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

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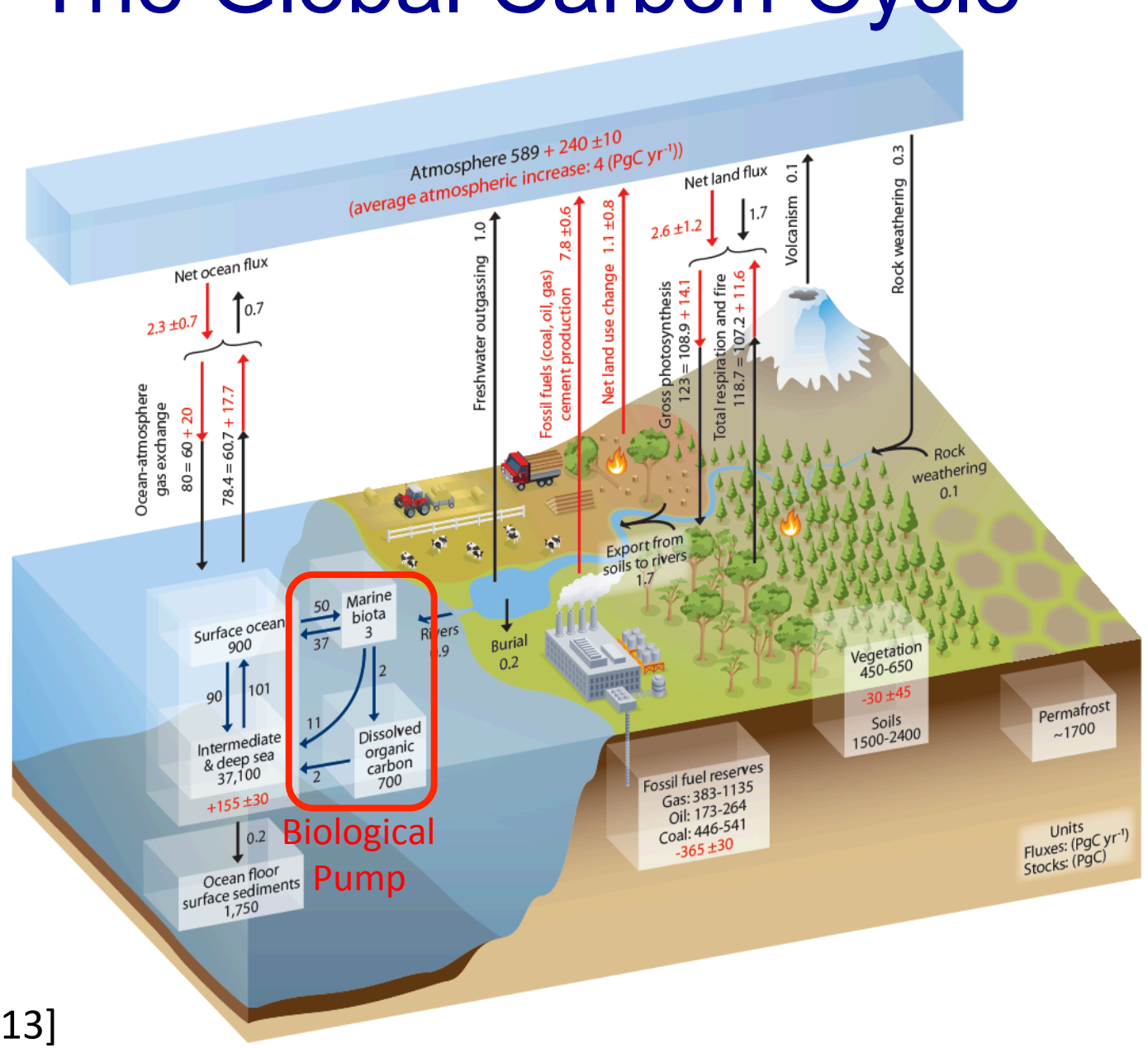
EXPORTS Science Plan Writing Team

Support from NASA Ocean Biology & Biogeochemistry Program

The Global Carbon Cycle

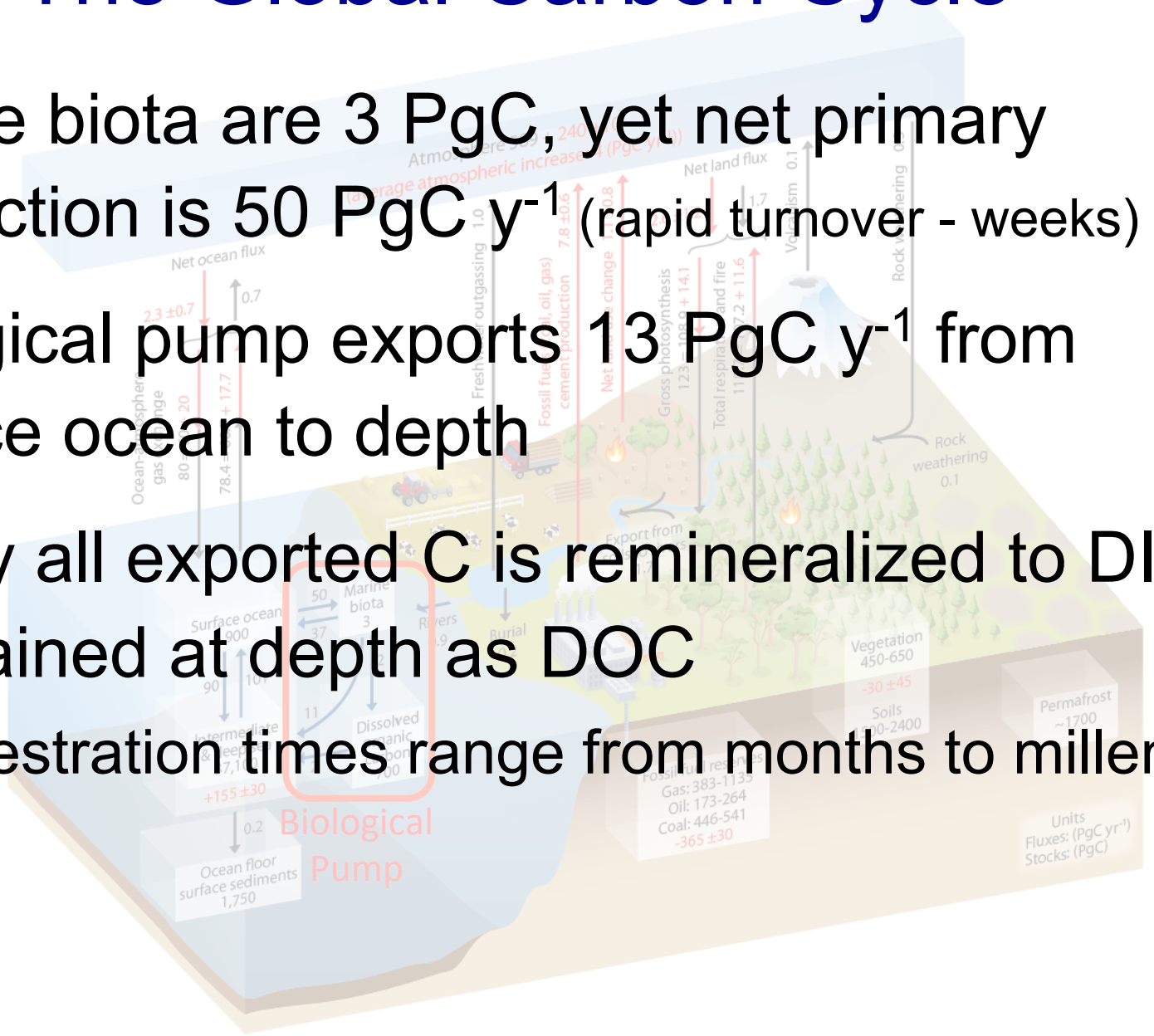


IPCC AR5 [2013]

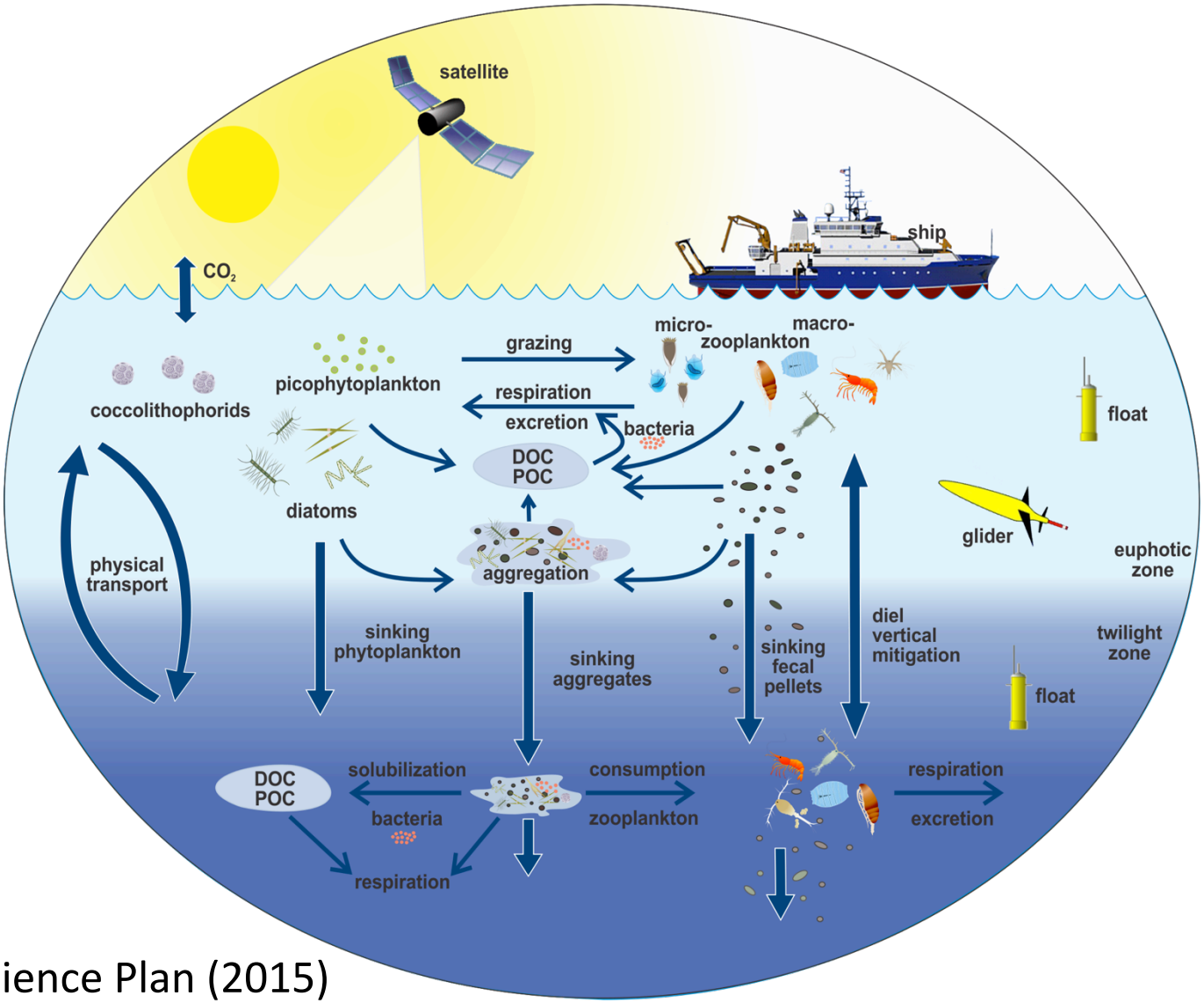
The Global Carbon Cycle

- 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

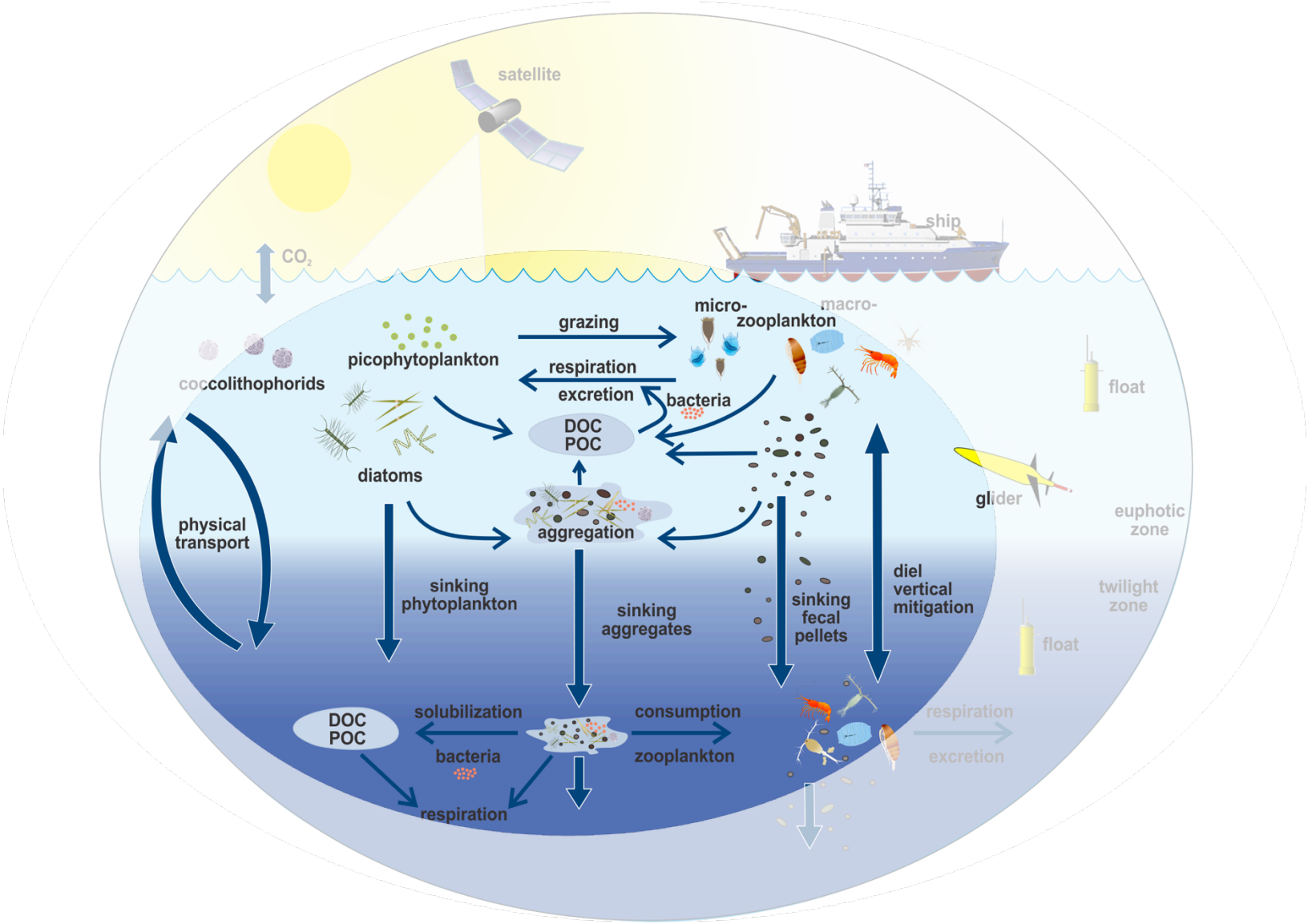


The Biological Pump is Complicated



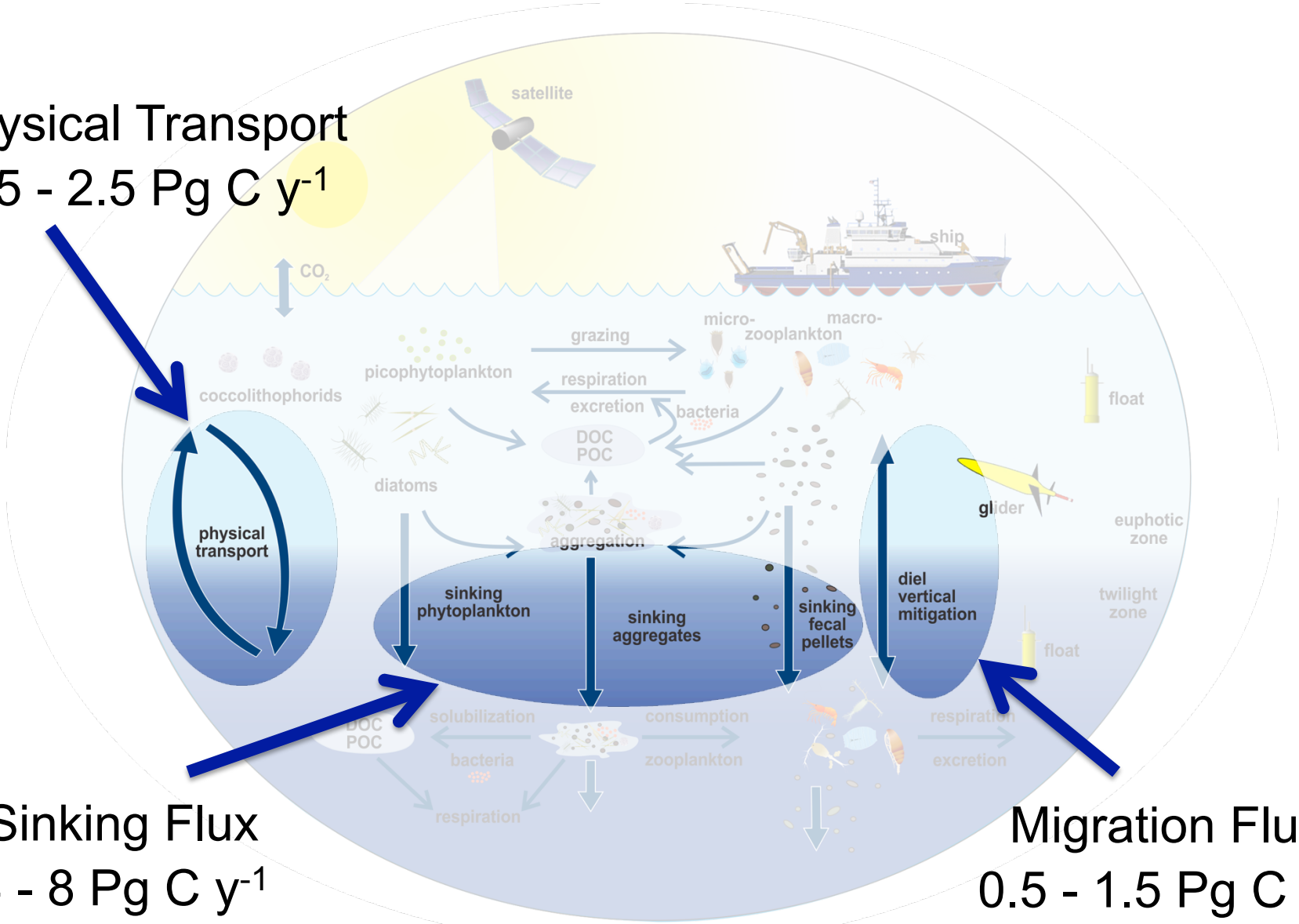
EXPORTS Science Plan (2015)

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})

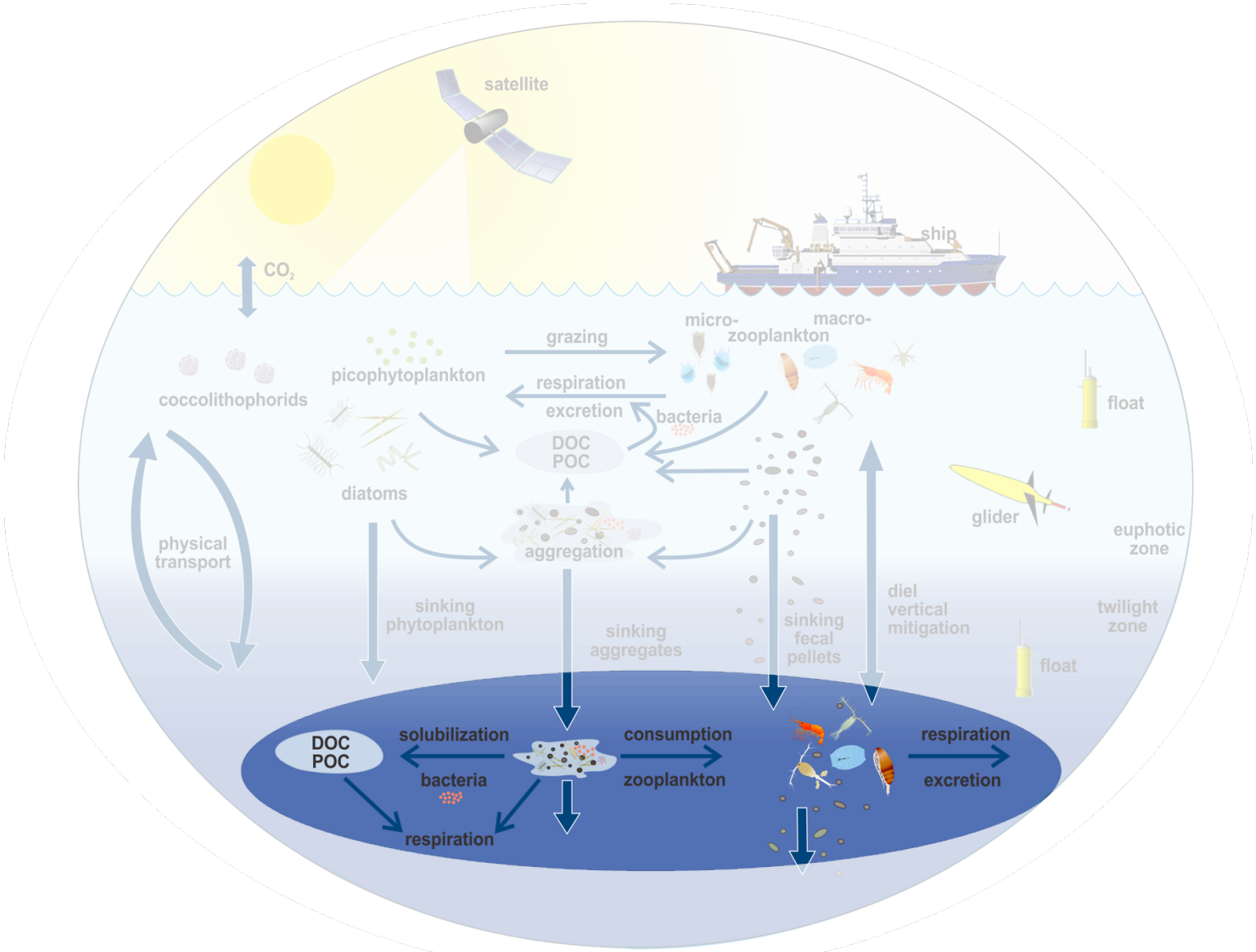
Physical Transport
0.5 - 2.5 Pg C y^{-1}



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

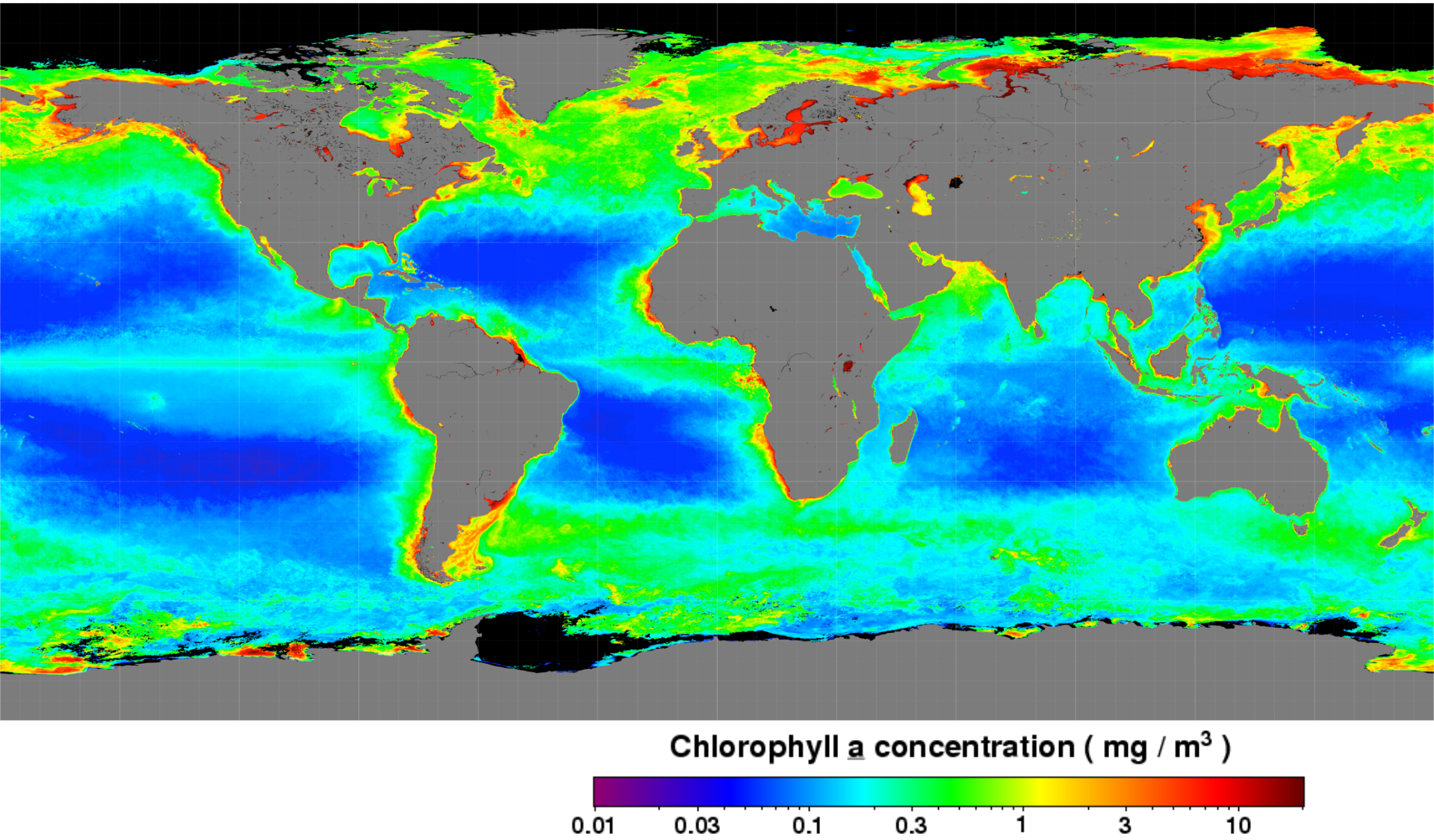
- This export is rapidly attenuated beneath the surface ocean where it is remineralized

  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…)

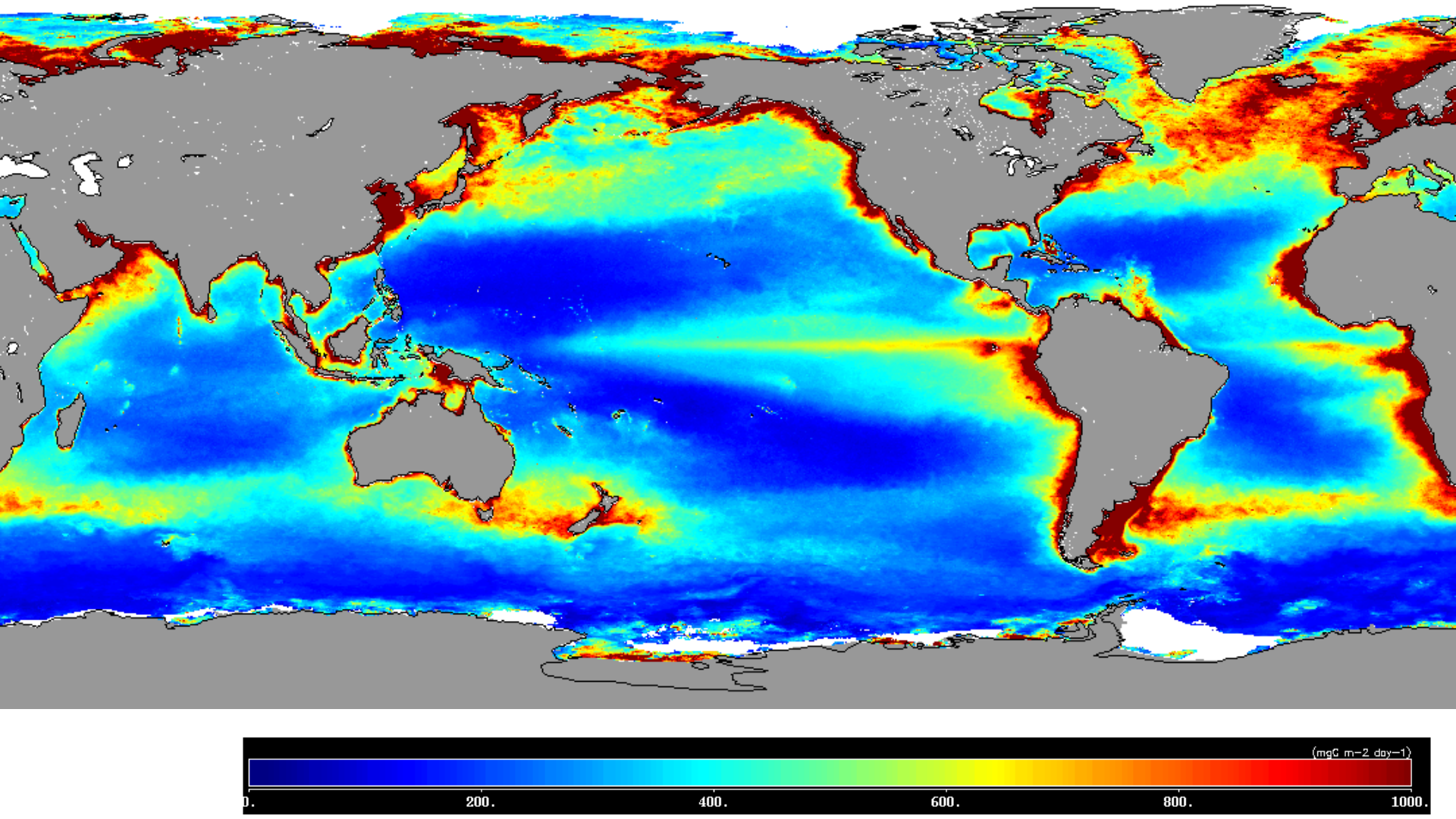
  We must do better

What Are Our Present-day Capabilities?



NPP-VIIRS Annual Mean for 2014 (ocean color webpage)

What Are Our Present-day Capabilities?

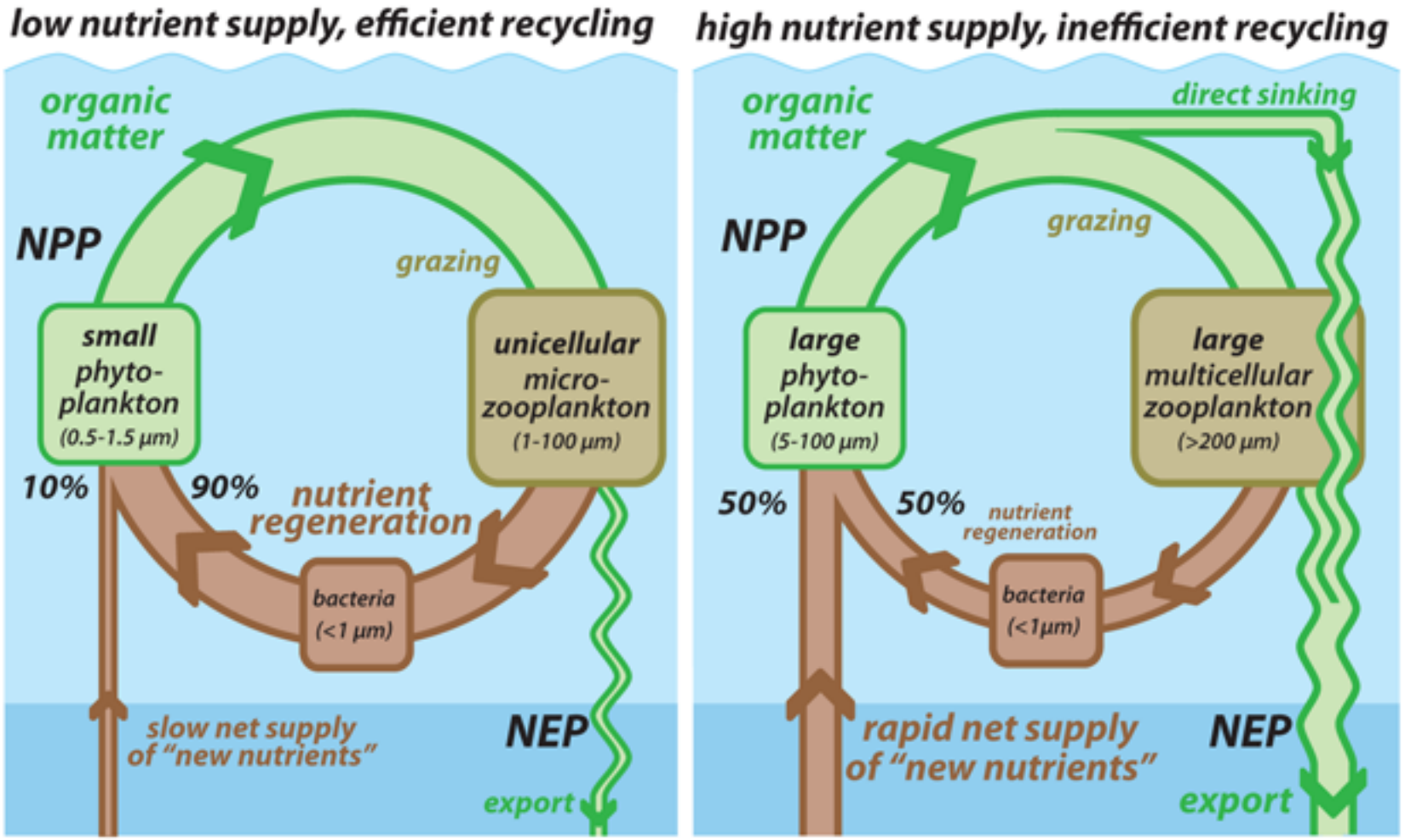


MODIS Annual Mean Net Primary Production rate for 2007 (VGPM)

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…)

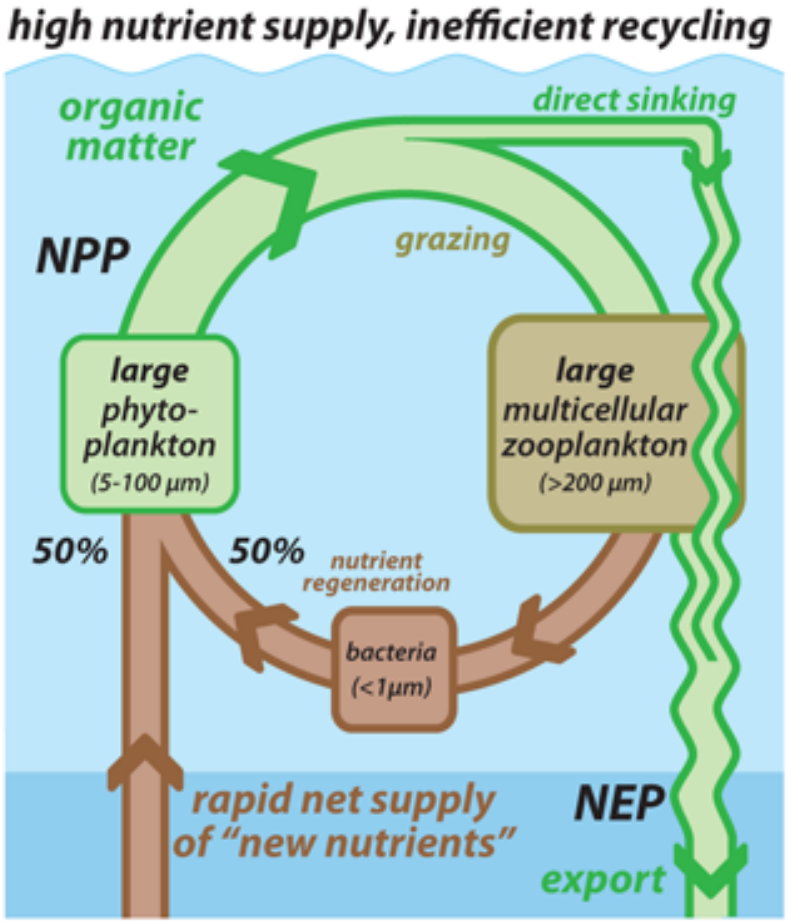
The Pelagic Food Web & C Export



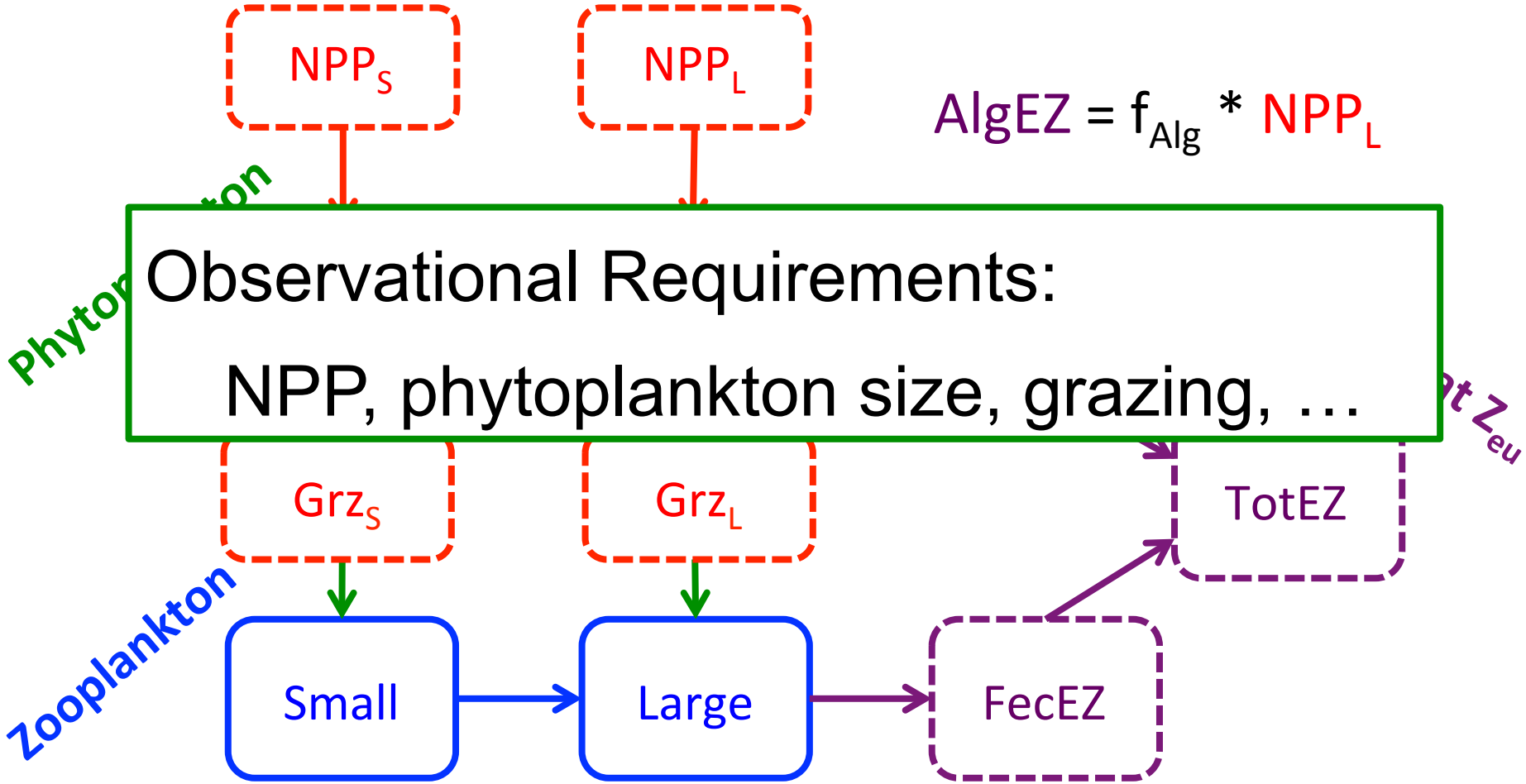
Sigman & Hain [2012] *Nature Education*

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…

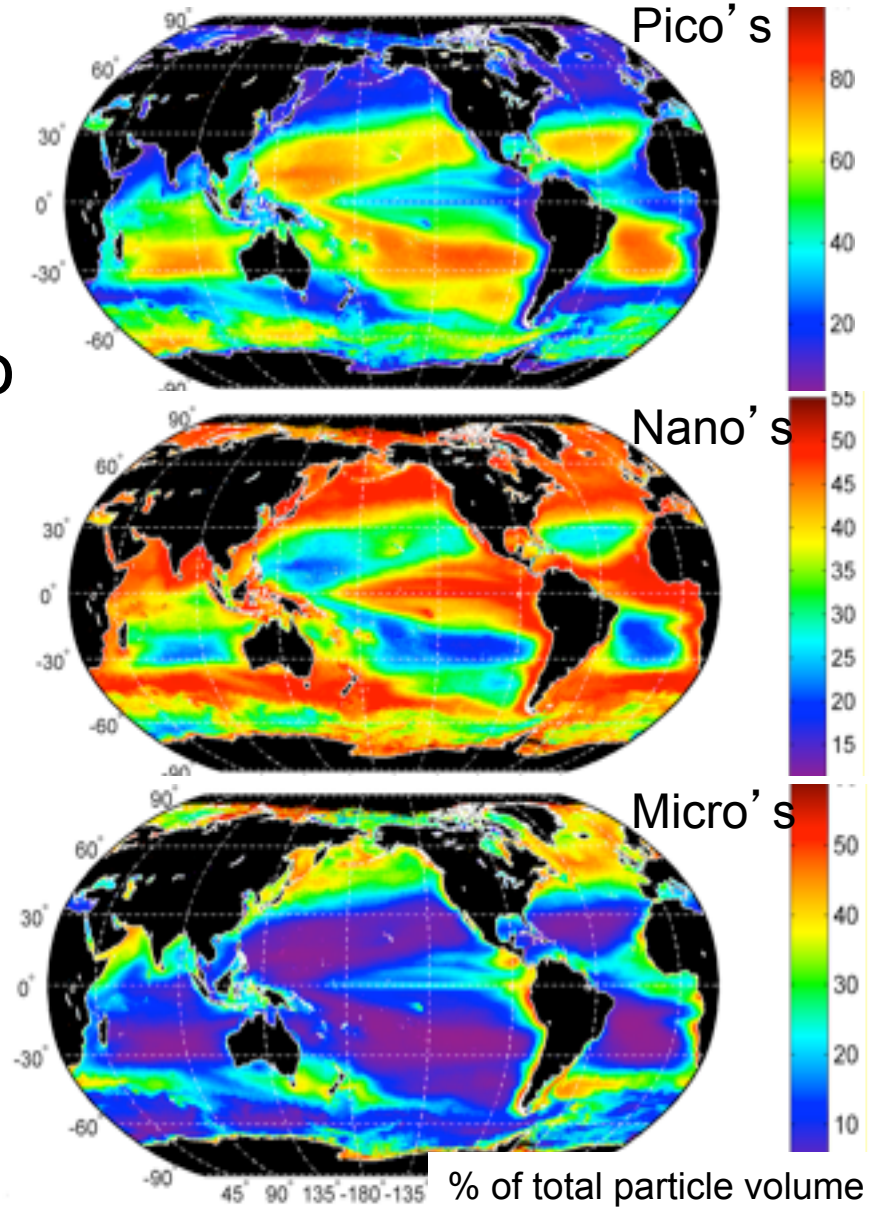


$$FecEZ = (f_{FecS} * Grz_S + f_{FecL} * Grz_L) * Z_{eu}$$

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



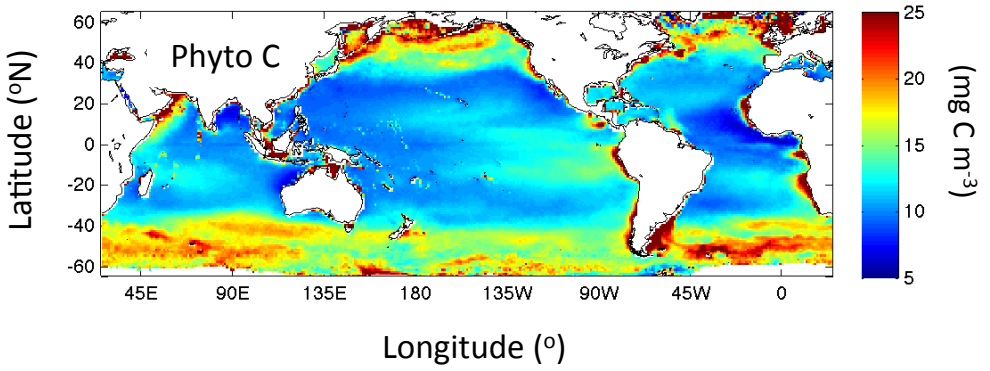
Loisel et al. [2007] *JGR-Oceans*

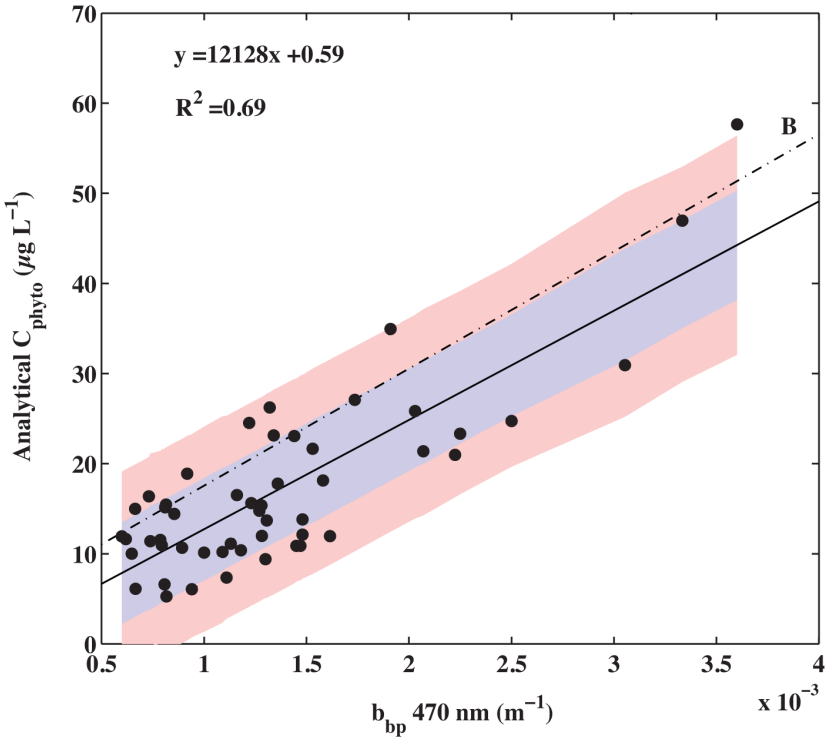
Kostadinov et al. [2009] *JGR-Oceans*

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





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

Diagnosing Grazing Rates

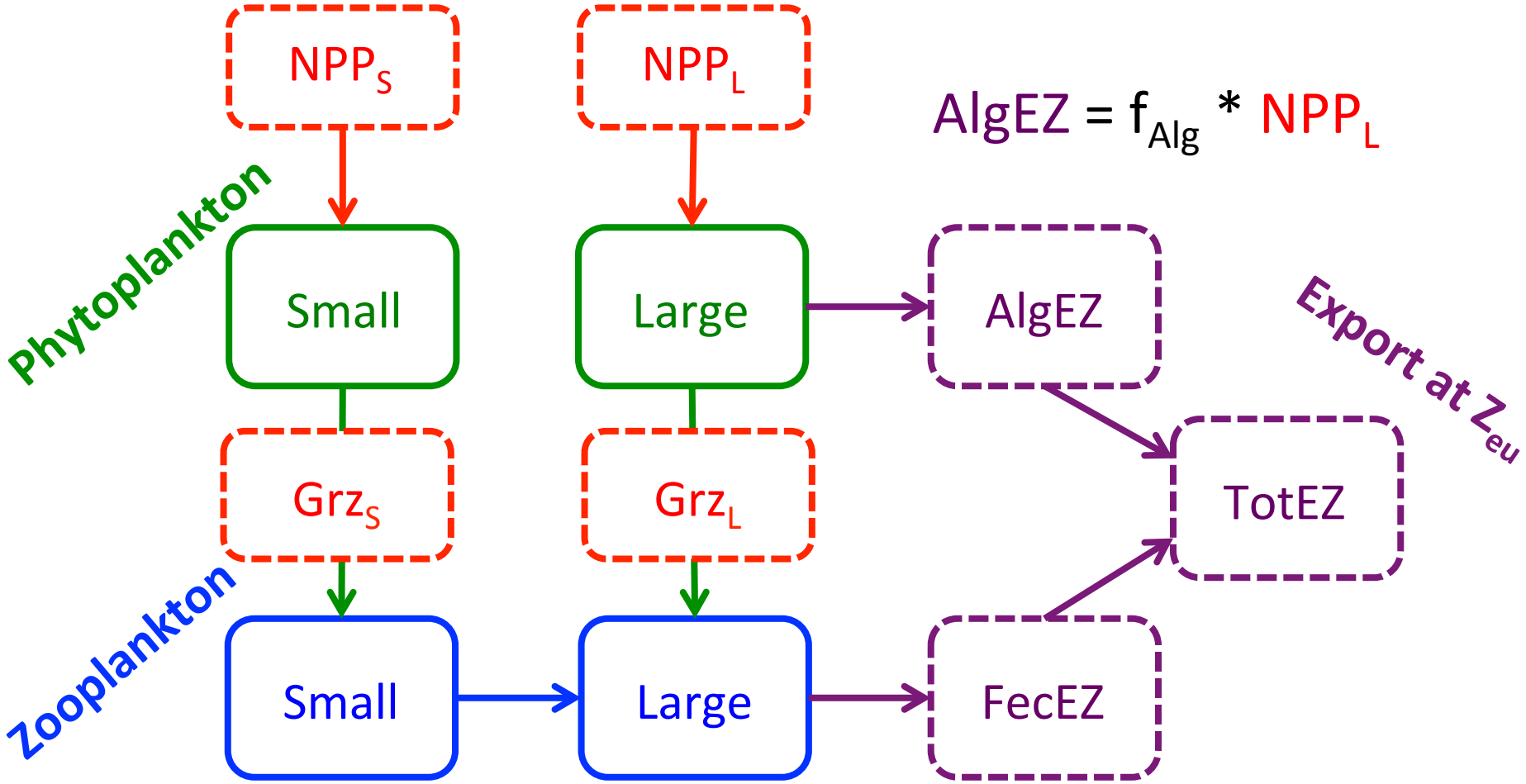
- Upper layer (Z_{ML}) phytoplankton biomass budget

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

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

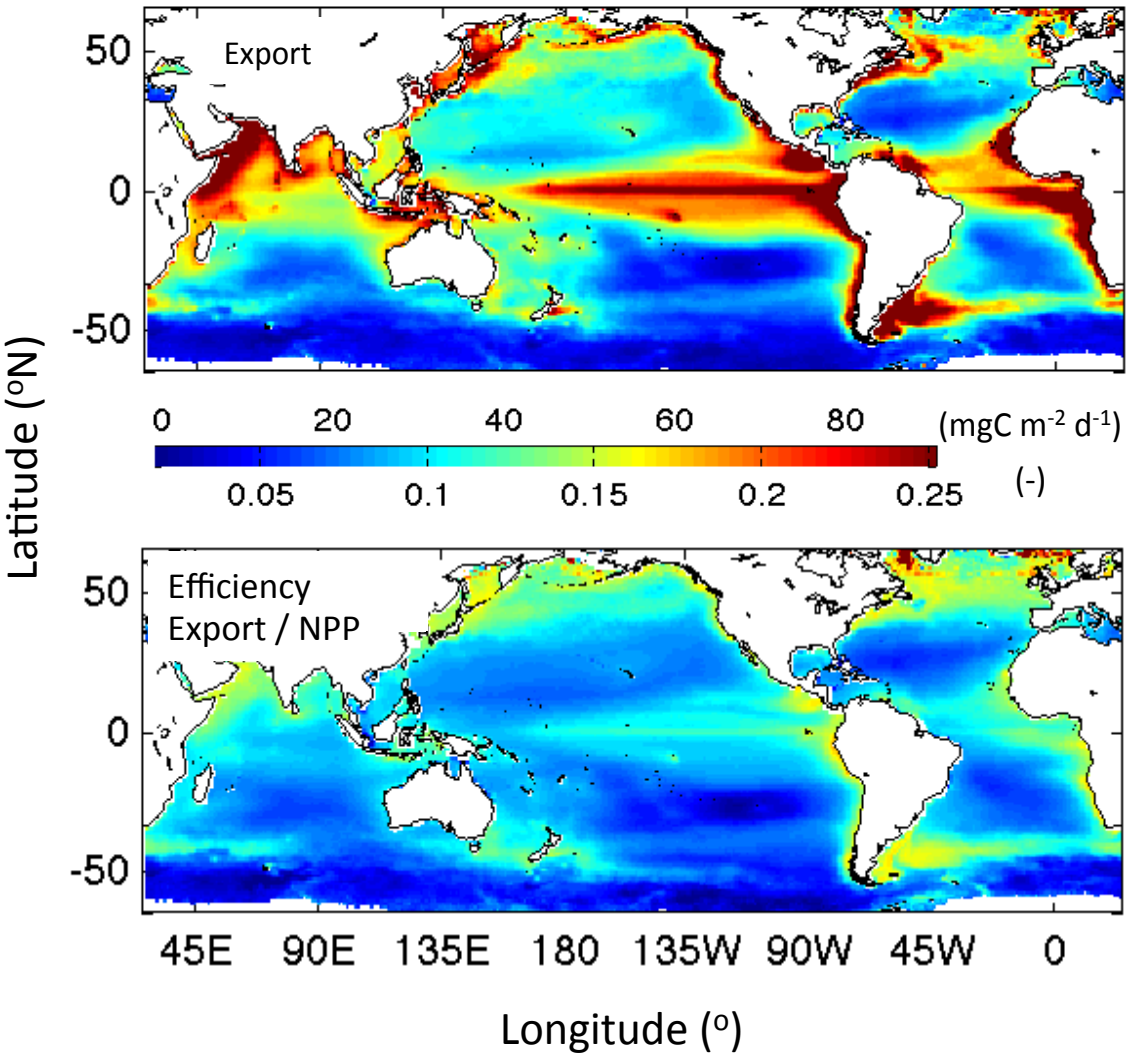
A Mechanistic Approach…



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]

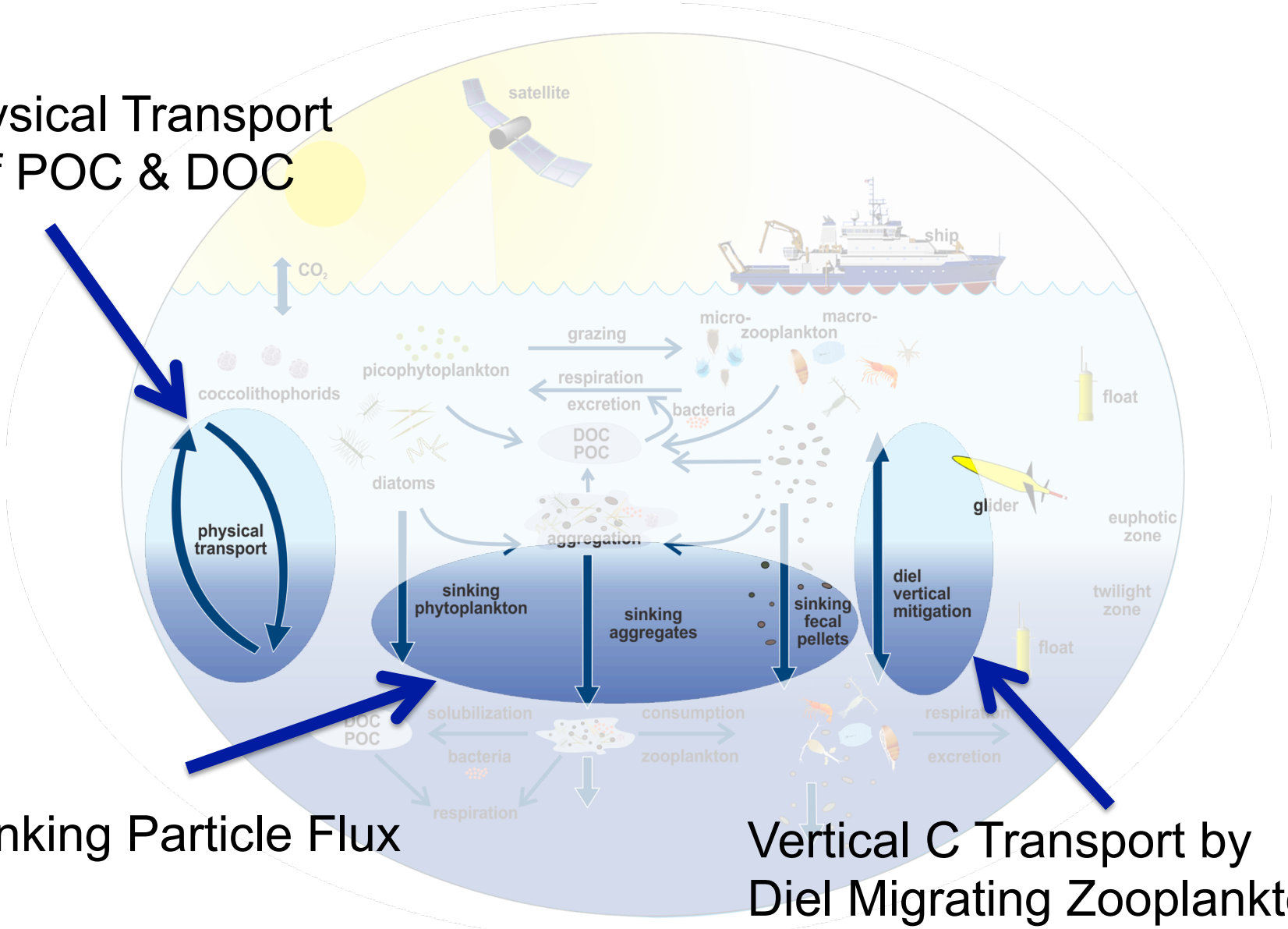
Export Flux

- 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...



Need to Know Ultimate Fate of Exported C

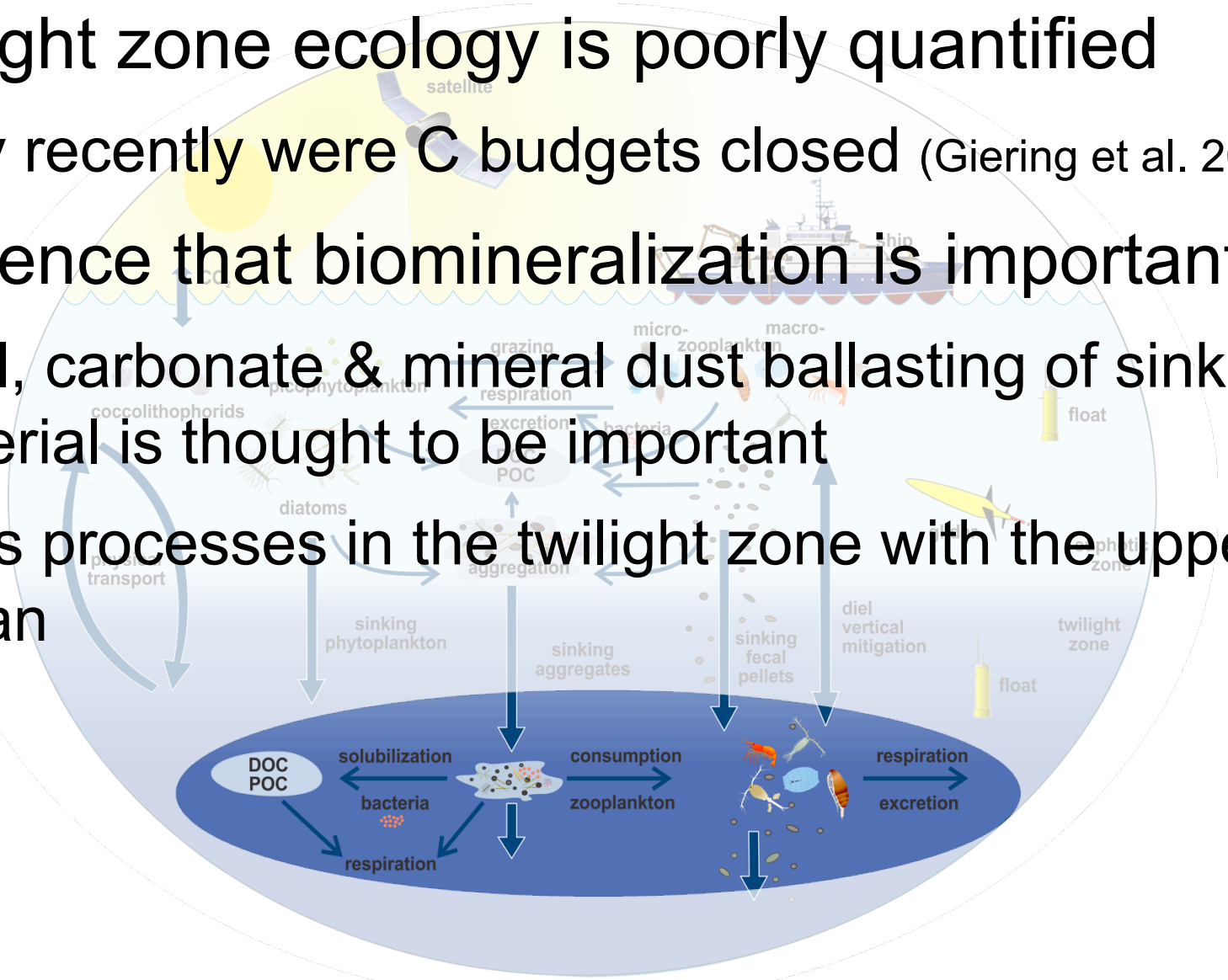
- Twilight zone ecology is poorly quantified

  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

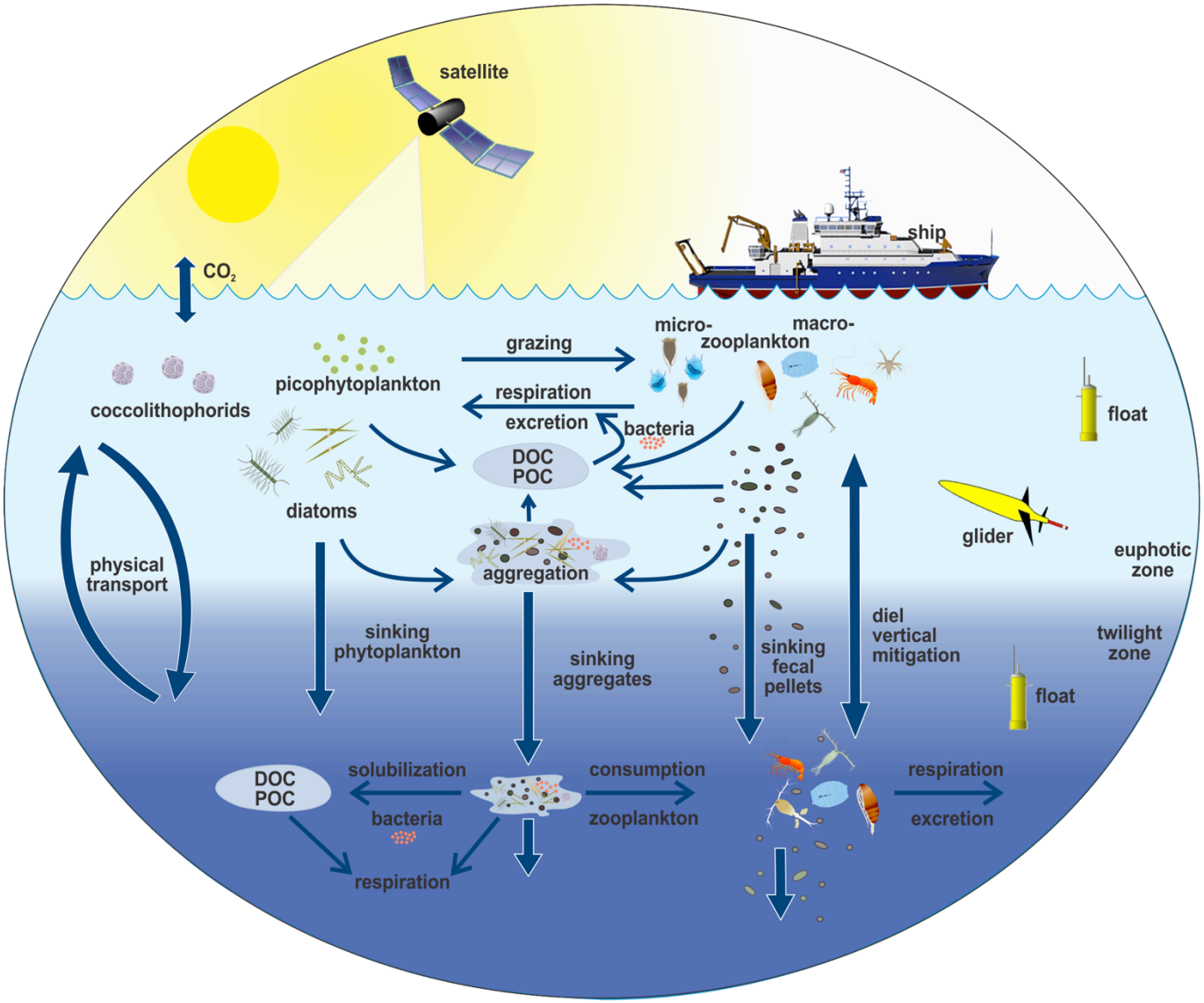


Steps Forward…

- 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

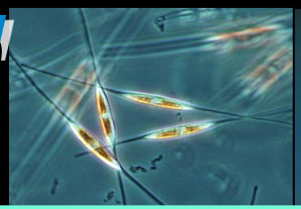
Goal: Predict the export & fate of ocean NPP from satellite & other observations

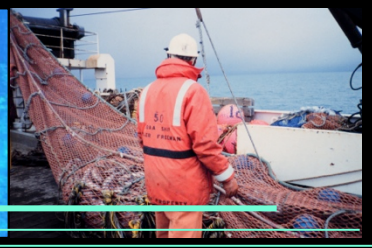
Hypothesis: Fate of ocean NPP is regulated by the state of the surface ecosystem

EXPORTS Science plan is under review

http://cce.nasa.gov/cce/ocean_exports_intro.htm

PaCE



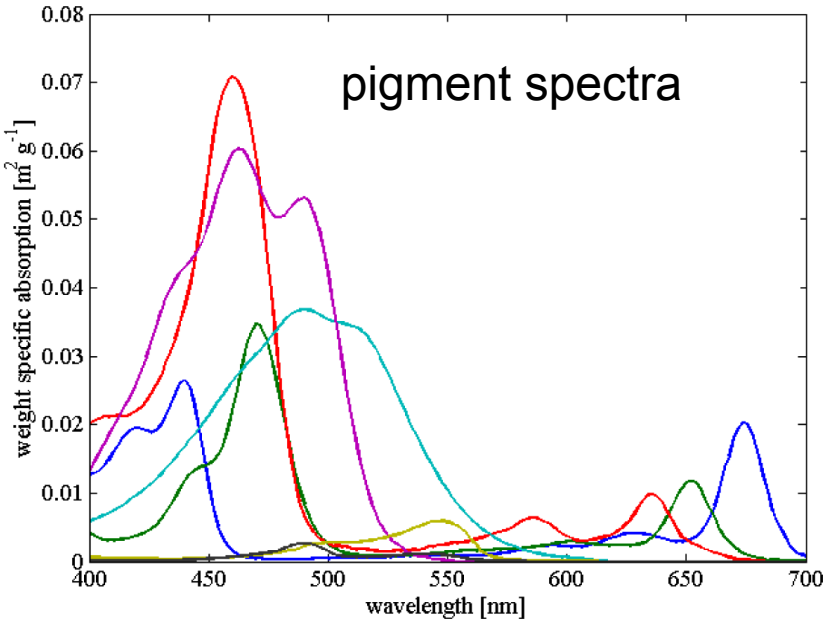
Pelagic and Coastal Ecosystems mission

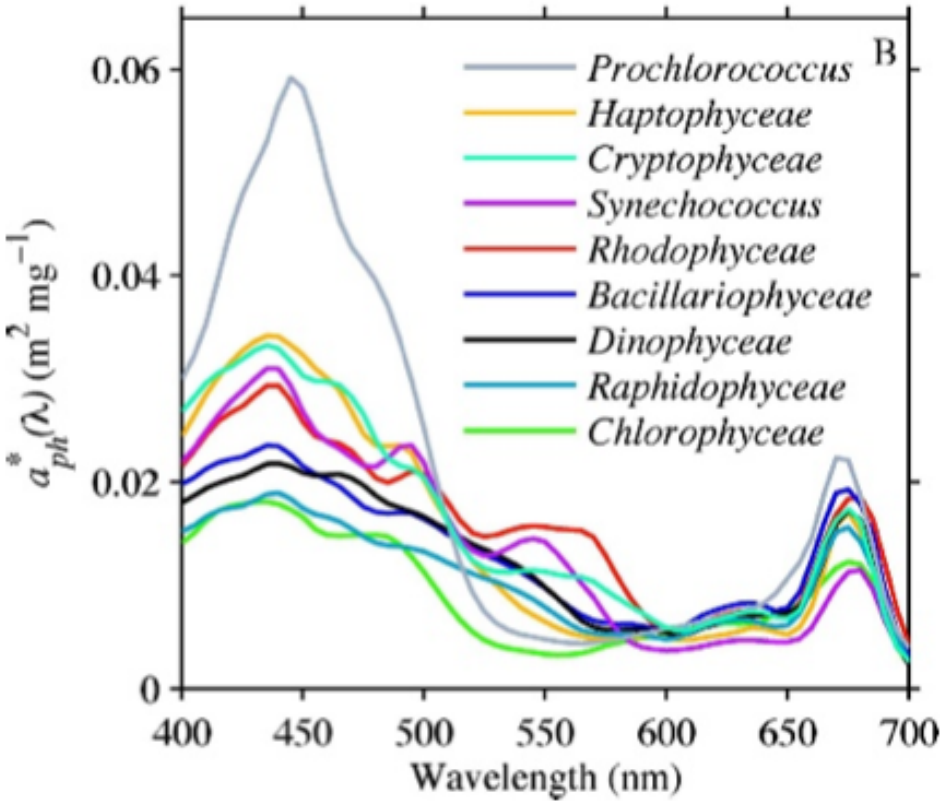
PACE will improve our understanding of ocean ecosystems and carbon cycling through its…

- 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

Phytoplankton Functional Types

Different phytoplankton functional types have different pigments and absorption spectra

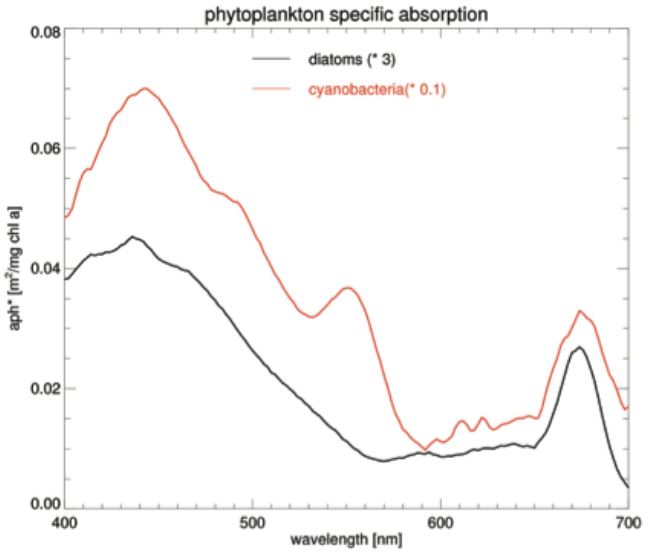




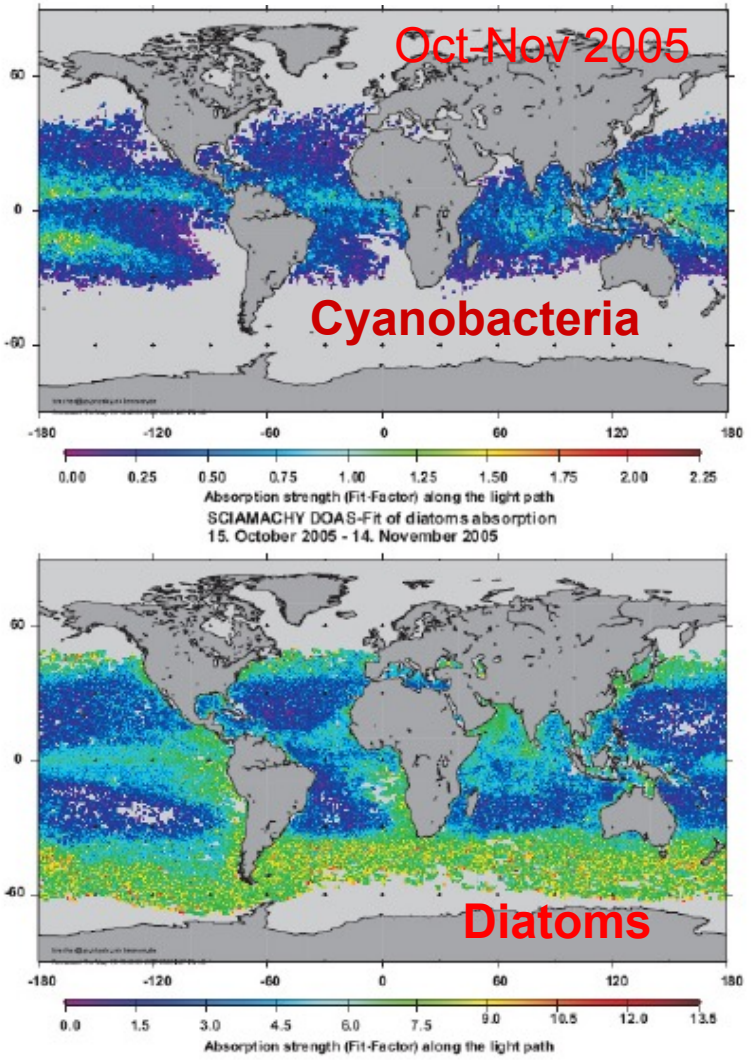
Dierssen et al. L&O [2006]

Phytoplankton Functional Types

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

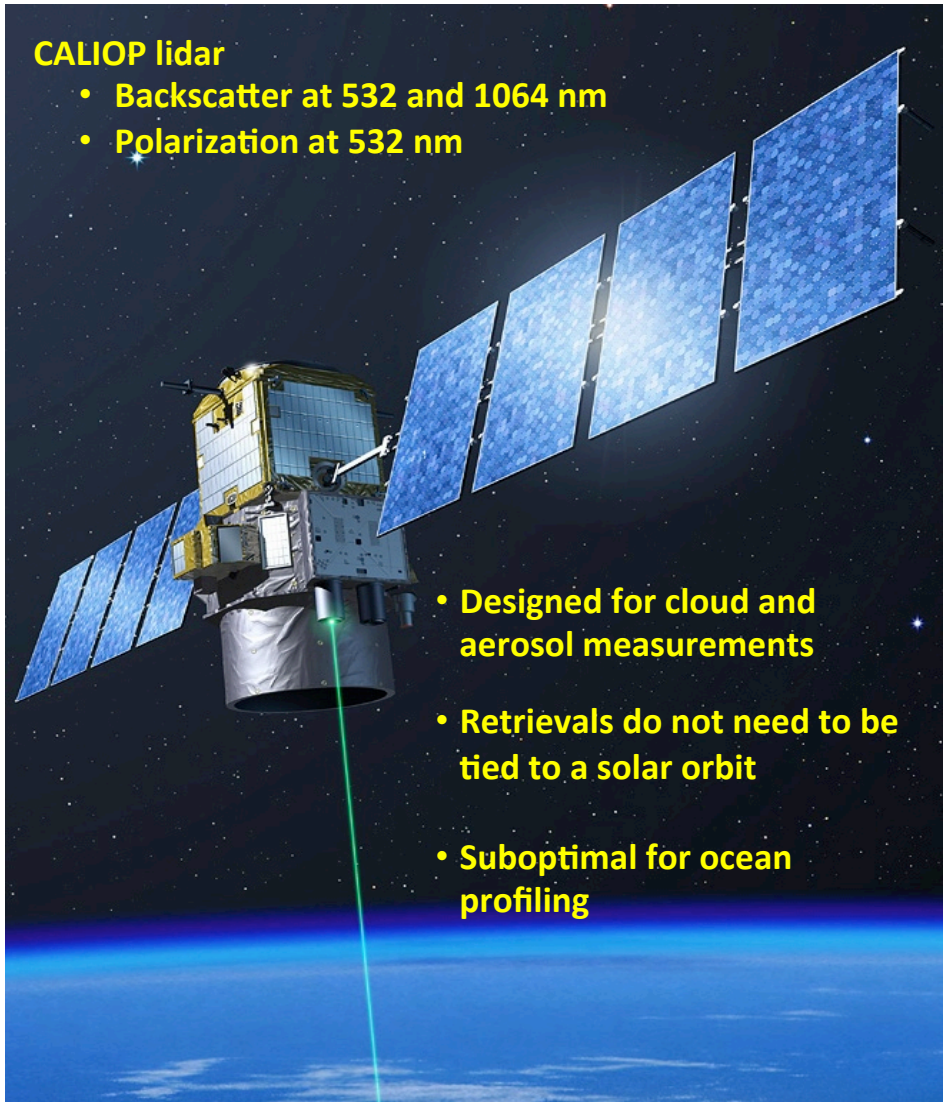


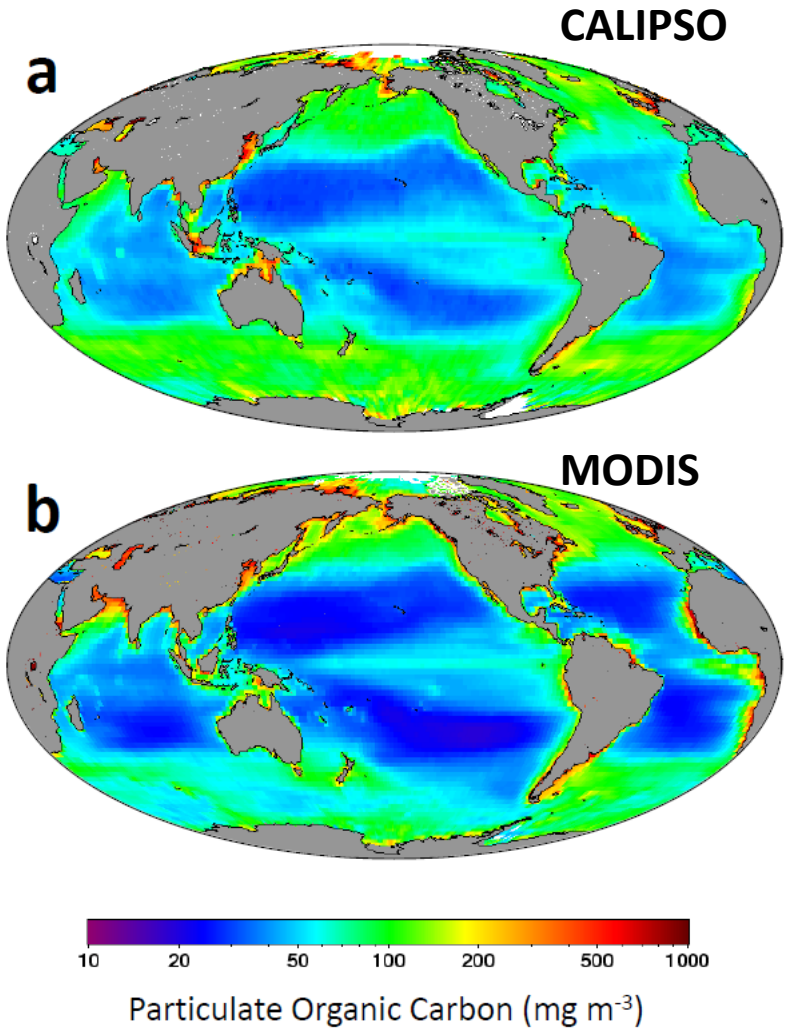
SCHIAMACHY PhytoDOAS



Bracher et al. BGS [2009]

Global POC from CALIOP Lidar

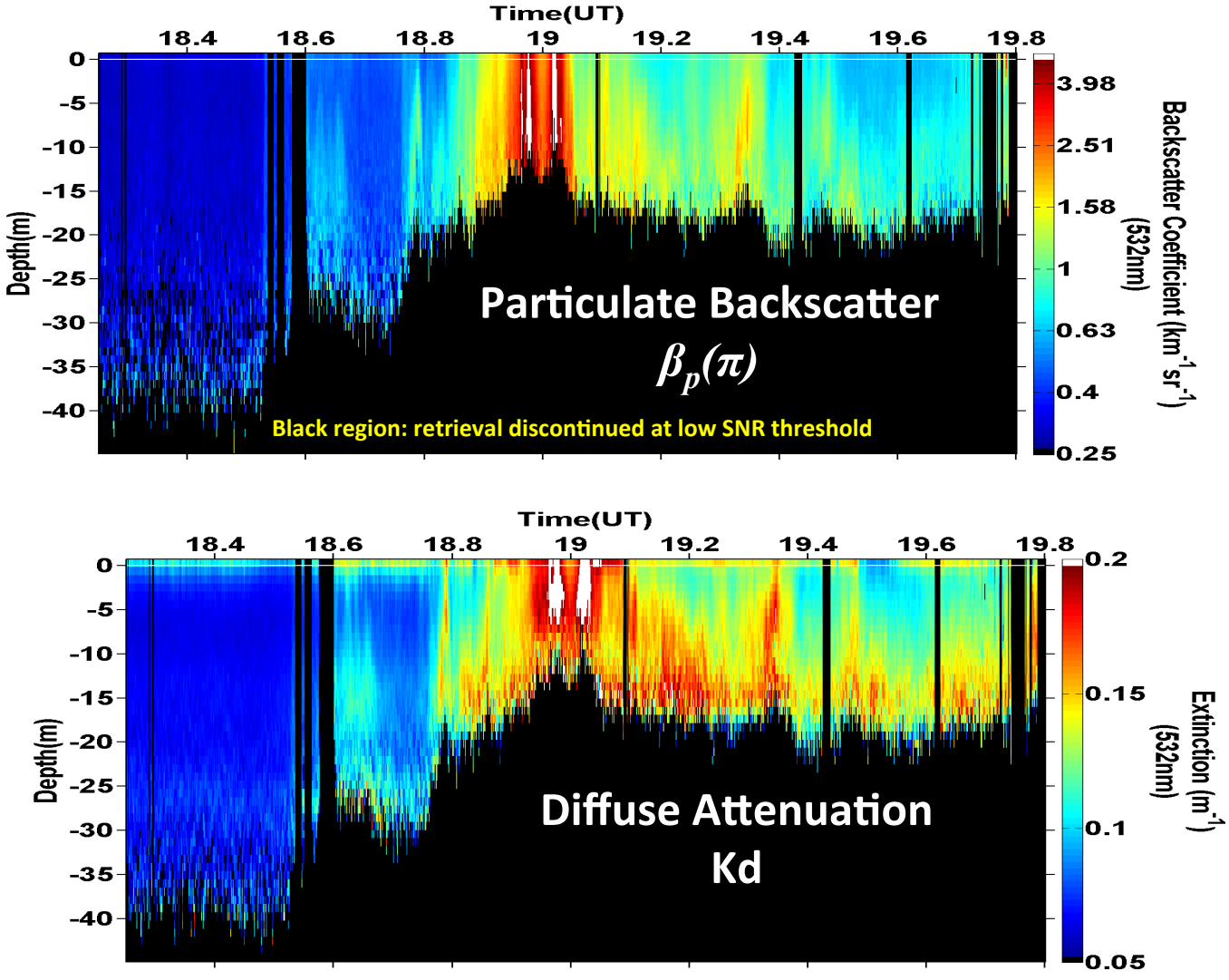




CALIPSO website: www-calipso.larc.nasa.gov

Behrenfeld et al. GRL [2013]

Airborne HSRL Retrievals of Particulate Backscatter & Diffuse Attenuation

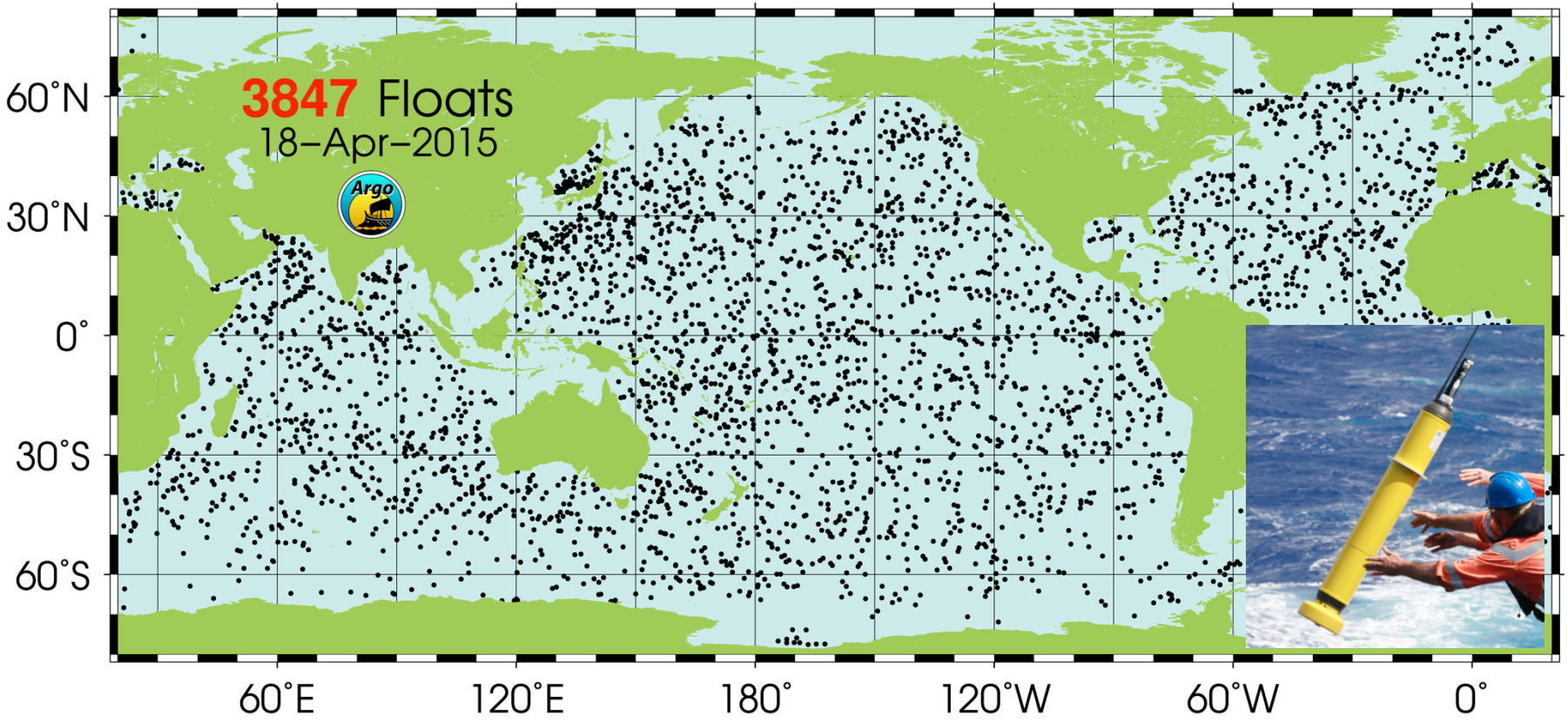


High Spectral Resolution Lidar
Chris Hostetler – NASA Langley

NASA's 2014 SABOR Experiment in Gulf of Maine
Preliminary field validation is very encouraging

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



argo.ucsd.edu

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