Backscatter, Particle Size Distribution & Ocean Color: Status & Path(s) Forward

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With help from:

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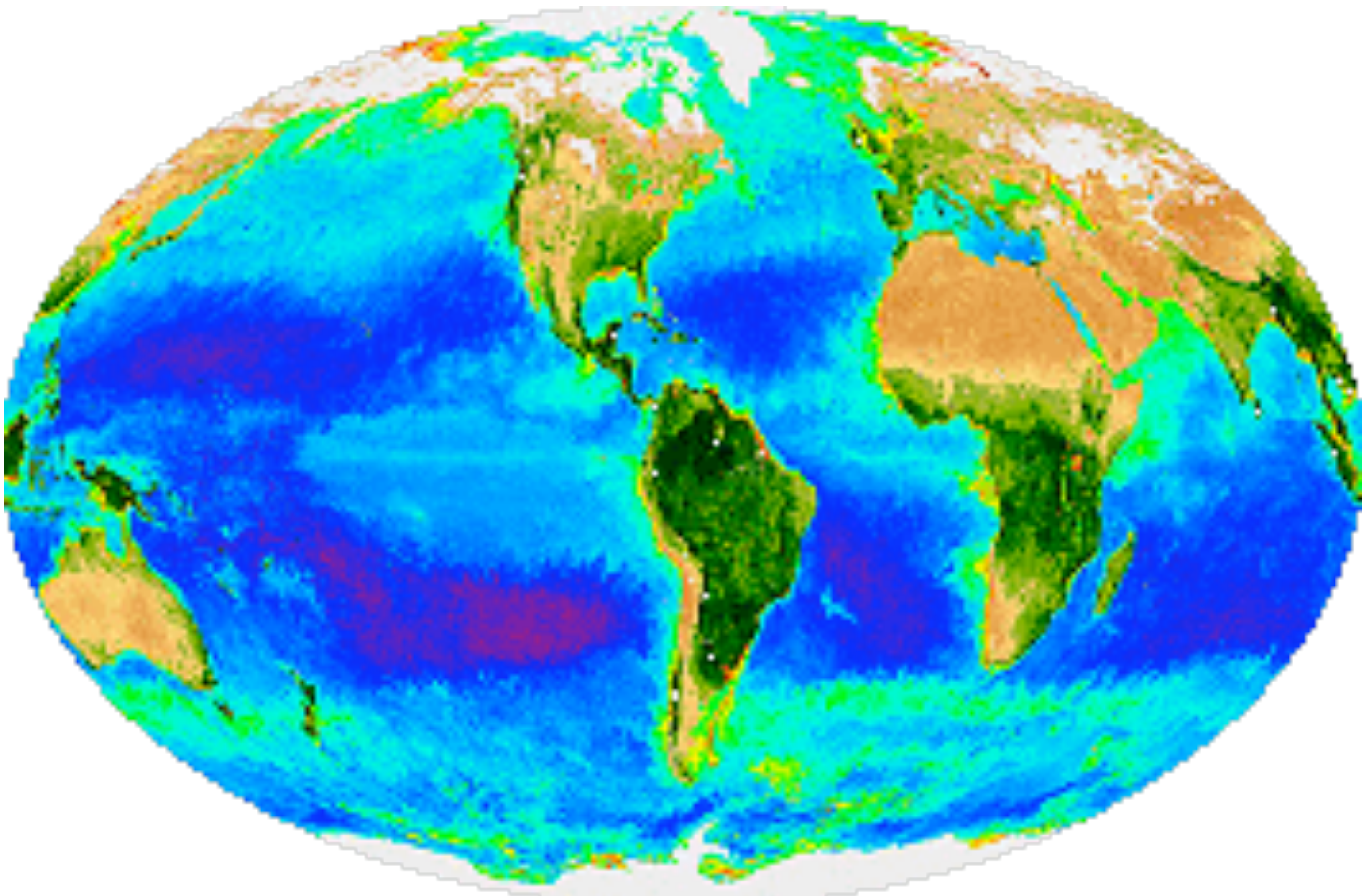
Global Chlorophyll



http://oceancolor.gsfc.nasa.gov/SeaWiFS/HTML/SeaWiFS.BiosphereAnimation.html

Chlorophyll is great…

We can [finally] see the ocean biosphere!

- Assess local to global scale variability
- Trends of change on decade time scales
- Global data for building & validating models

We can assess net primary production

- Model NPP as f(Chl & light) - other ways too…

But, chlorophyll is …

Not Often What We Want

- We want BGC-relevant measures (biomass)
- Need Chl/C to compare w/ BGC models
- But Chl/C = f(light, nuts, species, etc.)

Nor is it The Whole Story

- There’s more than just chlorophyll
- We need more information…

Particles are Important!

Plankton are "particles" & one goal is to assess changes in their stocks & rates

Particle aggregation & sinking drives the biological pump (~10 Gt/y)

Particle characteristics (POC, PIC, PhytoC, PSD, …) provide BGC-relevant information

Particle Parameter Retrievals

Empirical path

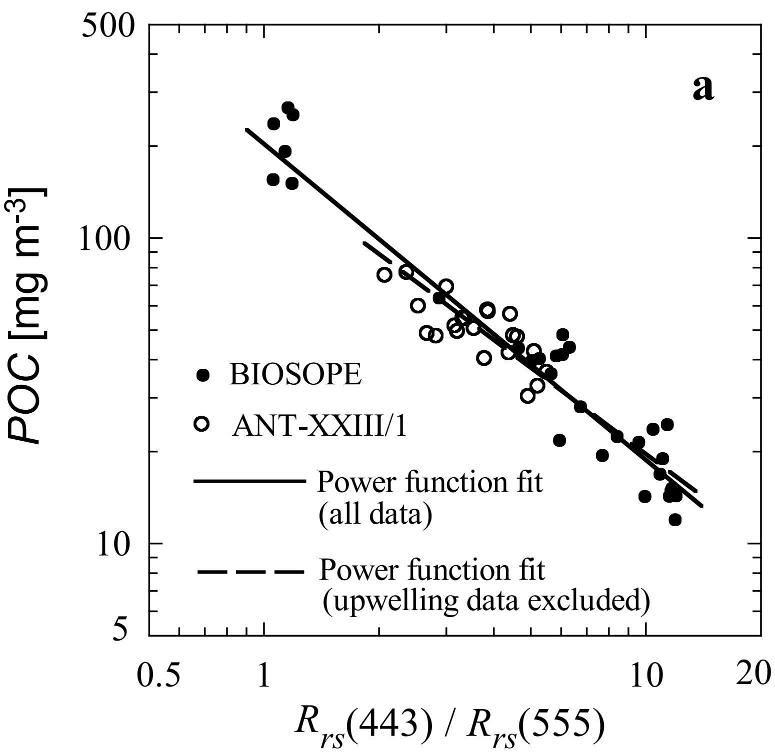
- Model directly using simultaneous particle & $L_{wN}(\lambda)$ observations

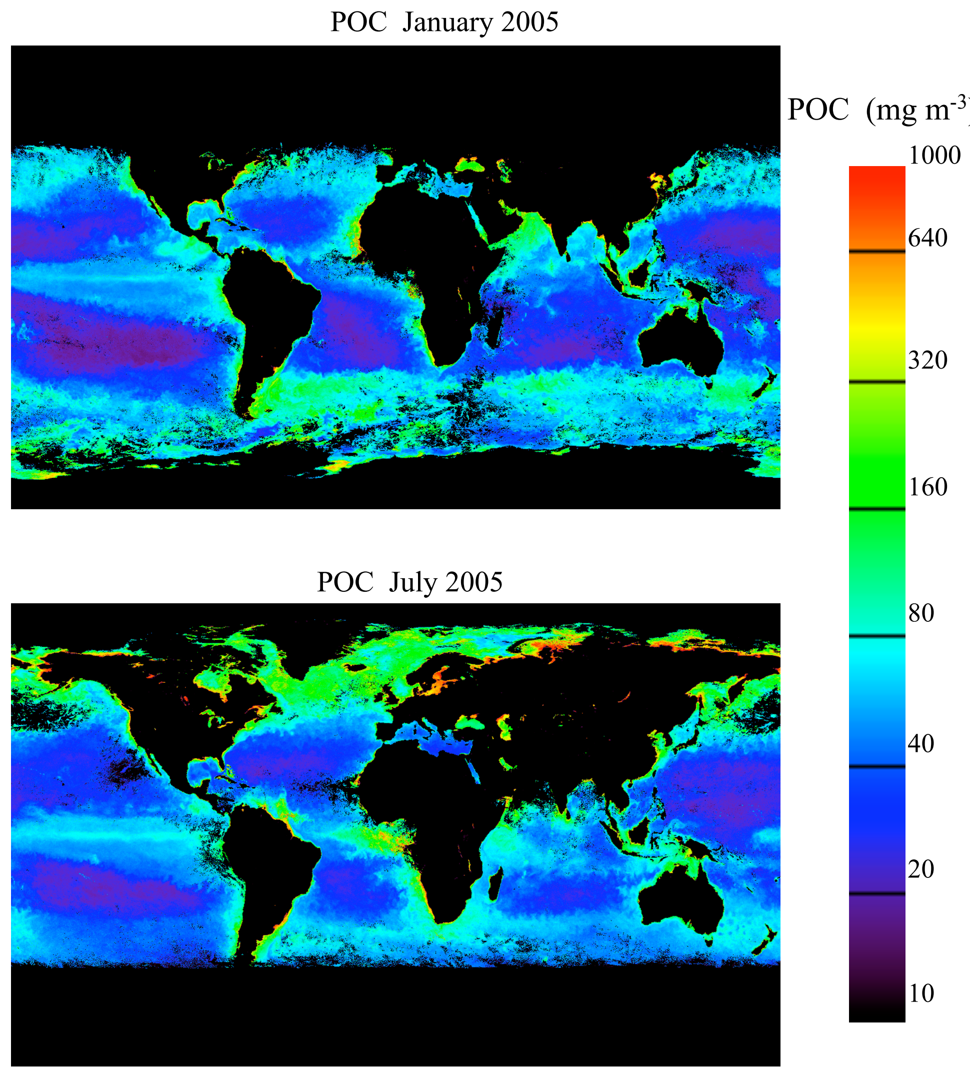
Backscattering path

- Retrieve particle backscatter coefficient, $b_{bp}(\lambda)$
- Model particle characteristics using $b_{bp}(\lambda)$

Both paths are data limited!!

Empirical POC Modeling

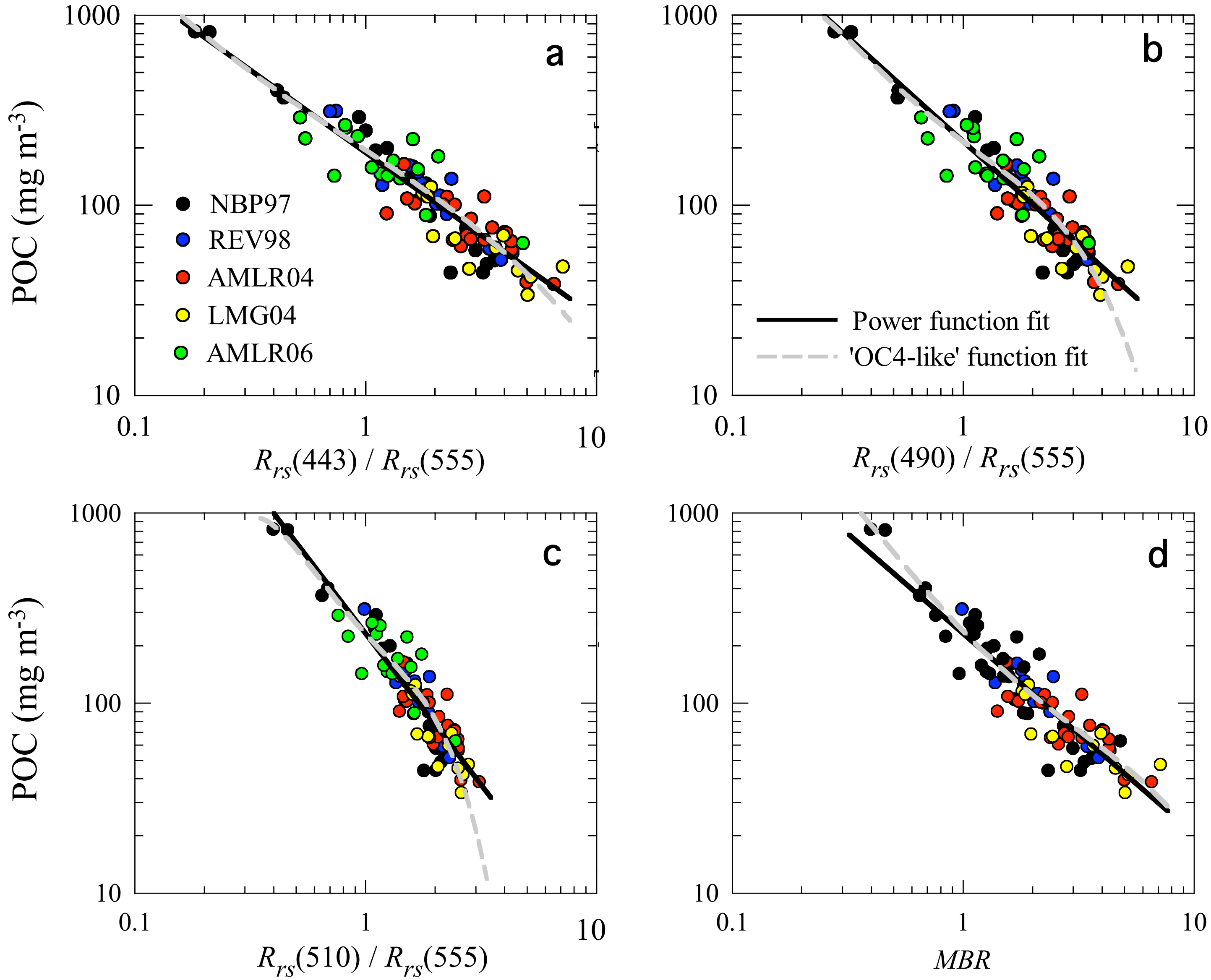




based on field data from the eastern South Pacific and eastern Atlantic

Stramski, Reynolds, Babin et al., *Biogeosciences*, 5, 171-201 (2008)

POC band-ratio algorithms for Southern Ocean

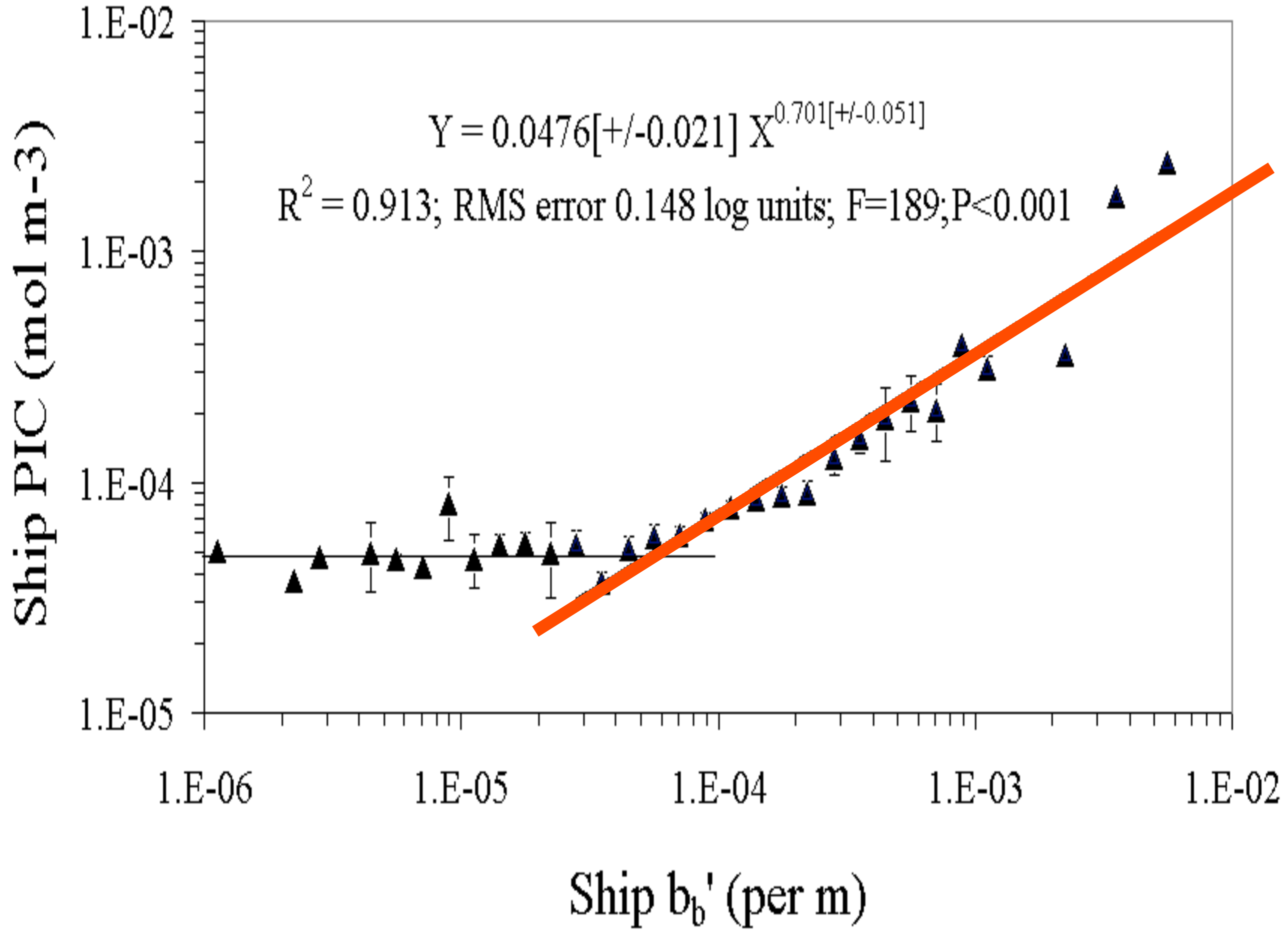


Allison, Stramski, and Mitchell, *Journal of Geophysical Research*, submitted (2009)

Observation & Retrieval of PIC

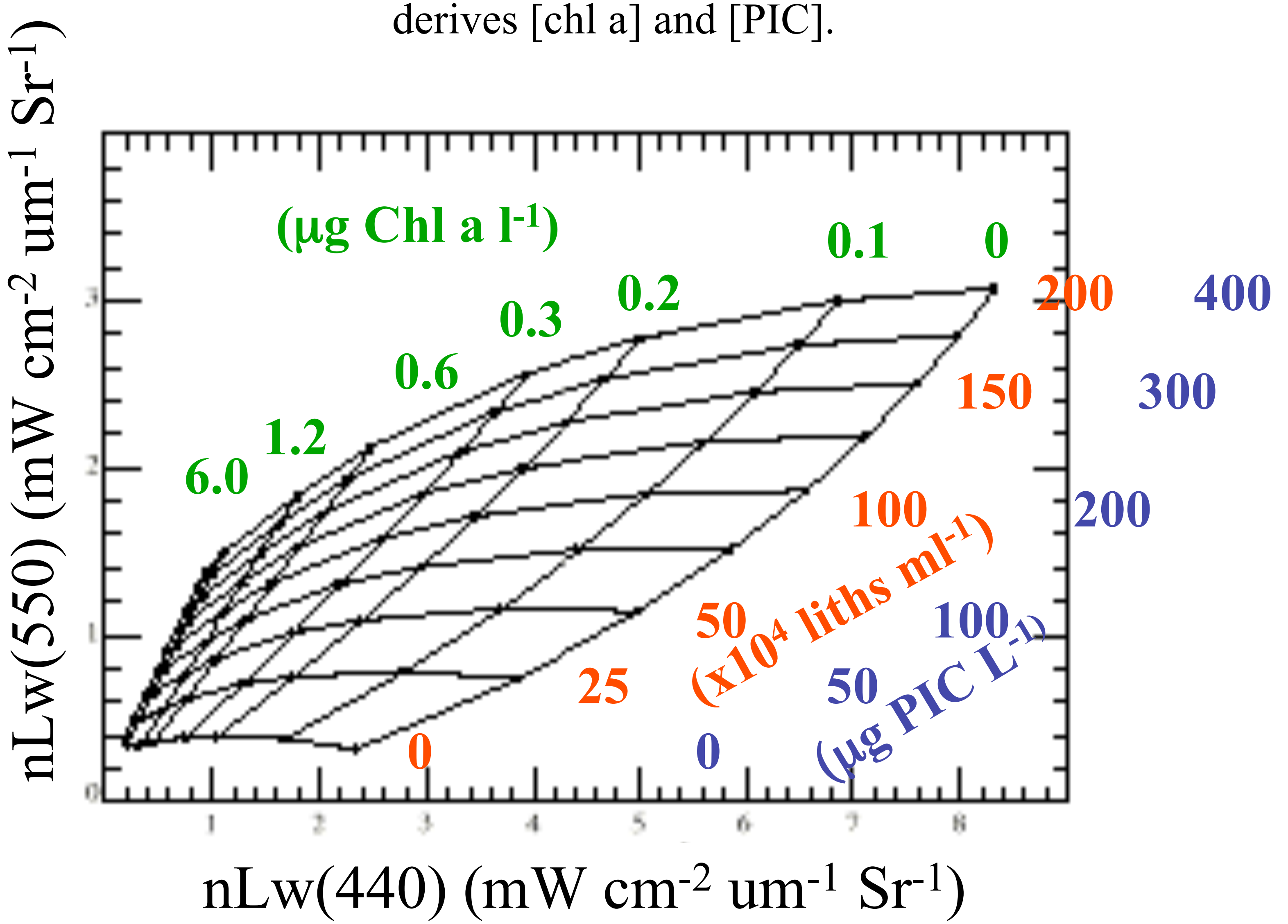
- Measure particulate backscattering (b_{bp}) in raw seawater = $b_{bp\ raw}$
- Reduce pH below dissociation point for calcite and aragonite (i.e. dissolve $CaCO_3$)
- Re-measure b_{bp}= $b_{bp\ acid}$
- $b_{bp}' = b_{bp\ raw} – b_{bp\ acid}$
- PIC [mol PIC(m^{-3})] = b_{bp}'/b_b^* [m^{-1} /(m^2 mol PIC)$^{-1}$]
- Good for ship surveys, resolution 1 sample/km

On average, total b_b' is well-correlated to PIC above a b_b' of ~$3x10^{-5}$ m^{-1}

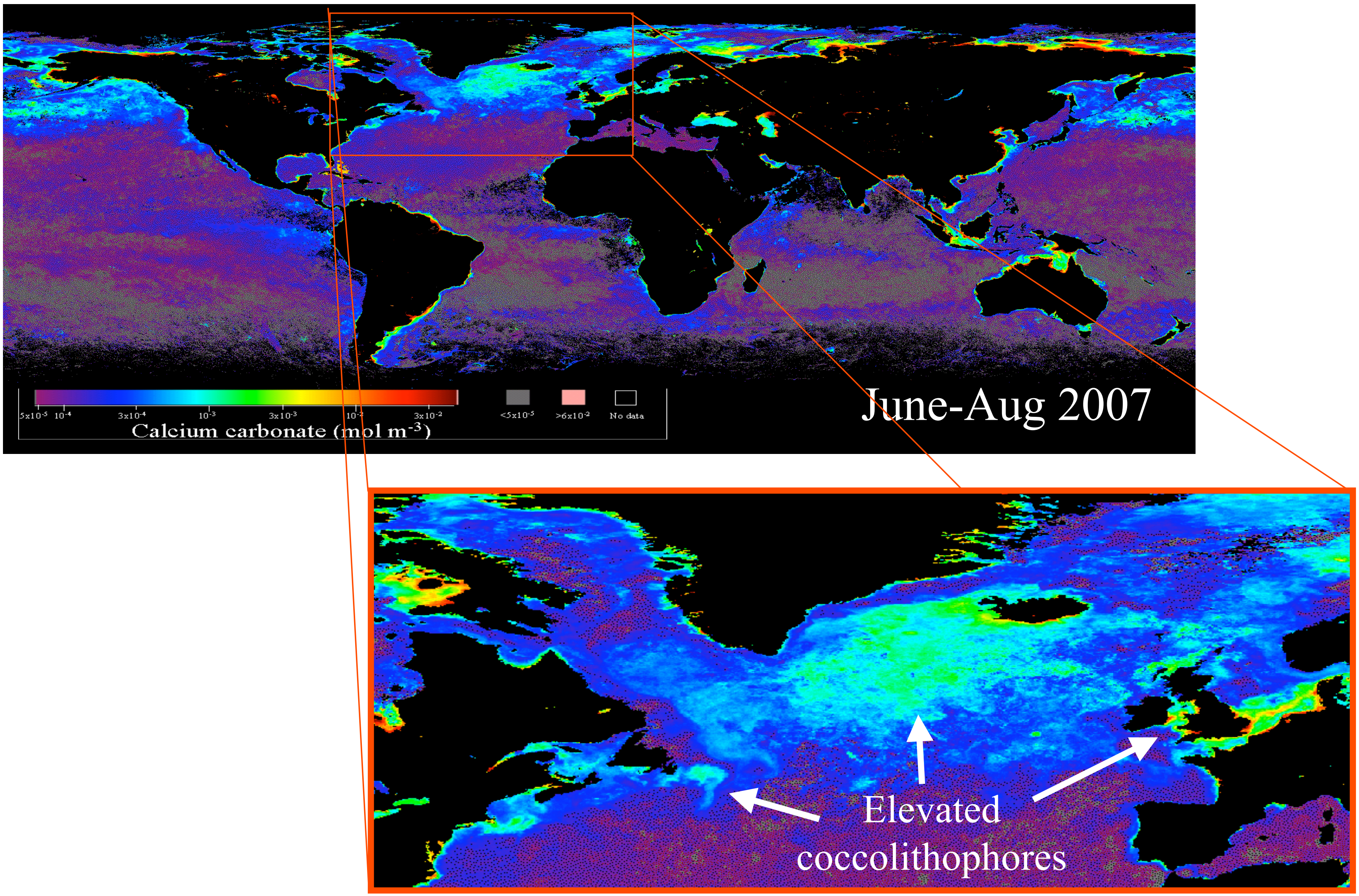


Two-band PIC algorithm

Uses absolute values of nLw (not ratios). Iteratively solves for $b_{bp\ nonPIC}$, $b_{bp\ PIC}$ and derives [chl a] and [PIC].



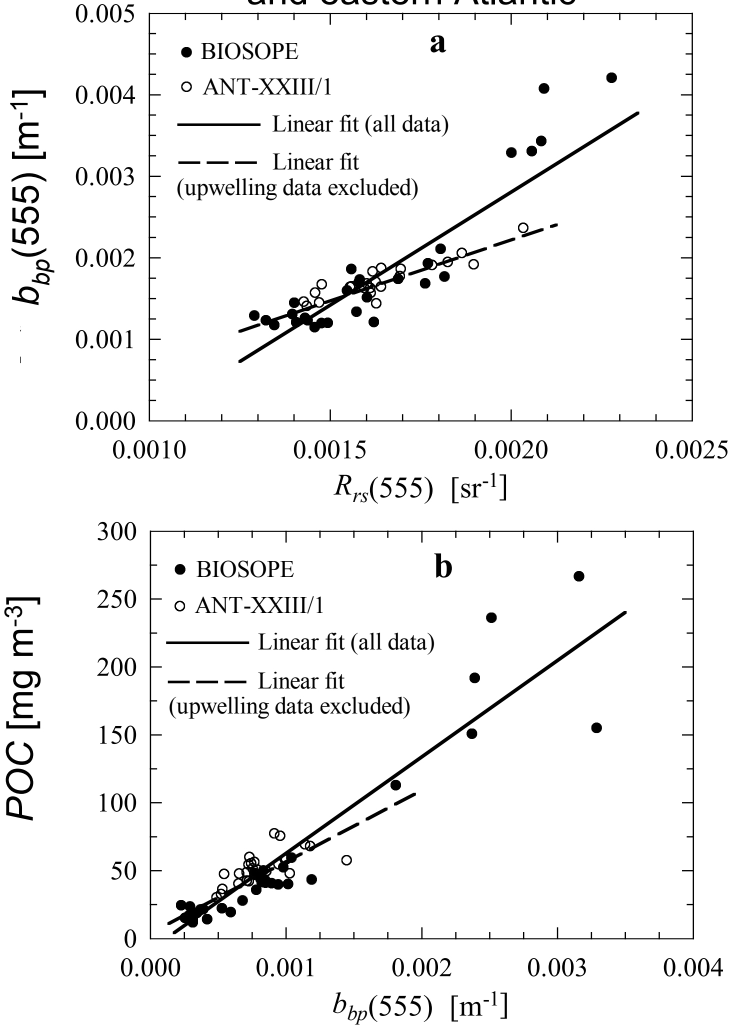
Global calcite: MODIS Aqua



Two-step single-wavelength POC algorithm

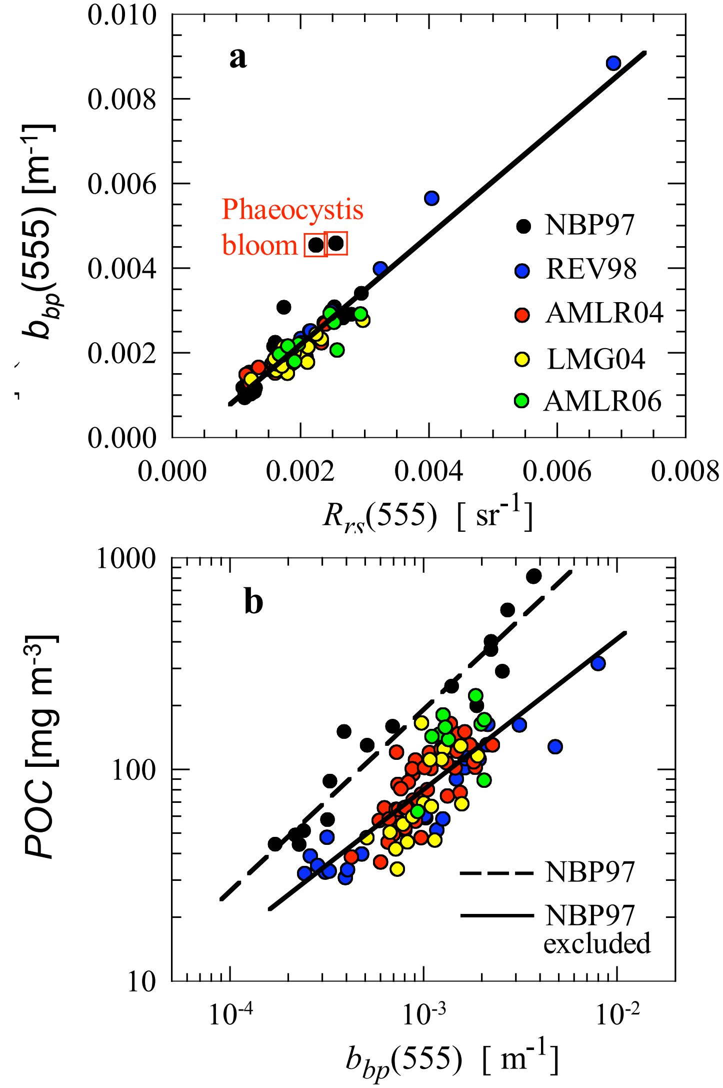
$R_{rs}(555)$ ---> $b_b(555)$ $b_{bp}(555)$ ---> POC

Eastern South Pacific and eastern Atlantic



Stramski, Reynolds, Babin et al.
Biogeosciences, 5, 171-201 (2008)

Southern Ocean



Allison, Stramski, and Mitchell
Journal of Geophysical Research, submitted (2009)

Retrieving Backscatter with Semi-Analytical Algorithms

- Semi-analytical algorithms

  Theoretically based with some empirical results

  Optimized using a global optical data set

- Garver-Siegel-Maritorena (GSM01)

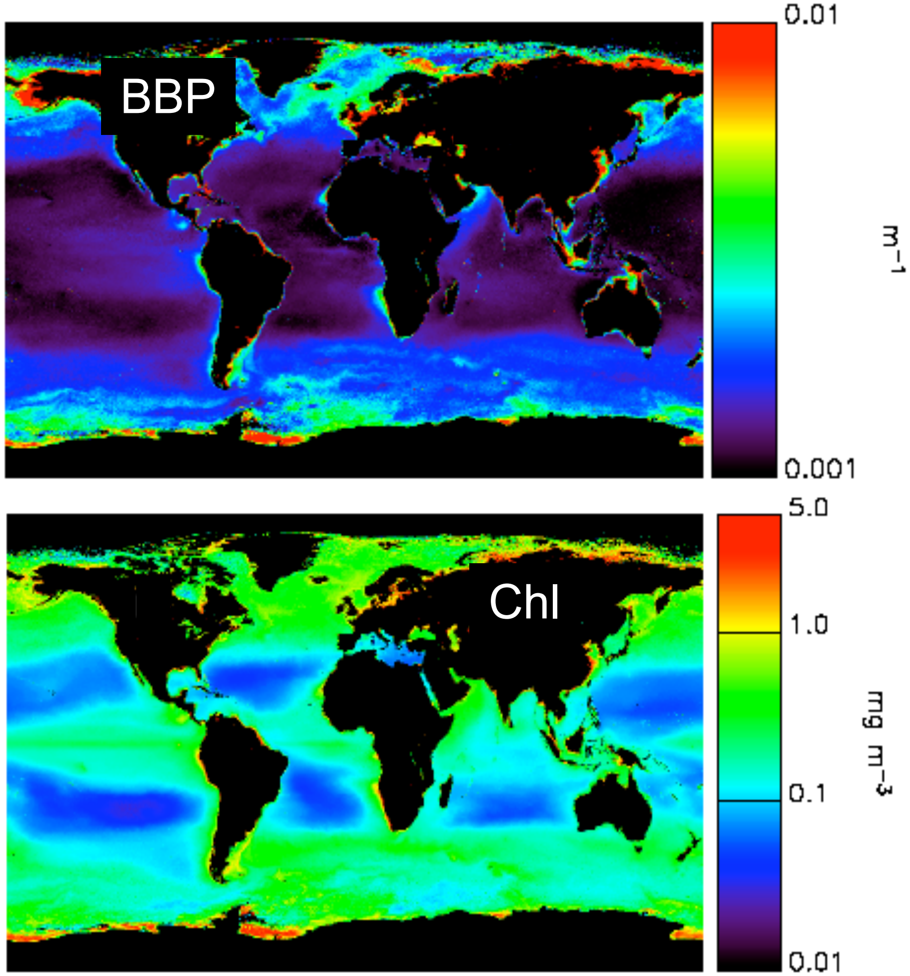
  Maritorena et al., 2002: *Applied Optics*

  Output = Chl, CDM (= $a_g(443)+a_{det}(443)$) & BBP ($b_{bp}(443)$)

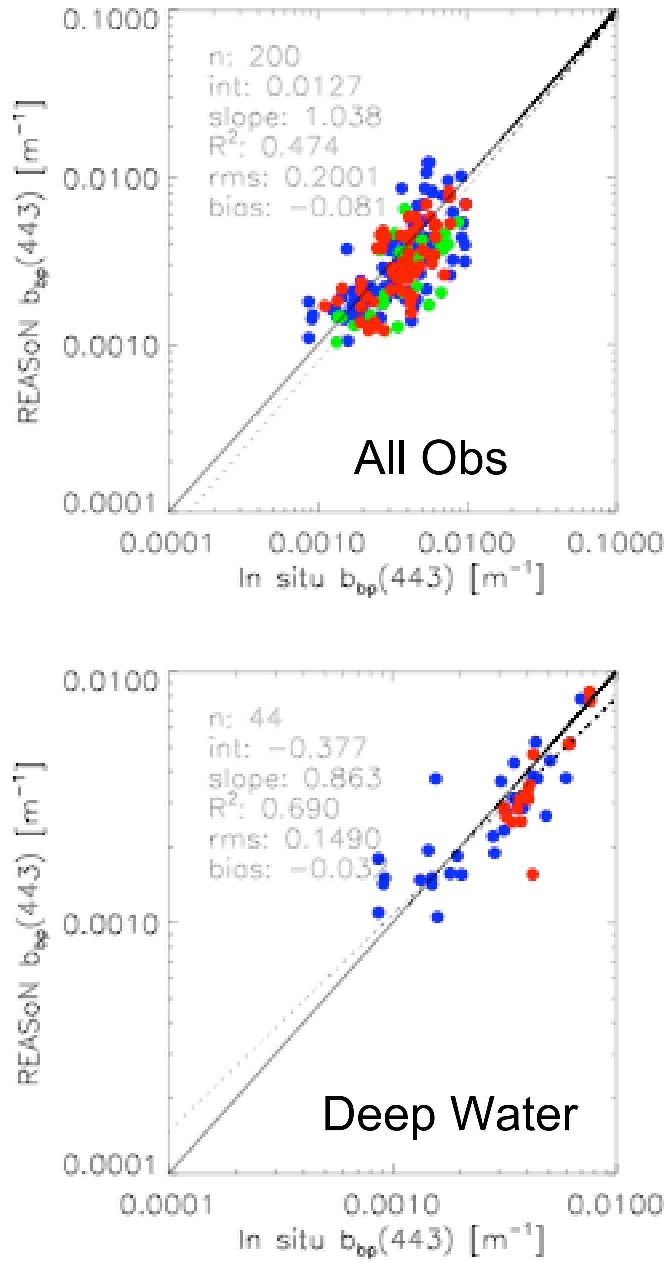
  Input = $L_{wN}(\lambda)$ for λ ranging from 412 to 670 nm

Data: http://wiki.icess.ucsb.edu/measures

GSM01 BBP



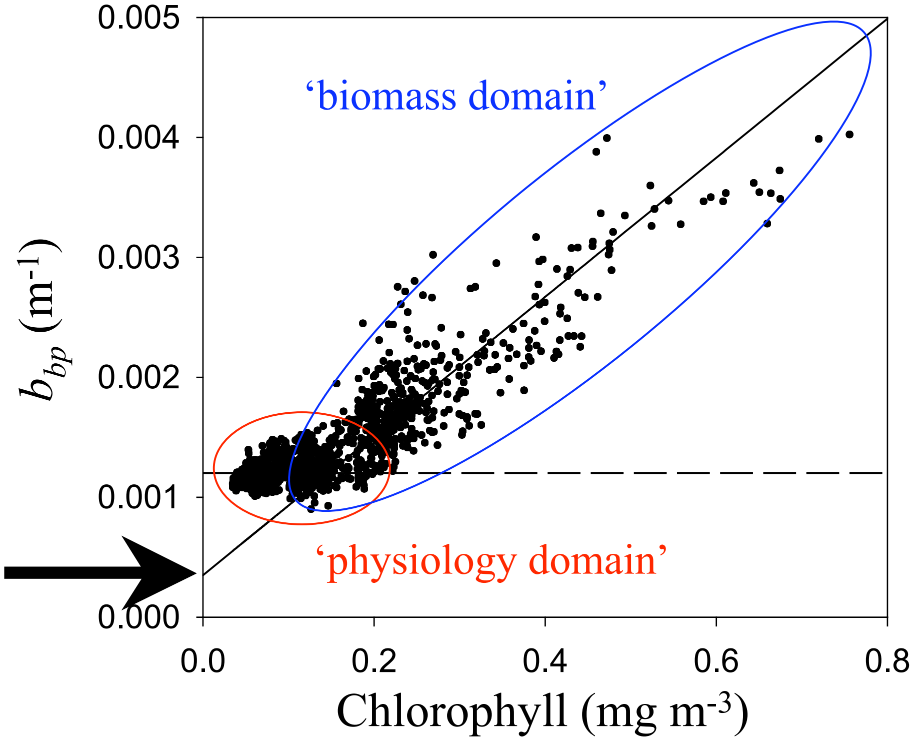
Siegel et al. (2005) JGR



Very little $b_b(\lambda)$ validation data are available

Maritorena et al. [in prep.]

Estimating PhytoC Using BBP



Intercept = b_{bp} from stable background component of particle assemblage

$$C = \text{scalar } H\,(b_{bp} - \text{intercept})$$
$$= 13{,}000\ H\,(b_{bp} - 0.00035)$$

Intercept = **0.00017 m^{-1}**
Stramski & Kiefer (1991) *Prog. Oceanogr.* 28, 343-383
Cho & Azam (1990) *Mar. Ecol. Prog. Ser.*, 63, 253-259

Phytoplankton Carbon = **25 – 35% POC**
Eppley et al. (1992) *J. Geophys. Res.*, 97, 655-661
DuRand et al. (2001) *Deep-Sea Res. II*, 48, 1983-2003
Gundersen et al. (2001) *Deep-Sea Res. II* 48, 1697-1718

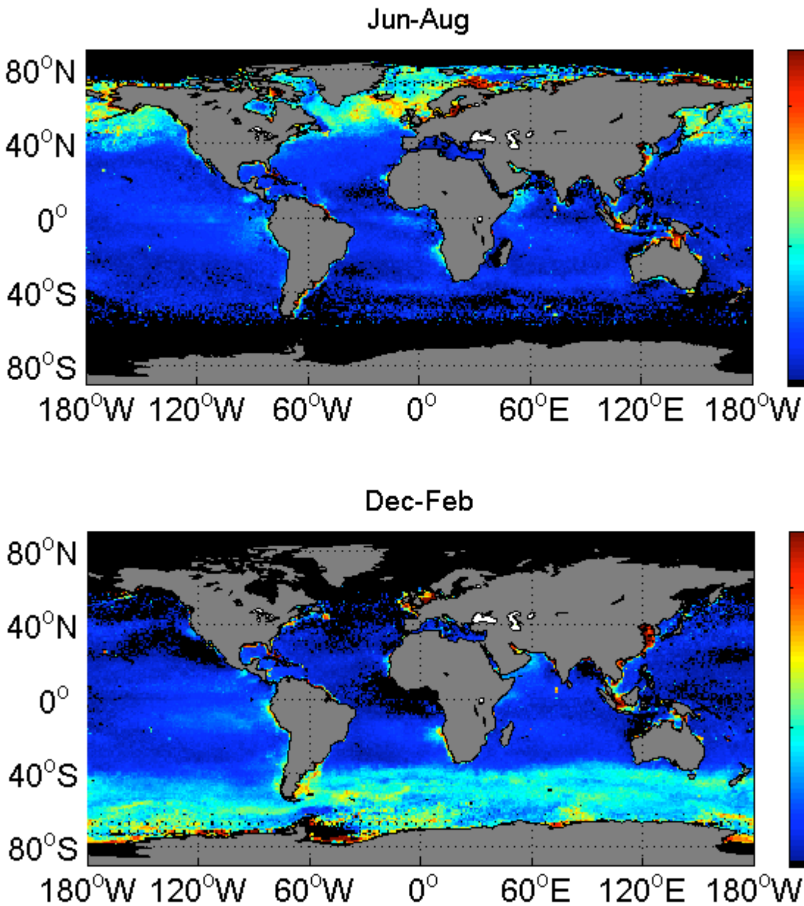
Behrenfeld et al. GBC [2005]

Virtually no PhytoC observations are available

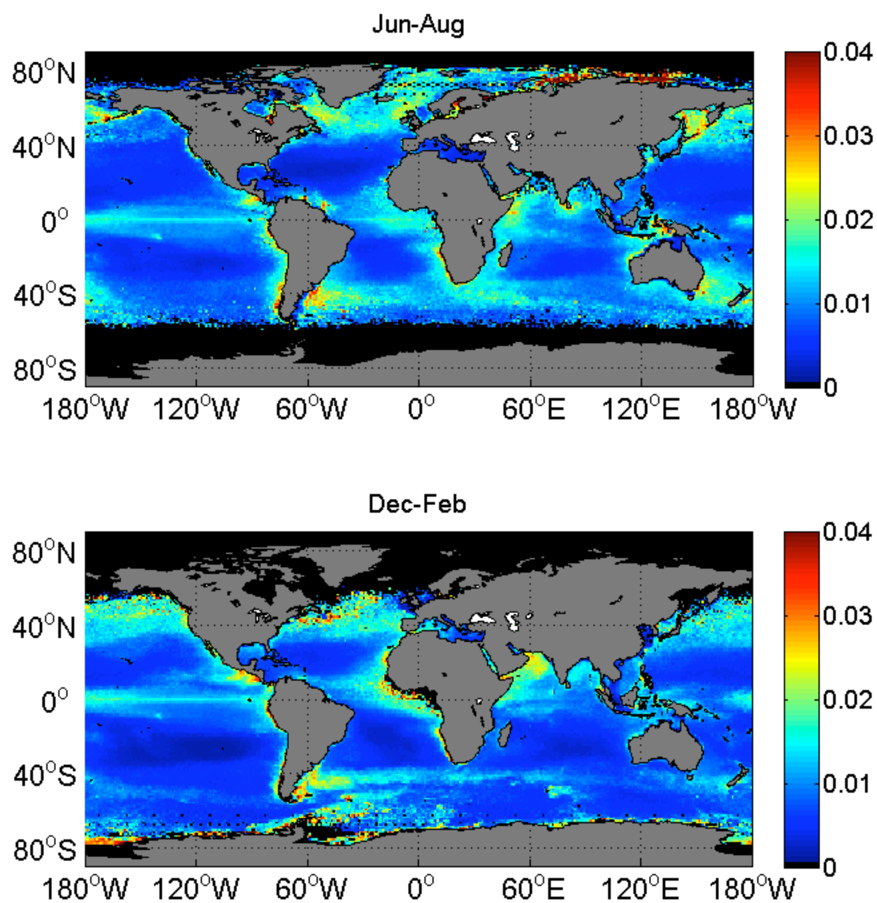
Some anecdotal evidence from SERIES Fe addition - Schultz et al. [in review]

Phyto C & Chl:C from Ocean Color

Phytoplankton Carbon (mg m^{-3})



Phytoplankton Chl:C

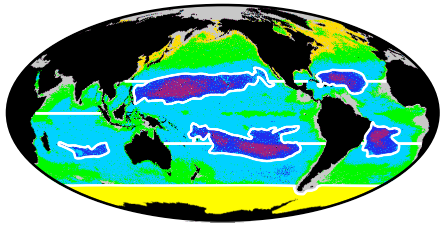


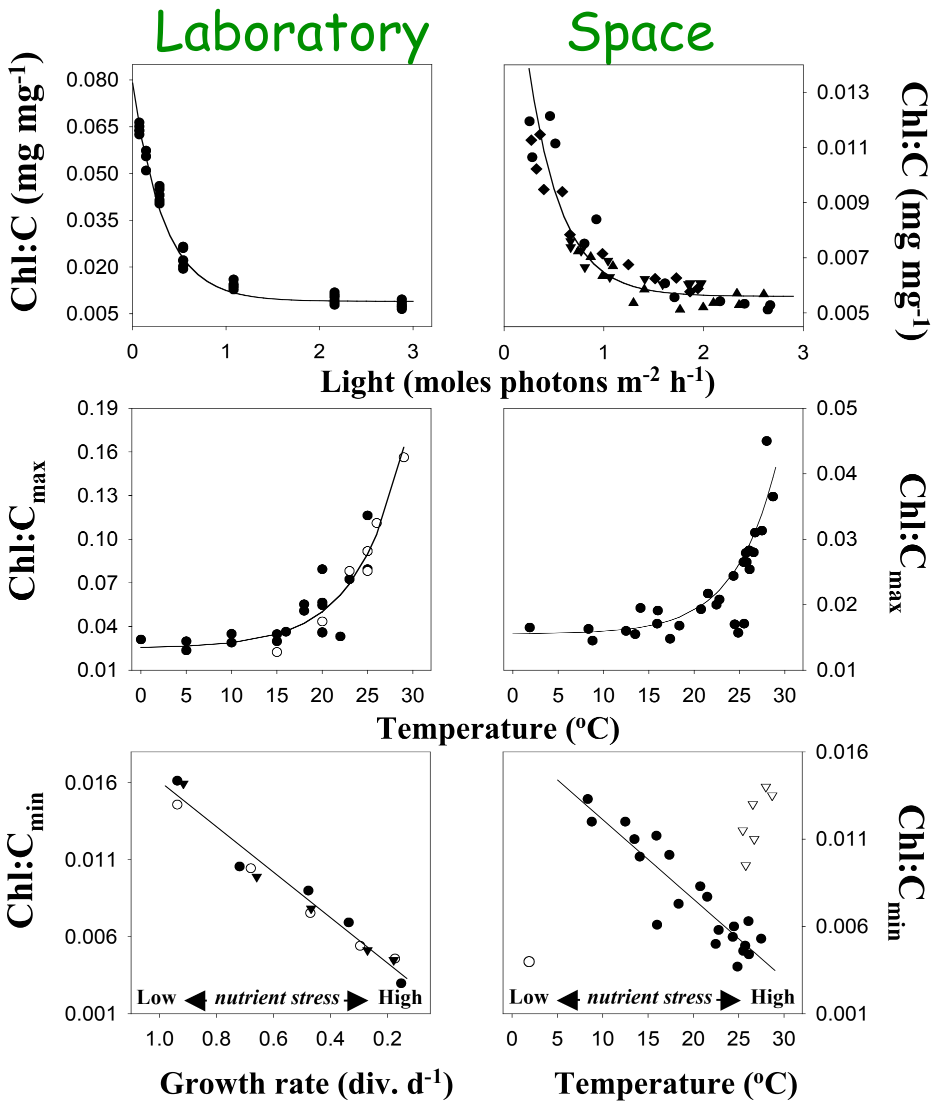
Carbon-based primary productivity modeling with vertically resolved photoacclimation

T. Westberry et al.

GLOBAL BIOGEOCHEMICAL CYCLES, VOL. 22, GB2024, doi:10.1029/2007GB003078, 2008

Chl:C from Ocean Color

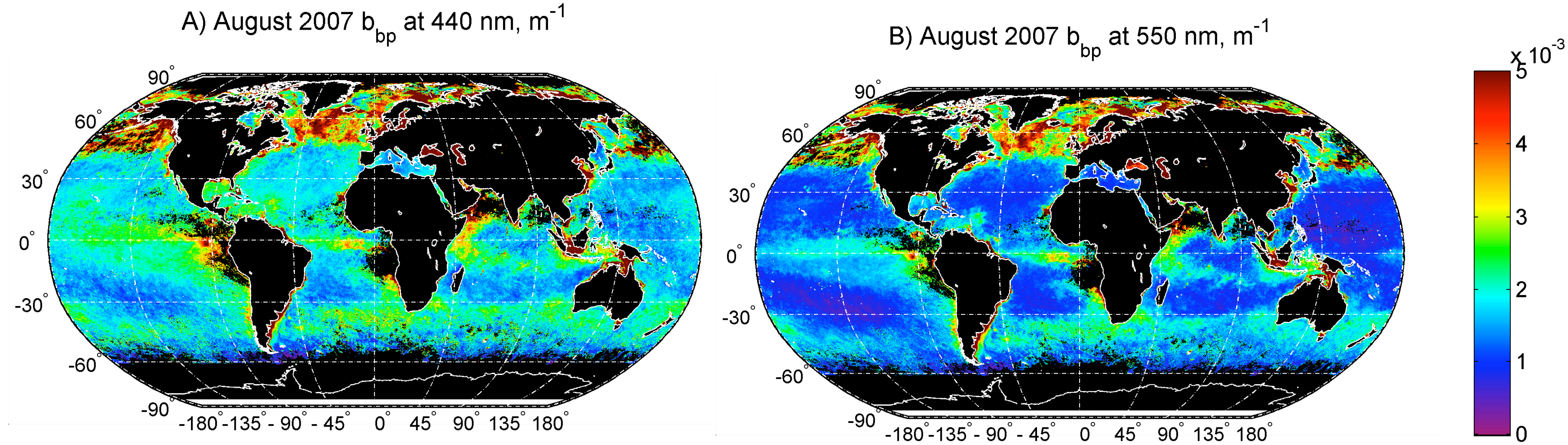


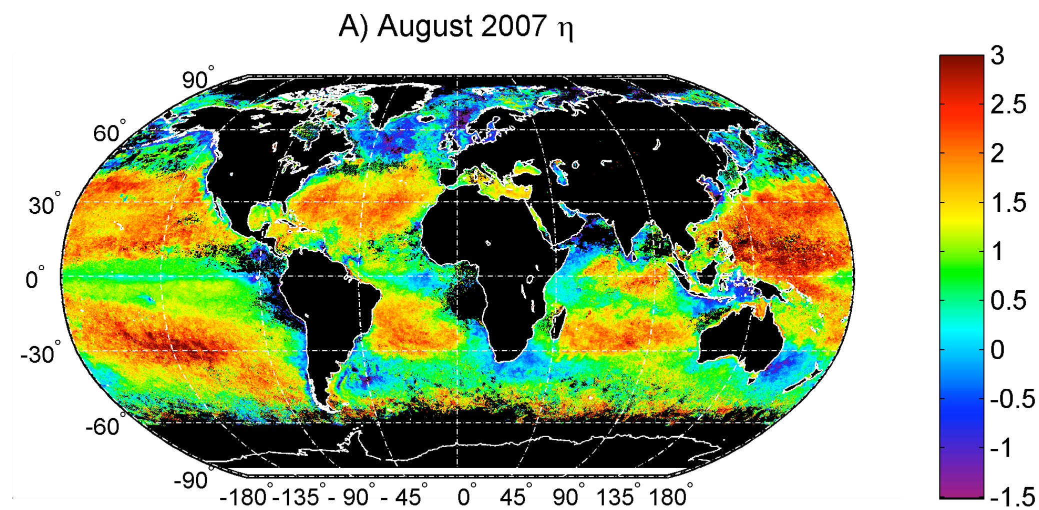


- Observed Chl:C vs. light relations are consistent with laboratory results
- Max & min Chl:C follow laboratory expectations as well
- Supports the use of BBP changes as a proxy for PhytoC changes

Behrenfeld et al. [2005]

Retrieving Backscatter Spectrum





Loisel & Stramski [2000] is used to retrieve $b_{bp}(\lambda)$

Estimate spectral slope, η, from $b_{bp}(\lambda) = b_{bp}(\lambda_o)\ (\lambda/\lambda_o)^{-\eta}$

After Loisel et al. [2006]

Linking Particles & Backscattering

$$b_{bp}(\lambda) = \int_{D_{\min}}^{D_{\max}} \frac{\pi D^2}{4} Q_{bb}(D,\lambda,m_r)\, N(D)\, dD$$

Cross-Section Area

Backscattering Efficiency

Particle Size Distribution

- Important goal is to retrieve N(D), the PSD
- The *normal* assumptions are likely to be poor

  $Q_{bb}(\ldots)$ from Mie theory for homogeneous spheres

  N(D) following power-law formulation ($N_o\,(D/D_o)^{-\xi}$)

Retrieving the PSD

Let's see what we can do with the *normal* assumptions

$$b_{bp}(\lambda) = \int_{D_{\min}}^{D_{\max}} \frac{\pi}{4} D^2 Q_{bb}(D, \lambda, m_r) N_o \left(\frac{D}{D_o} \right)^{-\xi} dD$$

Measured

$b_{bp}(\lambda)$ efficiency solved by Mie theory

Goal of retrieval

By measuring $b_{bp}(\lambda)$ for more than 2 λ's, we can retrieve N_o & ξ

Kostadinov, Siegel & Maritorena [accepted pending minor revision - JGR]

Algorithm Scheme

Input satellite LwNs

Retrieve $b_{bp}(\lambda)$ via Loisel et al. (2006)

Calculate spectral slope of the $b_{bp}(\lambda) = \eta$ using 490, 510, 550 nm

Input Mie model parameters for realistic open ocean:

1. $\xi = 2.5:0.05:6$
2. n = RANDN(1.05,0.05)
3. k = ABS(RANDN(0,0.00075))
4. $D_{min} = 0.002\ \mu m$
5. D_{max} = RAND(25,100) μm

Create two LUTs:

- $\xi = f(\eta)$
- $b_{bp}(440)/N_o = g(\eta)$

(w/ uncertainty bounds)

Use the LUTs and maps of η & $b_{bp}(440)$ to calculate…

Slope of the PSD, ξ

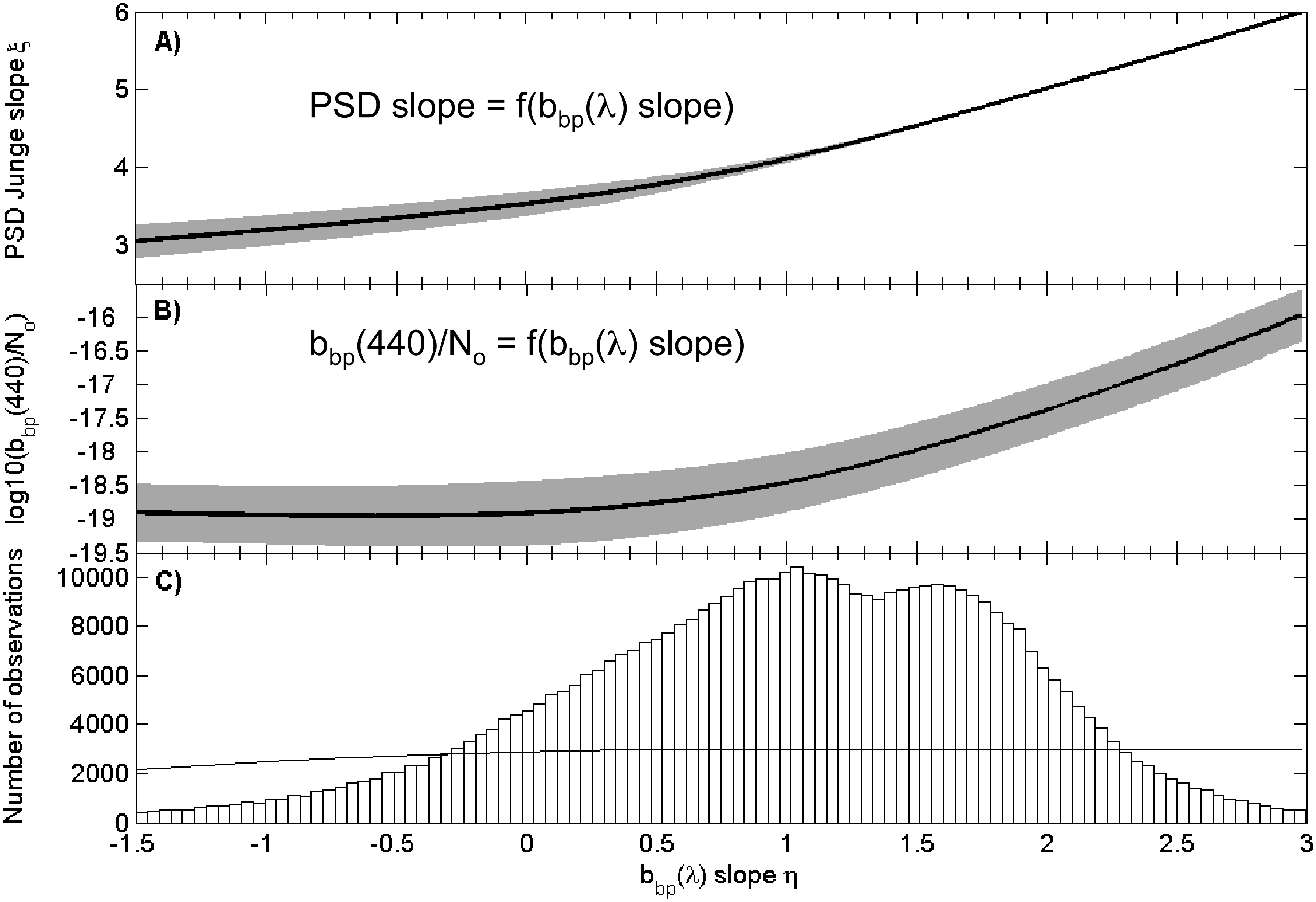
Scaling particle abundance, N_o

Calculate derived products:

1) Total and size fractionated particle volumes
2) Cell numbers in different size classes

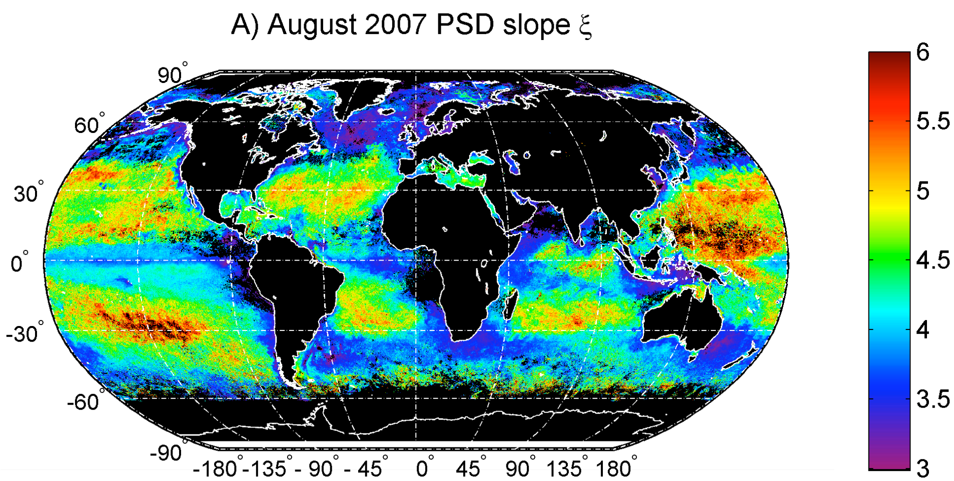
Kostadinov et al. [2009]

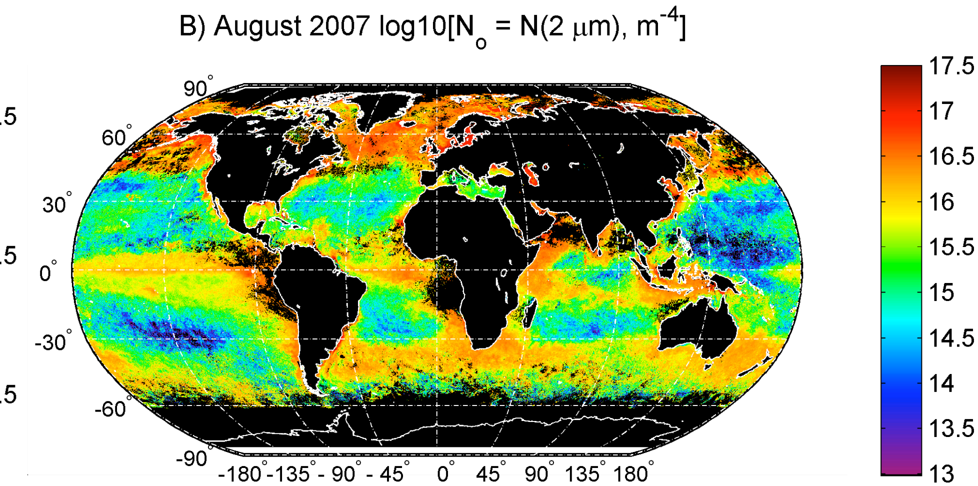
Algorithm Look-up Tables and Uncertainty Analysis



Kostadinov et al. [2009]

Power Law PSD Parameters



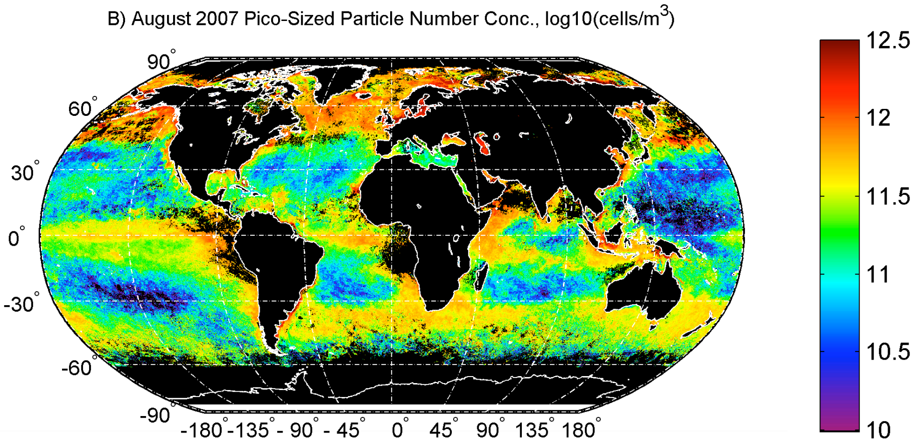


$$N(D) = N_o\,(D/D_o)^{-\xi}$$

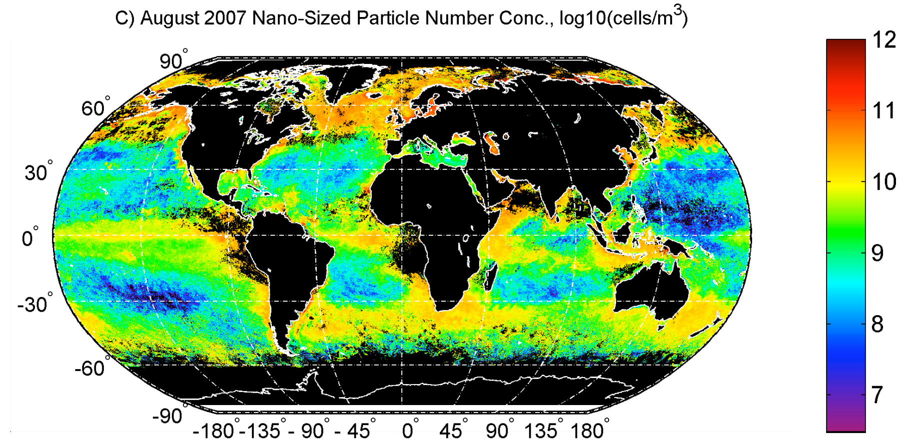
- High slopes (ξ) in oligotrophic water - low in eutrophic oceans
- High scaling abudndances (N_o) in productive waters - low in oligotrophic oceans
- Rough consistency with available Coulter PSD obs *(N<25!!)*

Partitioning Number Concentration

Pico-particles (0.5 μm to 2 μm)

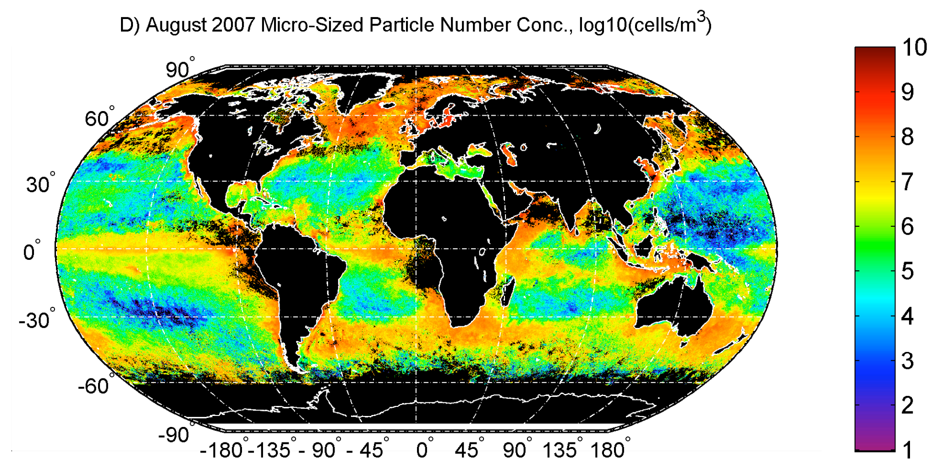


Nano-particles (2 μm to 20 μm)



log10(particles/m^3)

Micro-particles (20 μm to 50 μm)



Pico's vary ~100 times

Nano's vary ~ 10,000 times

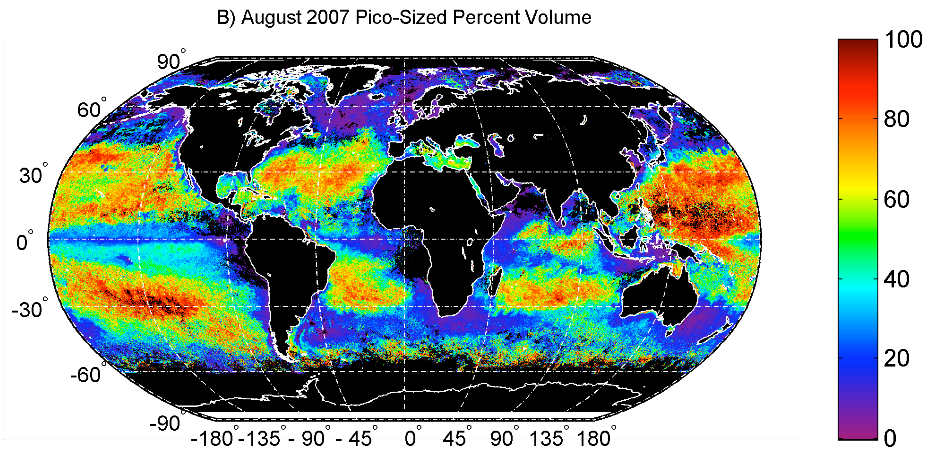
Micro's vary ~ 10^6 times

Ecologically consistent…

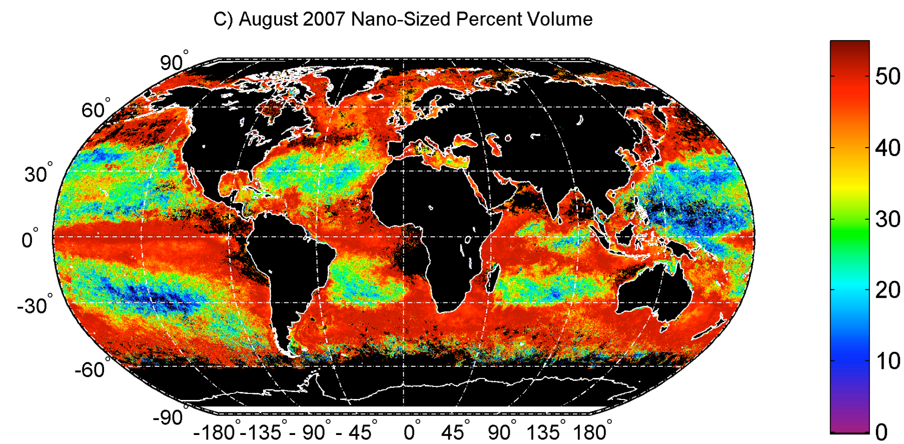
Kostadinov et al. [2009]

Partitioning Particle Volumes

% Pico's (0.5 μm to 2 μm)



% Nano's (2 μm to 20 μm)

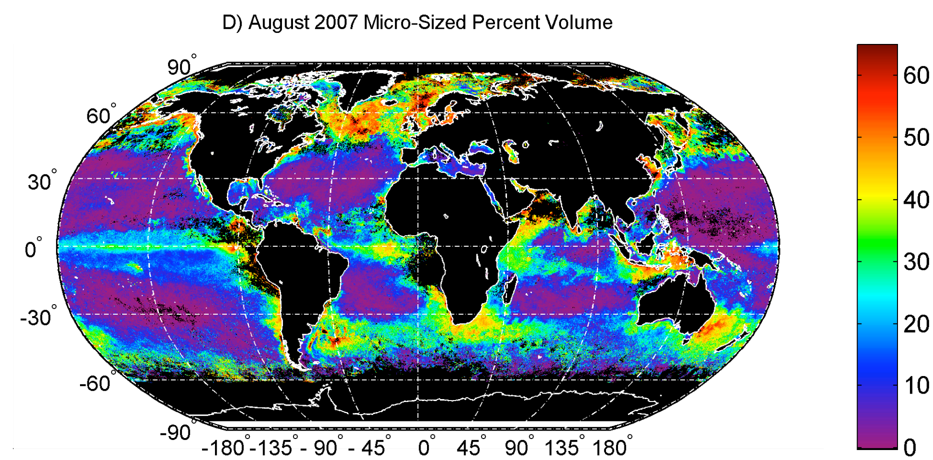


Pico's dominate oligotrophic ocean (>80%)

Nano's in transition regions (45%)

Micro's only found in upwelling zones & high latitudes (<40%)

% Micro's (20 μm to 50 μm)



Kostadinov et al. [2009]

Linking Particles & Backscattering

$$b_{bp}(\lambda) = \int_{D_{\min}}^{D_{\max}} \frac{\pi D^2}{4} Q_{bb}(D,\lambda,m_r)\, N(D)\; dD$$

- We know the usual assumptions are poor

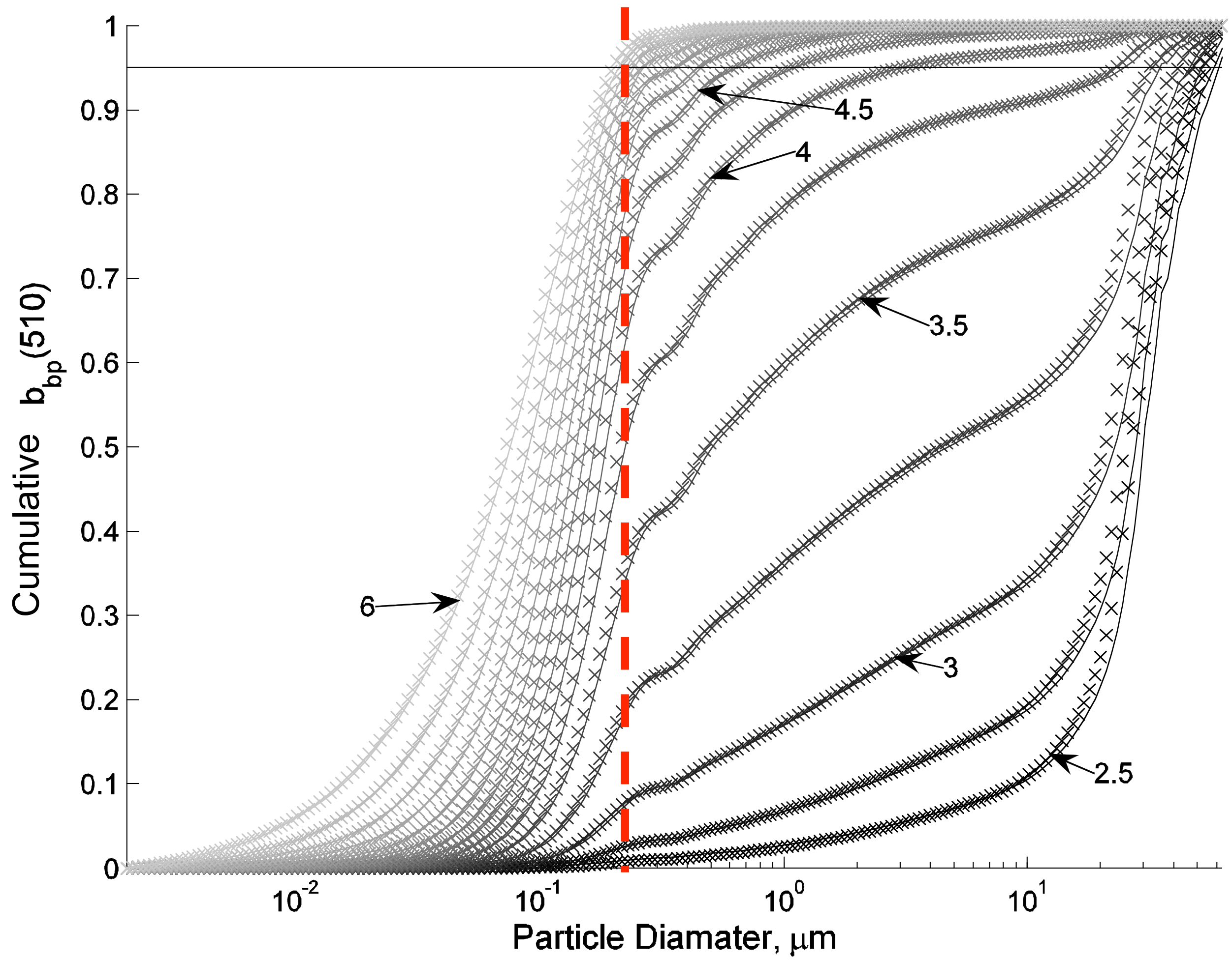
  $Q_{bb}(\ldots)$ from Mie theory for homogeneous sphere

  N(D) following power-law (= $N_o\ (D/D_o)^{-\xi}$)

  D_{max} also can be important (for low ξ)

- Let's examine implications of these assumptions…

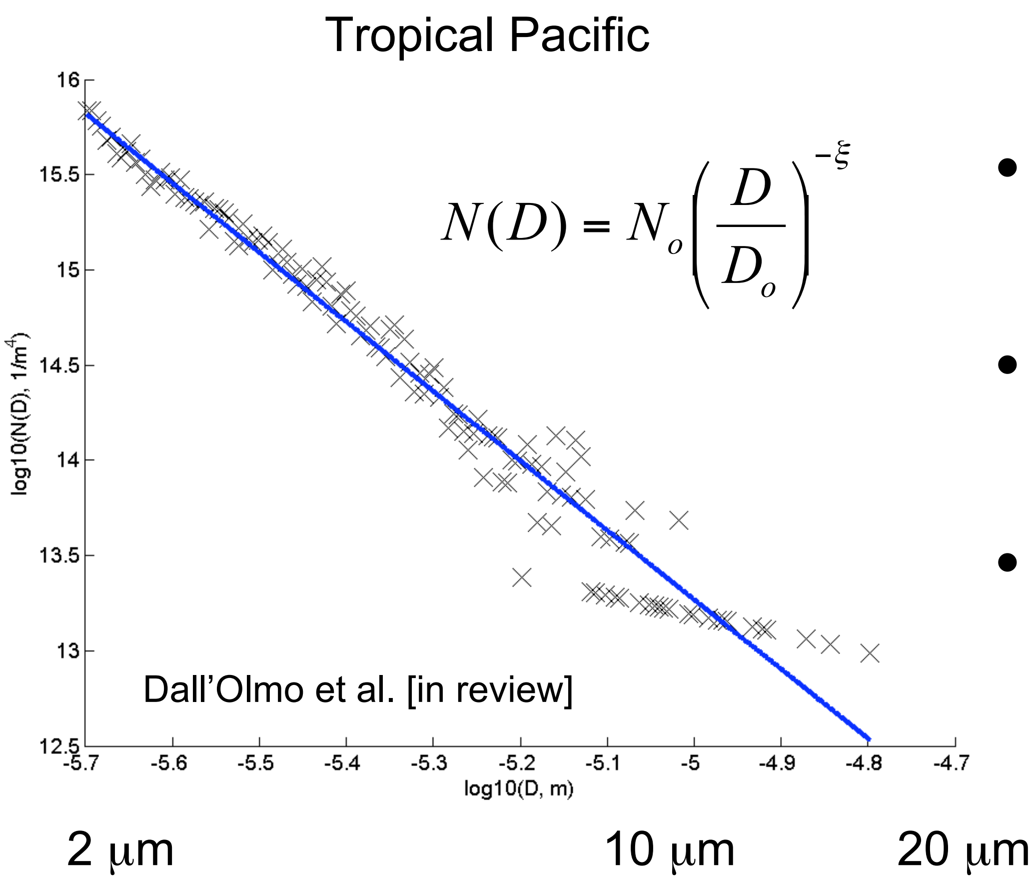
Implications of Mie & Power-Law PSD



After Stramski & Kiefer [1991] and many others…

Particles less than 0.2 μm dominate $b_{bp}(510)$ when assumptions of homogenous spheres & power-law N(D) are applied

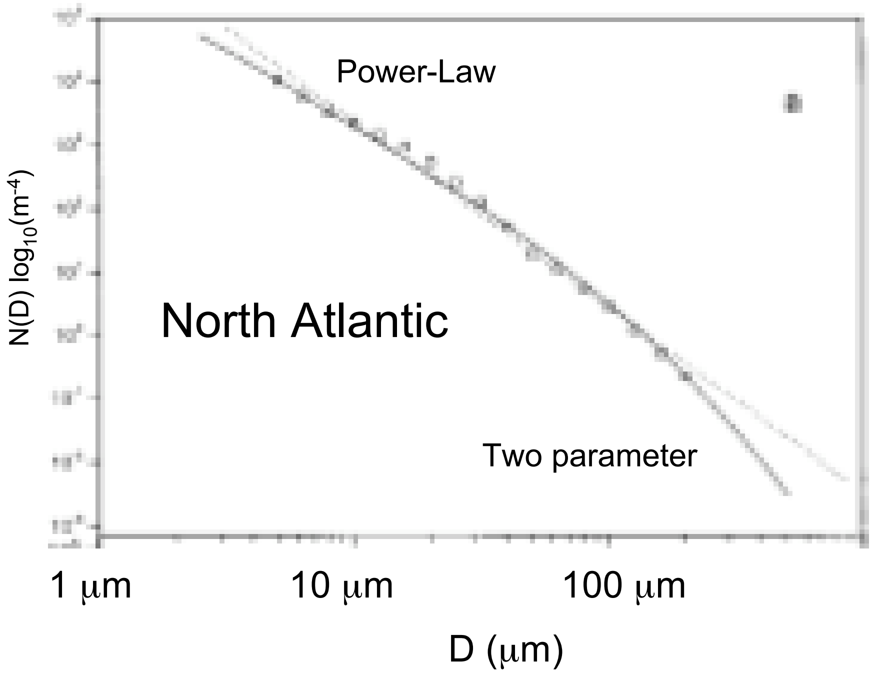
Typical PSD Observations

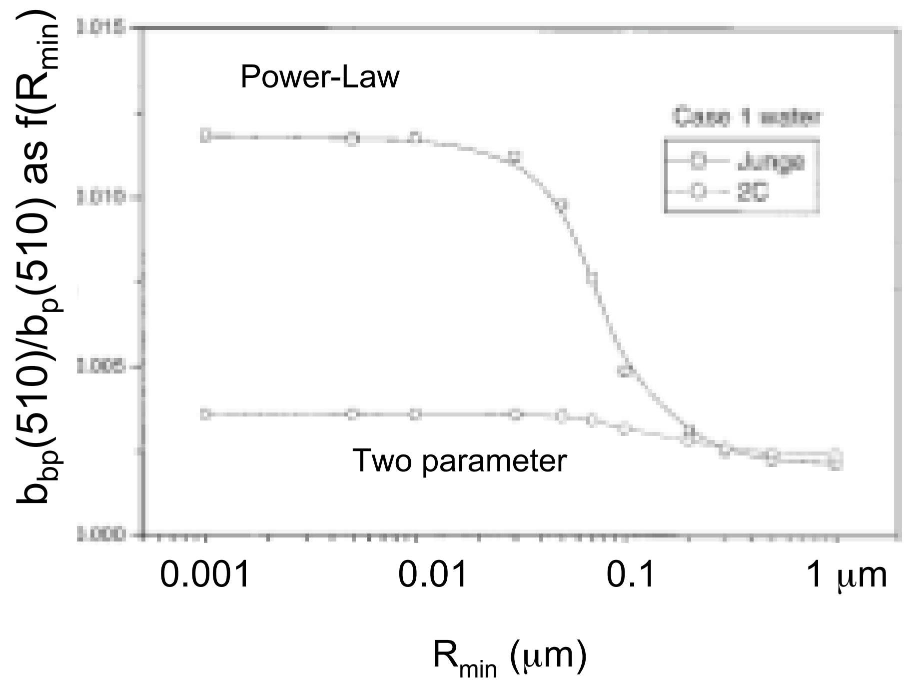


- Coulter PSD obs from tropical Pacific
- Power-law PSD "fits" observations
- Particle diameters range from 2 to 20 μm
- Not in the "optically relevant" range

We do not measure the right range of scales (supposedly)

Is it the Power-Law PSD Assumption?





PSD observation from open North Atlantic

Fit using power-law & two parameter PSD models

Mie is used to calculate backscattering ratio as $f(R_{min})$

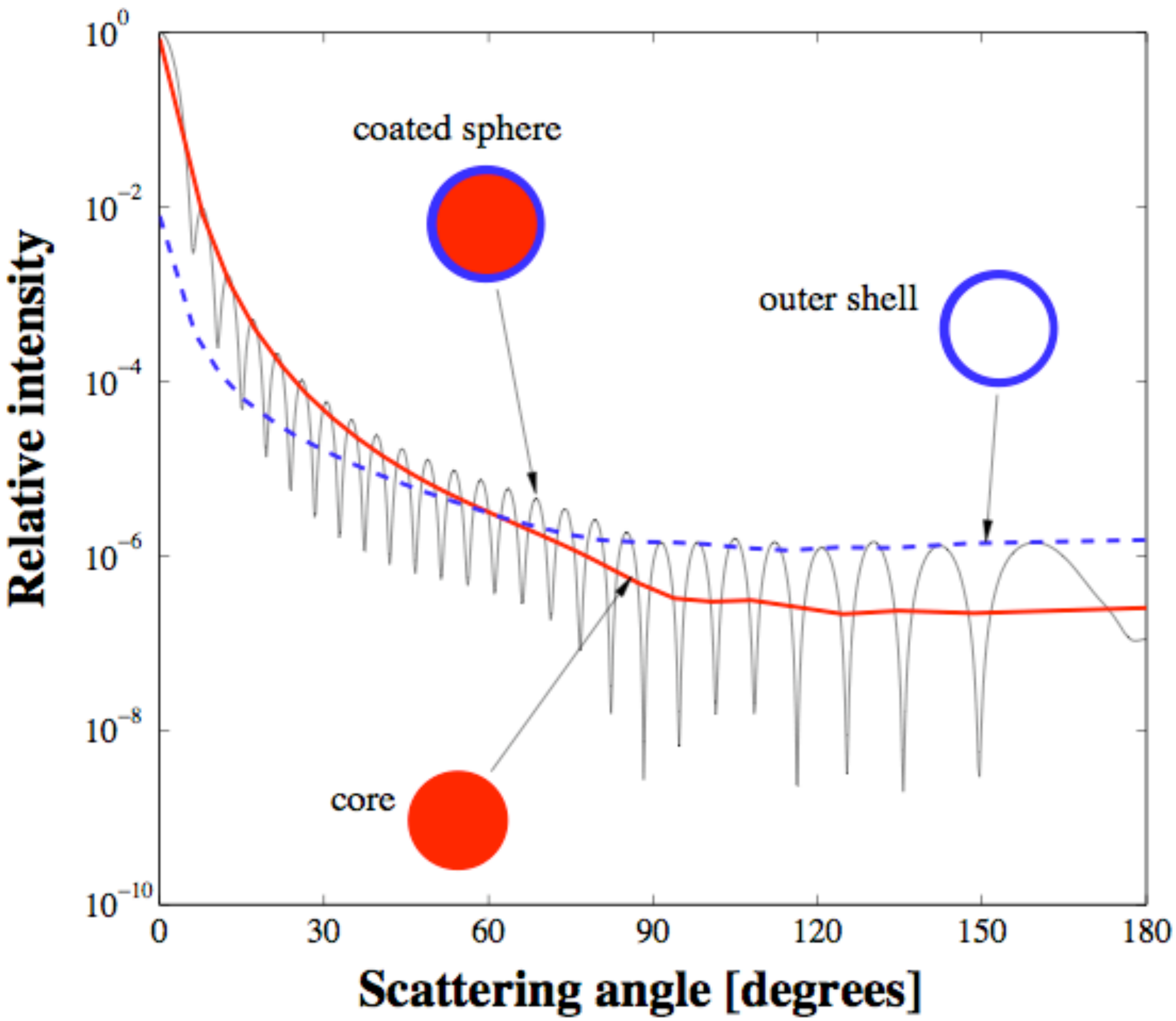
For power-law N(D), strong influence on R_{min} at ~0.07 μm

Matters how N(D) is modeled…

Risovic [2002] *Applied Optics*

Is it the Mie Theory Assumptions?

Mie model of coated sphere (Meyer, Applied Optics, 1979)



Outer shell m_r is 5x core m_r

Forward scatter goes as core m_r

Backscatter follows shell m_r

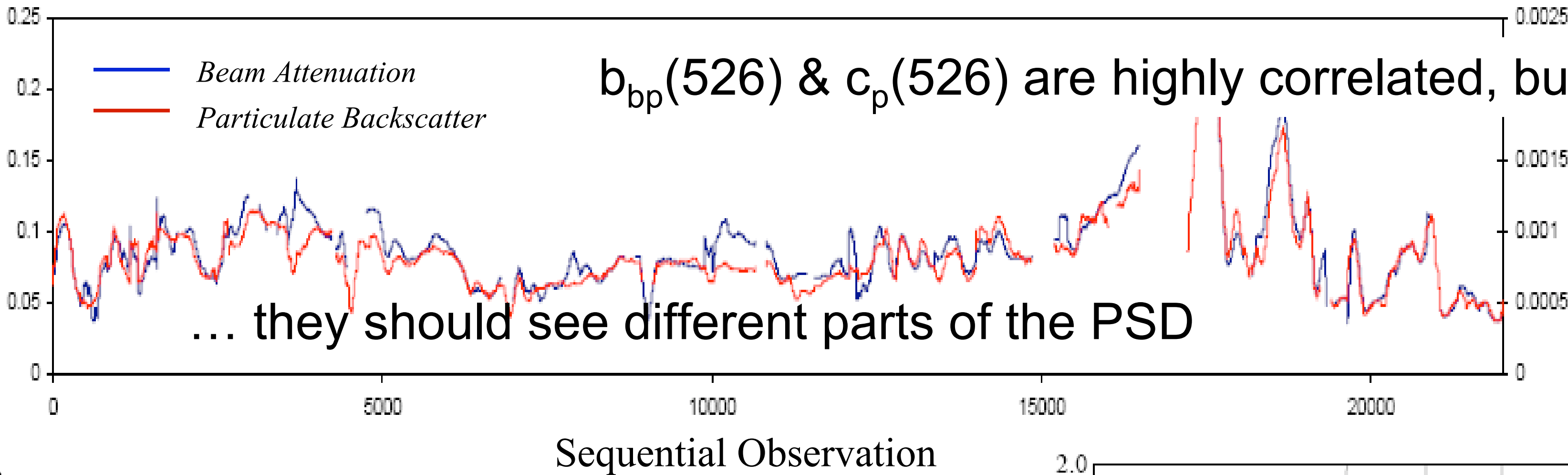
Still, highly idealized

Nonsphericity…

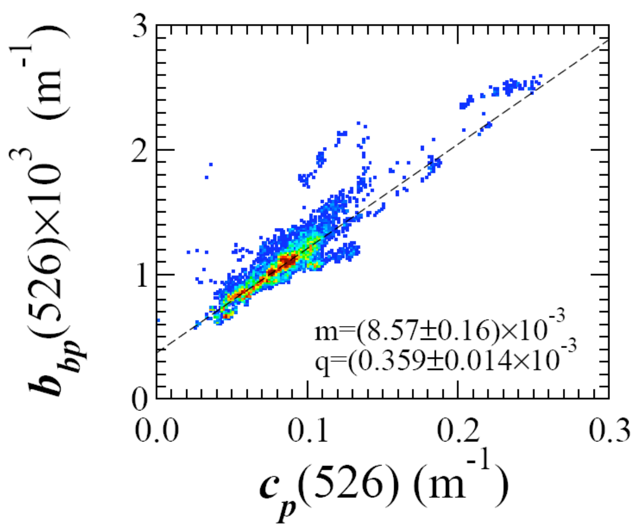
Matters how $Q_{bb}(\ldots)$ is modeled…

Observations of $b_{bp}(\lambda)$ & $c_p(\lambda)$ from Tropical Pacific

$b_{bp}(526)$ & $c_p(526)$ are highly correlated, but…

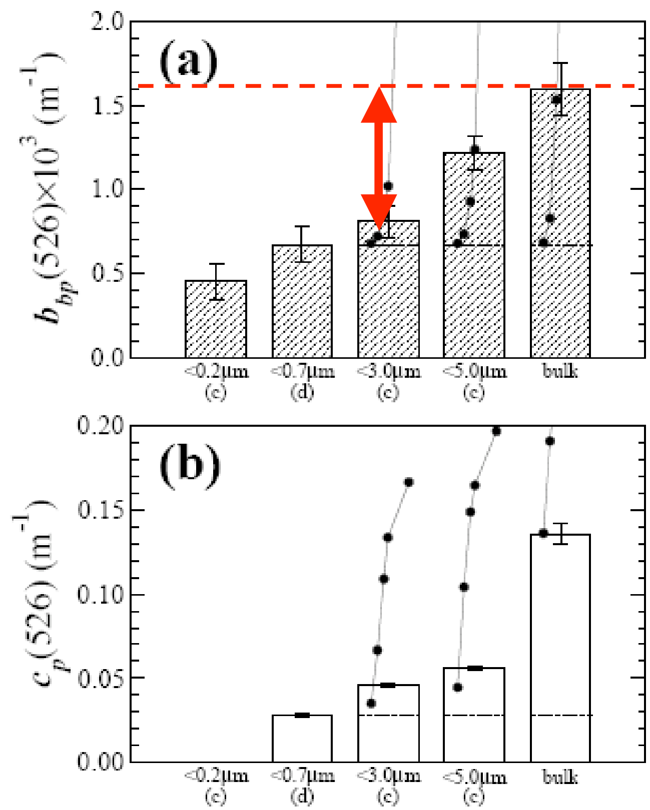


… they should see different parts of the PSD



Dall'Olmo et al. [in review] *Biogeosciences Discussion*

50% of $b_{bp}(526)$ from D > 3 μm



There's a problem here…

Linking Particles & Backscattering

$$b_{bp}(\lambda) = \int_{D_{\min}}^{D_{\max}} \frac{\pi D^2}{4} Q_{bb}(D,\lambda,m_r)\, N(D)\; dD$$

- Need observational improvements

  N(D) for D < 2 μm (something besides Coulter counters)

  General approaches for $Q_{bb}(\ldots)$

- Inverse modeling is one approach

  Use field observations of $c_p(\lambda)$ & $b_{bp}(\lambda)$ to

  constrain general forms for N(D) & $Q_{bb}(\ldots)$ (& $Q_c(\ldots)$)

We Want Carbon Stocks, But…

$$POC = \int_{D_{min}}^{D_{max}} \frac{\pi D^3}{6} \rho_c(D,\ldots)\, N(D)\, dD$$

Carbon content as f(D)

Particle Size Distribution

Need to know $\rho_c(D,\ldots)$ (Carbon / volume as f(D))

Need to know $\rho_c(D,\ldots)_{ph}$ for PhytoC

D_{max} & D_{min} are both *very* important which will make this approach difficult

Take Home Message(s)

- We can do a lot besides chlorophyll

  Lots of progress - POC, PIC, $b_{bp}(\lambda)$, PhytoC & N(D)

  Need more & better field data (differing biomes, protocols, …)

- We are *measurement limited*

  N(0.2<D<2μm), PhytoC, $\rho_c(D)$, …

- We are *model/concept limited*

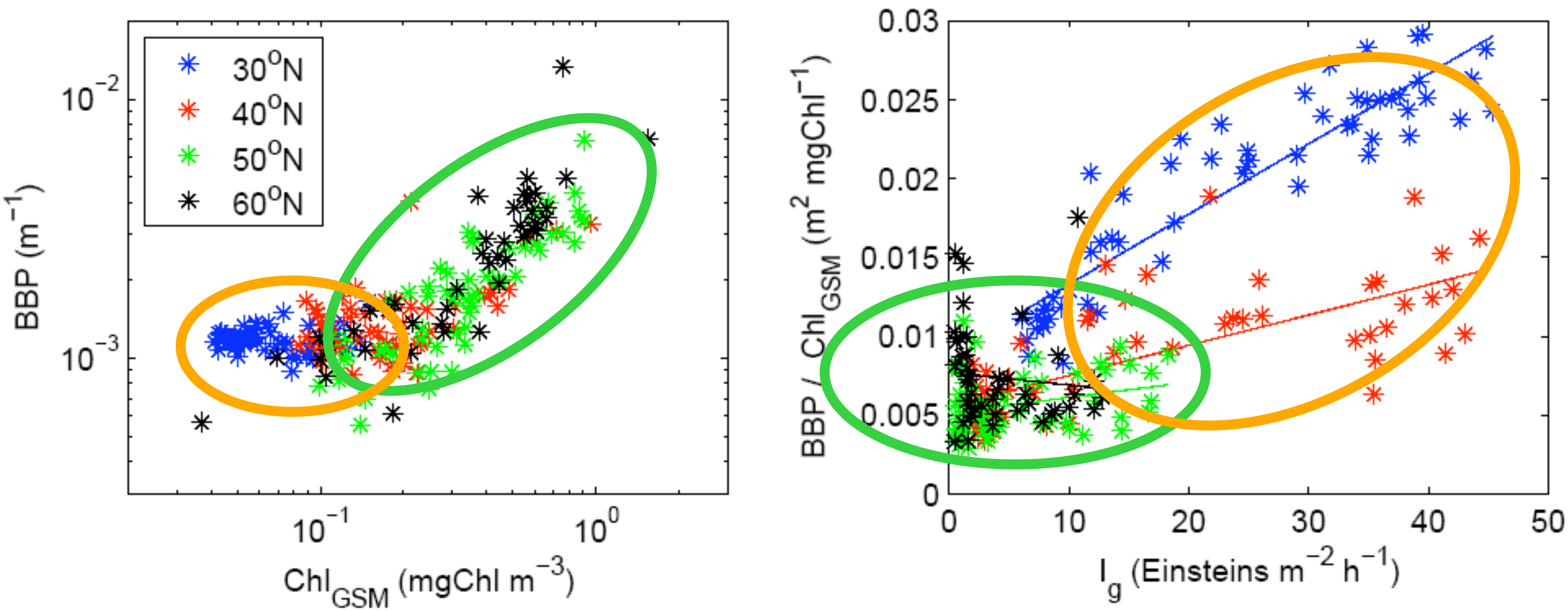
  Resolve the size paradigm for $b_{bp}(\lambda)$

  How to model $Q_{bb}(\ldots)$? (theory will not help much)

  Inversion of $b_{bp}(\lambda)$ & N(D) obs to model $Q_{bb}(\ldots)$??


Thank You!!

What about BBP & Chl



Data are from a North Atlantic transect along 30^{o}W

Modes for "growth" (f(Chl)) & "photoacclimation" (f(I_g))

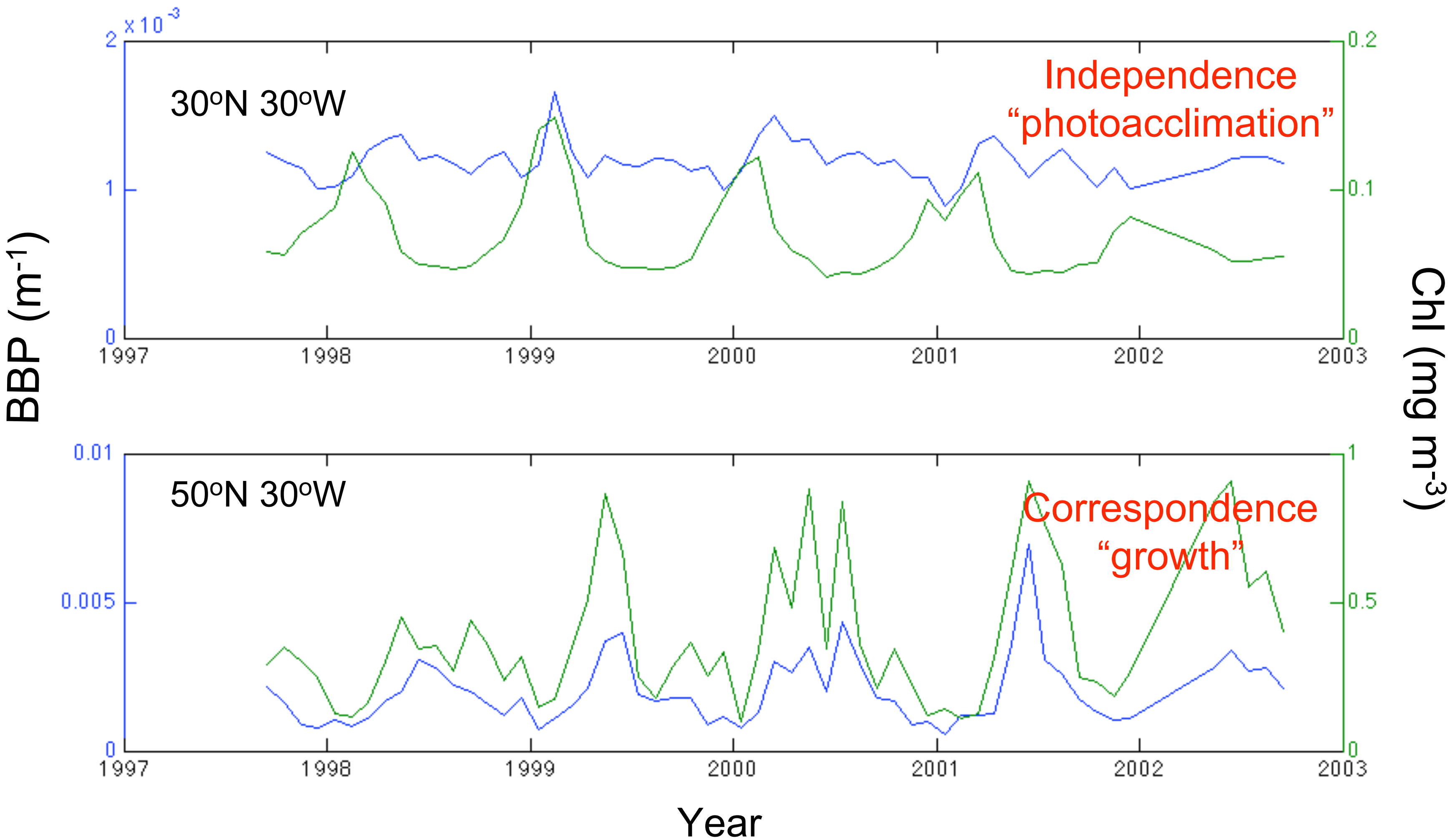
BBP acts like phytoplankton biomass…

Siegel et al. (2005) JGR

Improving Phyto C Assessments

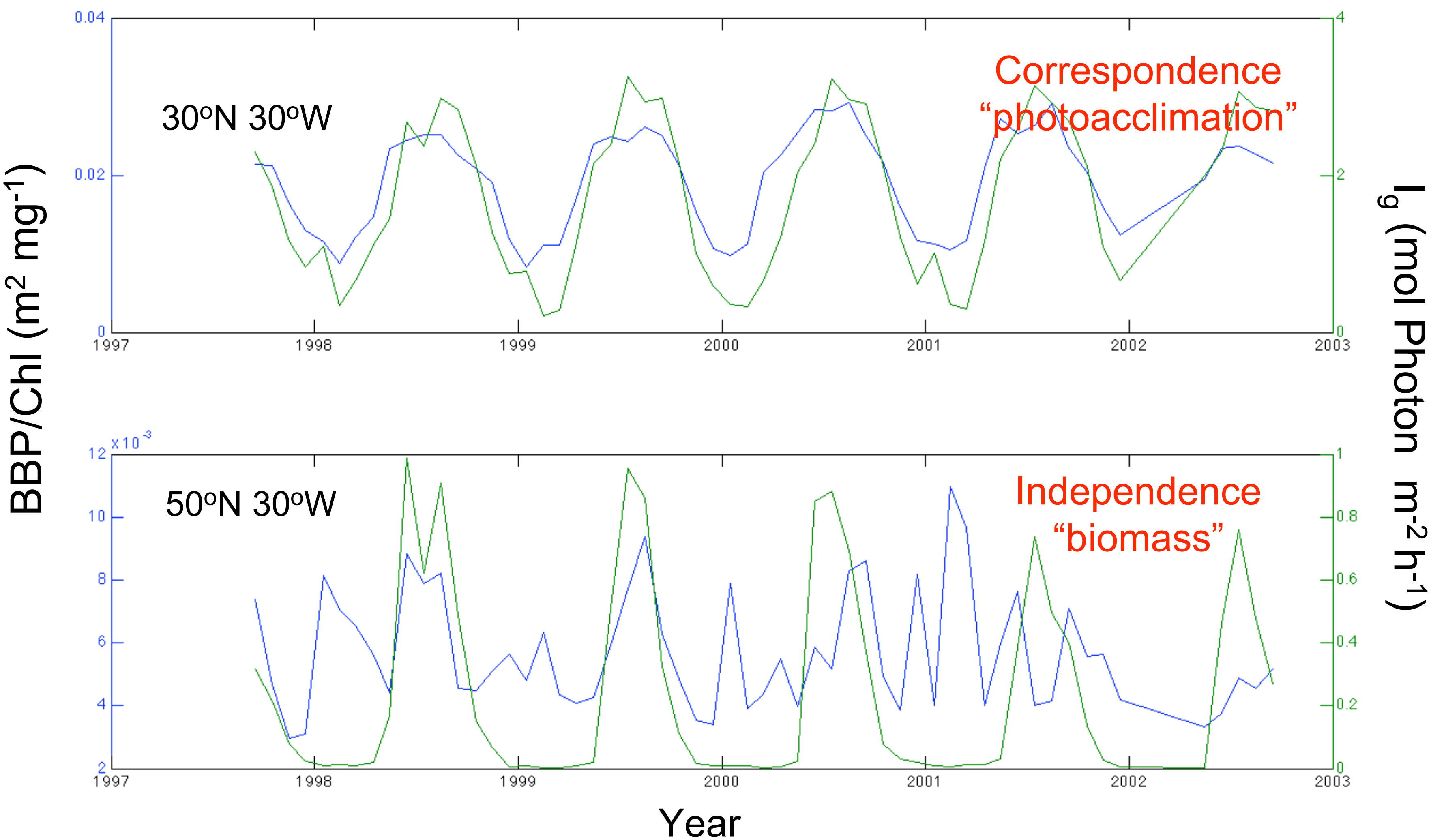
- Need useful field data!!
  - Routine protocols for phyto C do not exist
  - Differentiate autotrophic / heterotrophic / detrital C
  - Simultaneous optical & particle size observations
  - Wide range of biomes (GIGO…)
- Improve satellite methodologies
  - BBP is one way to get at Phyto C (but the linear model?)
  - Need to assess $\rho_C(D)_{ph}$

BBP & Chl vs. Time



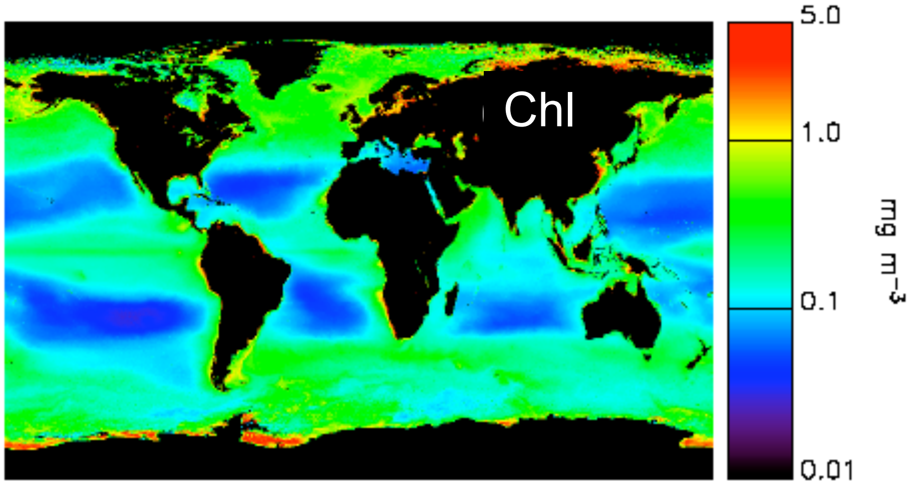
after Siegel et al. (2005) JGR

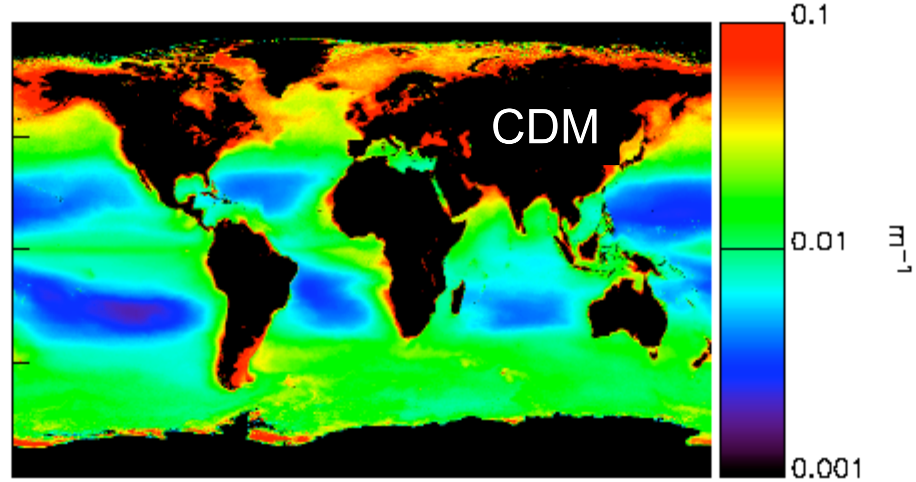
BBP & Chl vs. Time



after Siegel et al. (2005) JGR

The Ocean Color Trio



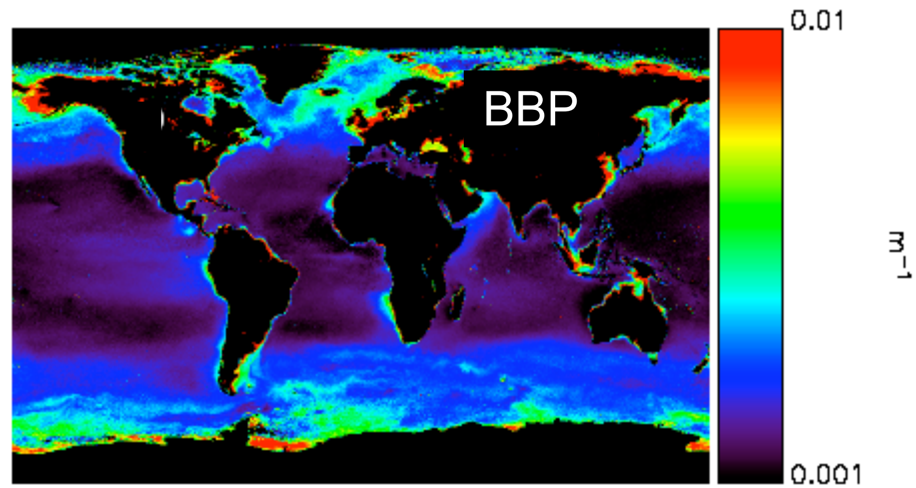


SeaWiFS 5 y climatology

Oceanic structures

Gyres, upwelling, etc.

Large variability in Chl & CDOM but not BBP



Siegel et al. (2005) JGR