The beam attenuation coefficient and its spectra

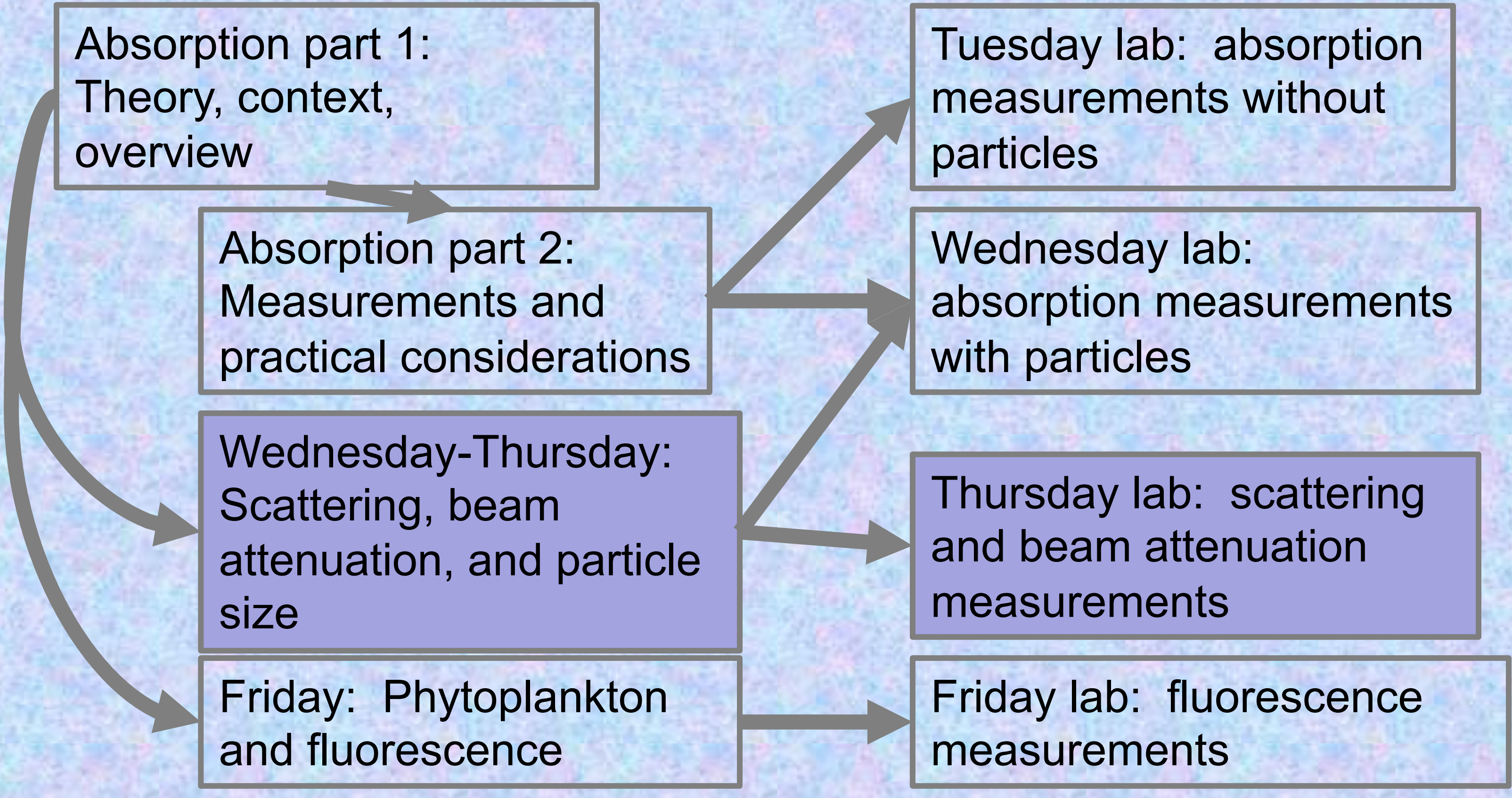
(also known as beam-c or extinction coefficient).

Emmanuel Boss, U. of Maine

What I hope you learn:

- Why we measure the beam attenuation.
- How we measure the beam attenuation.
- How does it vary in the ocean (x, z, t).
- Creative ways to use it.

Class context: Week 1 roadmap



Absorption part 1: Theory, context, overview

Absorption part 2: Measurements and practical considerations

Wednesday-Thursday: Scattering, beam attenuation, and particle size

Friday: Phytoplankton and fluorescence

Tuesday lab: absorption measurements without particles

Wednesday lab: absorption measurements with particles

Thursday lab: scattering and beam attenuation measurements

Friday lab: fluorescence measurements

Why do we measure the beam attenuation?

Related to concentration of suspended particulate and dissolved materials.

Longest IOP for which commercial instrumentation exist.

What do we measure?

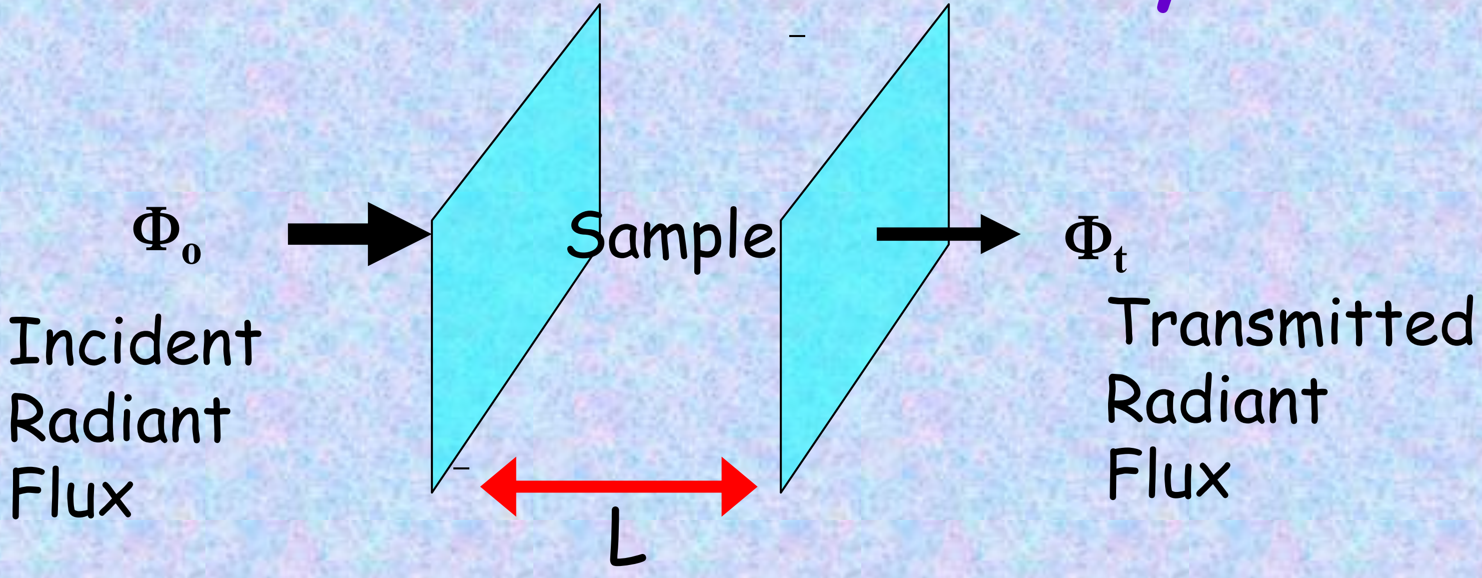
How much light makes it from source to detector.

Not absorbed nor scattered along the path.

Collimated beam – spreads minimally as it propagates. Source can be polarized (laser).

Detector and source need to be aligned along the beam.

Review: Theory



Beer-Lambert-Bouguer's extinction law:

$\Phi_t=\Phi_o\exp(-c\mathrm{L})$

$c = a + b$

Review: Theory

$\Phi_t = \Phi_0 \exp(-cL) \rightarrow c = (-1/L) \ln(\Phi_t/\Phi_0)$

Φ_t/Φ_0 – "transmission"

Additive with both concentration and substances. $c = \Sigma c_i = c^* \times$ [concentration]

Assumptions: no interaction between components or with light. Single scattering. Monochromatic.

Measurement Reality

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

We typically never measure Φ_o (some instruments do monitor changes in lamp intensity).

We measure a reference material:

$$c_{ref} = (-1/L)\ \ln(\Phi_{t,ref}/\Phi_o)$$

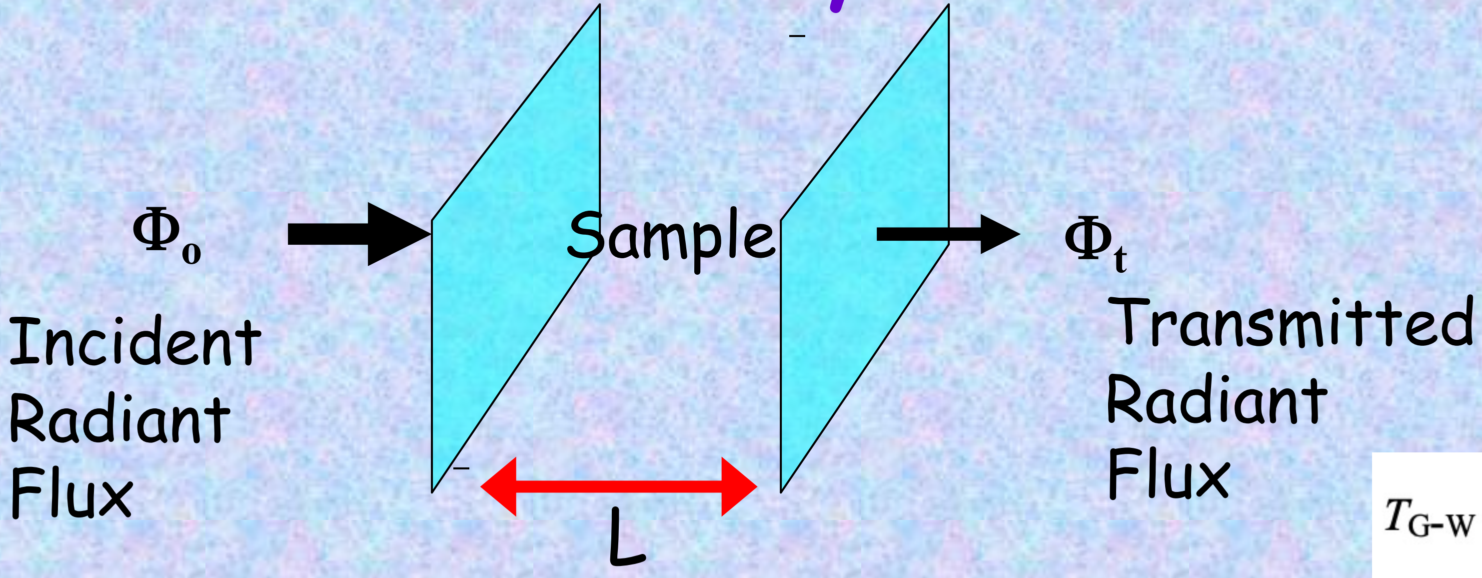
$$c_{sample} = (-1/L)\ \ln(\Phi_{t,sample}/\Phi_o)$$

$$c_{sample}-c_{ref} = (-1/L)\ \ln(\Phi_{t,sample} / \Phi_{t,ref})$$

Remember:
$\ln A-\ln B=\ln(A/B)$

Works as long as Φ_o is stable or its stability monitored.

Review: Theory - a little more



Φ_o

Incident
Radiant
Flux

Sample

L

Φ_t

Transmitted
Radiant
Flux

$$T_{\text{G-W}} = \frac{4 n_G n_W}{(n_G + n_W)^2}$$

What about the windows?

$$\Phi_{t,w} = \Phi_o T^2_{\text{G-W}} \exp(-c_w L)$$

$$\Phi_{t,sam+w} = \Phi_o T^2_{\text{G-W}} \exp(-(c_{sam} + c_w) L)$$

$$\Phi_{t,sam+w} / \Phi_{t,w} = \Phi_o \exp(-c_{sam} L)$$

Issues: air, salts

How do we choose a pathlength?

We want to maximize signal/noise.

We want to minimize multiple scattering.

Uncertainty in beam attenuation:

$$c = \frac{\log(Tr)}{L} \rightarrow |\delta c| = \left|\frac{\delta L \log(Tr)}{L^2}\right| + \left|\frac{\delta Tr}{Tr L}\right| \rightarrow \frac{|\delta c|}{c} = \left|\frac{\delta L}{L}\right| + \left|\frac{\delta Tr}{Tr \log(Tr)}\right|$$

Largest relative error when *Tr=1* or *Tr=0*.

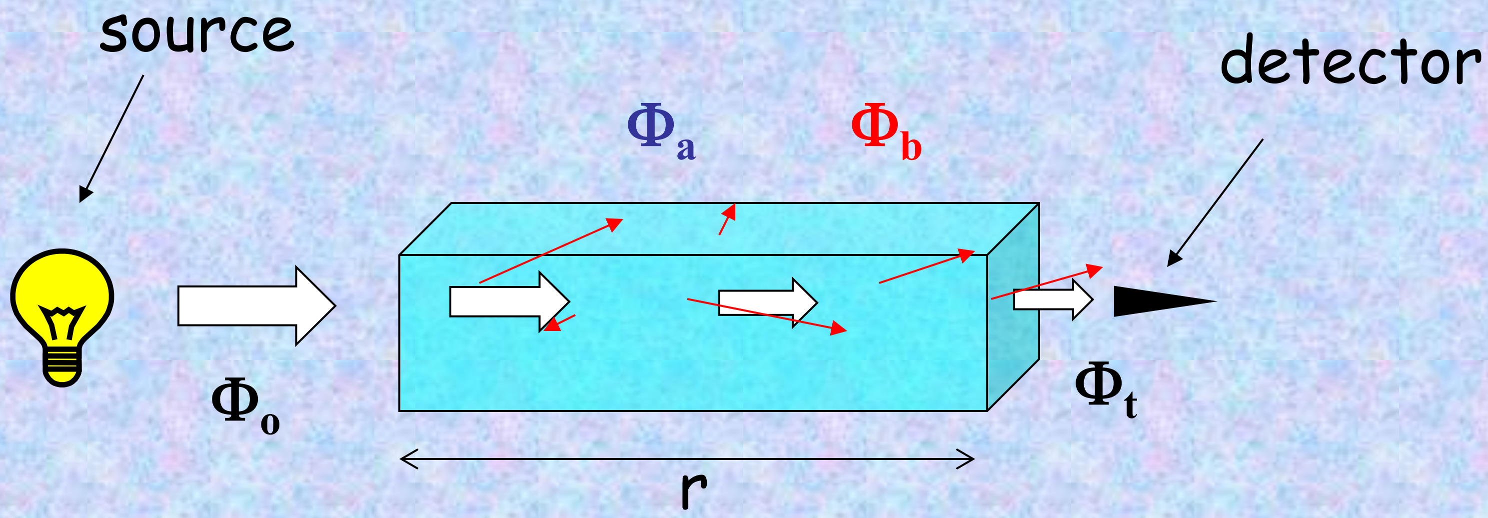
Minimal relative uncertainty is when *Tr=1/e* or when *c=1/L*.

With a 0.25m sensor, *c=* 4m^{-1}. With a 0.1m sensor, *c=* 10m^{-1}.

Measurement Reality

Roesler and Boss, 2008

$$\boxed{c = (-1/L)\ln(\Phi_t/\Phi_o)}$$



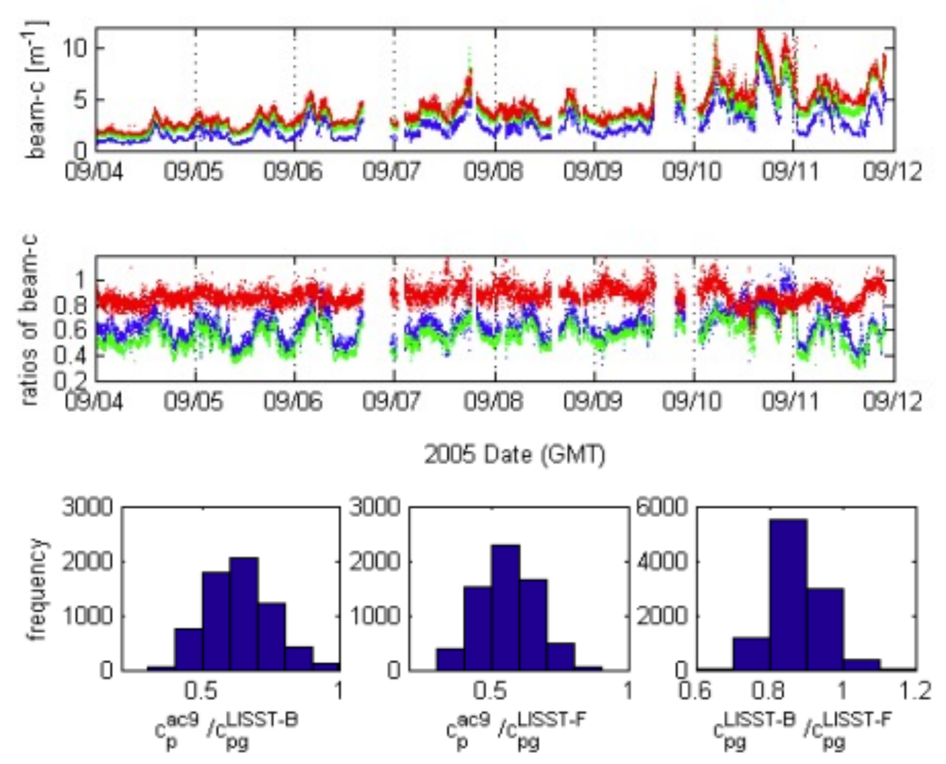
Detected flux (Φ_t) measurement must exclude scattered flux

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

Beam-c issues: acceptance angle.

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



Another issue:
Near-froward scattering by turbulence. (Bogucki et al., 1988)

Boss et al., 2009

Measurement Reality

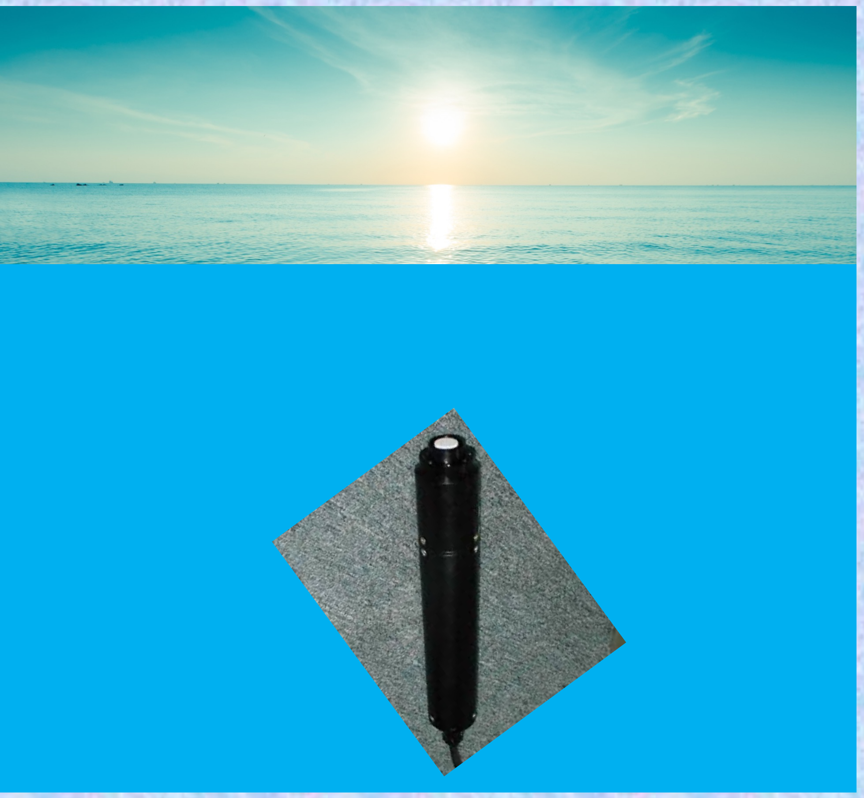
$$c_{sample} - c_{ref} = (-1/L)\ \ln(\Phi_{t,sample} / \Phi_{t,ref})$$

Your reference material could be a deep water mass (e.g. Gardner).

Another wrinkle: Many sensors report a signal even when no light hits the detector (dark signal). For accurate measurements this signal needs to be removed:

$$c_{sample} - c_{ref} = (-1/L)\ \ln(\{\Phi_{t,sample} - \Phi_{dark}\} / \{\Phi_{t,ref} - \Phi_{dark}\})$$

Beam vs. diffuse attenuation



Beam attenuation measurement

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.

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

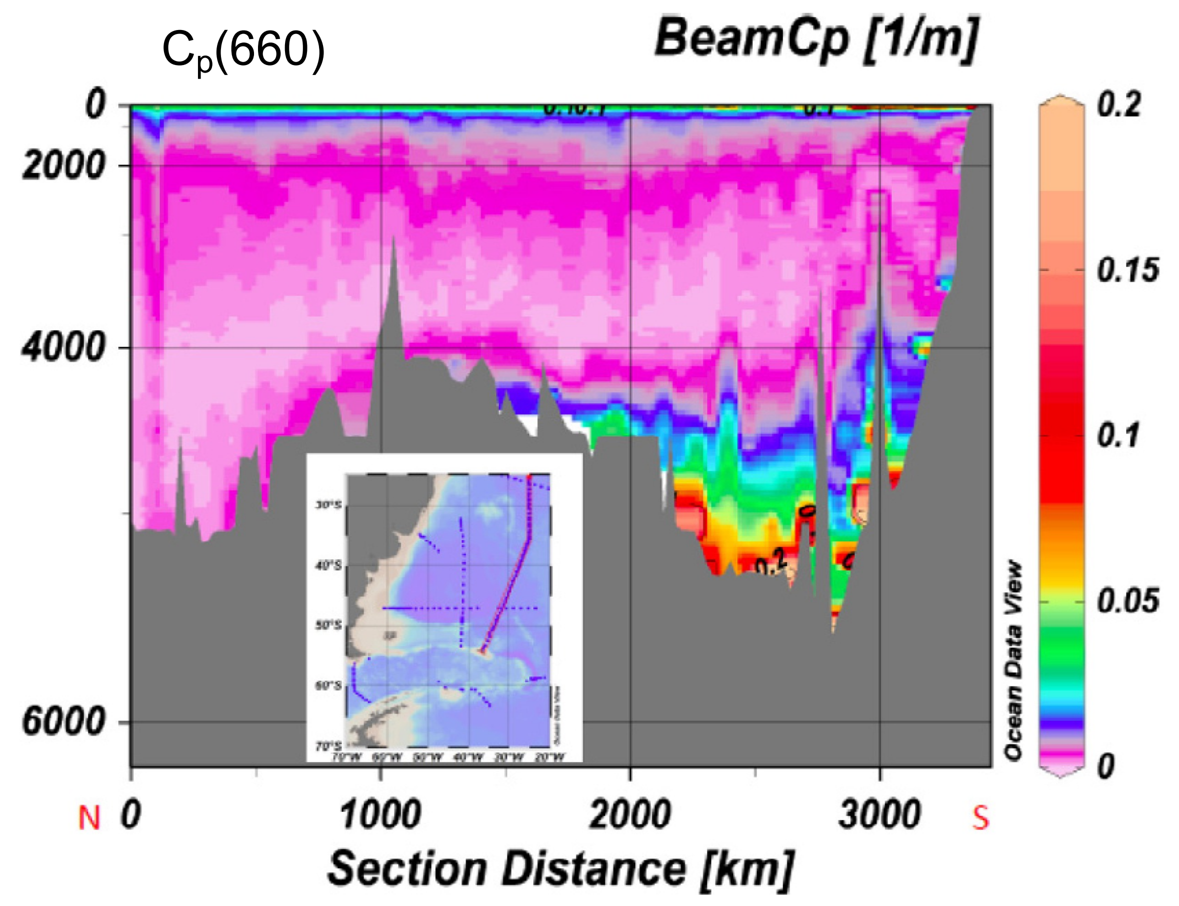
What is a typical distribution of the beam attenuation?

Why 660nm?

What do we learn from measurements at a single wavelength?

What are the particles affecting $C_p(660)$ at different parts of the water column?

What are the processes that may cause them to be present?



Boss et al., 2013 – based on Gardner et al.

typical upper ocean distribution

ON THE NONCORRELATION OF THE VERTICAL STRUCTURE OF LIGHT SCATTERING AND CHLOROPHYLL *a* IN CASE I WATERS

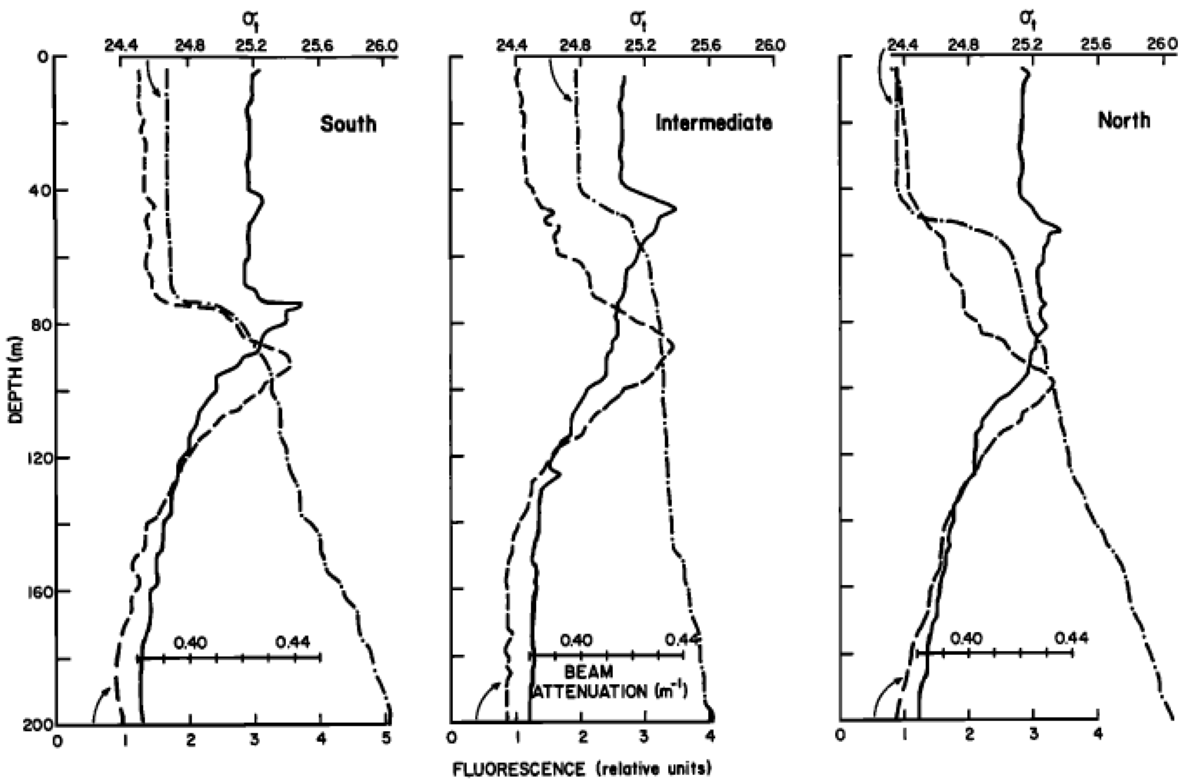
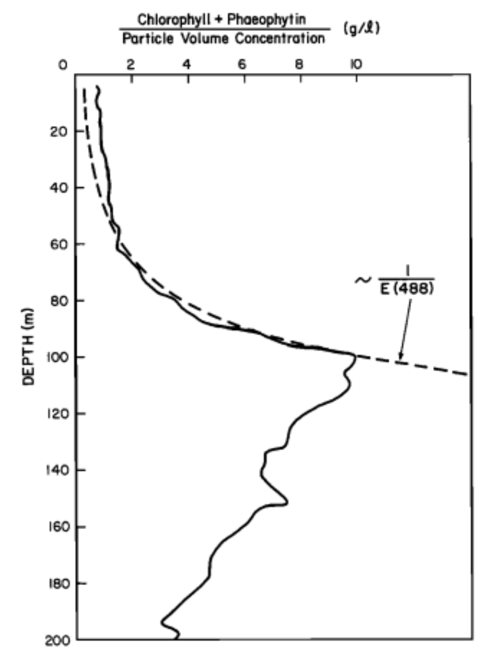


Fig. 1. Profiles of fluorescence, beam attenuation (665 nm) and σ_t for Pacific Central Gyre stations typical of waters north, south and in the Subtropical Front, Oct.-Nov., 1982.

Chl/(Total volume):



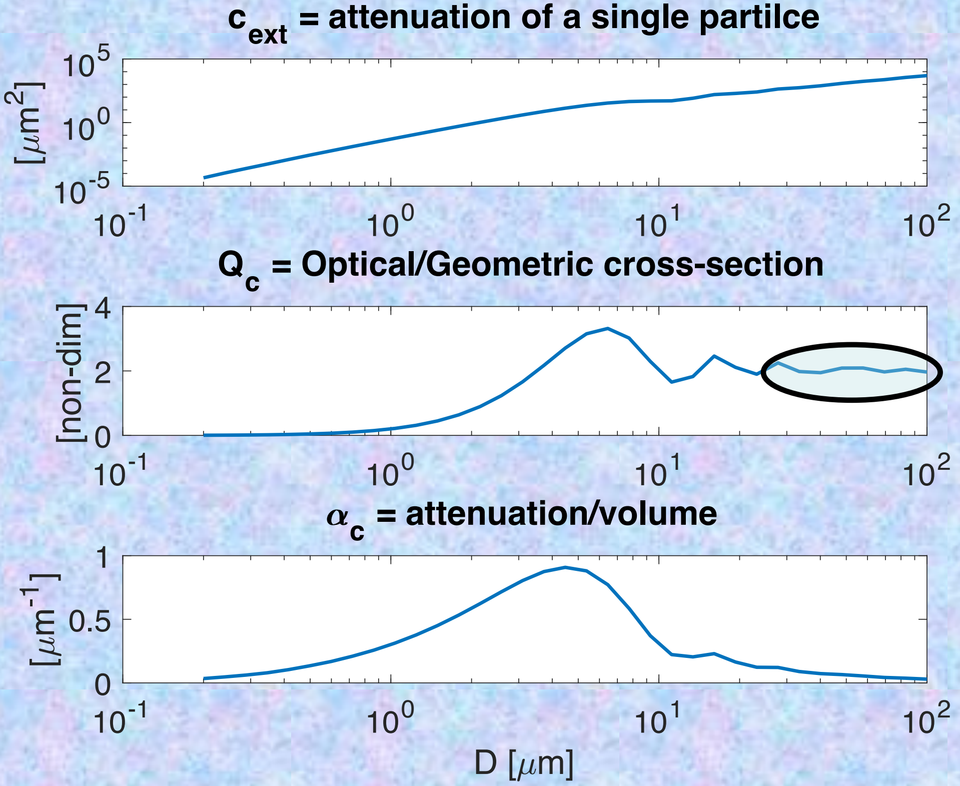
Why is this so amazing?

Kitchen and Zaneveld, 1990

Theoretical beam Attenuation:

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

Many ways to showcase it (which is relevant? Units?):



n=1.05

λ=650nm

$$\frac{\text{Area }(100\mu\text{m})}{\text{Area }(0.2\mu\text{m})} = 2.5 \times 10^5$$

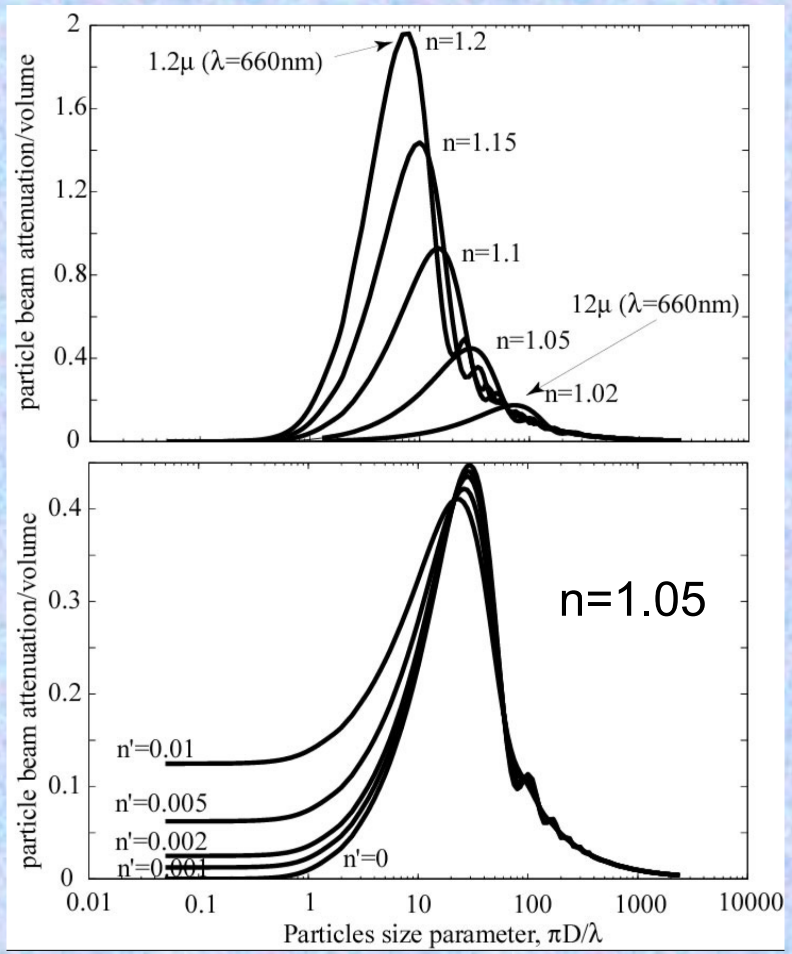
$$\frac{\text{Vol }(100\mu\text{m})}{\text{Vol }(0.2\mu\text{m})} = 1.25 \times 10^8$$

Theoretical beam Attenuation:

Particle specific beam-attenuation, Beam-c/volume(mass) depends on:

- Size.
- Index of refraction.
- Absorption.

To further 'compact' the presentation size is normalized by wavelength



Interestingly,

Empirical Beam attenuation/mass only changes by a factor of 2 between organic and inorganic particles (e.g. Babin et al., 2003).

How come?

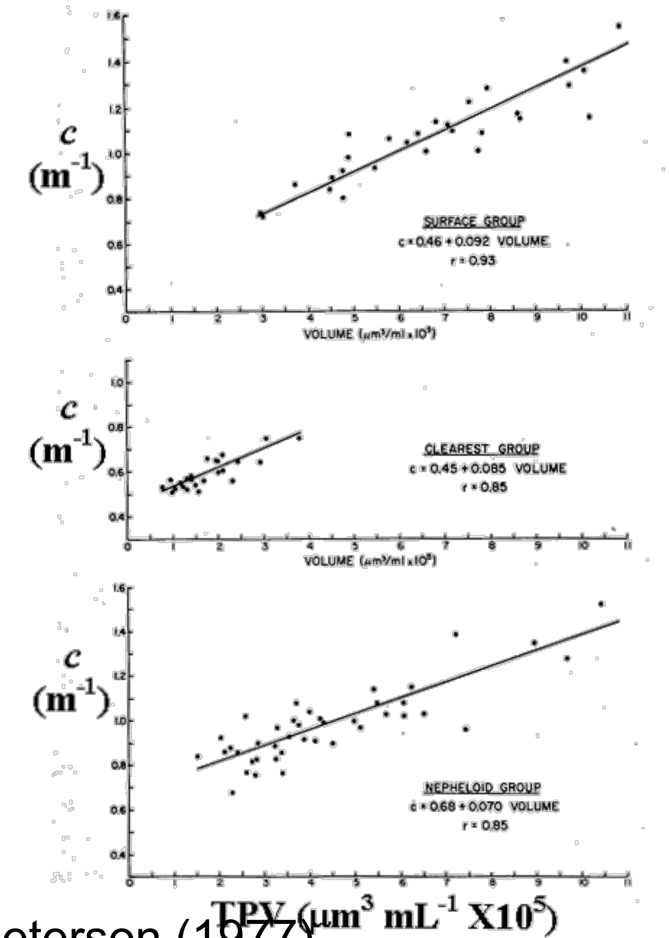
Answer: most organic material are water filled ‘bags’ where the dry material (sugar, protein, lipids) are of high index of refraction (Aas, 1996).

Single wavelength beam attenuation and biogeochemistry:

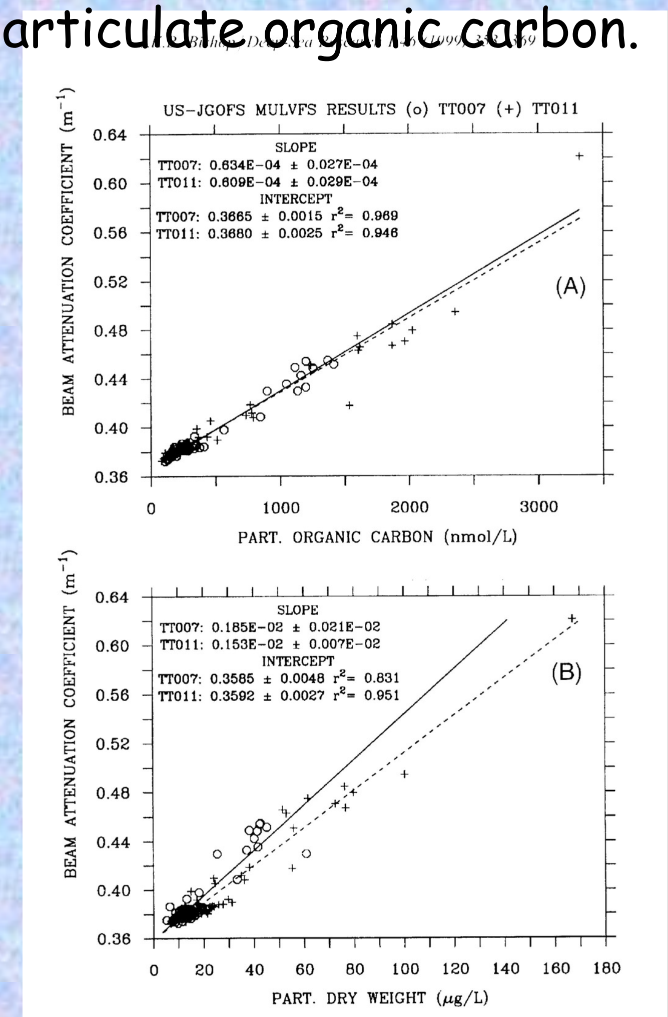
Found to correlate well with:

- Total suspended mass
- Particulate organic carbon
- Particulate volume
- Phytoplankton pigments in areas where light MLD is stable and light relatively constant.

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



Peterson (1977)



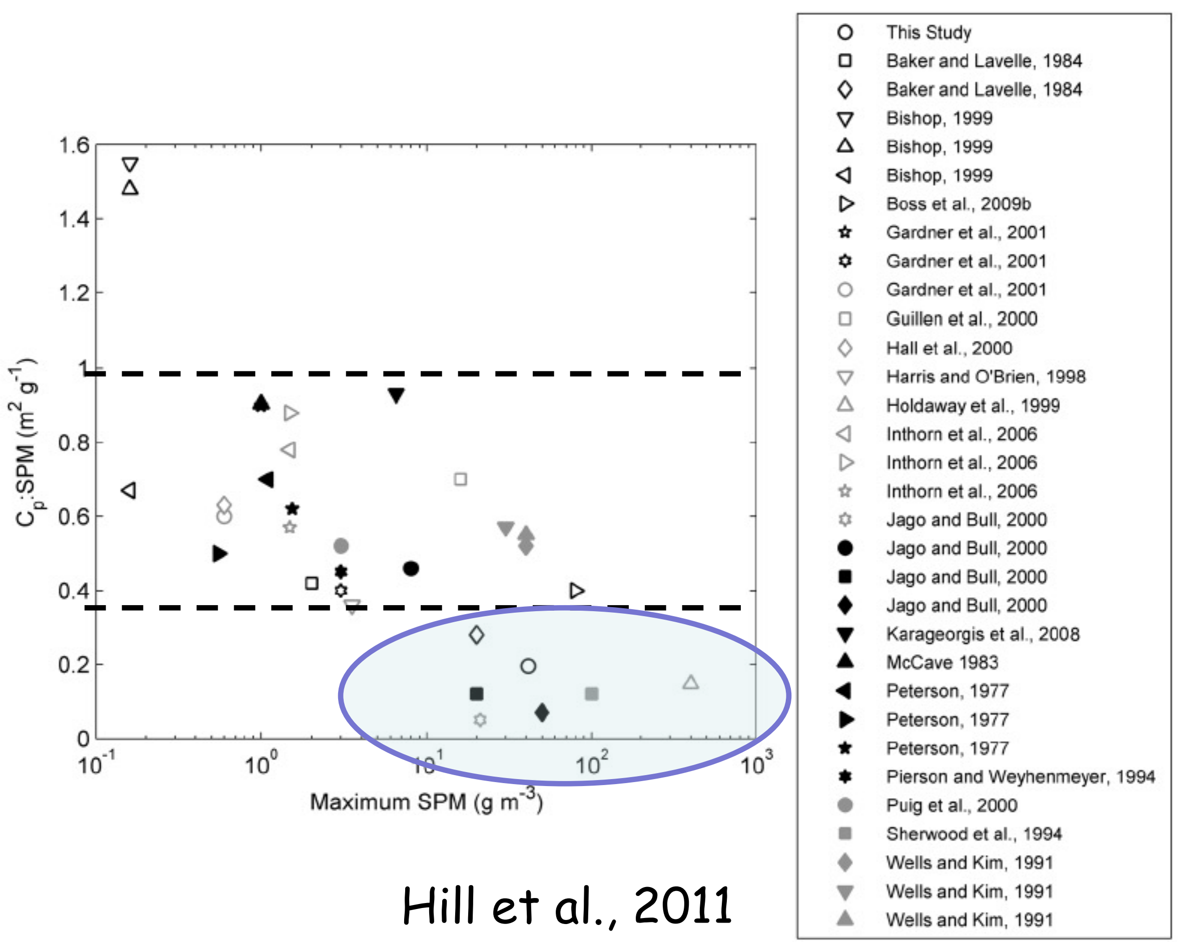
Bishop (1999)

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

Q. How would you expect c_p/SPM to be if c_p is proportional to cross-sectional area?

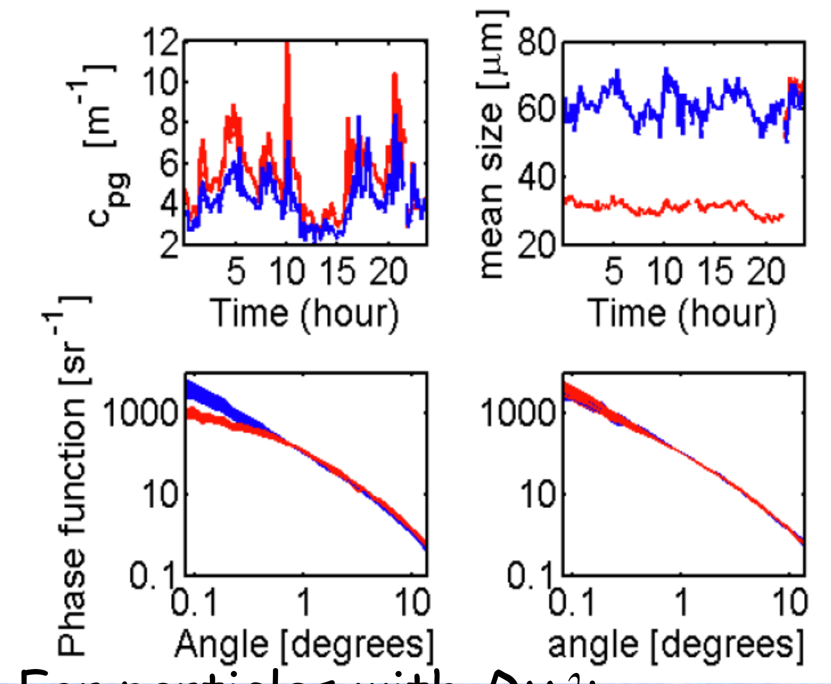
If c_p is proportional to volume (mass)?

Q. How would acceptance angle affect particles we capture?

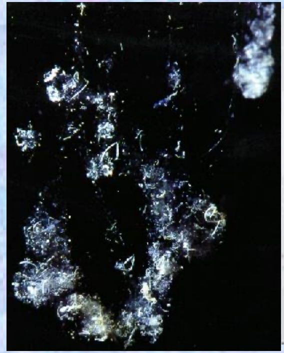


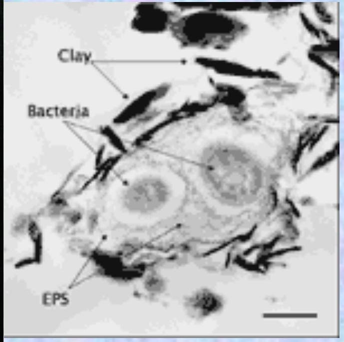
Hill et al., 2011

Handling and aggregates:



Aggregates:



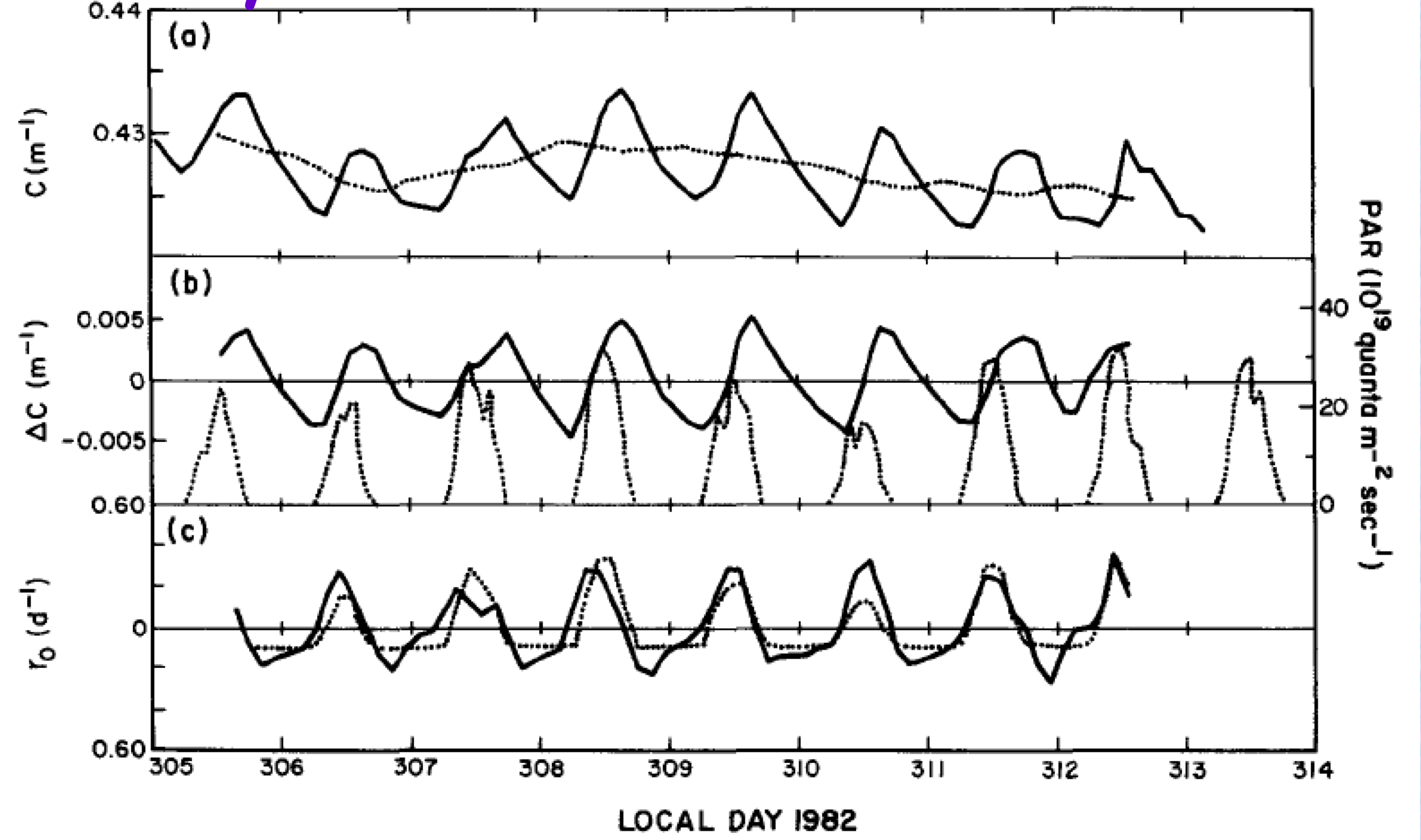


Boss et al., 2009
Slade et al., 2010, 2011

C_p vs. mass as <D> changes?

For particles with $D \gg \lambda$:
When scattering centers are far enough, IOPs are additive.
Optical properties $\propto$ cross-sectional area.
Depends on aggregate packaging ('fractal' dimension).
Spectral dependence of scattering $\propto \lambda^0$

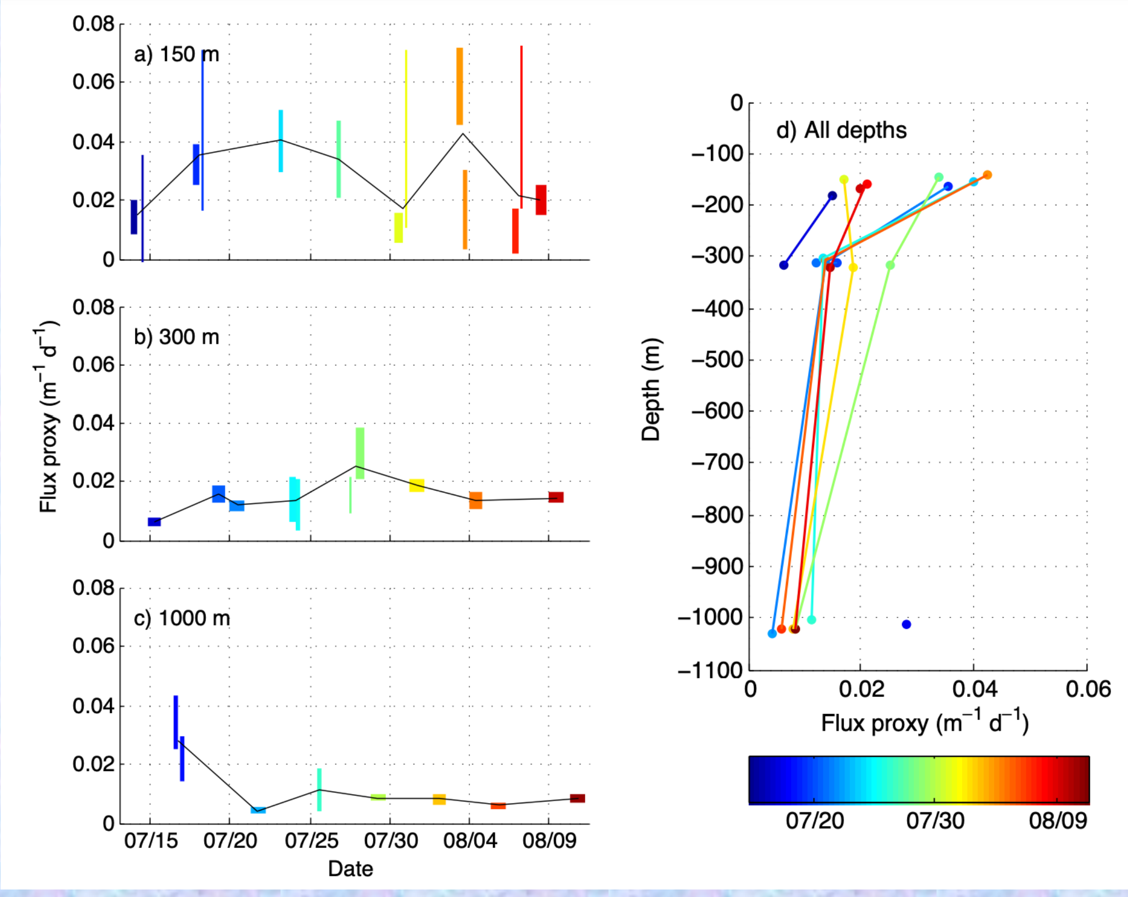
Diel cycles in beam-attenuation



+relevant work by Lewis, Stramski, Claustre

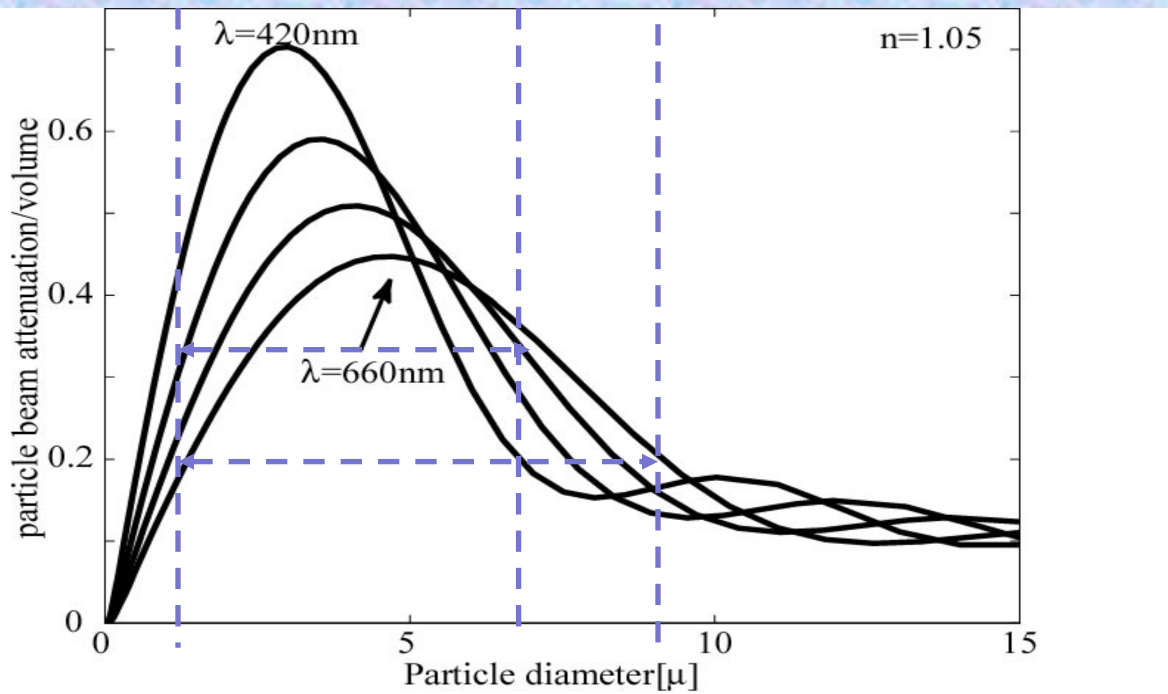
Siegel et al., 1989

beam-attenuation and carbon flux



Estapa et al., 2013 (original idea by J. Bishop)

c_p is sensitive to the wavelength of measurement:



The instrumental ‘filter’ is size dependent:
Particle size where maximum c/volume occurs and its width changes between blue to red wavelengths.

Beam-c and PSD relation:

Mie Theory (homogenous spheres):

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

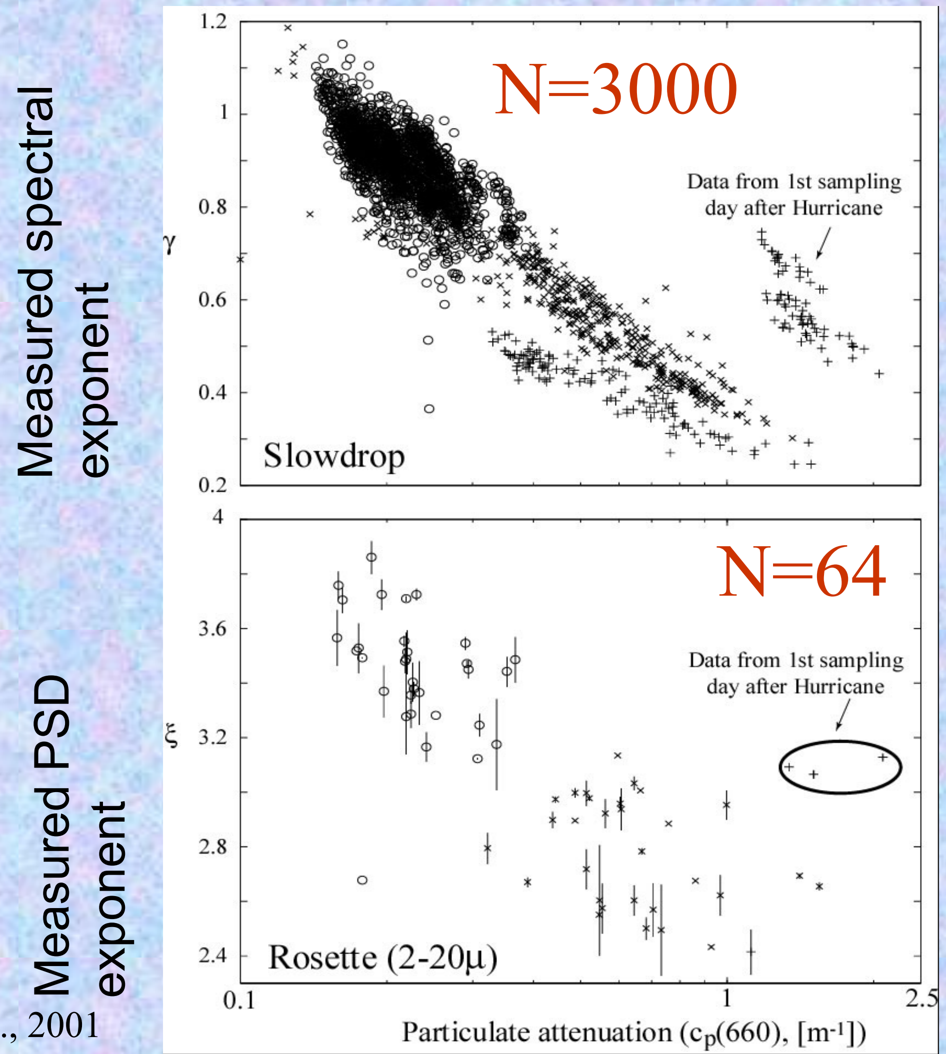
$$N(D)=N_o(D/D_o)^{-\xi}$$

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

→ expect a relation between attenuation spectrum and PSD.

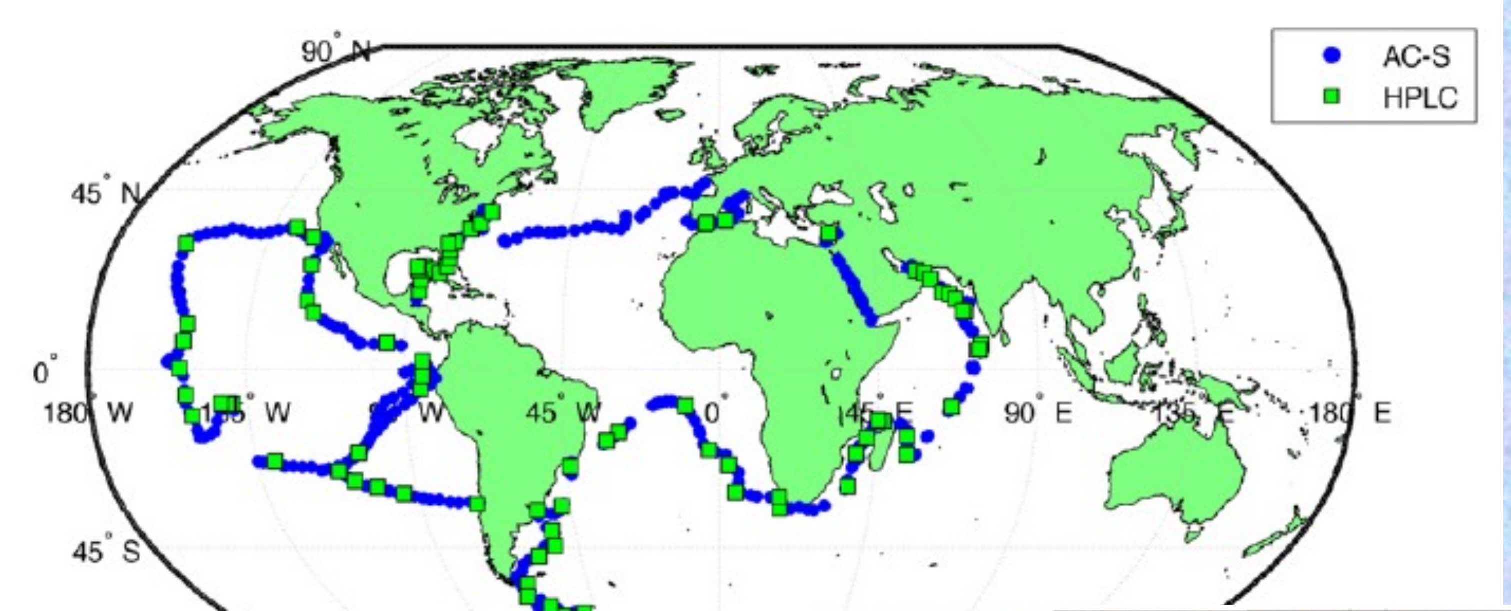
How does theory work?

Do we expect the assumptions to be valid?

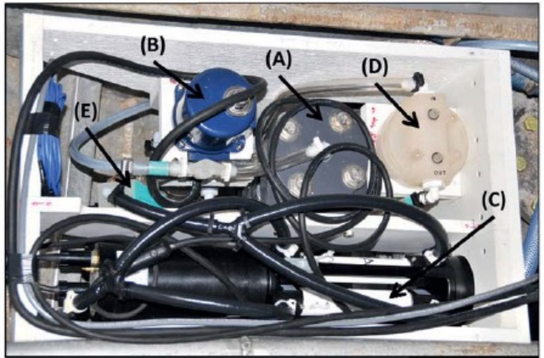


Boss et al., 2001

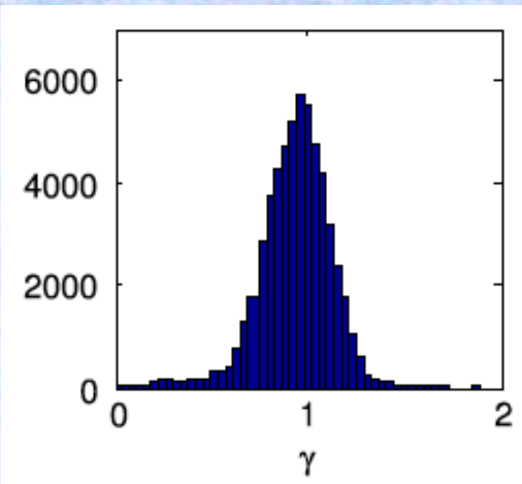
Global stats of spectral shapes

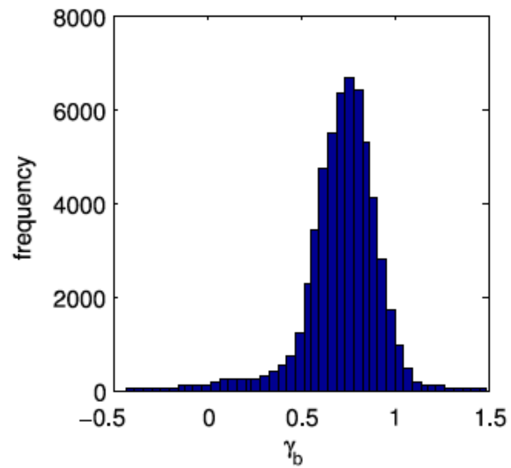


Boss et al., 2013

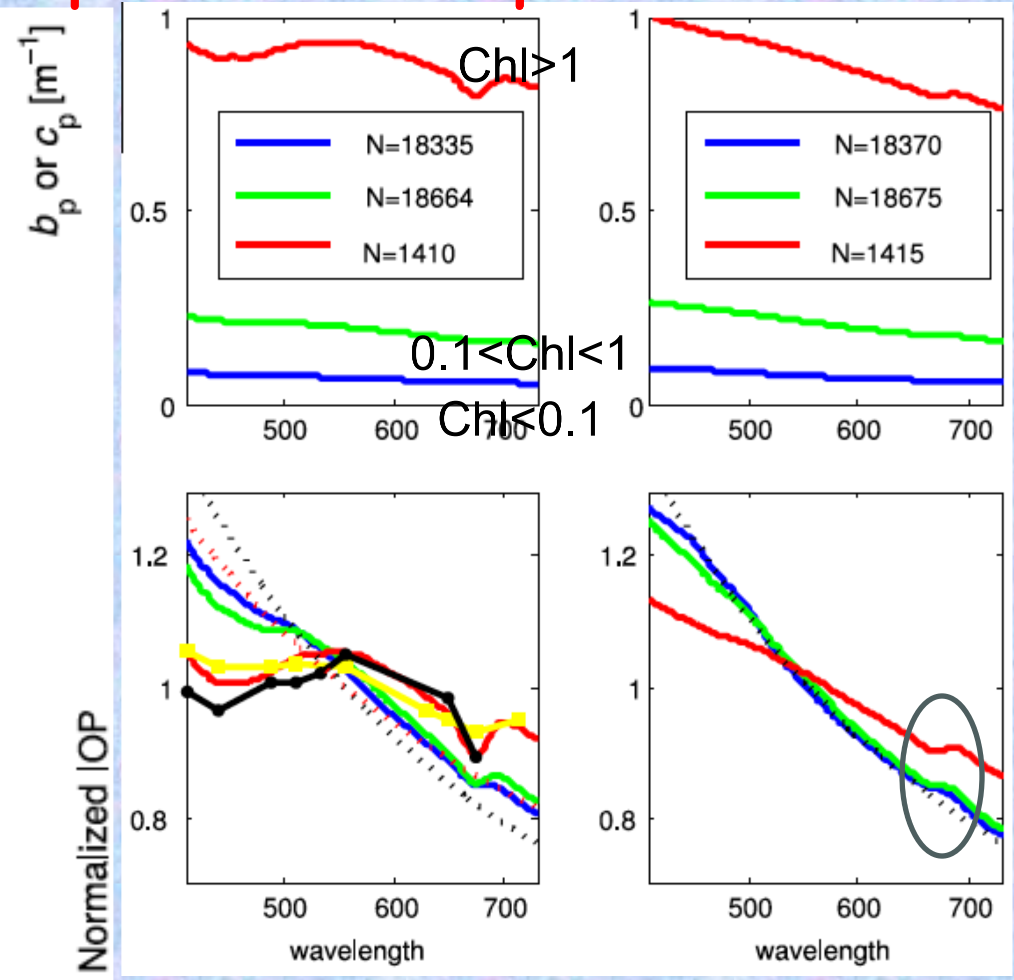


Global stats of spectral shapes





Boss et al., 2013



Chl>1

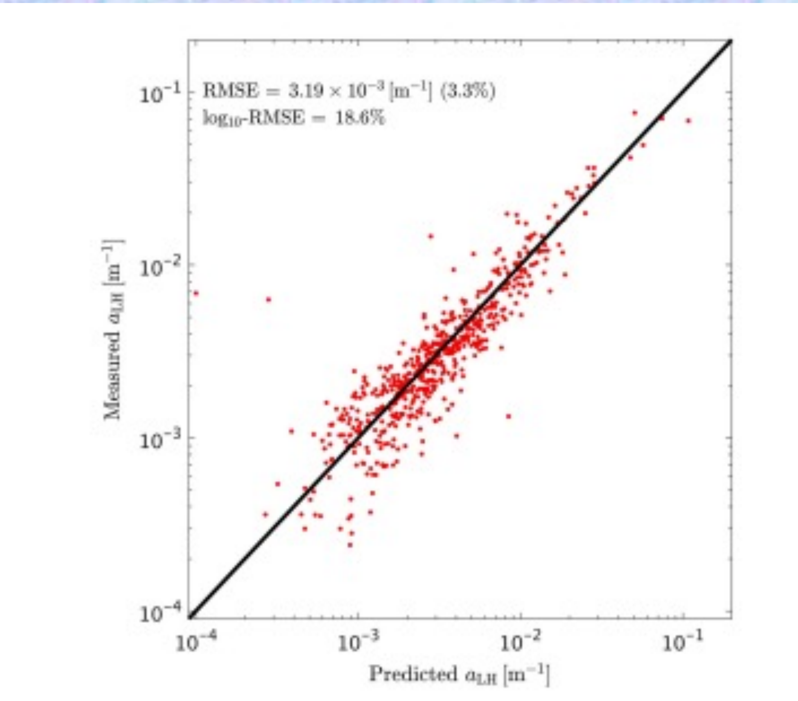
0.1<Chl<1

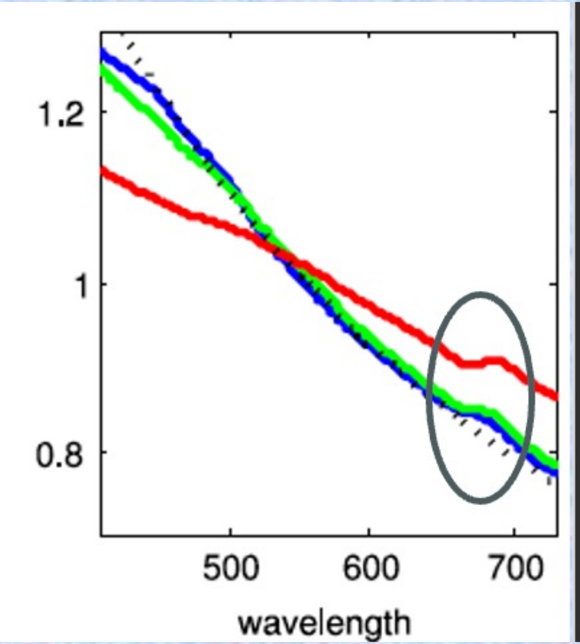
Chl<0.1

Another application of spectral shape:

$$c_p'(\lambda) = c_p(\lambda) - A\left[\frac{532\ \mathrm{nm}}{\lambda}\right]^{\gamma} \quad [\mathrm{m}^{-1}]$$

Chlorophyll from beam-c vs. from *a*(λ)





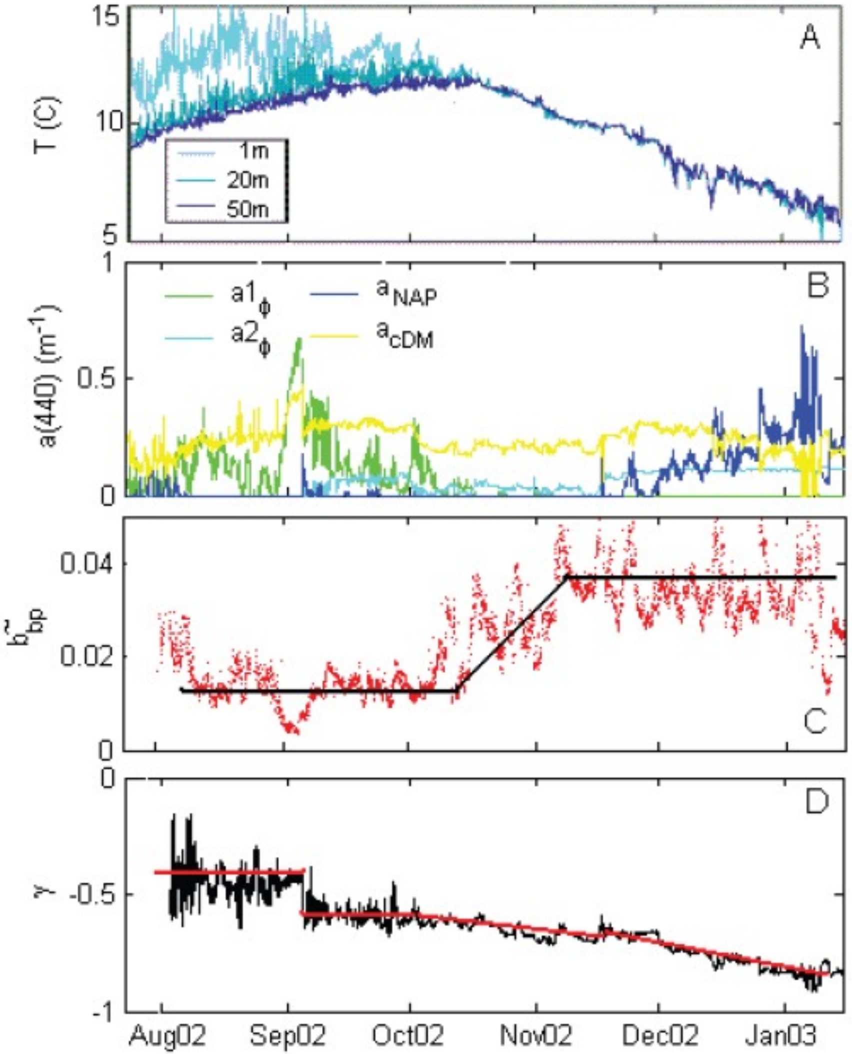
+ size index for phytoplankton

Houskeeper et al., 2020

Seasonality: Particulate attenuation spectra as a tool to study particle composition and species succession.

IOP data from z = 3 m

Phytoplankton type $a1_\phi$ is inferred to be high-light adapted, $a2_\phi$ is low-light adapted



Roesler and Boss, 2008

Summary:

- If I had to do a single optical measurement, it would be c(660)
- Beam attenuation is a robust IOP (no need to correct).
- Beam-attenuation has a long history as proxy for mass.
- Spectral beam attenuation has significant more information.
- Remember caveat (acceptance angle, dark, blank etc’).