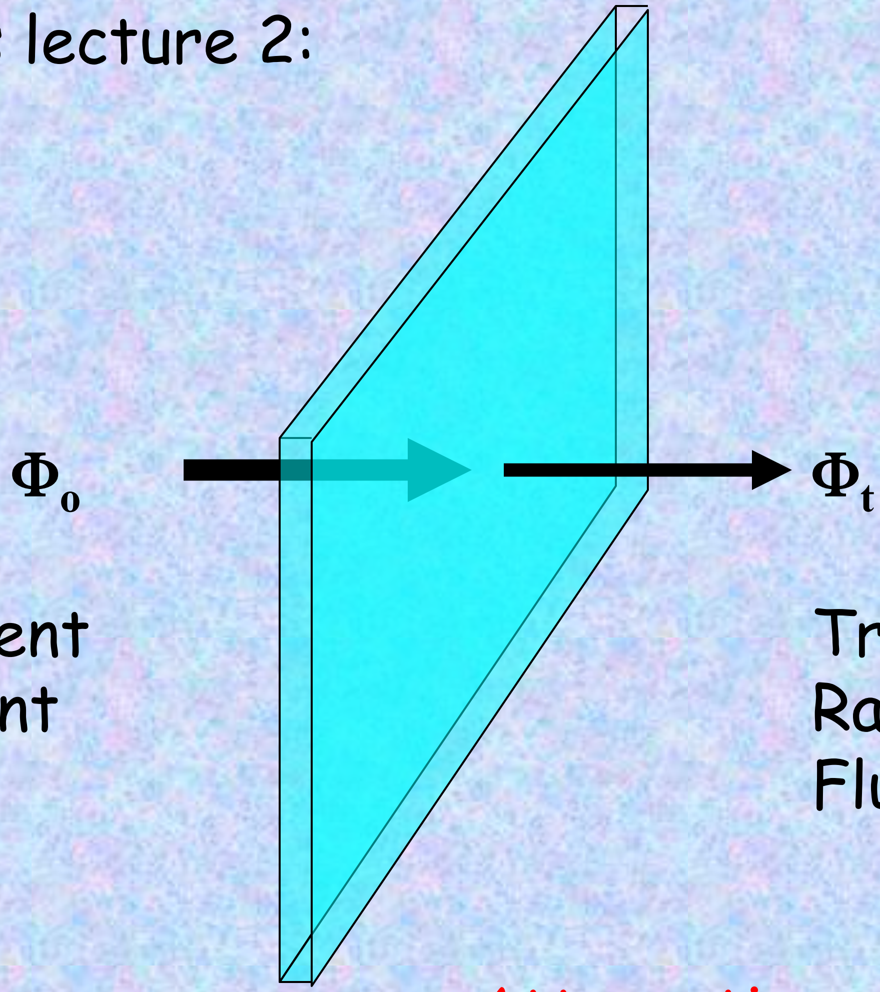
The beam attenuation coefficient and its spectra

(also known as beam-c or extinction coefficient).

Emmanuel Boss, U. of Maine

Review: IOP Theory

Collin's lecture 2:



Incident
Radiant
Flux

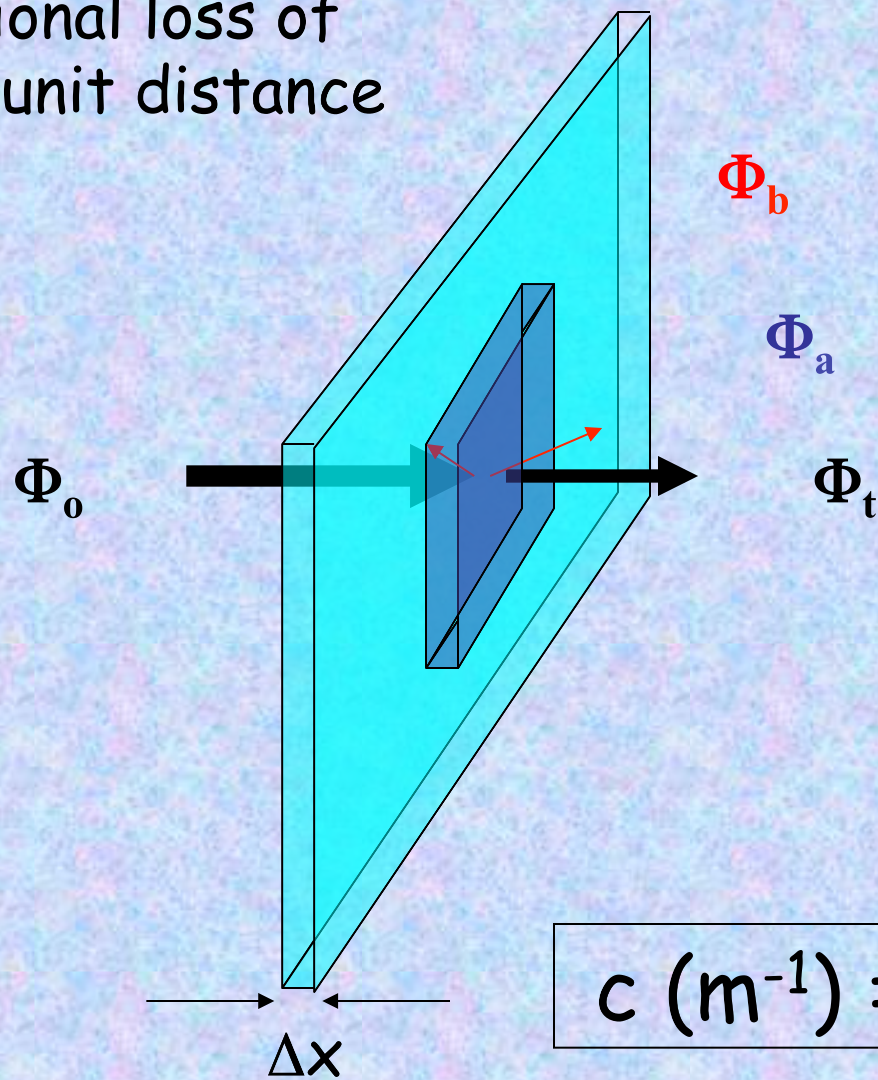
Transmitted
Radiant
Flux

Attenuation

Collimated
Monochromatic

Beam Attenuation Measurement Theory

c = fractional loss of light per unit distance



$$c\,\Delta x = -\,\Delta\Phi/\Phi$$

$$\int_0^x c\,dx = -\int_0^x d\Phi/\Phi$$

$$c(x-0) = -[\,\ln(\Phi_x)-\ln(\Phi_0)]$$

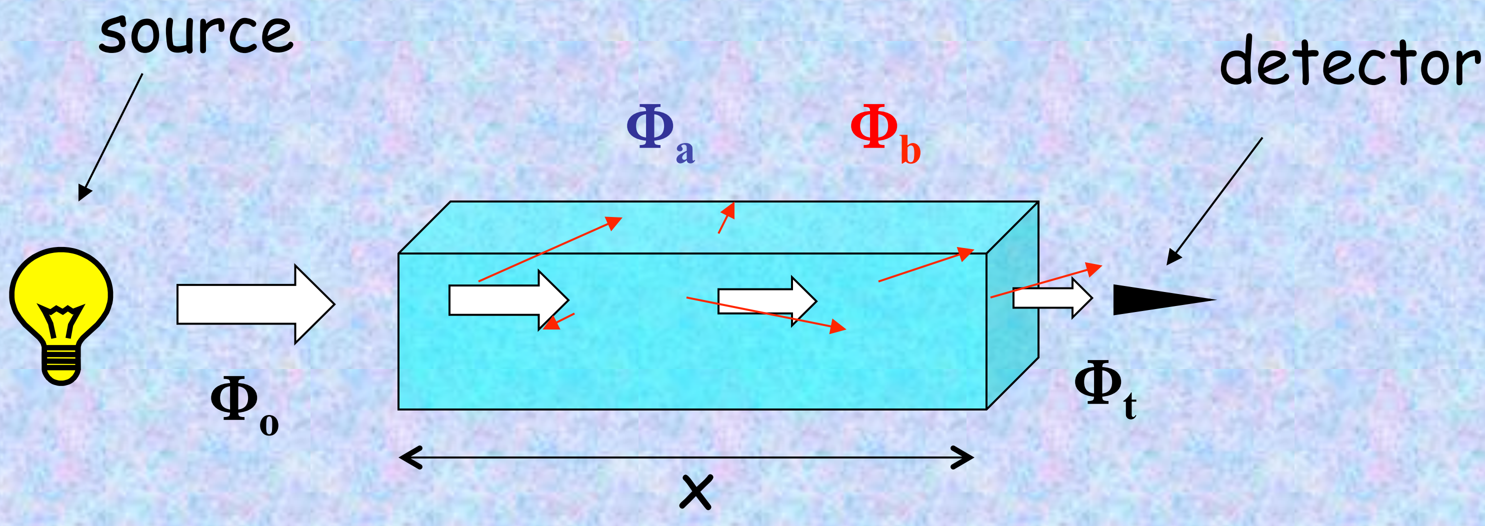
$$c\,x = -[\,\ln(\Phi_t)-\ln(\Phi_o)]$$

$$c\,x = -\,\ln(\Phi_t/\Phi_o)$$

$$\boxed{c\,(m^{-1}) = (-1/x)\,\ln(\Phi_t/\Phi_o)}$$

Beam Attenuation Measurement Reality

$c = (-1/x) \ln(\Phi_t/\Phi_o)$



Detected flux (Φ_t) measurement must **exclude** scattered flux

To get a signal detector has finite acceptance angle – some forward scattered light **is** collected.

Beam attenuation measurement (single wavelength)

Advantages:

Well defined optical quantity (for a given acceptance angle).

No need to correct for absorption or scattering along the path (unlike the VSF and a).

Pathlength matters- assumes single scattering regime.

Not dependent on polarization state.

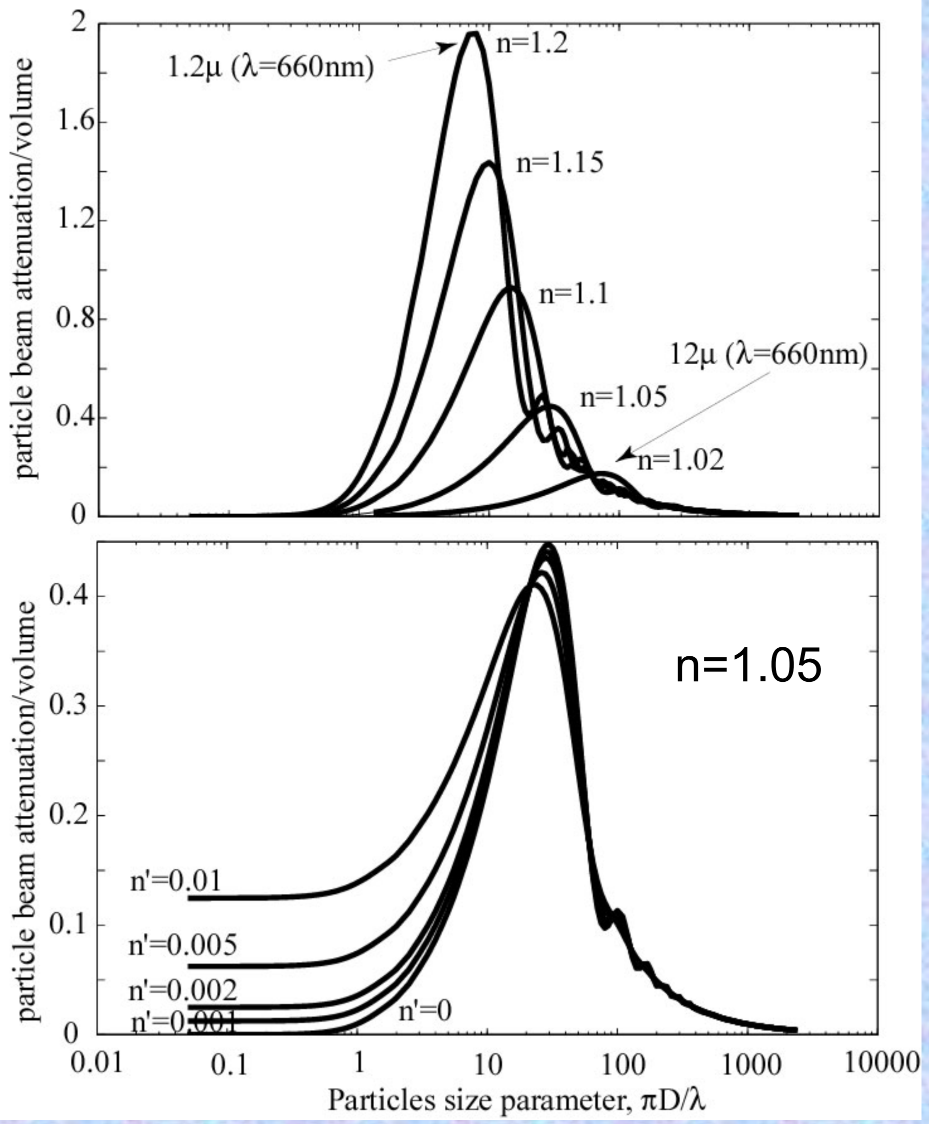
First commercial inherent optical quantity measured (O(1980)) ← long history.

Theoretical beam Attenuation:

Like all IOP, c_p is dependent on size and composition:

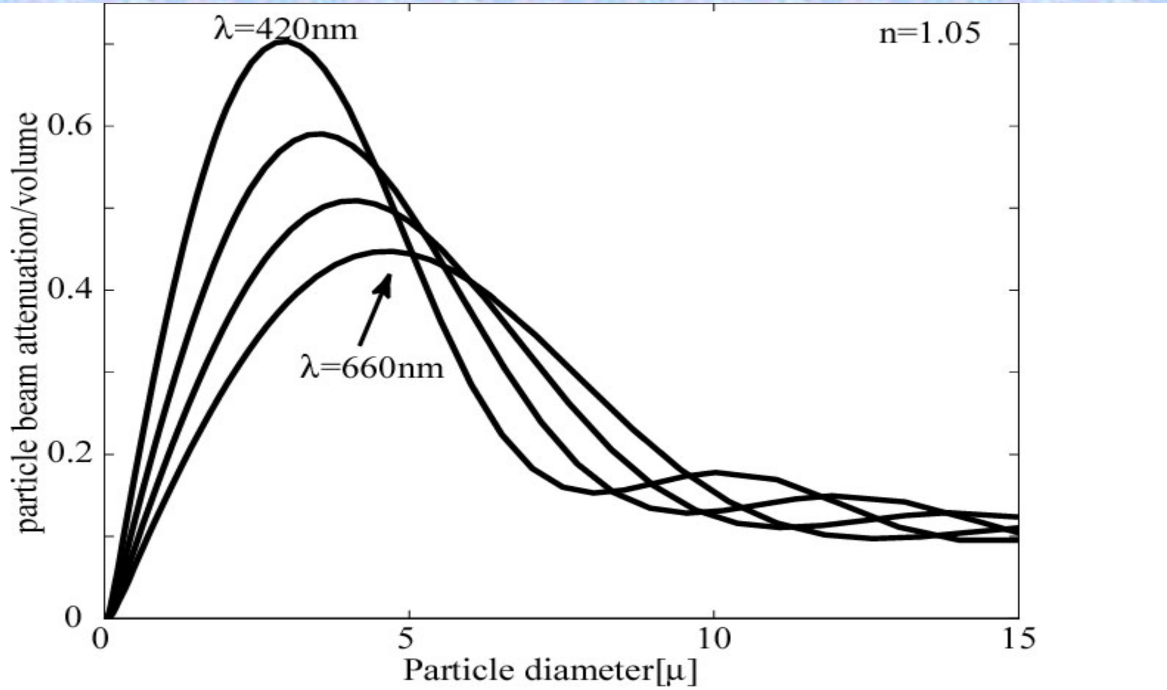
Particle specific beam-attenuation, Beam-c/volume dependence on:

- Size.
- Index of refraction.
- Absorption.



Boss et al., 2001

c_p is sensitive to the wavelength of measurement:



The instrumental 'filter' is size dependent:

- Particle size where maximum occurs changes by ~ 2 between blue to red wavelengths.

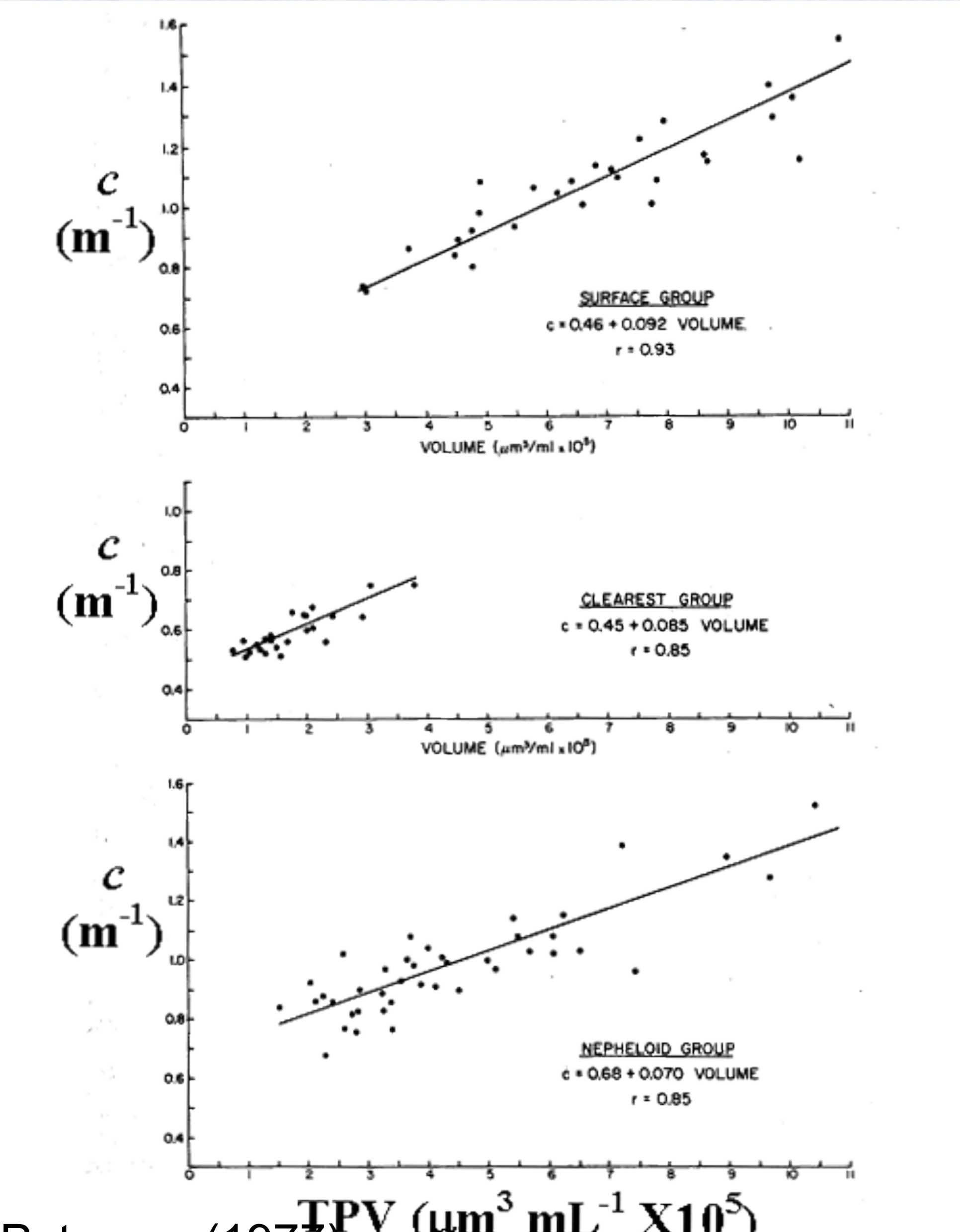
- Magnitude and width of maximum change with λ.

Single wavelength beam attenuation and biogeochemistry:

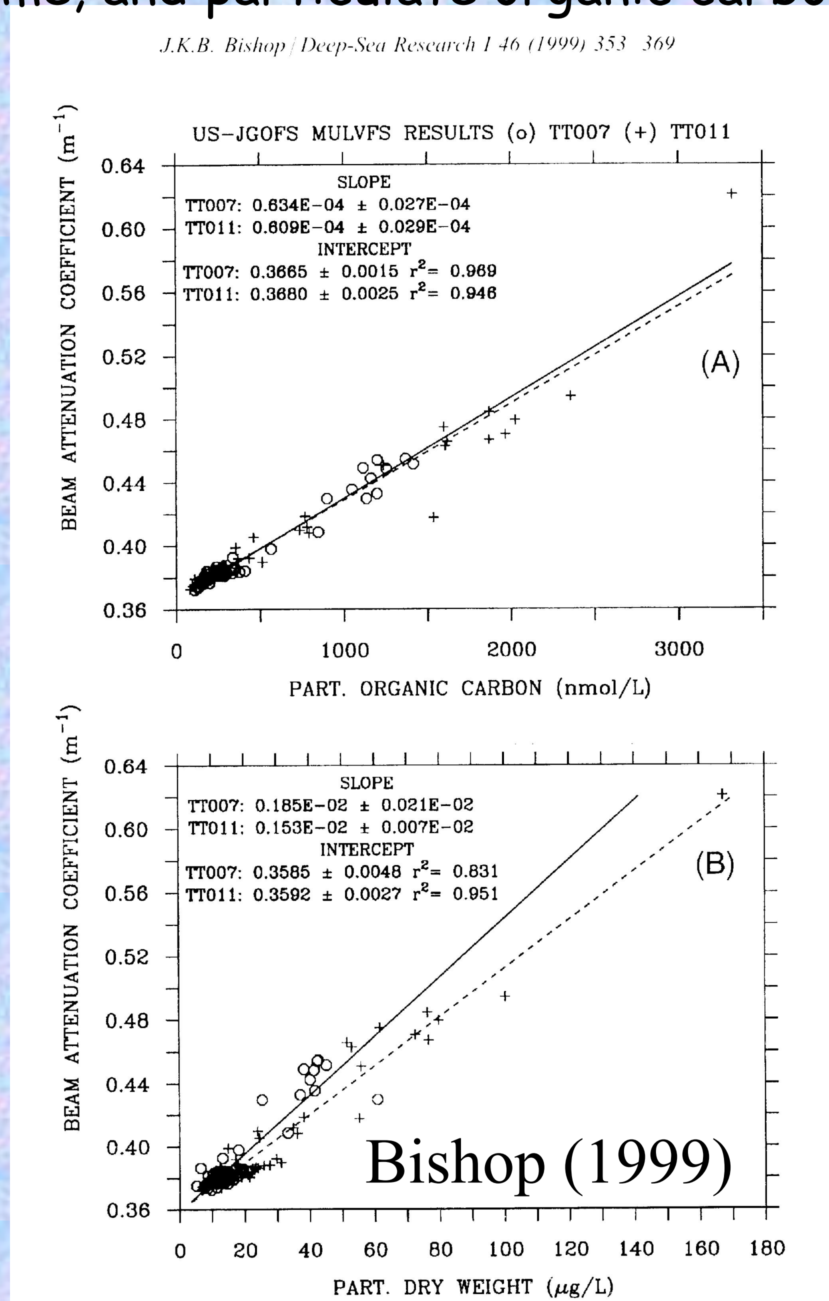
Found to correlate well with:

- Total suspended mass
- Particulate organic carbon
- Particulate volume
- Phytoplankton pigments in area where growth irradiance is stable.

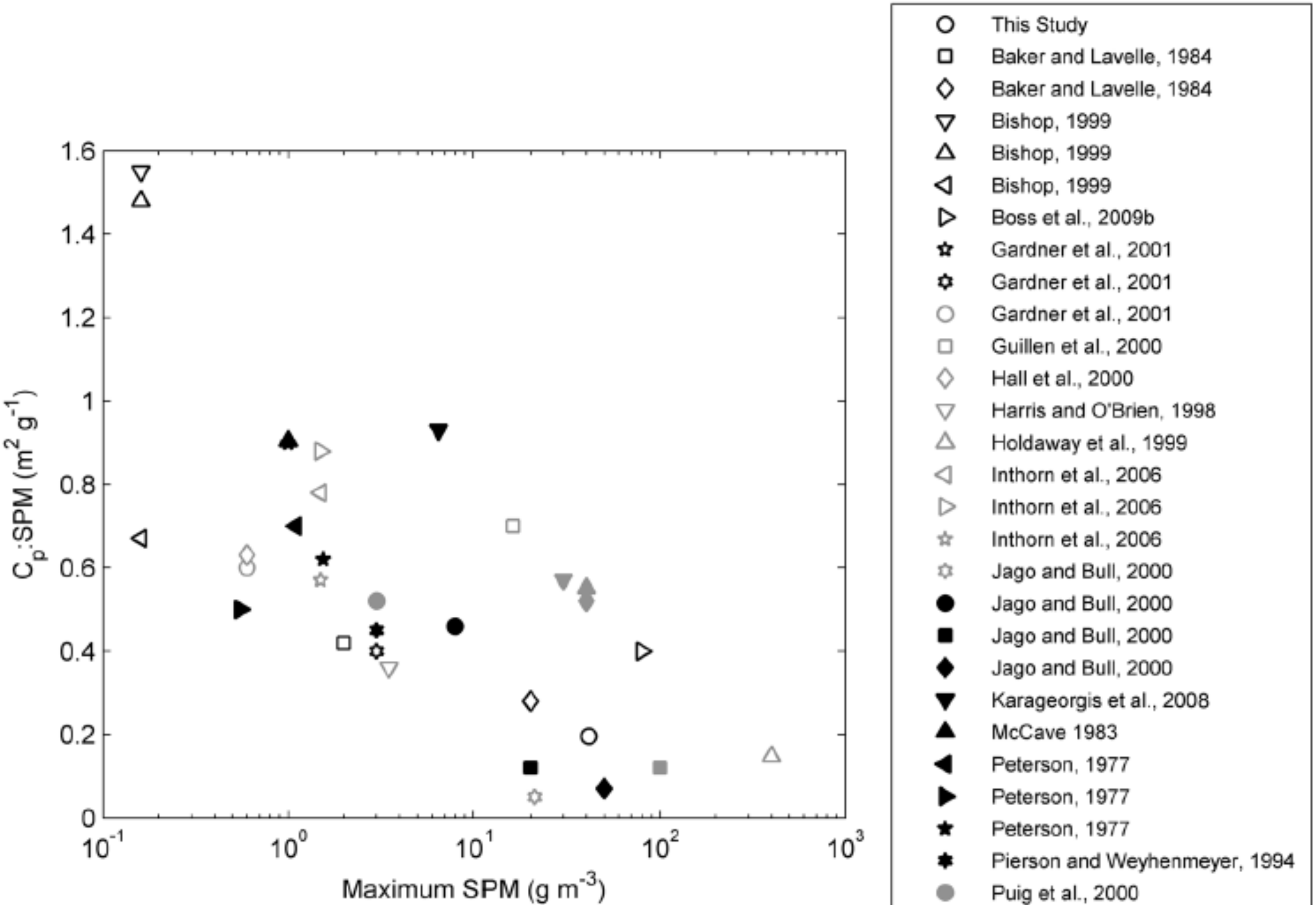
Good correlation with total particle volume, and particulate organic carbon.



Peterson (1977)



But, there is variability in attenuation/mass between studies:



Hill et al., 2011

Particulate Beam Attenuation spectrum

Advantages:

Well defined optical quantity (for a given acceptance angle).

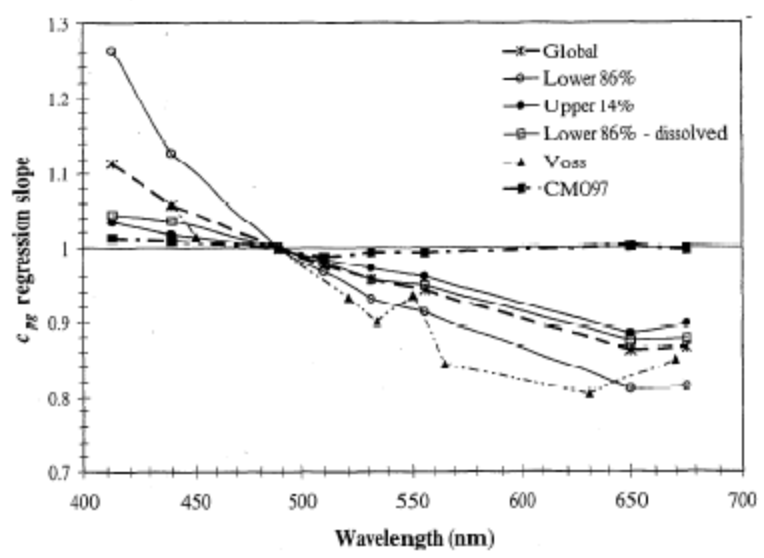
No need to correct for absorption or scattering along the path (unlike the VSF and a).

Not dependent on polarization state of source.

Available commercially since 1994.

Beam Attenuation spectrum

Advantage:
Simple spectral shape.
Little effect due to absorption bands (light that is absorbed is not scattered).



Barnard et al., 1998, JGR

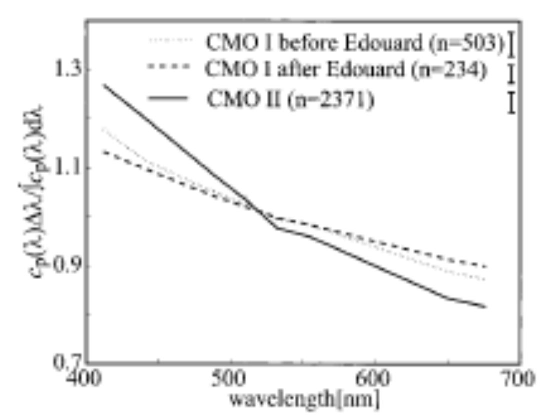
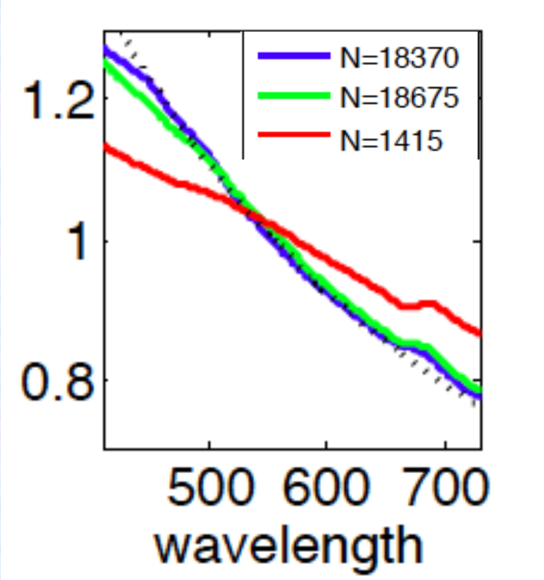


Figure 1. Medians of the area-normalized shape of the particle attenuation spectra $c_p(\lambda)$ (the average of normalized shape is 1). Bars on the right-hand side denote the mean deviation from the 16th to the 86th percentile. Numbers in parentheses denote the number of spectra used for the analysis.

Boss et al., 2001, JGR



Tara Oceans,
40,000 1km^2 spectra

An aside:

Limnol. Oceanogr., 37(3), 1992, 501–509

A spectral model of the beam attenuation coefficient in the ocean and coastal areas

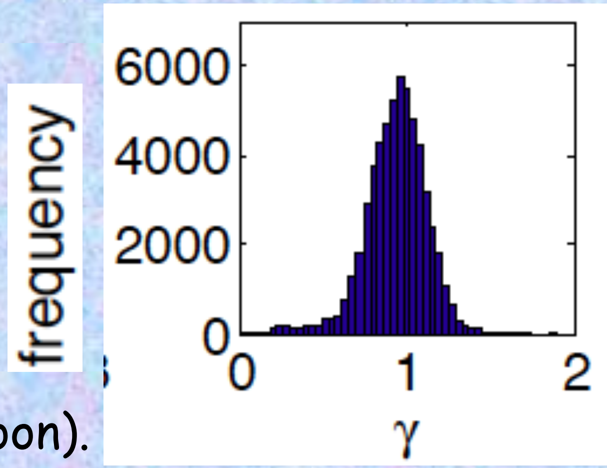
Kenneth J. Voss
Department of Physics, University of Miami, Coral Gables, Florida 33124

Abstract

A large set (~100 data points at each wavelength) of multispectral beam attenuation, $c(\lambda)$, data at nine wavelengths (440, 450, 490, 520, 535, 550, 565, 630, and 670 nm) is used to develop a spectral model of the beam attenuation coefficient. The relationship $c(\lambda) - cW(\lambda) = [c(490\text{ nm}) - cW(490\text{ nm})](1.563 - 1.149 \times 10^{-3}\lambda)$ describes the spectral variation of $c(\lambda)$ where $cW(\lambda)$ is the pure water beam attenuation and λ is the wavelength in nm. From a subset of the data a relationship of chloropyll (Chl) to $c(490)$ was found to be $c(490) = 0.39\text{ Chl}^{0.57}$; however there is significant scatter in this relationship. The spectral c model was tested with independent data sets and the average percent difference of the measured to predicted values ranged from 0.4 to 5% for the different spectral bands.

$$\frac{C(\lambda)-C_w(\lambda)}{C(490)-C_w(490)} = 1.563 - 0.001149\lambda$$

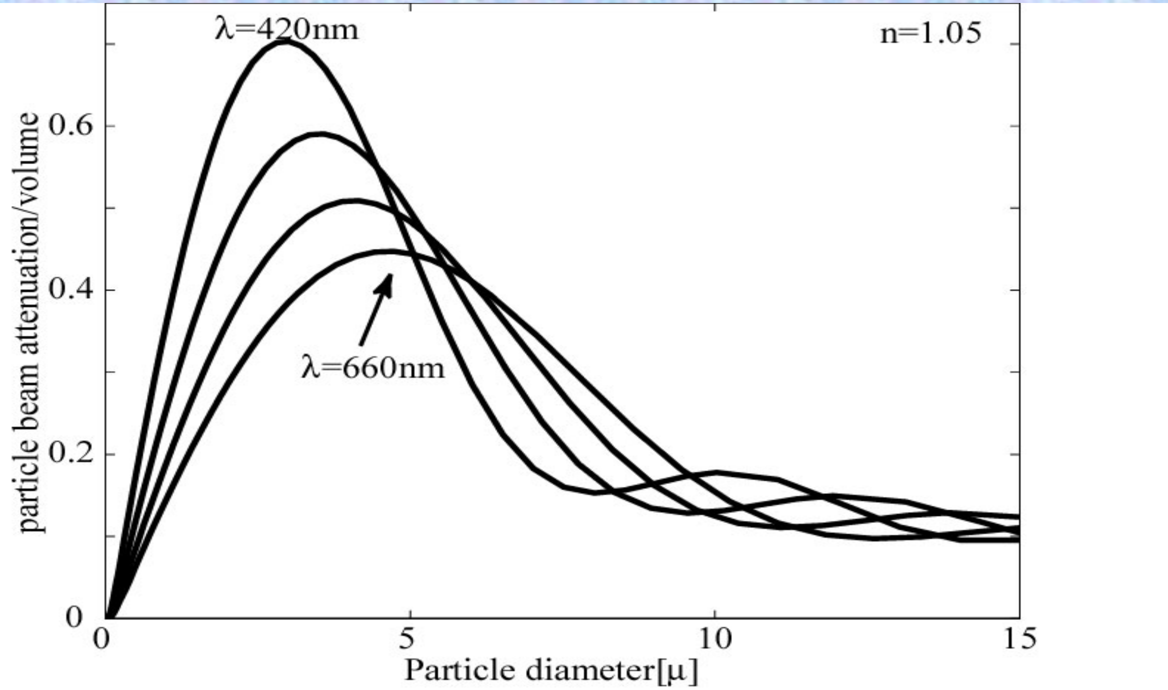
Tara Oceans:



$$C(\lambda)-C_w(\lambda) \propto \lambda^{-\gamma}$$

Corollary:
1. CDOM contribution relatively constant.
2. PSD does not change (we will get there soon).

Another advantage: $c_p(\lambda)$ is sensitive to size



The instrumental 'filter' is size dependent:

•Particle size where maximum occurs changes by ~ 2 between blue to red wavelengths.

•Magnitude and width of maximum change with λ.

Beam-c and Particle size distribution (PSD):

If a power-law ('Junge-like') PSD function:

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

Is often used to described oceanic PSDs.

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

Typically, $2.5<\xi<5$

Most frequently $3.5<\xi<4$

3.4 Particle Size Distributions 79

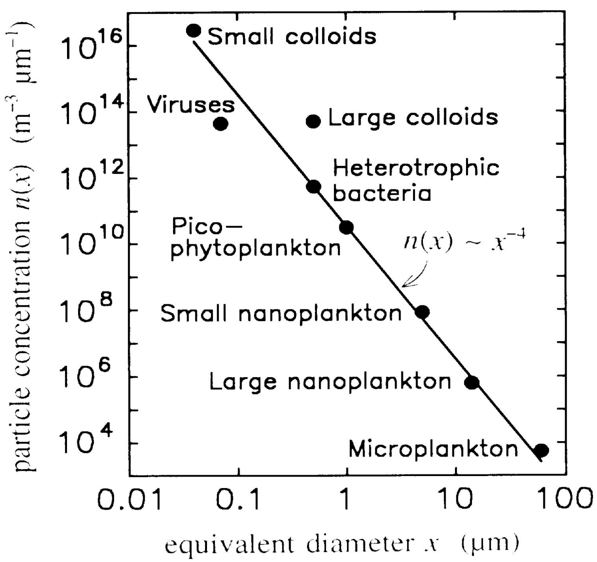
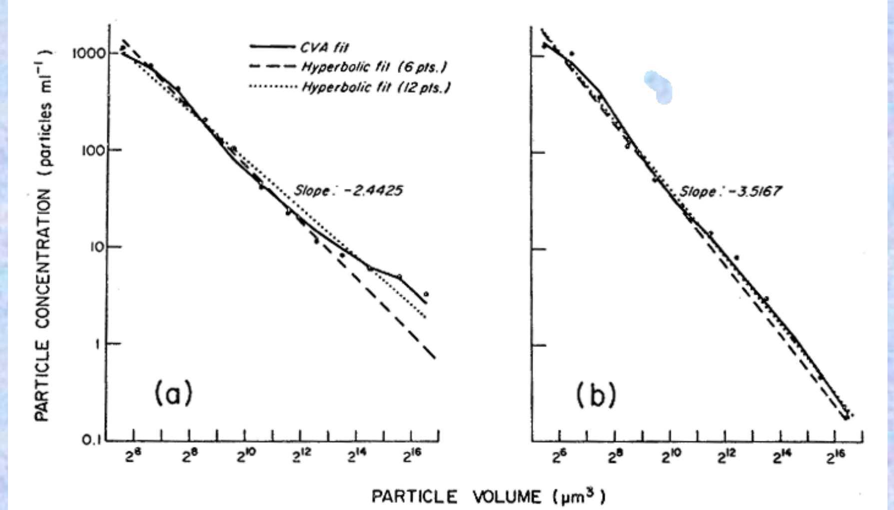
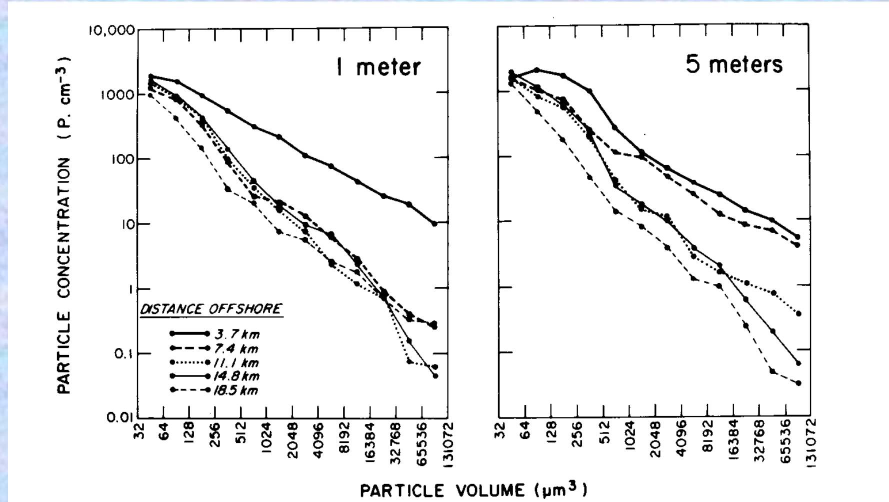


Fig. 3.2. Number size distribution typical of biological particles in the open ocean. [figure courtesy of D. Stramski]



Kitchen (1977)



Zaneveld and Pak, 1979, off Oregon coast

Beam-c and PSD relation:

Mie Theory (homogenous spheres):

Volz (1954): For non-absorbing particles of the same *n* and an hyperbolic distribution from $D_{min}=0$ to $D_{max}=\infty$,

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

$$c_p(\lambda)=c_p(\lambda_0)\left(\frac{\lambda}{\lambda_0}\right)^{-\gamma}, \xi=\gamma+3$$

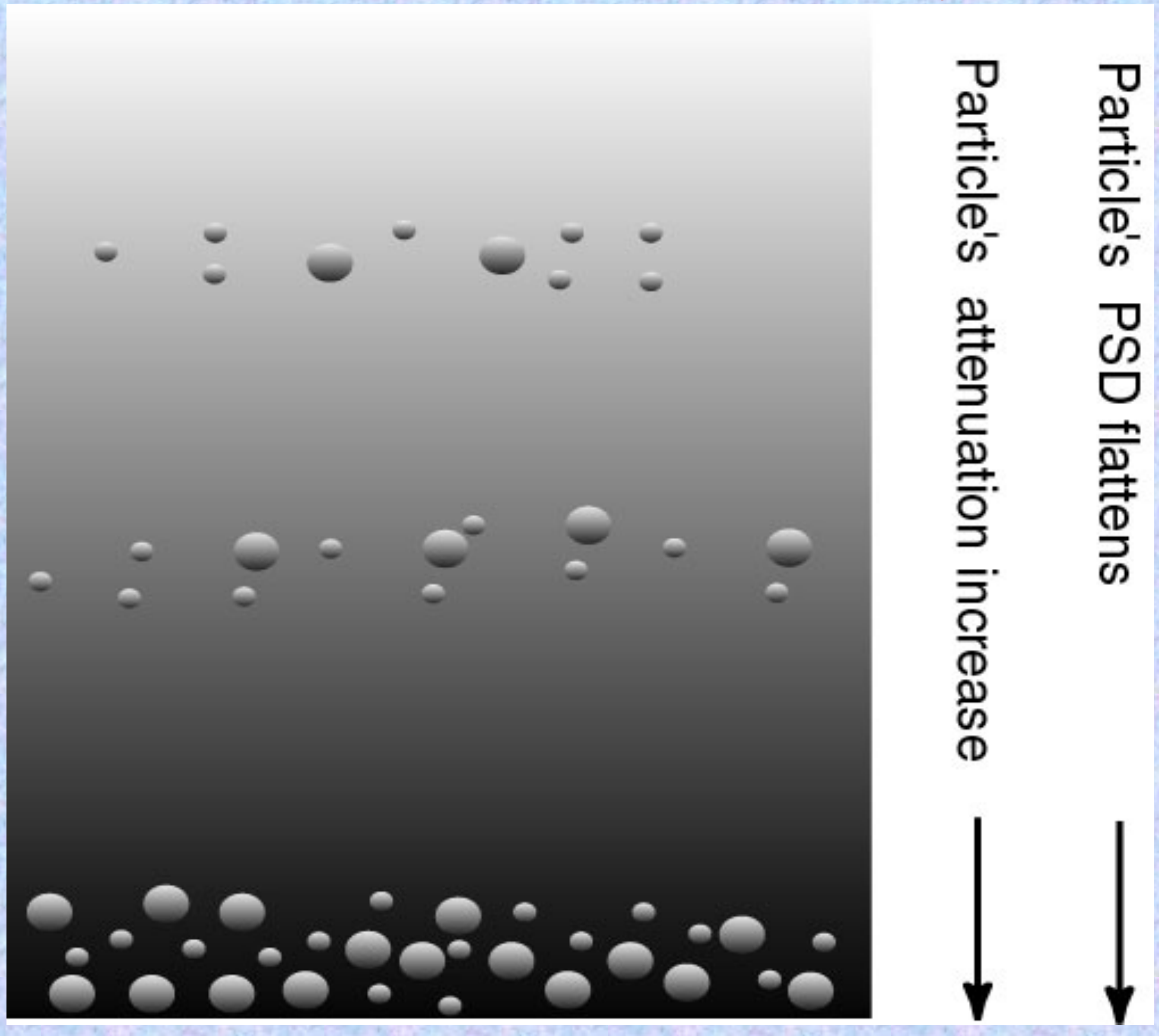
→ expect a relation between attenuation spectrum and PSD.

Example: particles distribution in the bottom boundary layer

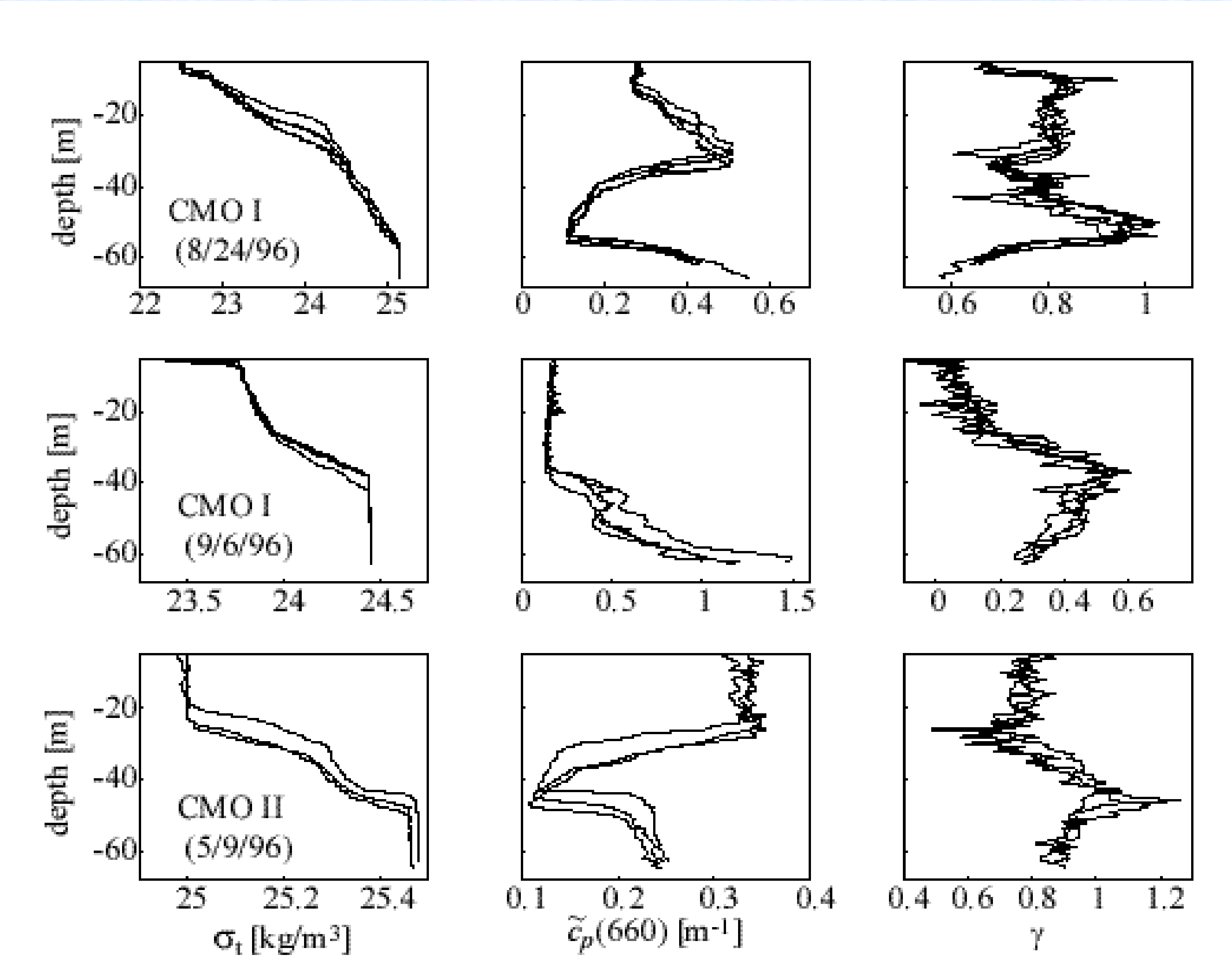
In BBL we expect that concentration and PSD will co-vary because

Particle settling is size dependent.

Expected distribution with depth:

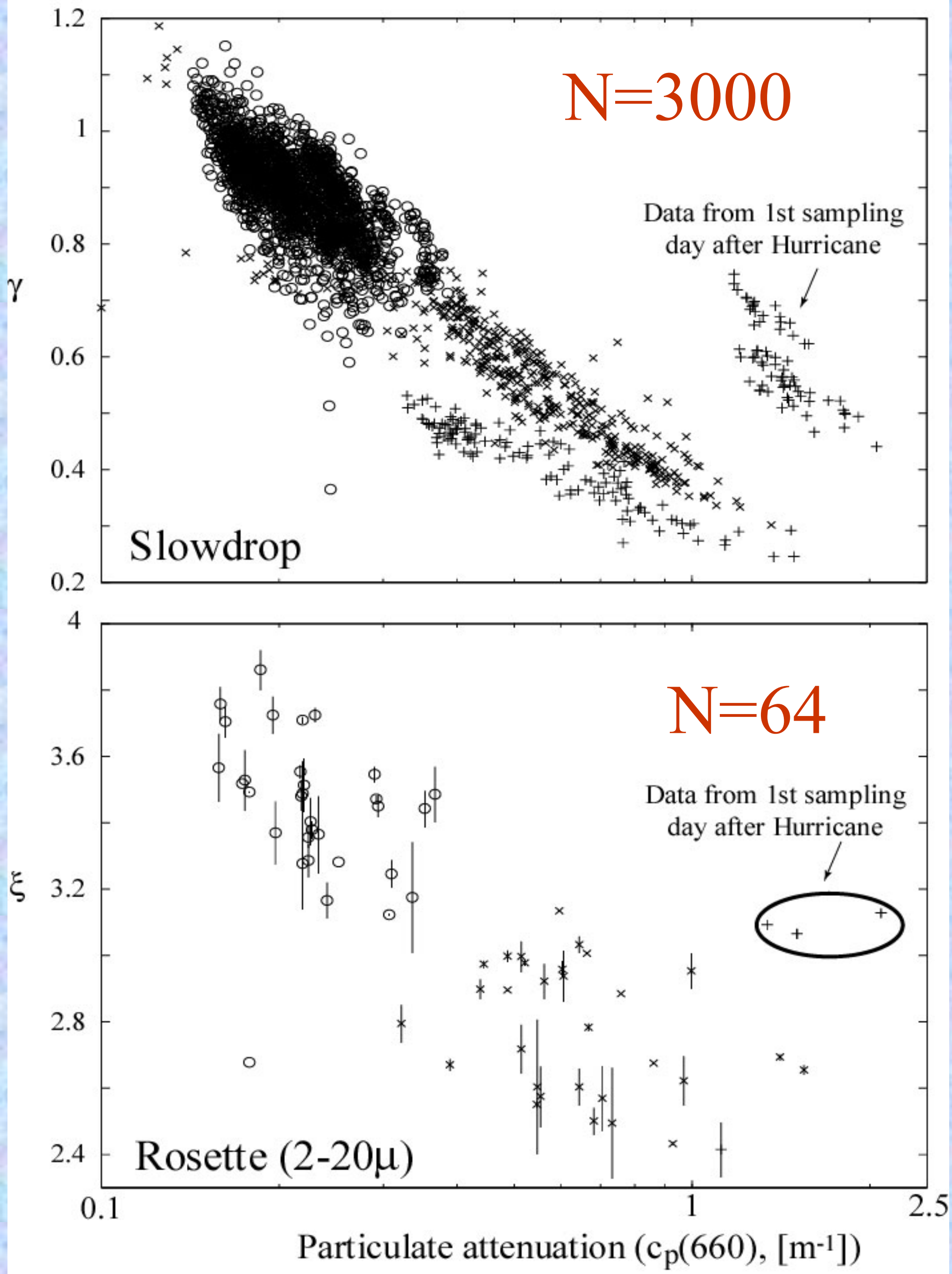


Observations: bottom boundary layer



Boss et al., 2001

Particulate attenuation (c_p) and its spectral slope (γ) are inversely related in the BBL.



Boss et al., 2001

Observations:

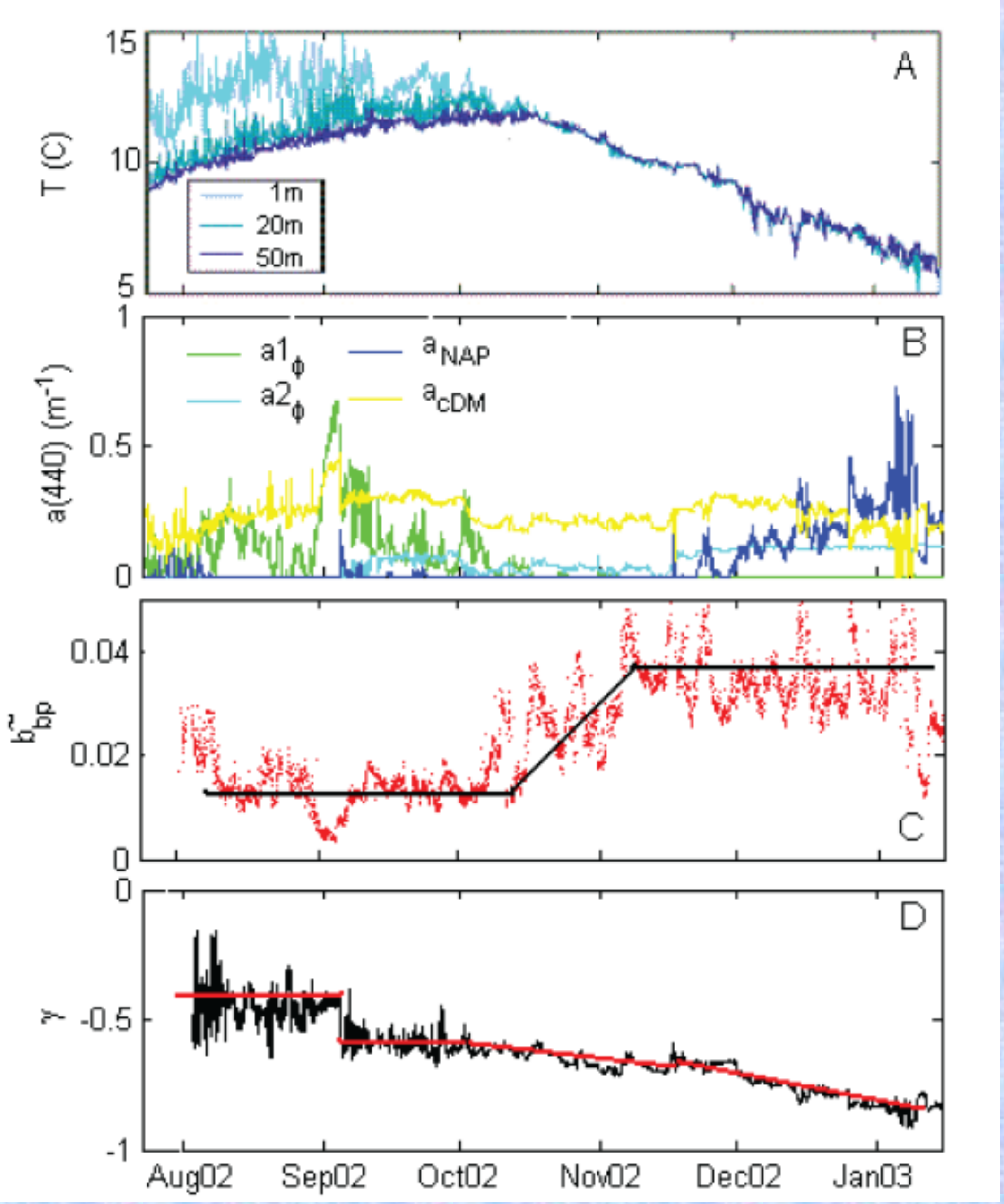
•Both ξ and γ decrease monotonically with decreasing attenuation.

•Theoretical and observed relationship between x and γ are within 30% of ξ, despite the potentially large error bars associated with the sampling methods.

•Better agreement modified theory:
$\gamma \geq 0$ in observation for ξ<3.

•Supports the use of γ as a tool to estimate the PSD slope. In the least, it describes the changes in the mean particle diameter (proportion of big vs. small).

Particulate attenuation spectral slope as a tool to study particle composition and species succession:

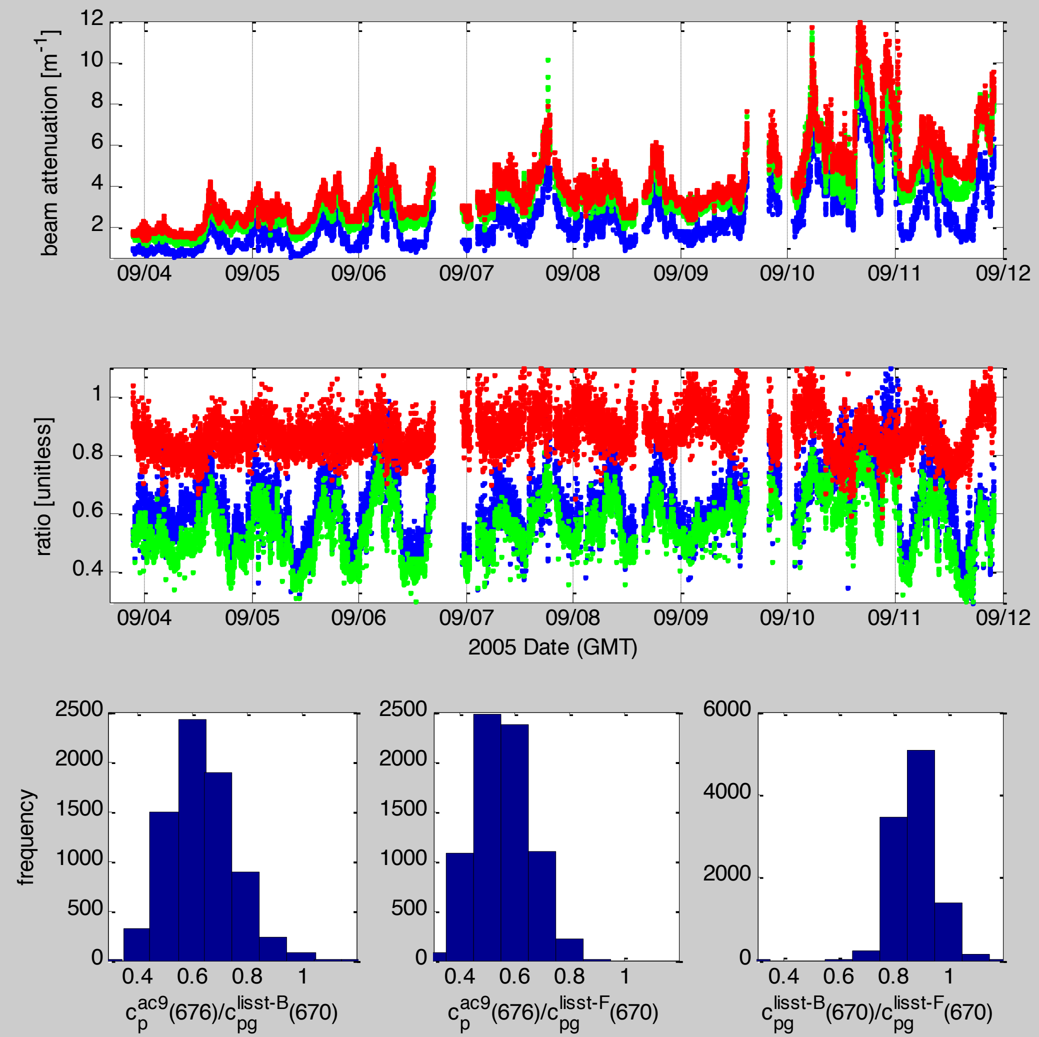


Roesler and Boss, 2007, Ch. 5, Habwatch

Beam-c issues: acceptance angle.

Jerlov, 1976: less than 5% of scattering in first 1°.
Petzold, 1972: up to ~30% of scattering in first 1°.

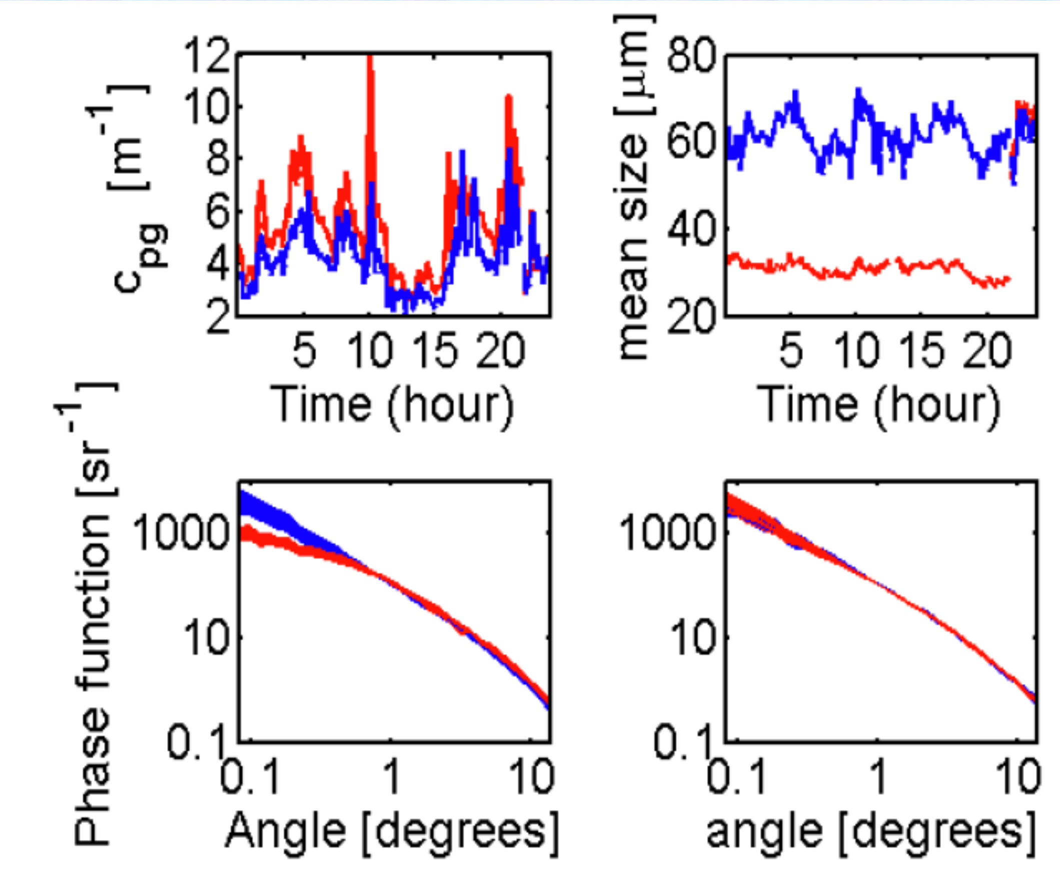
Instrument	Acceptance angle (in-water)	Path-length
AC-9	0.93	10cm
LISST-B	0.0269°	5cm
LISST-Floc	0.006°	5cm



OASIS: Boss & Slade, unpublished

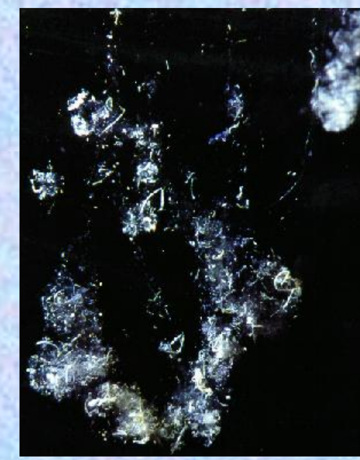
Another issue:
Turbulence. (Bogucki et al., 1988)

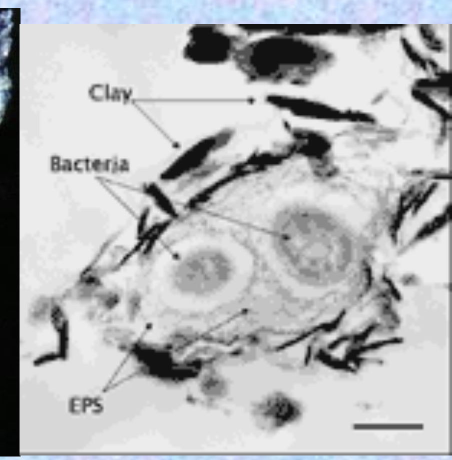
Handling and aggregates:



Boss et al., 2009, Slade et al., 2010, 2011

Aggregates:





For particles with $D >> \lambda$:

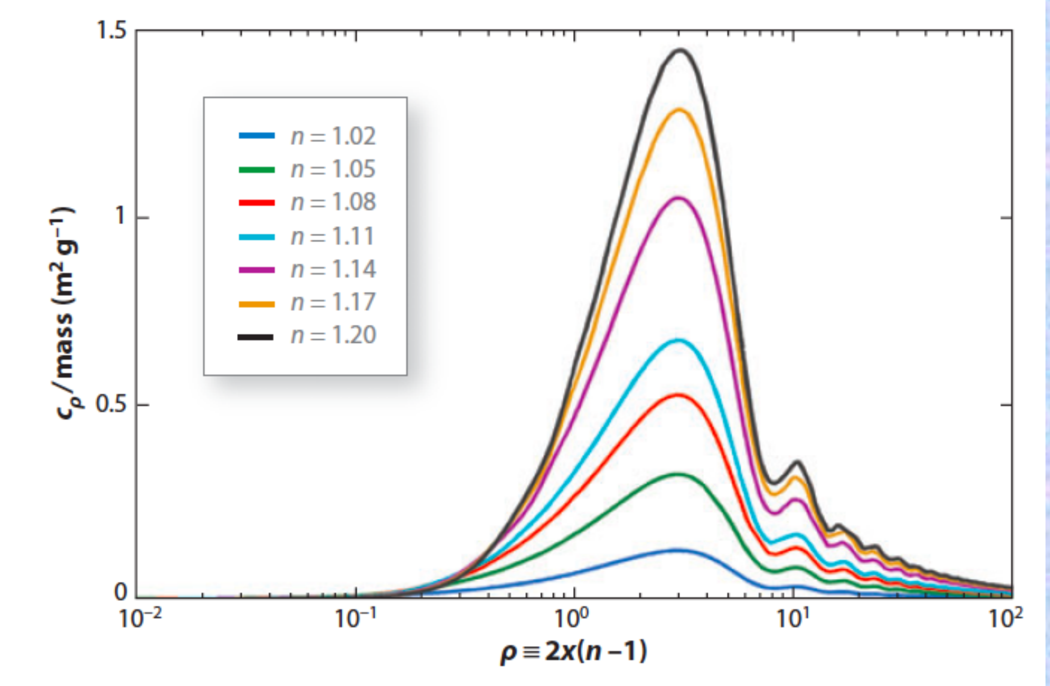
When scattering centers are far enough, IOPs are additive.

Optical properties ∝ cross-sectional area, additive

Depends on aggregate packaging ('fractal' dimension).

Spectral dependence of scattering ∝ λ^0

Beam attenuation of single particles vs. aggregates

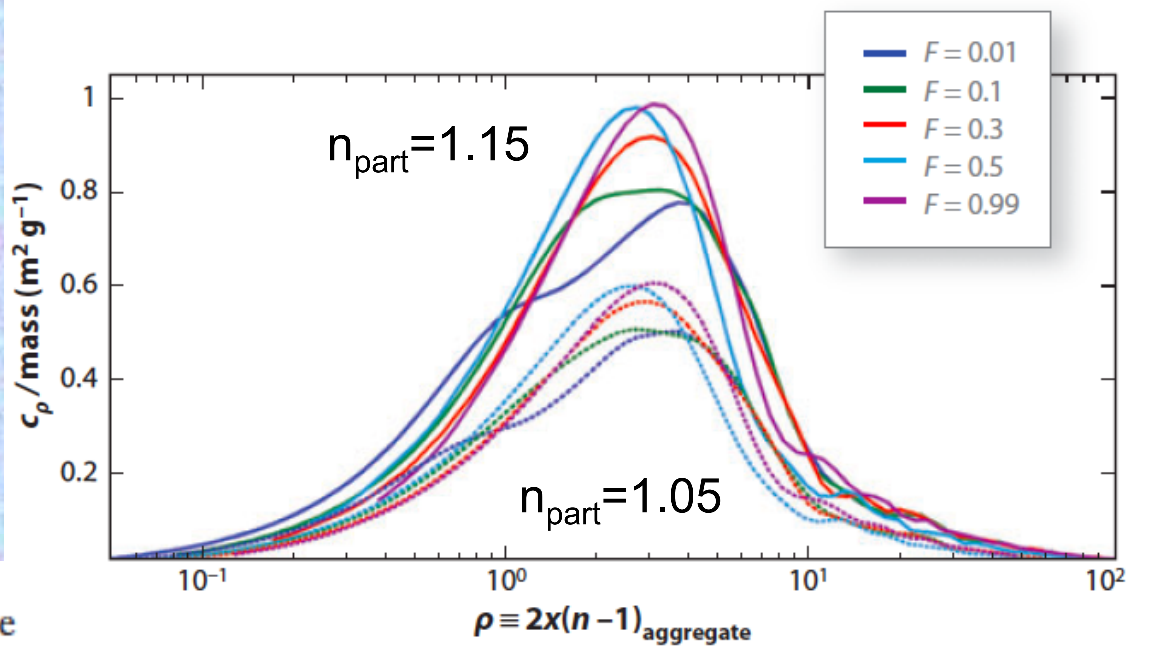


$x = \pi D/\lambda$

$\rho = 2\pi D/\lambda(n-1)$

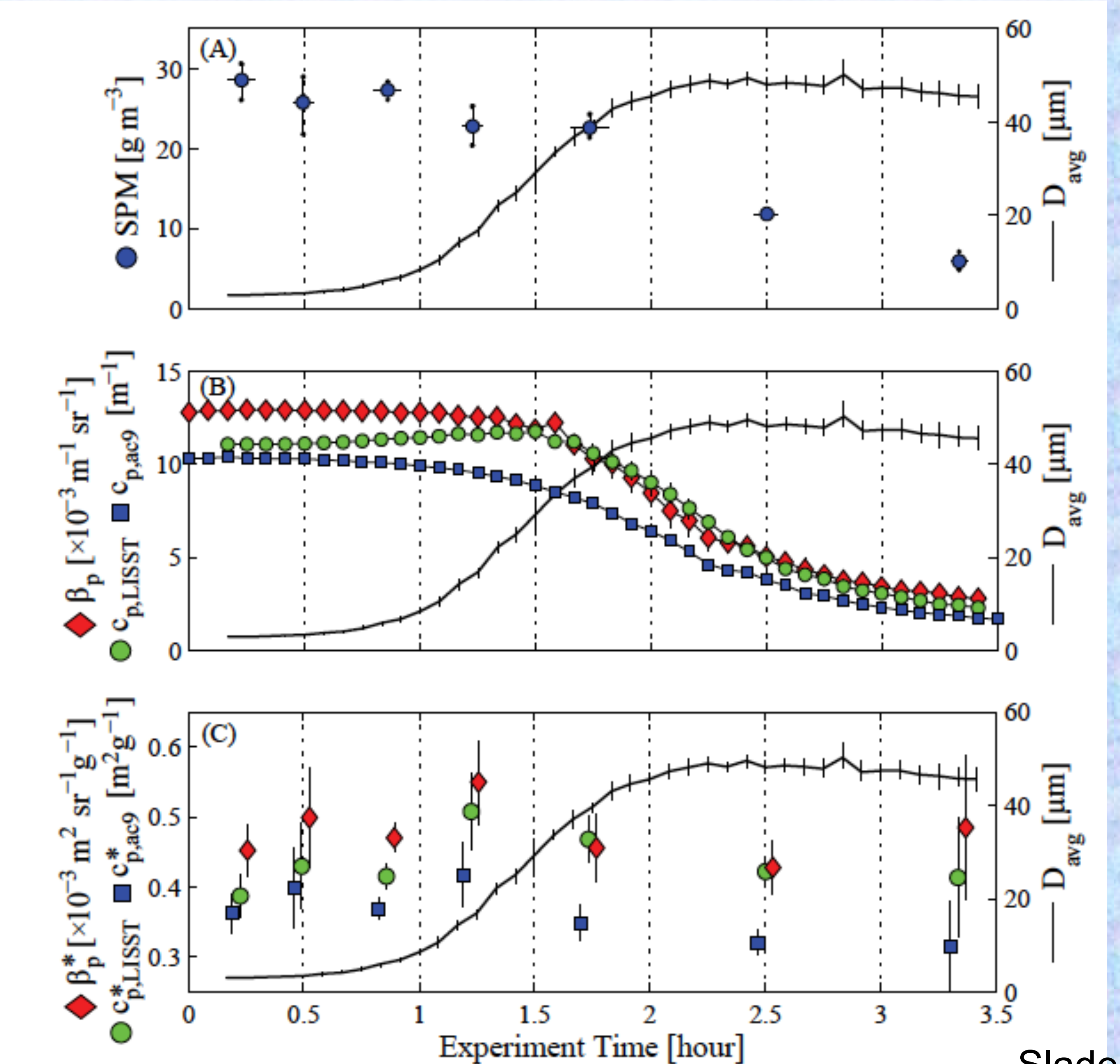
F-solid fraction

Stemmann and Boss, 2012



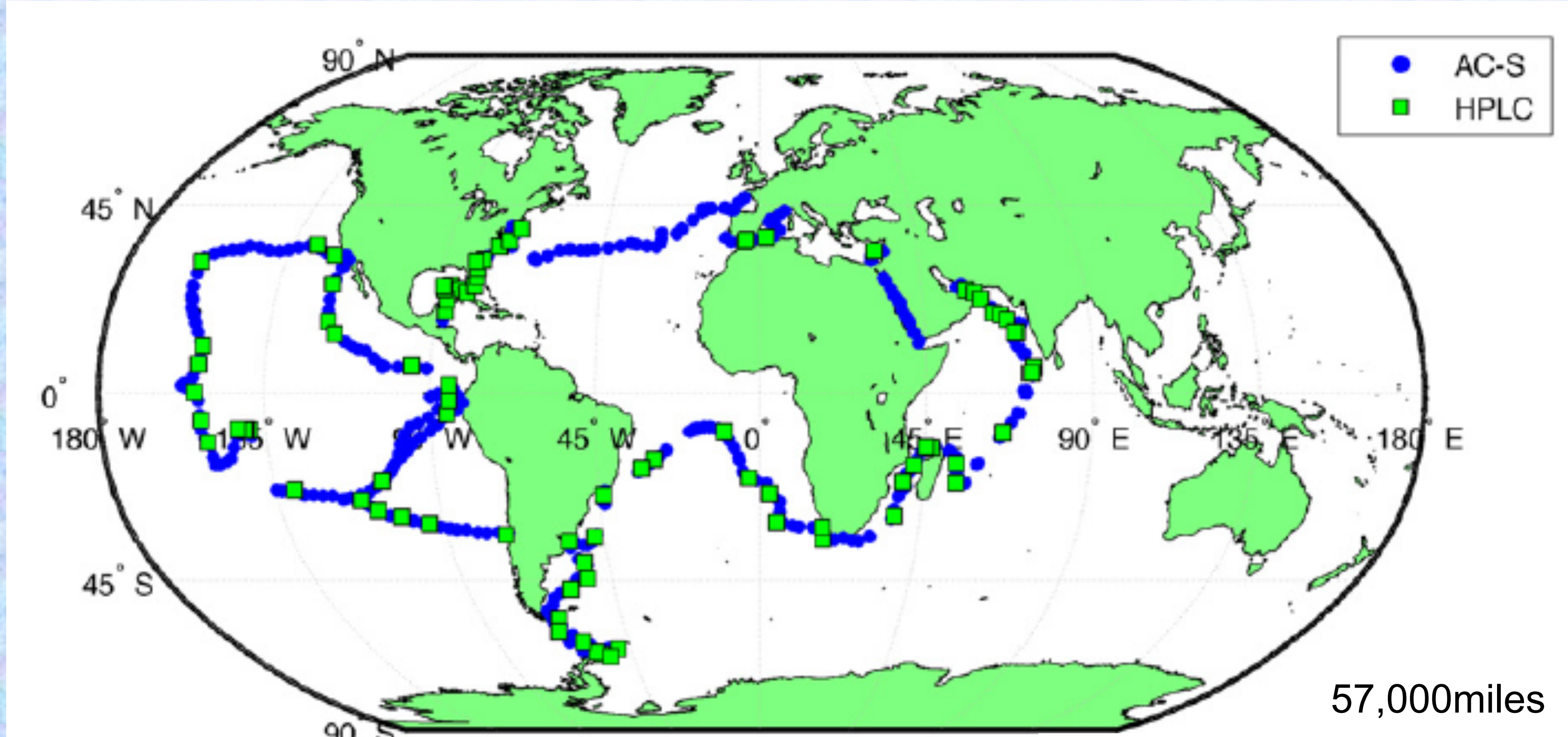
$$(n-1)_{\text{aggregate}} = F(n-1)_{\text{particle}}$$

Effect of aggregation on mass specific attenuation – lab experiment:

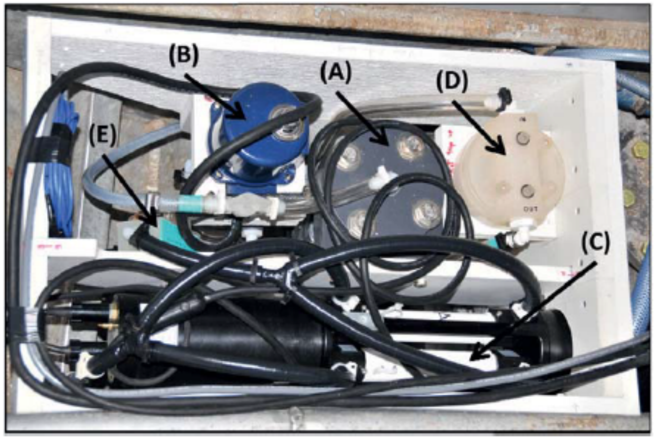


Slade et al., 2011

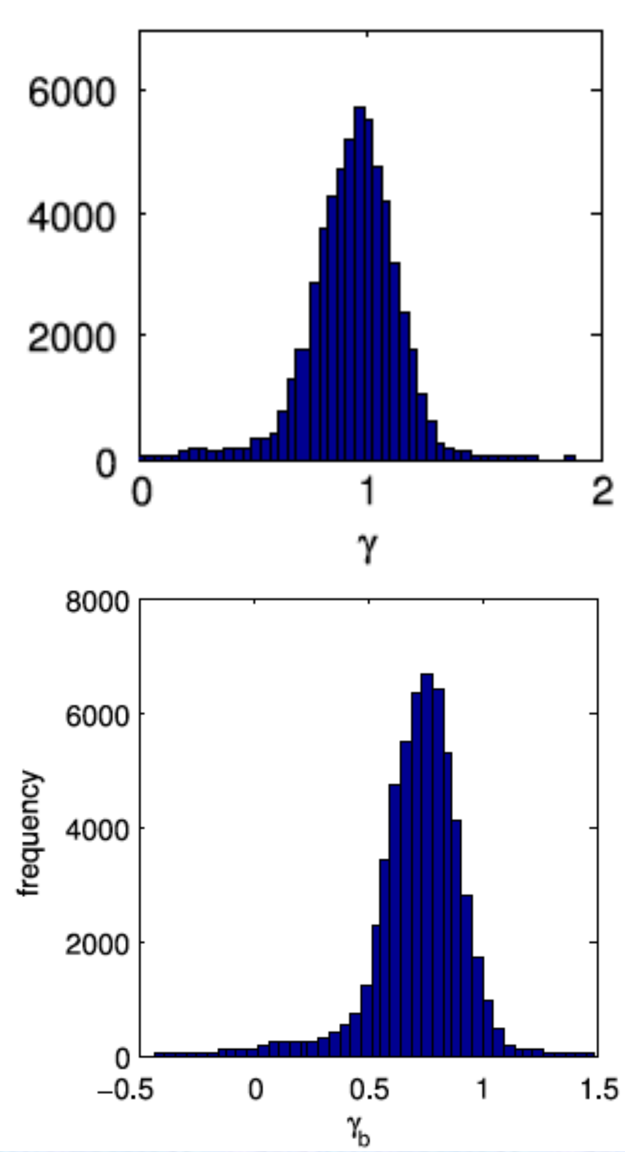
Global statistics of spectral shape:

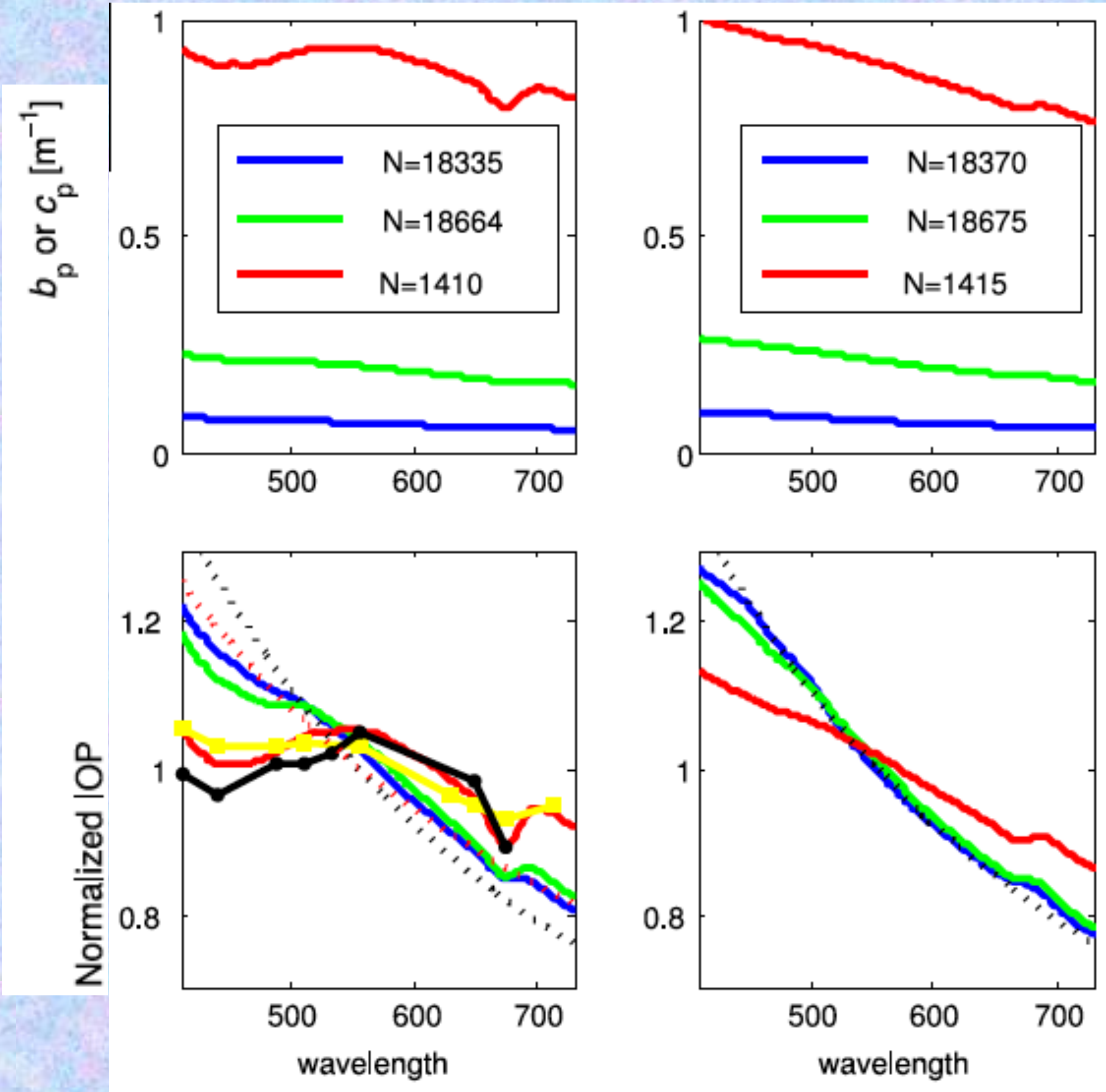


57,000miles



Global statistics of spectral shape:





Boss et al., 2013

Summary:

- Beam attenuation is a robust IOP.

- Beam-attenuation has a long history.

- If I had to do a single optical measurement, it would be c(660). Why?

- Relationship between *spectral* c_p and PSD provide tool to track changes in community composition and sediment dynamics.

Selected references:

Measurement issues:

Pegau, W. S., J. R. V. Zaneveld, and K. J. Voss (1995), Toward closure of the inherent optical properties of natural waters, J. Geophys. Res. 100, 13,193–13,199 .

Voss, K. J., and R. W. Austin (1993), Beam-attenuation measurements error due to small-angle scattering acceptance, J. Atmos. Oceanic Technol., 10, 113–121.

Relationship to biogeochemistry:

Behrenfeld, M.J. and E. Boss, 2006. Beam attenuation and chlorophyll concentration as alternative optical indices of phytoplankton biomass. Journal of Marine Research, Vol. 64, pp. 431-451.

Bishop, J.K.B., 1999. Transmissometer measurements of POC. Deep-Sea Research I 46, 353–369.

Boss, E., M. S. Twardowski, and S. Herring. 2001. Shape of the particulate beam attenuation spectrum and its inversion to obtain the shape of the particulate size distribution. Appl. Opt. **40: 4885–4893.**

Gardner, W. D., M. J. Richardson, C. A. Carlson, D. Hansell and A.V. Mishonov. 2003. Determining true particulate organic carbon: bottles, pumps and methodologies. Deep-Sea Res. II., *42,*655–674.

Kitchen, J. and J. R. Zaneveld. 1990. On the noncorrelation of the vertical structure of light scattering and chlorophyll *a in case I waters. J. Geophys. Res., 95, 20,237–20,246.*

Roesler, C.S. and E. Boss (2007). "In situ measurement of inherent optical properties and potential for harmful algal bloom detection and coastal ecosystem observations" in Real-time Coastal Observing Systems for Marine Ecosystem Dynamics and Harmful Algal Blooms: Theory, Instrumentation and Modelling, Eds. M. Babin, C.S. Roesler and J.J. Cullen.

Spinrad, R. W., J. R. V. Zaneveld, and J. C. Kitchen, A study of the optical characteristics of the suspended particles in the benthic nephloid layer of the Scotian shelf, *J. Geophys. Res., 88, 7641–7645,*1983.

Global distribution:

Barnard, A. H., A. H., W. S. Pegau, and J. R. V. Zaneveld. 1998. Global relationships of the inherent optical properties of the oceans. J. Geophys. Res. 103: 24955–24968.

Boss, E., M. Picheral, T. Leeuw, A. Chase, E. Karsenti, G. Gorsky, L. Taylor, W. Slade, J. Ras, and H. Claustre, 2013. The characteristics of particulate absorption, scattering and attenuation coefficients in the surface ocean; Contribution of the Tara Oceans expedition. Methods in Oceanography, http://dx.doi.org/10.1016/j.mio.2013.11.002.