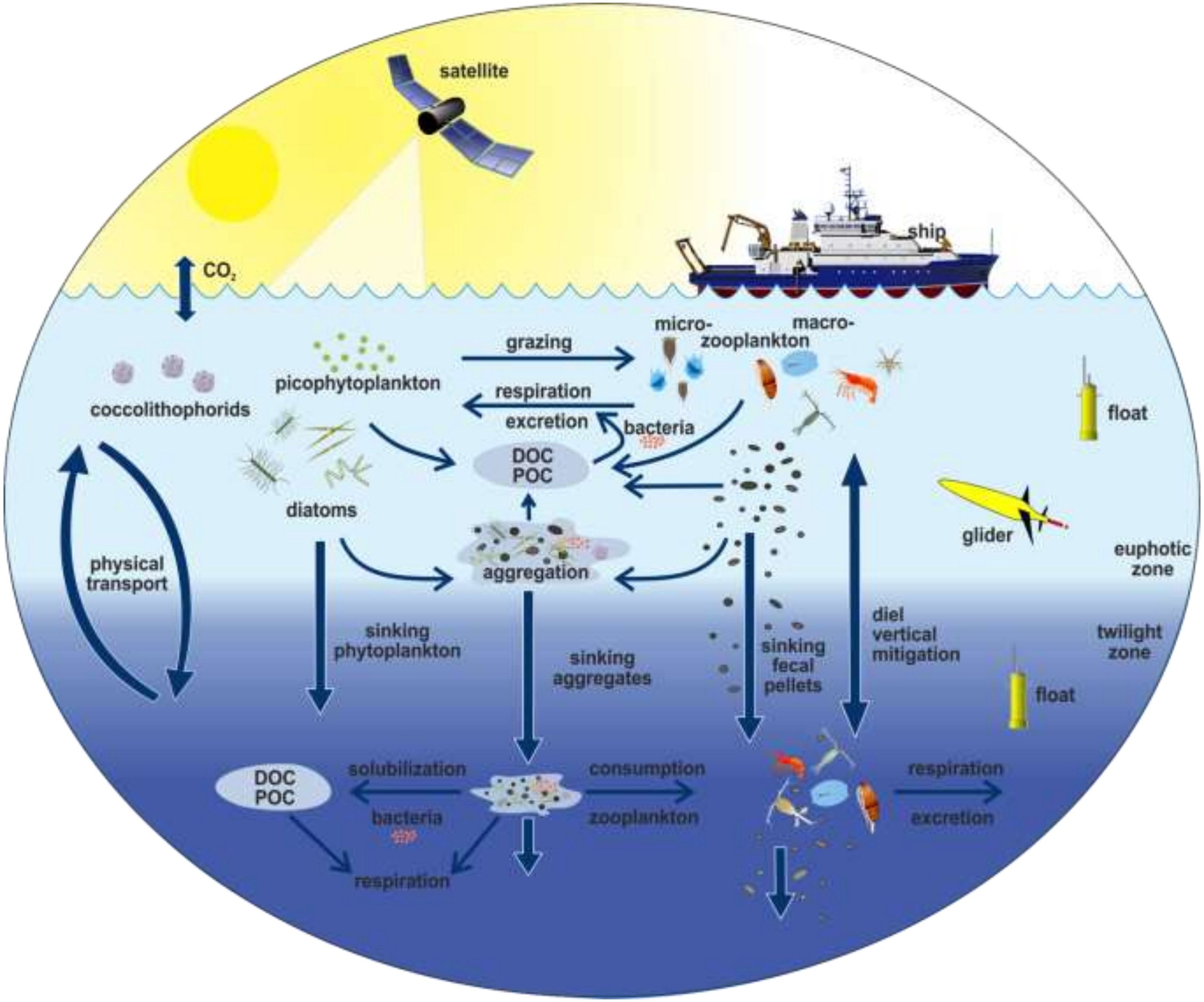


Steps Forward…

- 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 **P**rocesses in the **O**cean from **R**emo**T**e **S**ensing



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

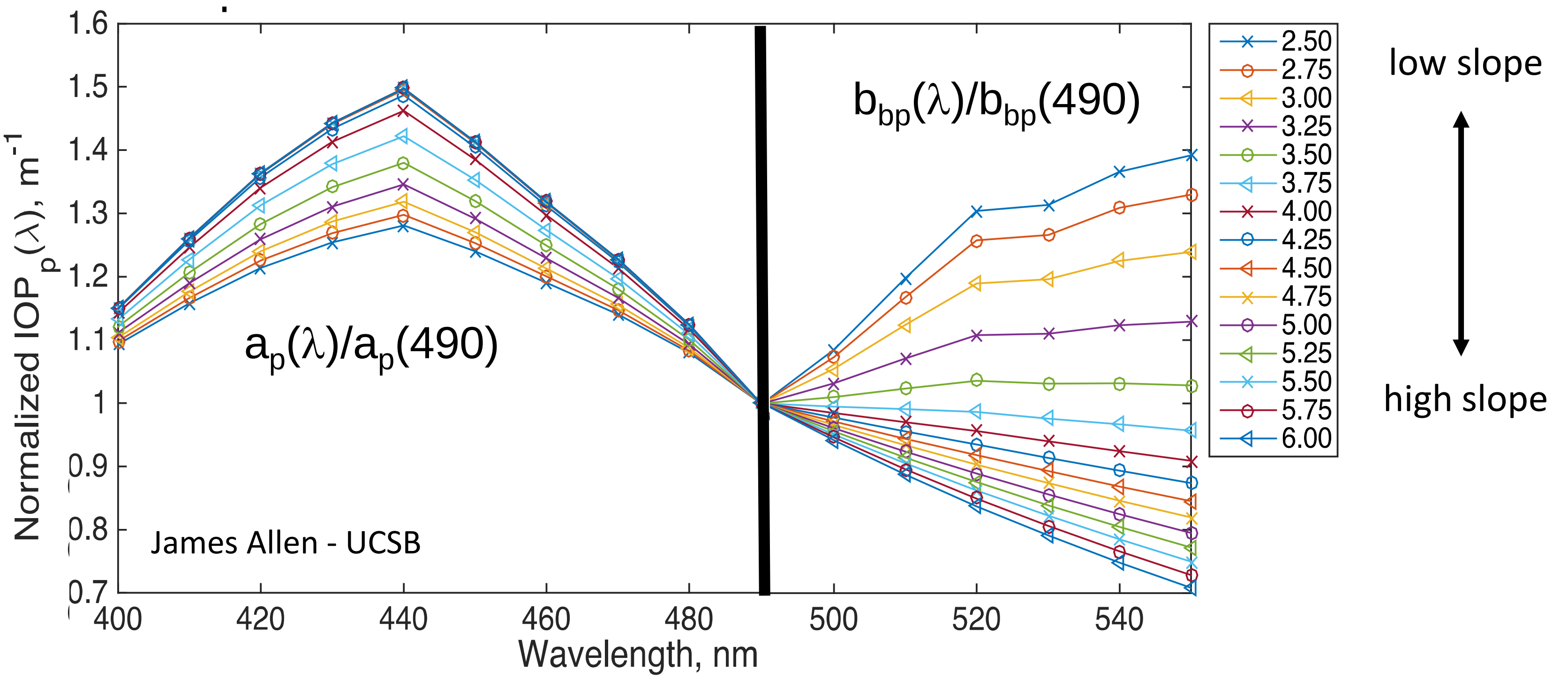
Pelagic and Coastal Ecosystems mission

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

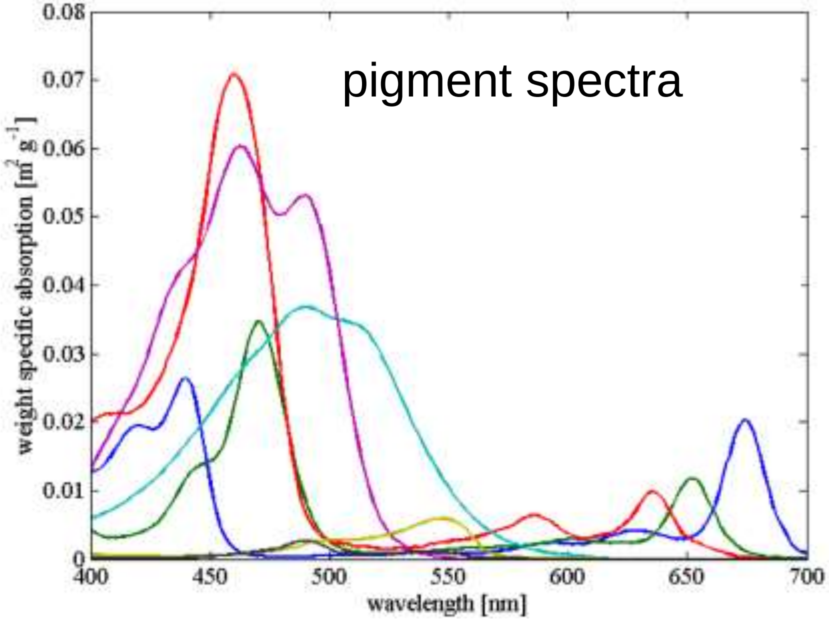
- Mie calculations of $a_p(\lambda)$ and $b_{bp}(\lambda)$ for different linear PSD slopes (normalized to 490 nm)

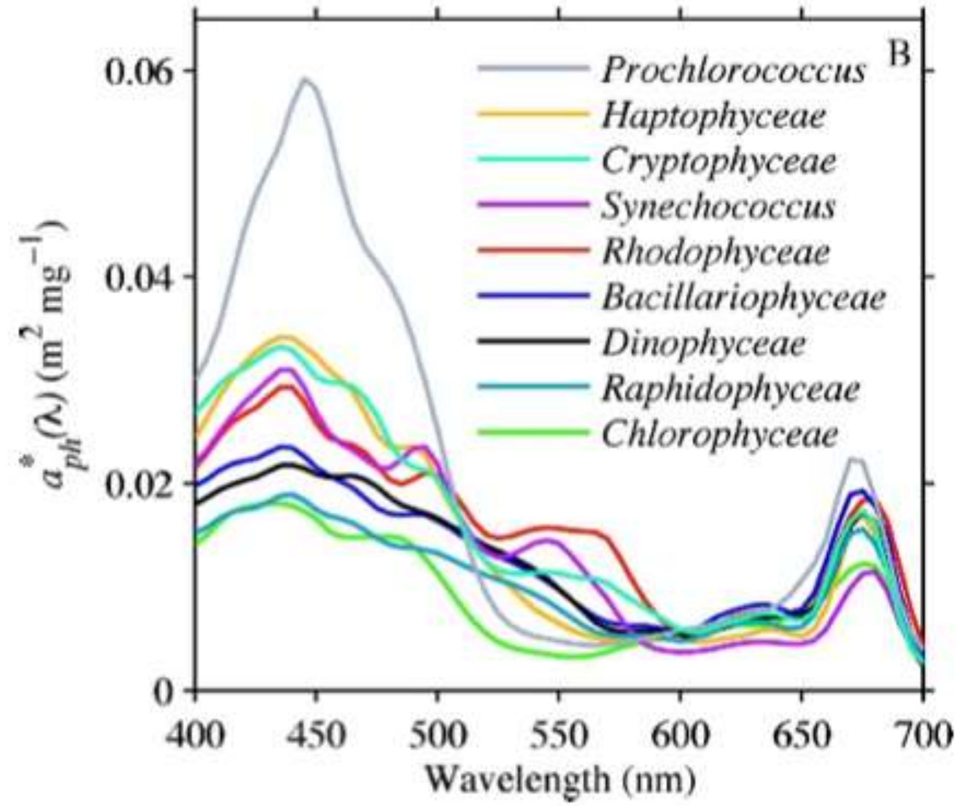


- Use both Δ's in $b_{bp}(\lambda)$ slope & $a_p(\lambda)$ shape to constrain PSD slope & retrieve (maybe) more…
- Need hyperspectral data to do this!!!

Phytoplankton Functional Types

Different phytoplankton functional types have different pigments and absorption spectra





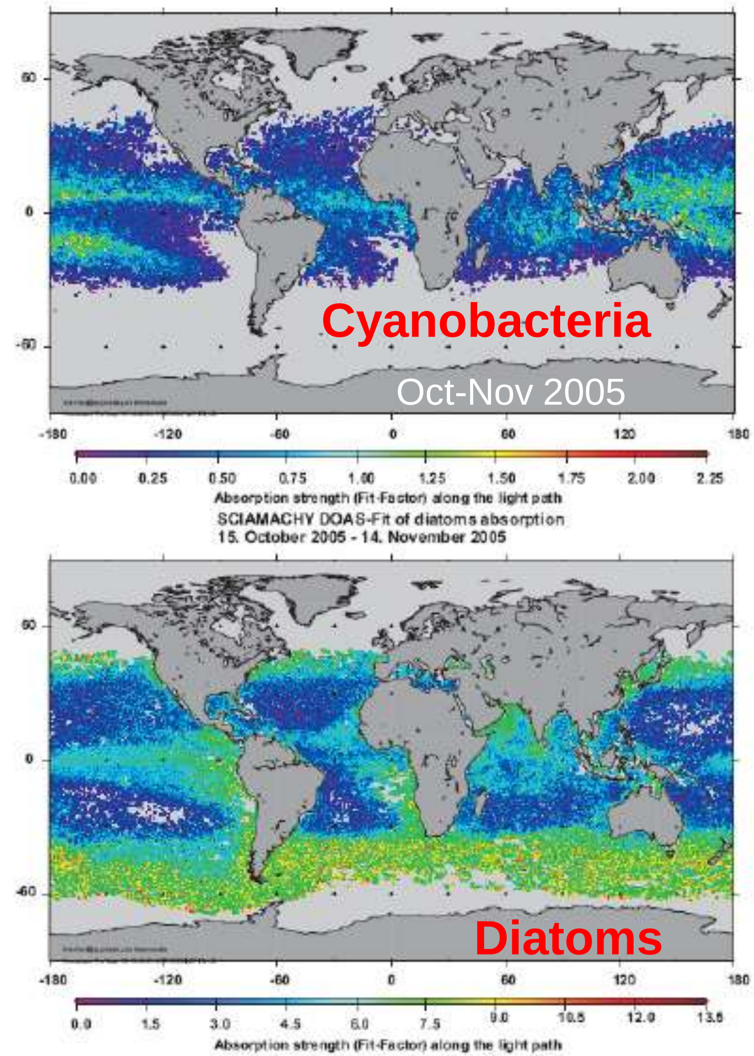
Dierssen et al. L&O [2006]

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

SCHIAMACHY PhytoDOAS



Bracher et al. BGS [2009]

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