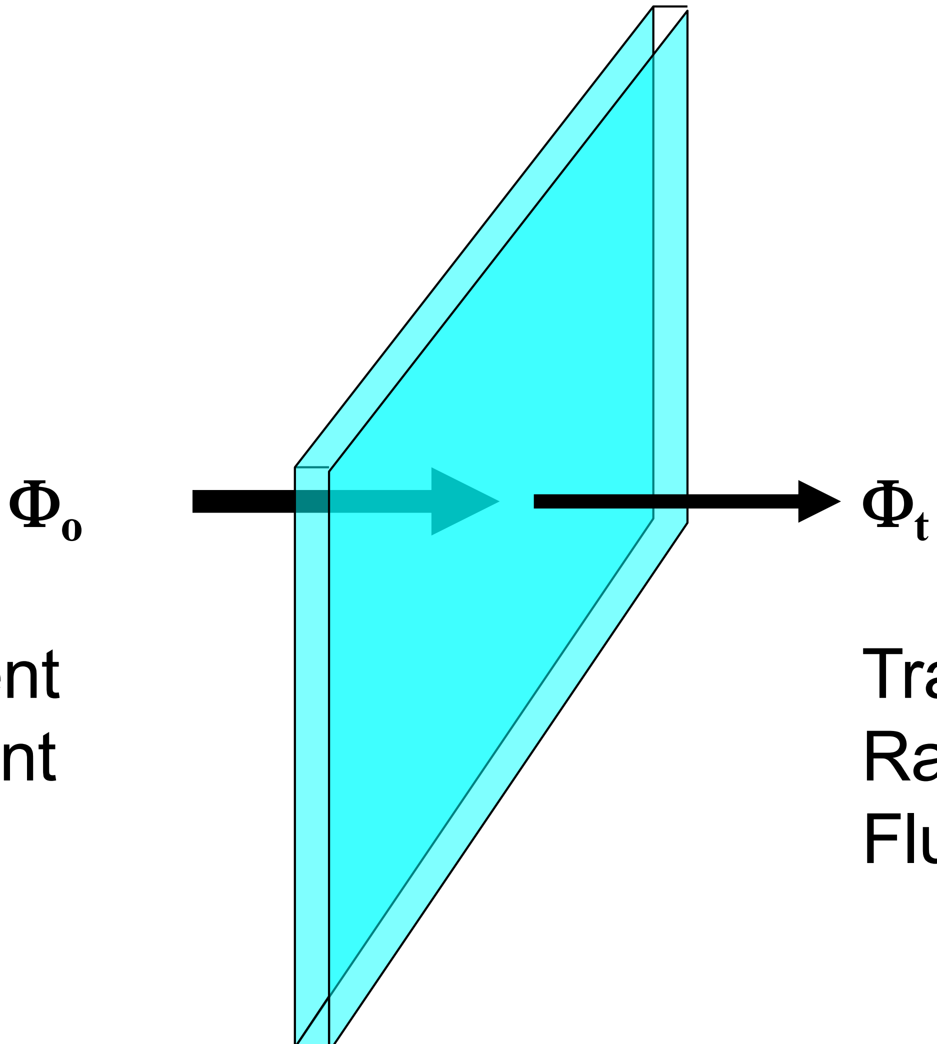
Beam attenuation
(aka extinction, beam-c)

- Theory of measurement… reality of measurement
- Distribution in ocean
- Theoretical beam attenuation (model predictions for idealized particles with different sizes/compositions)
- A few applications

Meg Estapa, UMaine
Modified from slides by Emmanuel Boss, Umaine
Some graphics courtesy Collin Roesler, Bowdoin College

Review: IOP Theory



Incident
Radiant
Flux

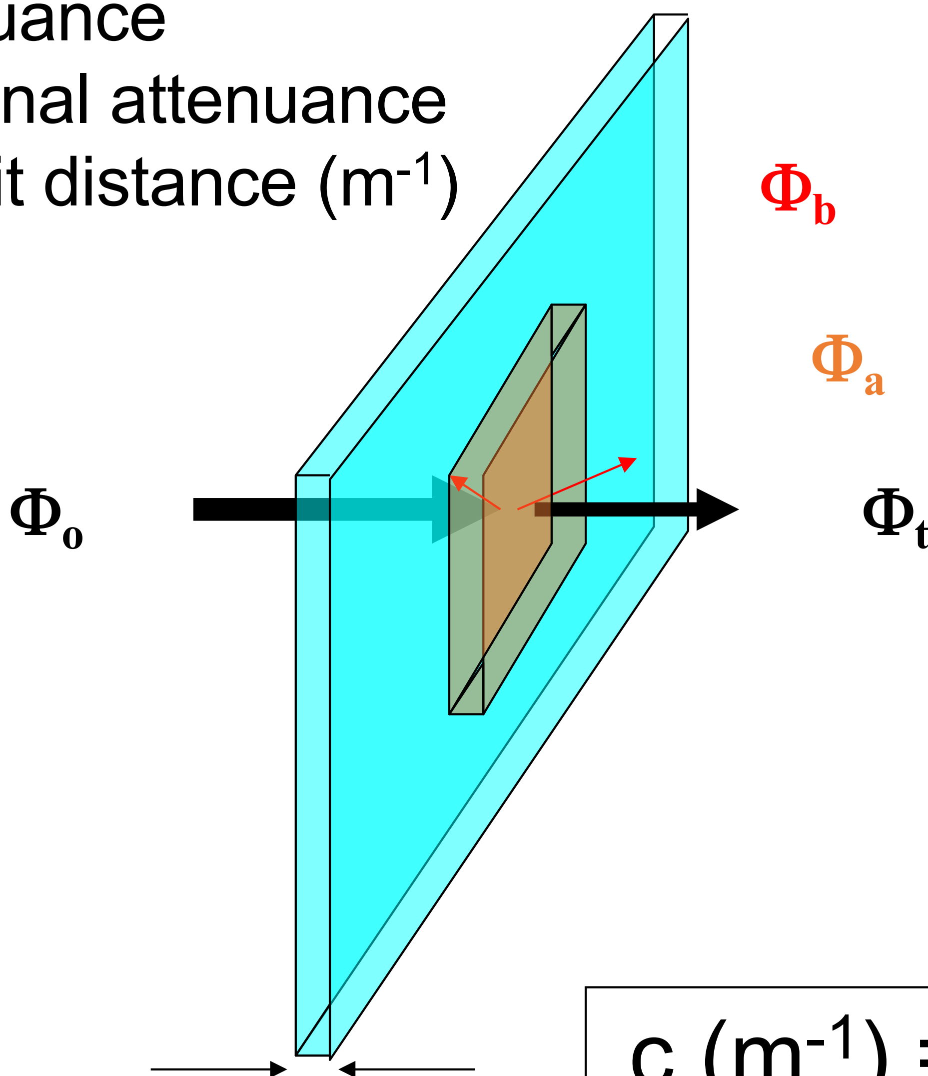
Transmitted
Radiant
Flux

Attenuation

Roesler and Boss, 2008

Beam Attenuation Measurement Theory

C = attenuance
c = fractional attenuance
per unit distance (m^{-1})



$$c = \Delta \boldsymbol{C} / \Delta x$$

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

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

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

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

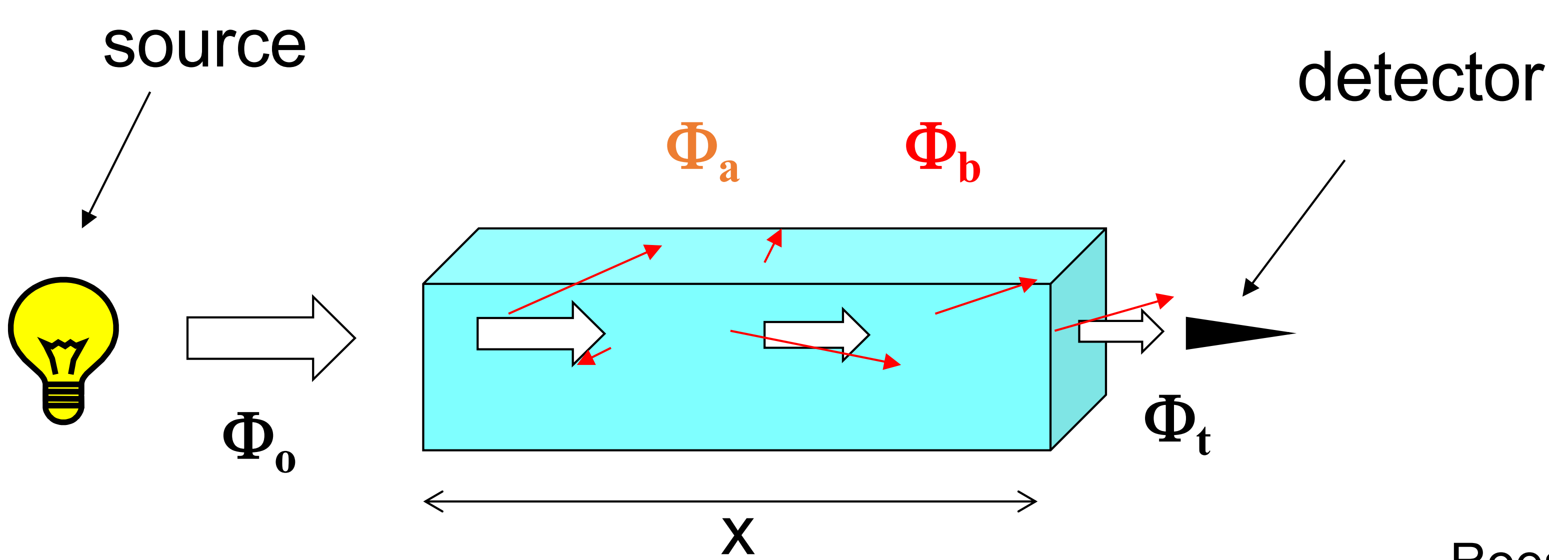
$$c\,x = -\ln(\Phi_t/\Phi_o)$$

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

Roesler and Boss, 2008

Beam Attenuation Measurement Reality

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



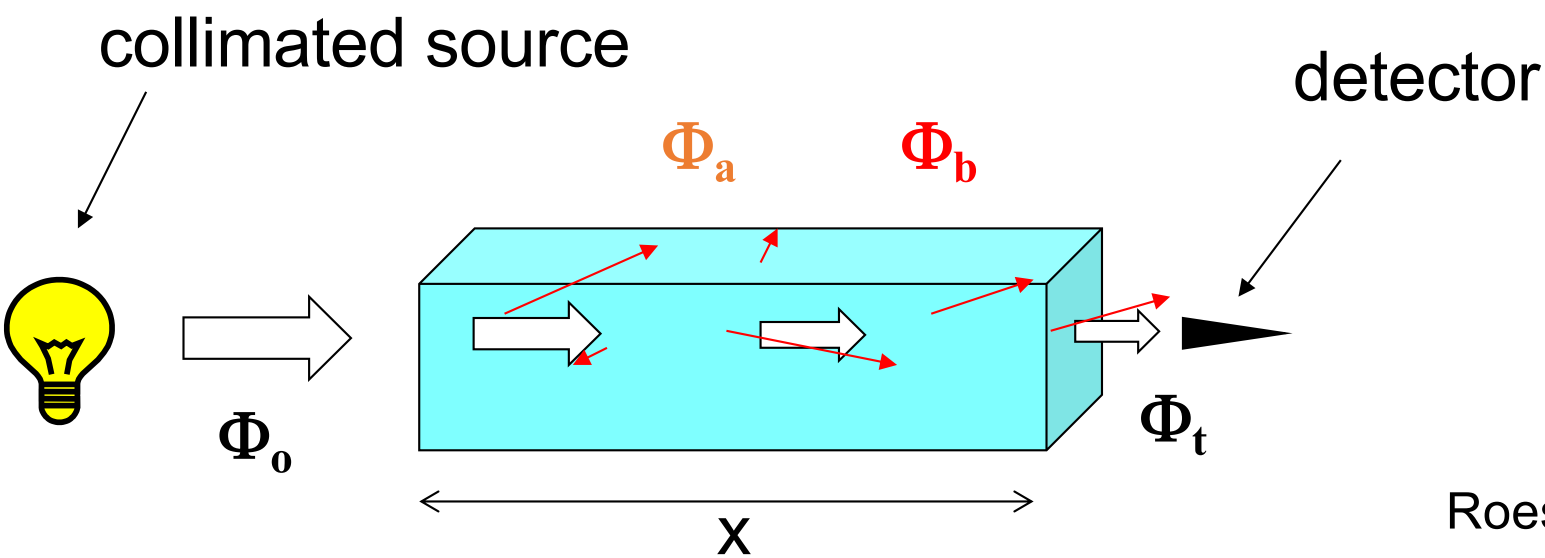
Roesler and Boss, 2008

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 Reality

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



Roesler and Boss, 2008

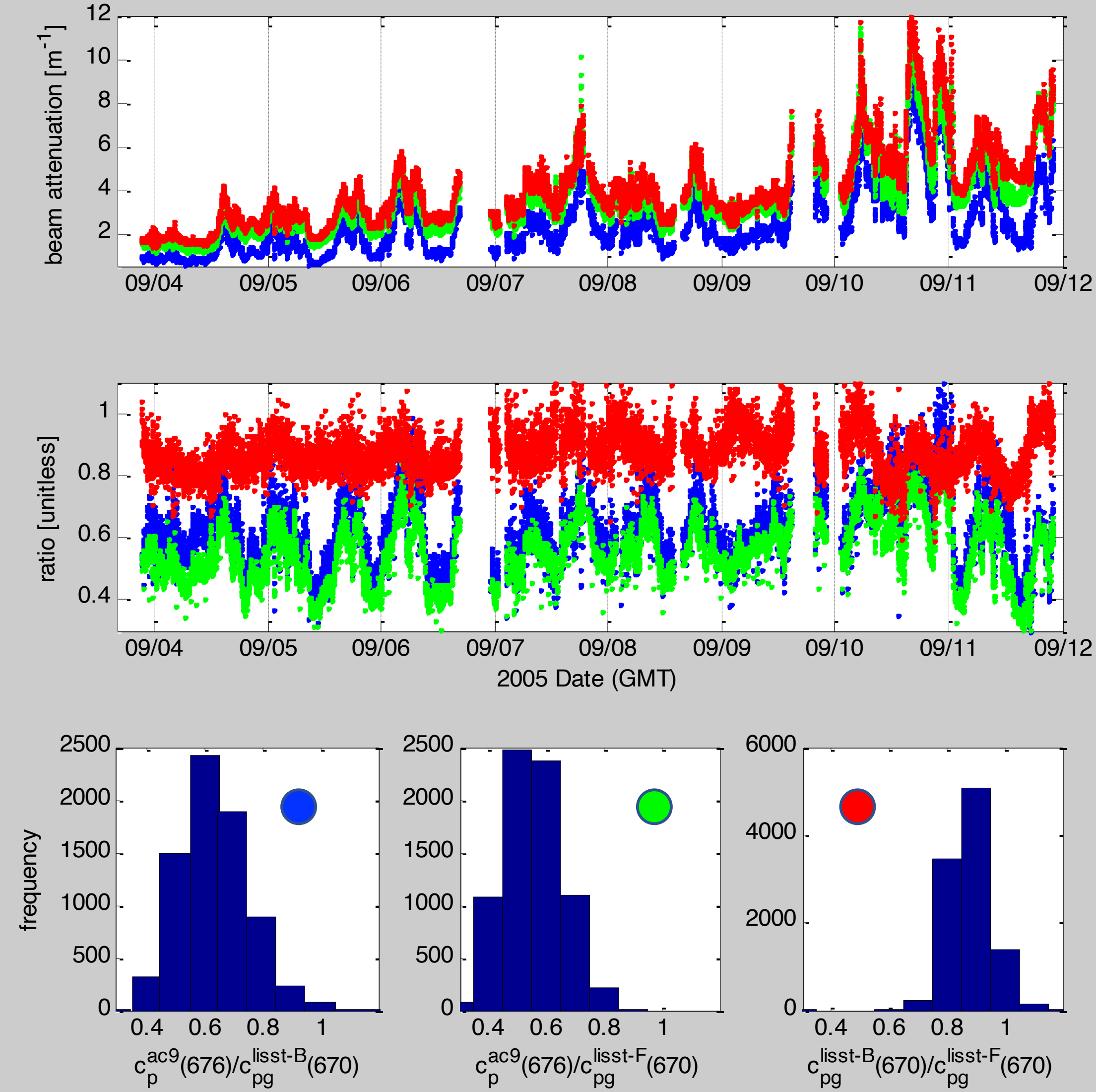
Instrument	Acceptance angle (in-water)
AC-meter	0.93
LISST-B	0.0269°

Which instrument will give the higher value of c, all other things being equal?

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

Beam-c issues: reference materials

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

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

Instead, we measure a reference material:

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

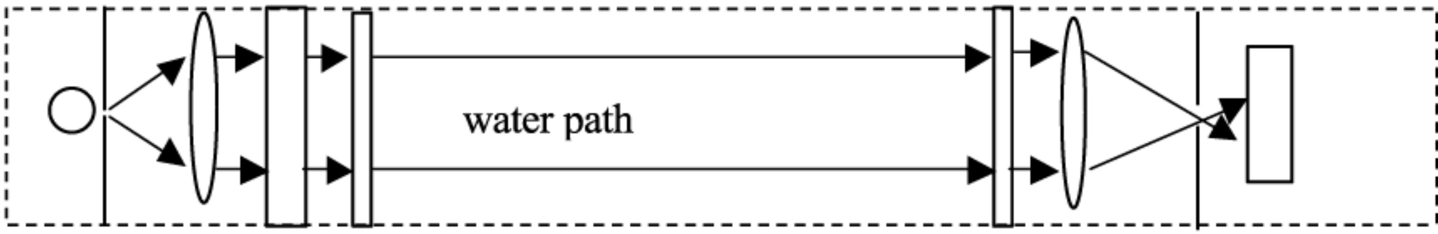
$$c_{sample} - c_{ref} = (-1/x) \ln(\Phi_{t,sample} / \Phi_{t,ref})$$

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

Scenario: You collect some LISST data in the Dead Sea ($S = 270$ g kg^{-1}) and the instrument gives you negative values for beam attenuation. You collect a bottle sample of the same water, filter it, and measure the absorption coefficient in a 1 cm cuvette on a benchtop spectrophotometer, but the problem is even worse. Both measurements are referenced against the same MilliQ.

What's going on?

Beam-c issues: reference materials



Fresnel equation, normal incidence

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

$$I(L) = I(0) T^2{}_{\text{G-}W} e^{-cL}$$

$$I_{DIW}(L) = I(0) T^2{}_{G\text{-}DIW} e^{-c_{\text{DIW}} L}$$

$$I_{sample}(L) = I(0) T^2{}_{G\text{-}SW} e^{-c_{sample+SW} L}$$

$$Tr = \frac{I_{sample}(L)}{I_{DIW}(L)} = \frac{T^2{}_{G\text{-}SW}}{T^2{}_{G\text{-}DIW}} e^{-(c_{sample+SW} - c_{DIW})L}.$$

$$c_{measured} = \frac{\log(Tr)}{L} = c_{sample+SW} - c_{DIW} - \frac{2}{L} \log\left(\frac{T_{G\text{-}SW}}{T_{G\text{-}DIW}}\right)$$

Boss et al. 2013; figure: Boss et al., 2019

Beam-c issues: “Dark” signal removal

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

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:

$$c_{sample} - c_{ref} = -\frac{1}{x} \ln\left(\frac{(\phi_{sample} - \phi_{dark})}{(\phi_{ref} - \phi_{dark})}\right)$$

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.

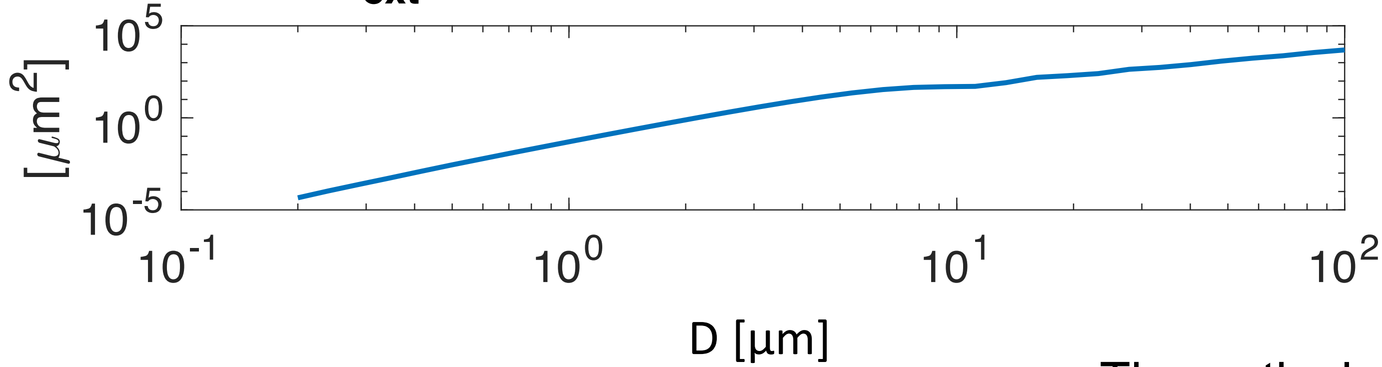
Scenario: You go on a cruise where the ship's rosette carries a C-Star transmissometer of unknown provenance. What info do you need to get from the ship's technician (and/or find out on your own) before using the data from the sensor?

Theoretical Beam Attenuation:

Like all IOPs, c_p is dependent on **size** and composition.

Attenuation cross section

C_{ext} = attenuation of a single particle

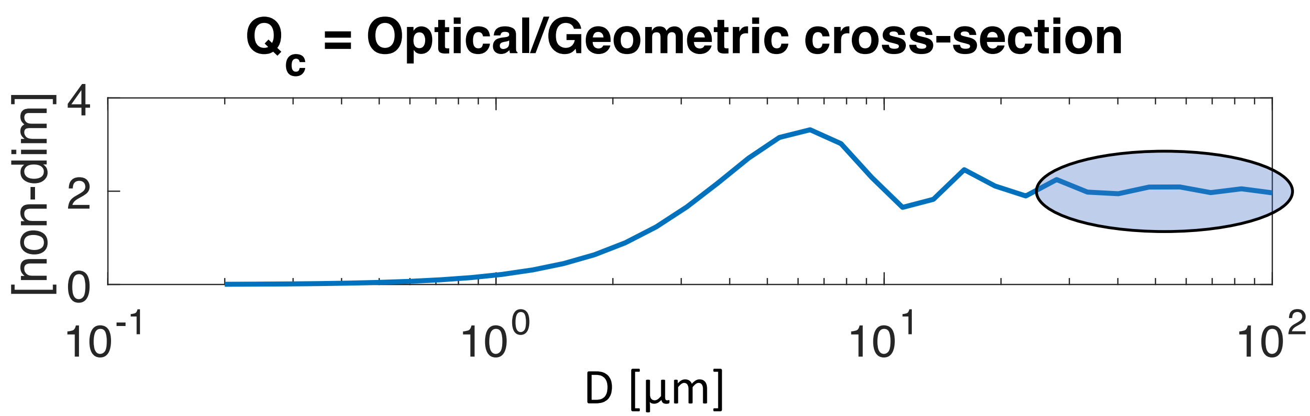


Theoretical particle with ”phytoplankton-like” refractive index, for λ=650nm

Theoretical Beam Attenuation:

Like all IOPs, c_p is dependent on **size** and composition.

Extinction (or attenuation) efficiency



Note that Q_c approaches 2 for large sizes.

Theoretical Beam Attenuation:

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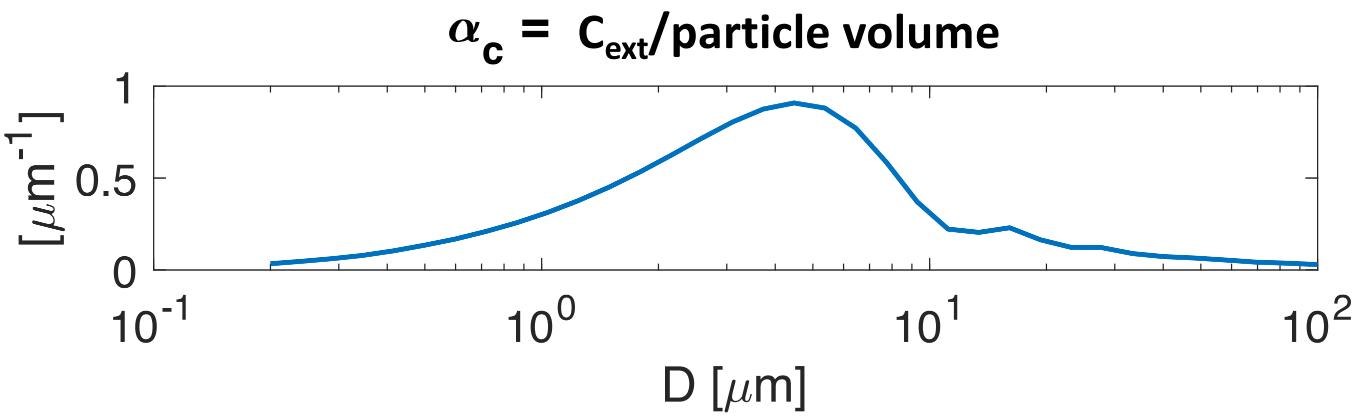


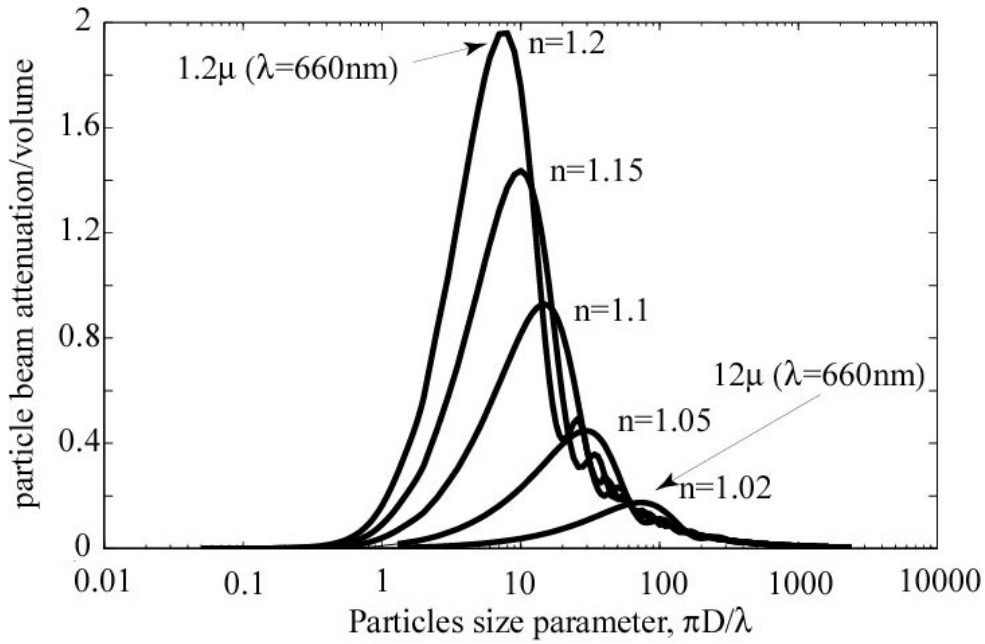
Peak sensitivity is to particles with diameter 10^0-10^1 microns
This IOP model is for λ = 650 nm ... more to come on wavelength dependence

Theoretical Beam Attenuation:

How does c_p/volume depend on:

✓ Size?

- **Composition?**
  - Modeled using index of refraction ("real" and "complex" parts)



(To further 'compact' the presentation size is normalized by wavelength;
also here "n" is index *relative* to seawater)

Boss et al., 2001

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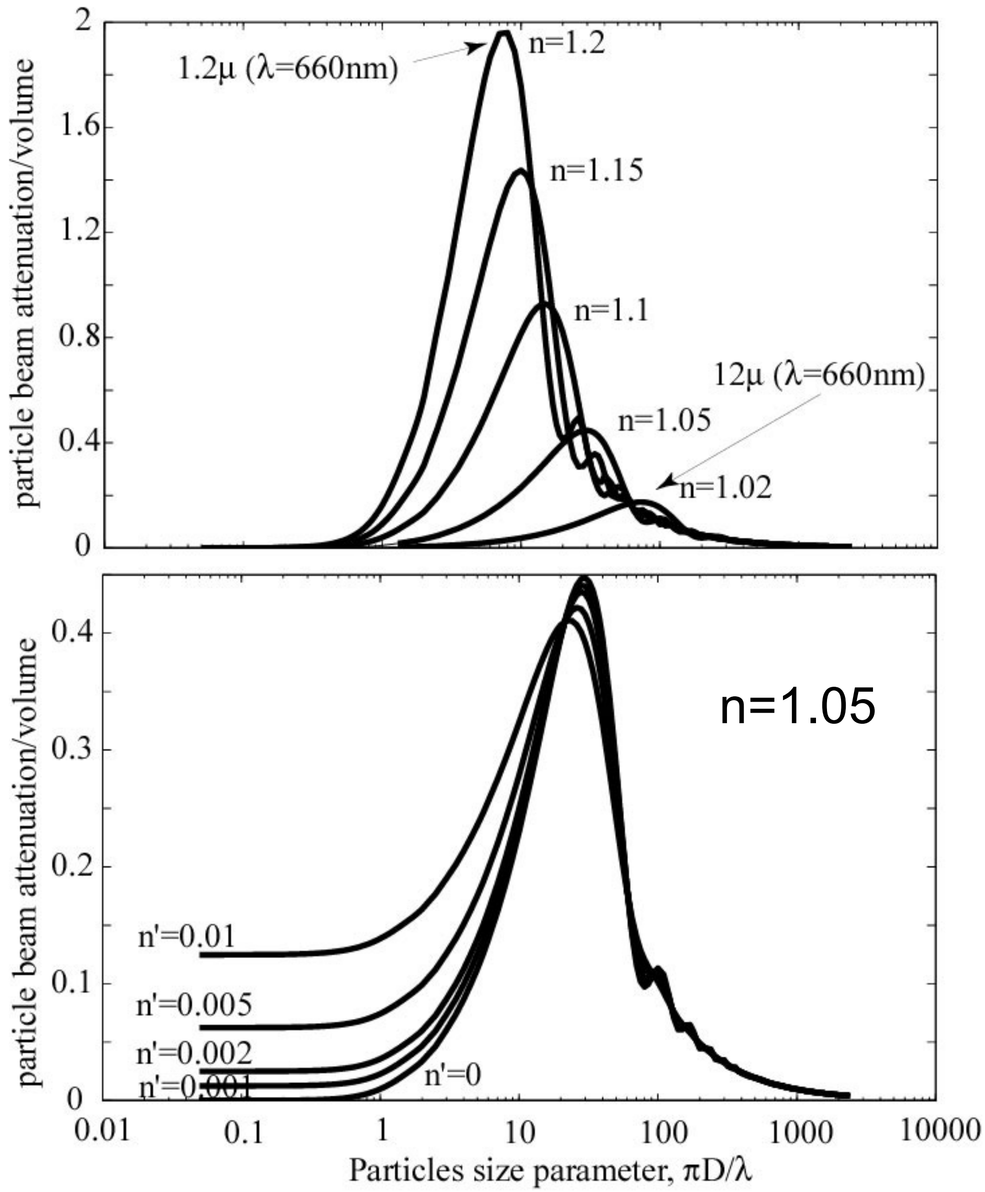

Boss et al., 2001

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Theoretical Beam Attenuation:

How does c_p/volume depend on:

✓ Size?

- **Composition?**
  - Modeled using index of refraction (“real” and “complex” parts)

- However, *mass*-normalized scattering (~attenuation) only varies by a factor of 2...

(To further ‘compact’ the presentation size is normalized by wavelength;
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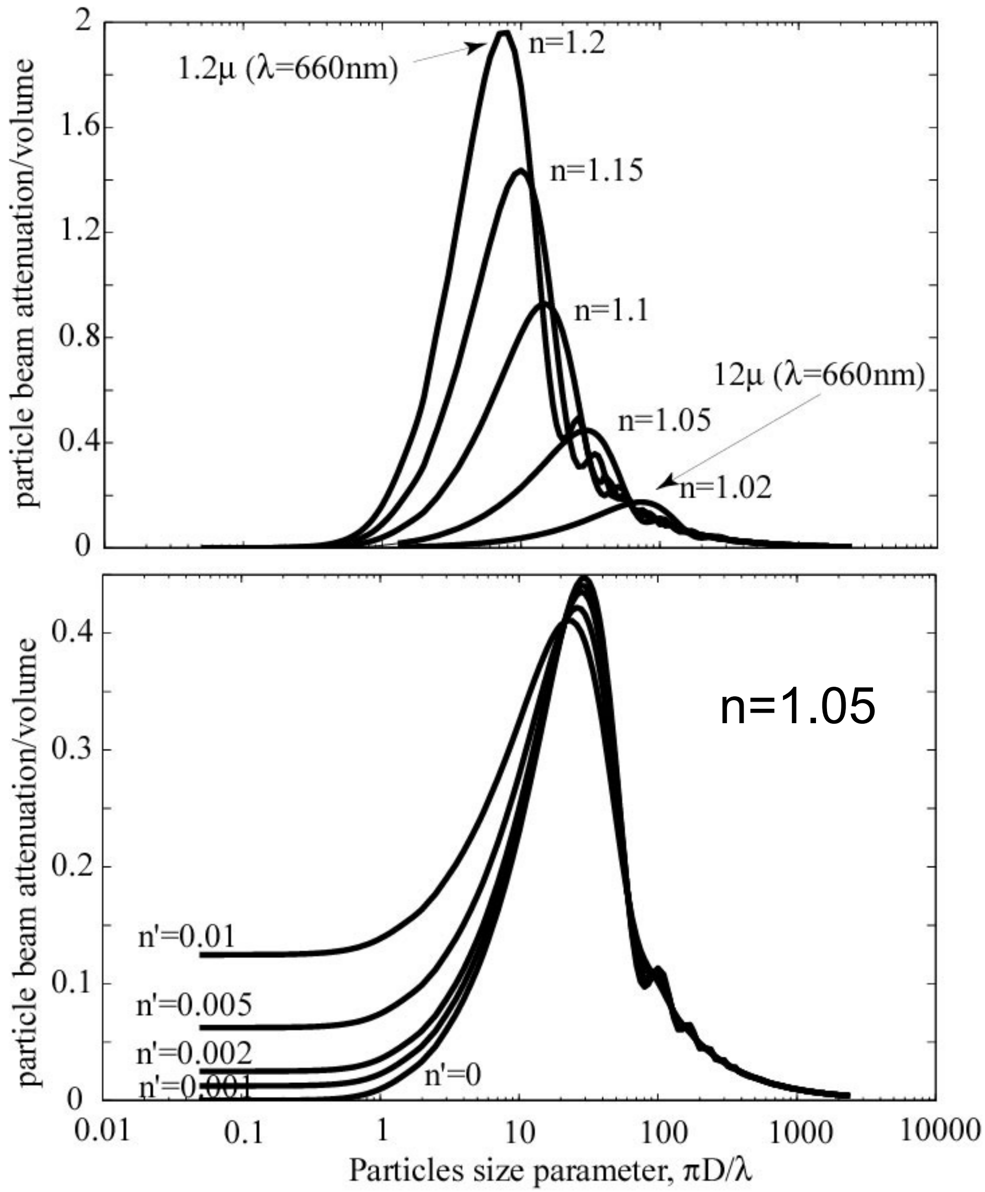
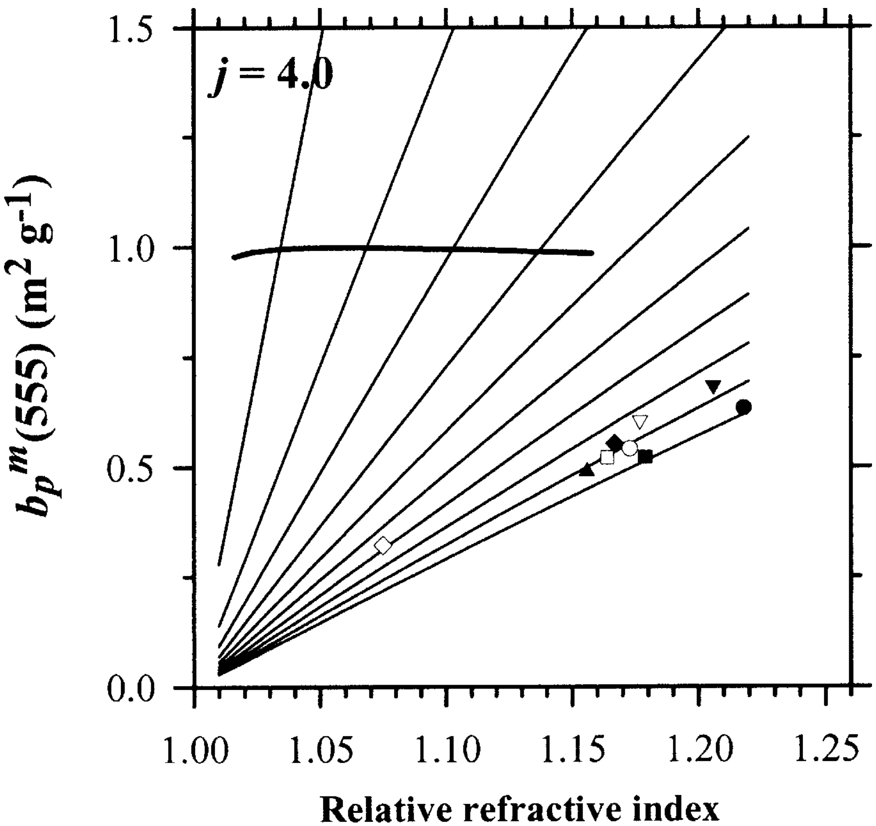


Boss et al., 2001

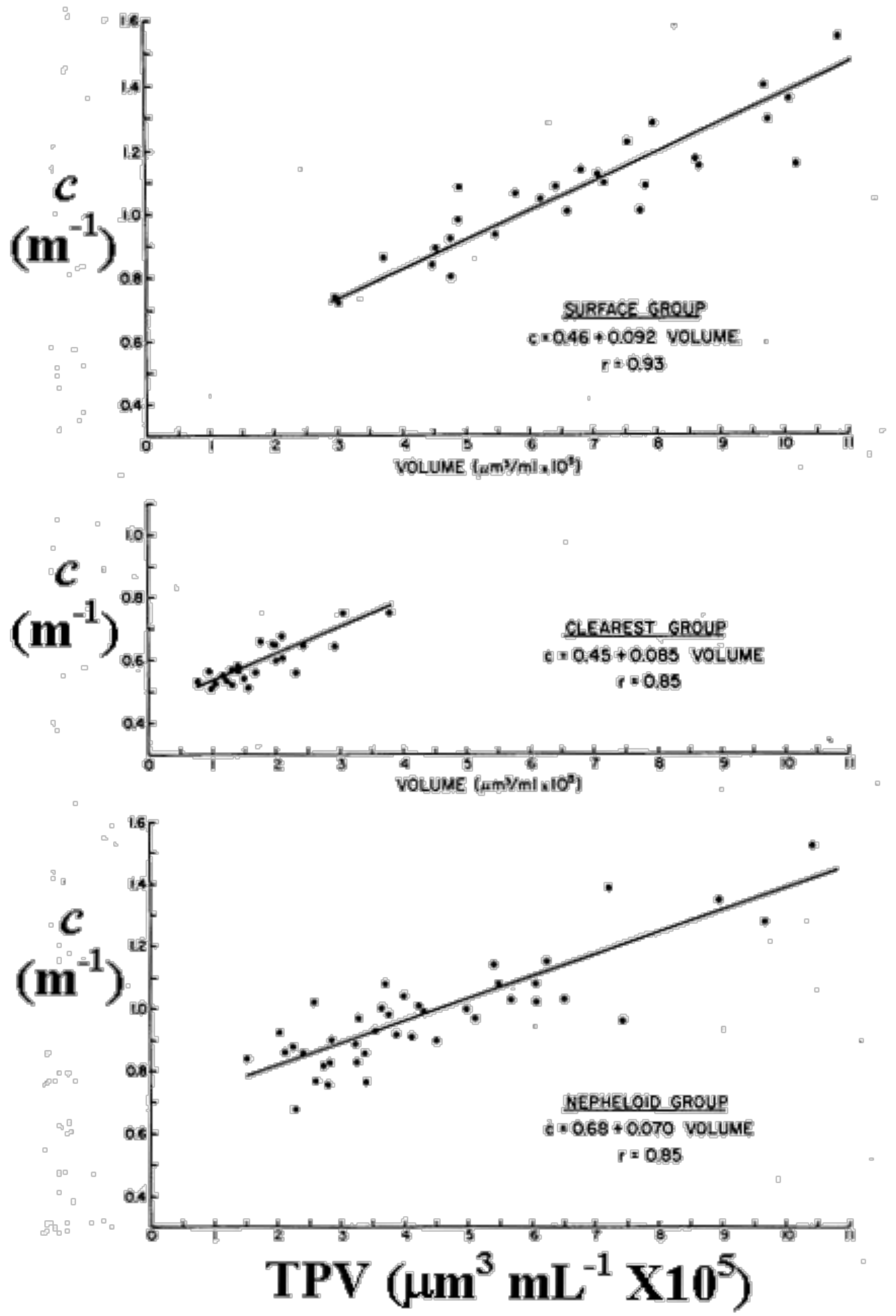
Mass-normalized scattering (b_p^m) only varies by a factor of ~2



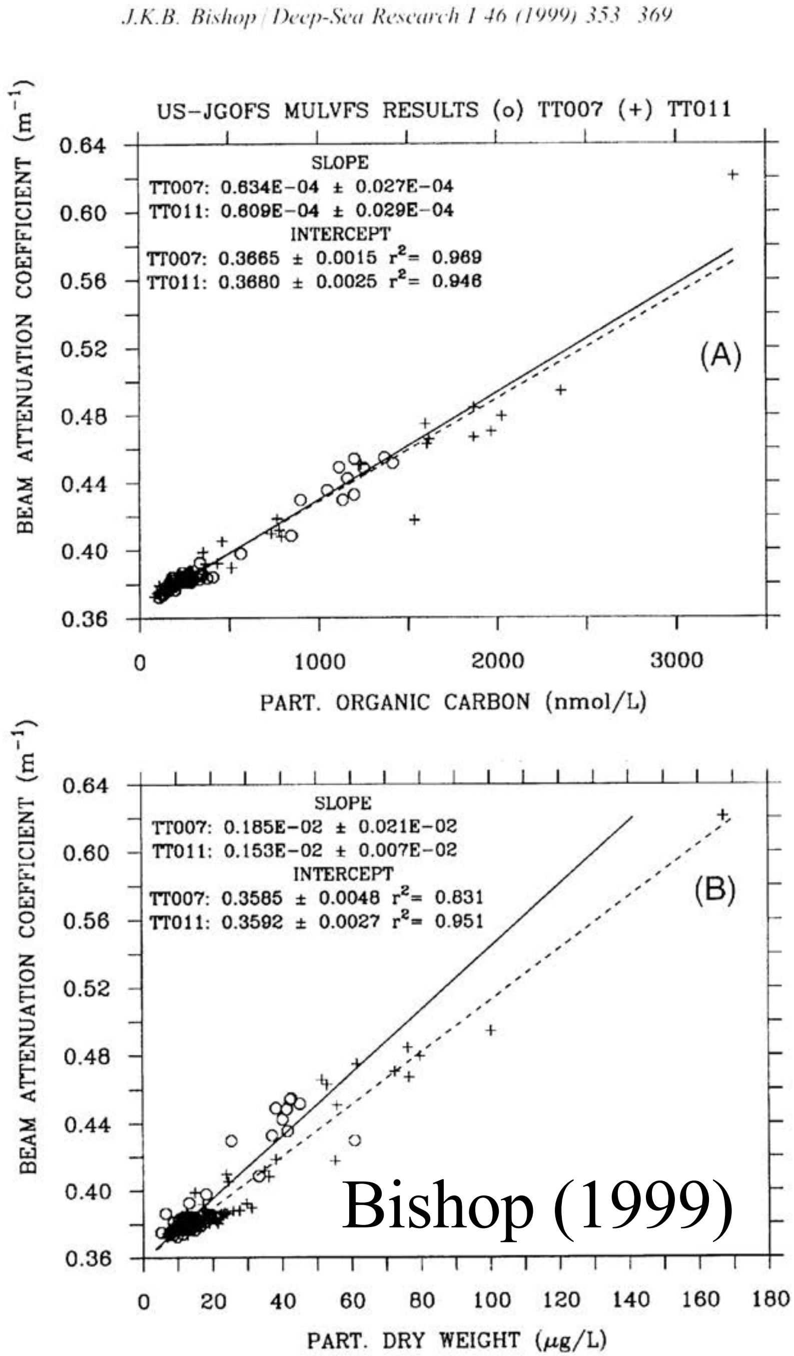
- Modeled, mass-normalized scattering coefficient (b_p^m(555)) for *non-absorbing particles*
- Line = organic particles (more→less hydrated). Symbols = mineral particles.
- Most organic particles are water-filled "bags" where the dry material (carbohydrates, proteins, lipids) have higher indices of refraction (Aas, 1996)

Babin et al. 2003

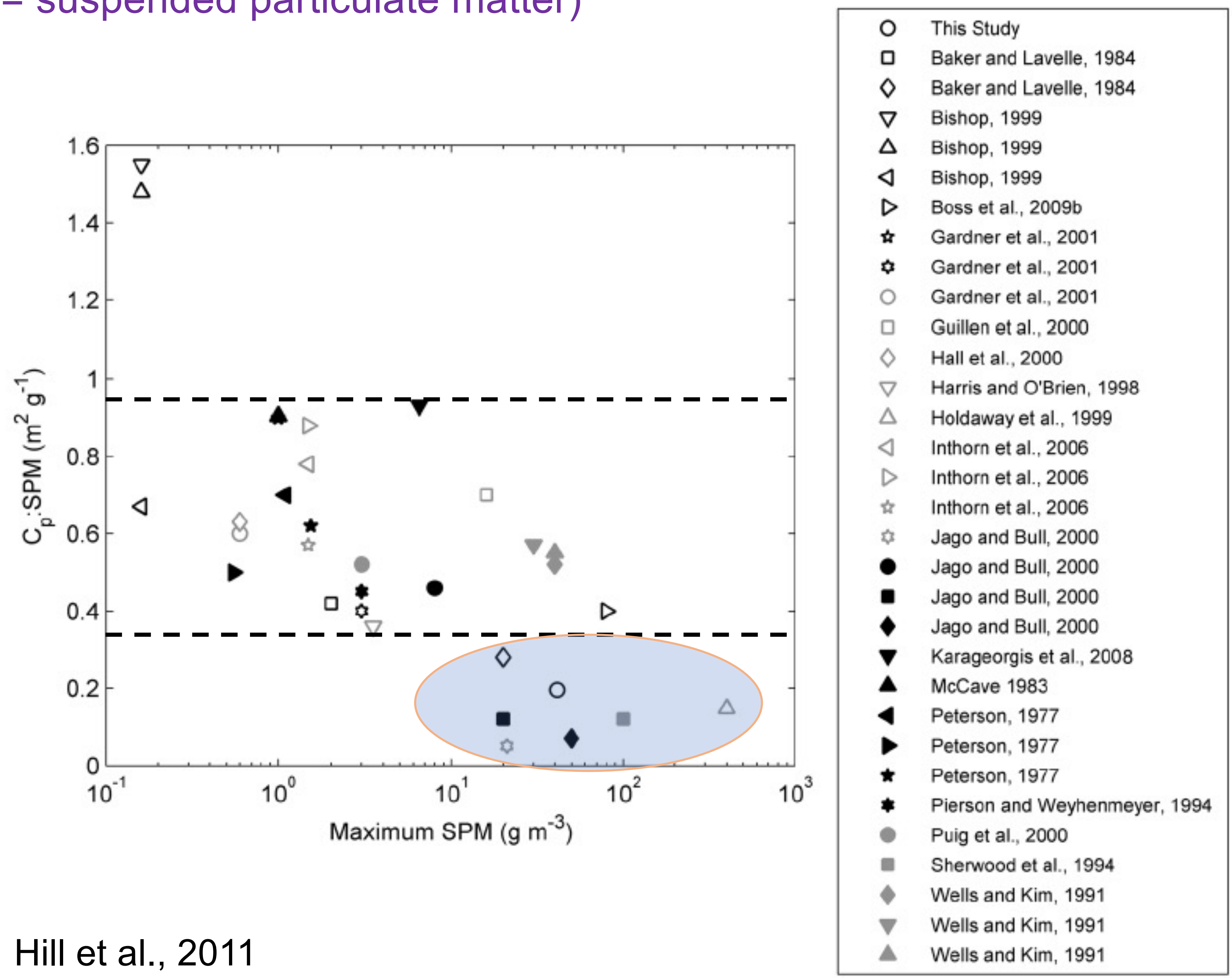
Good correlation with total particle volume, and particulate organic carbon.



Peterson (1977)



Lower attenuation/mass in high SPM settings
(SPM = suspended particulate matter)



Hill et al., 2011

What is the typical distribution of the beam attenuation?

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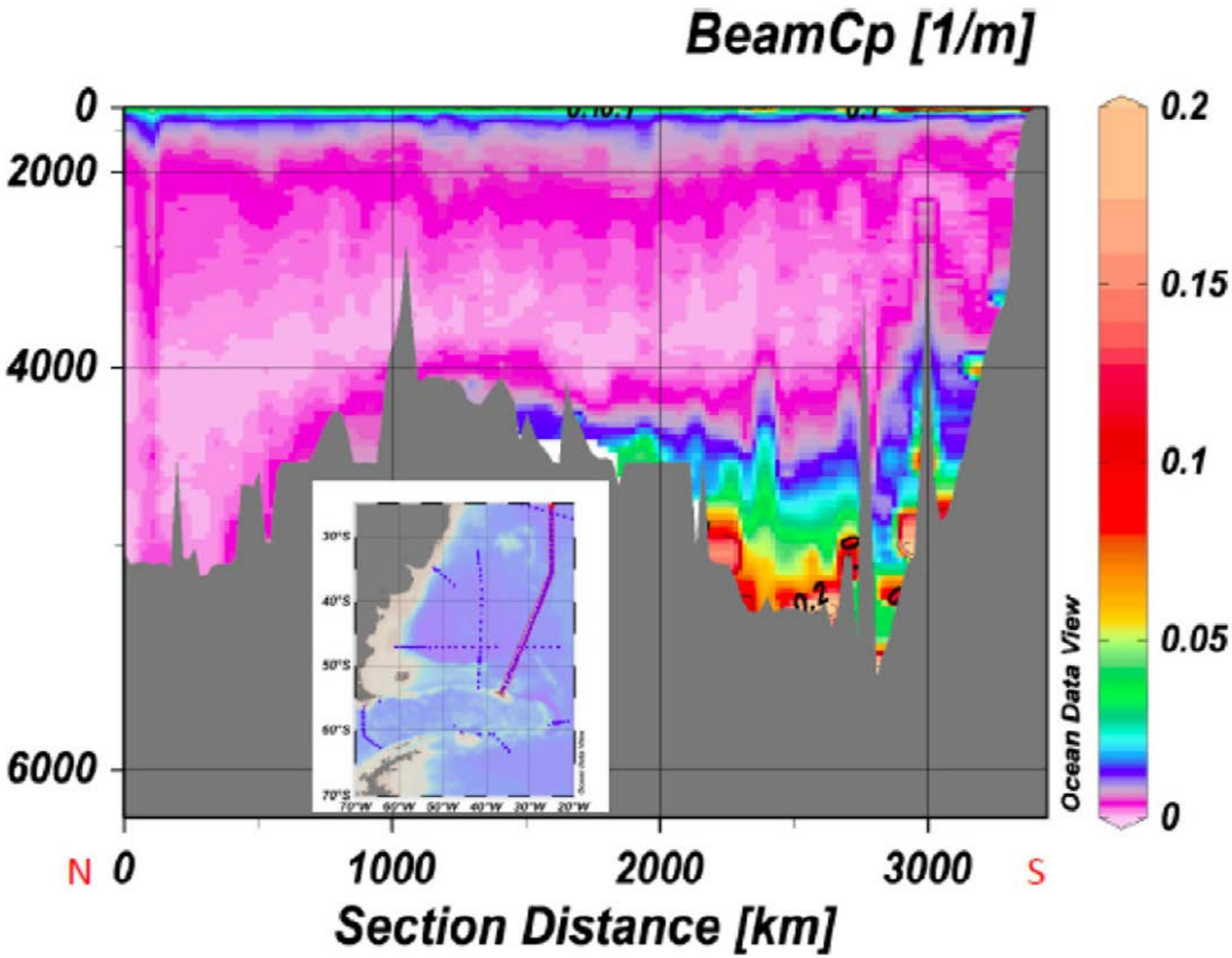


Boss et al., 2013 – based on Gardner et al.

Typical distribution

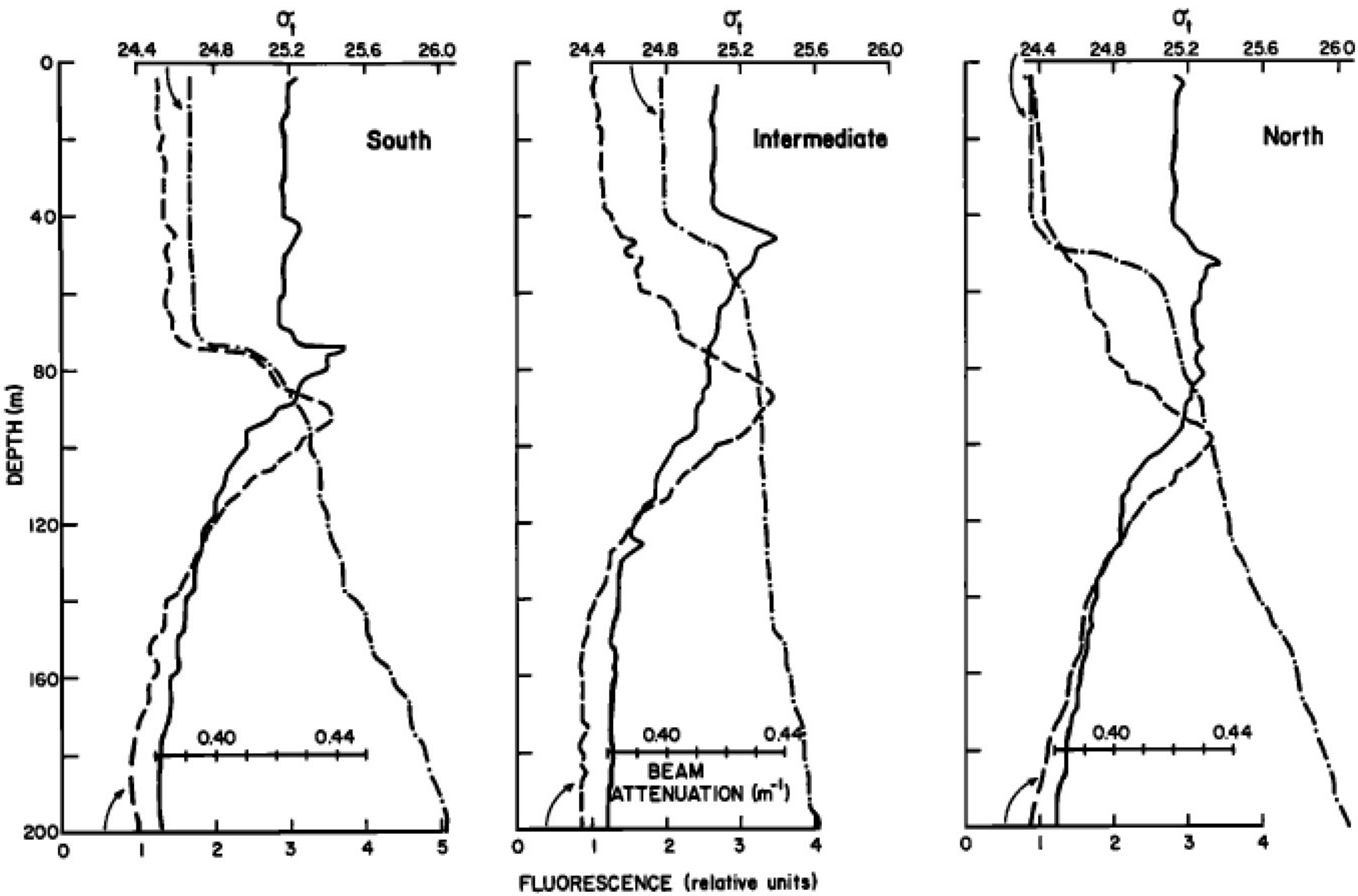


Fig. 1. Profiles of fluorescence, beam attenuation (665 nm) and σ_t for Pacific Central Gyre stations typical of waters north, south and in the Subtropical Front, Oct.-Nov., 1982.

Kitchen and Zaneveld, 1990

Single wavelength beam attenuation and biogeochemistry:

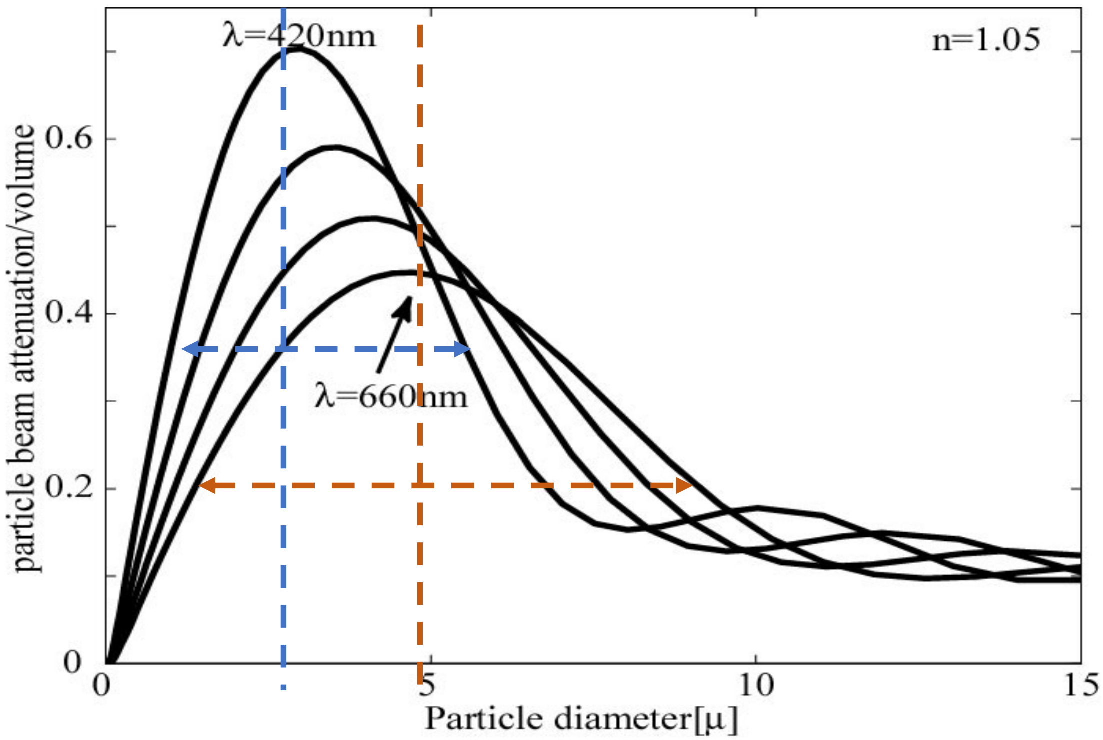
Found to correlate well with:

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

Beam attenuation: proxies and applications

- Particle size distribution from c_p spectral slope
- Particle composition and species succession
- Response of c_p during particle aggregation/disaggregation
- Biological rates from diel cycles in c_p

C_{ext}/volume is sensitive to the wavelength of measurement:



The particle size where the maximum occurs, and the width of the peak, changes between blue to red wavelengths. *Spectral* c_p contains size information!

Beam-c and PSD relation (more tomorrow):

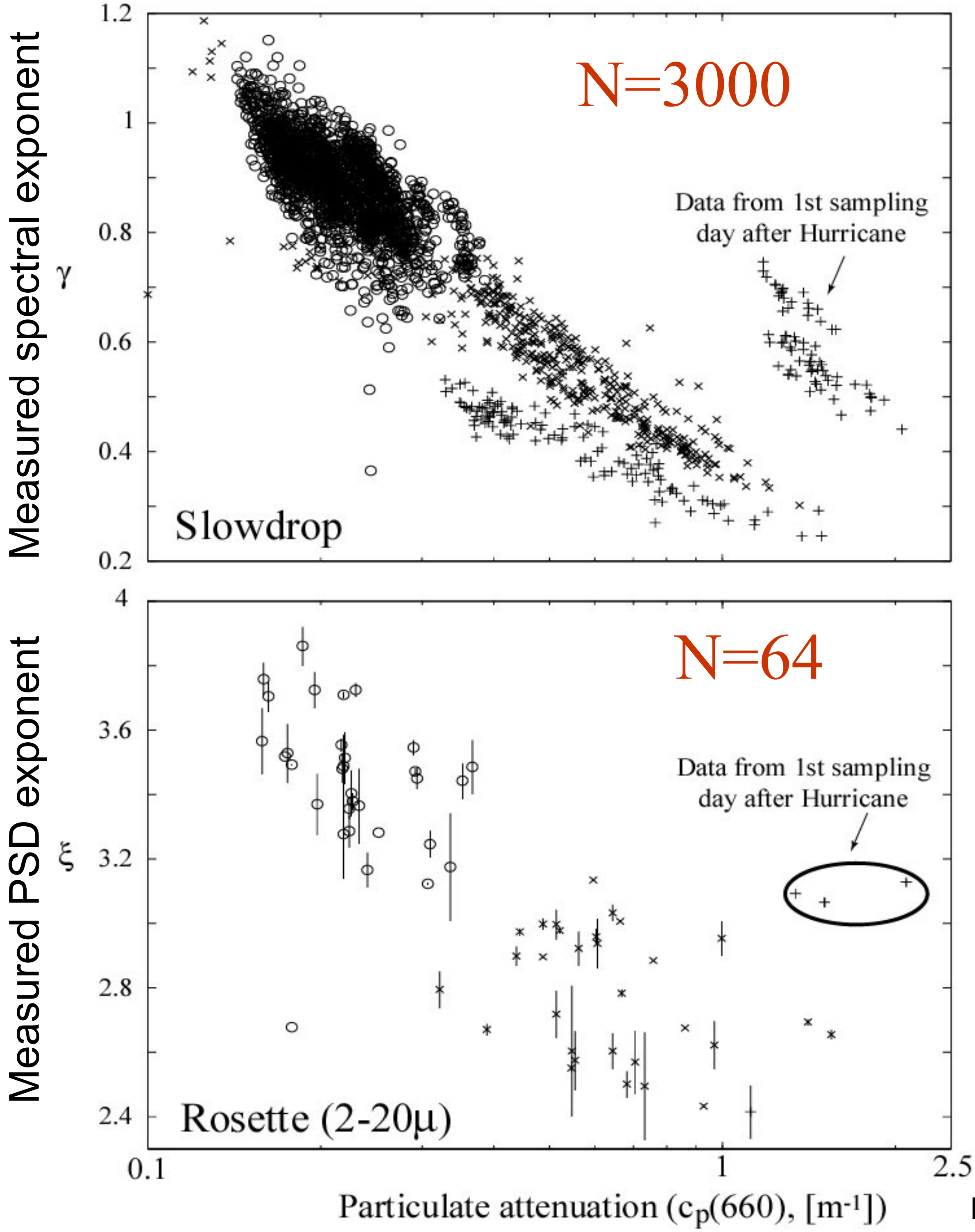
Mie Theory (homogenous spheres):

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.

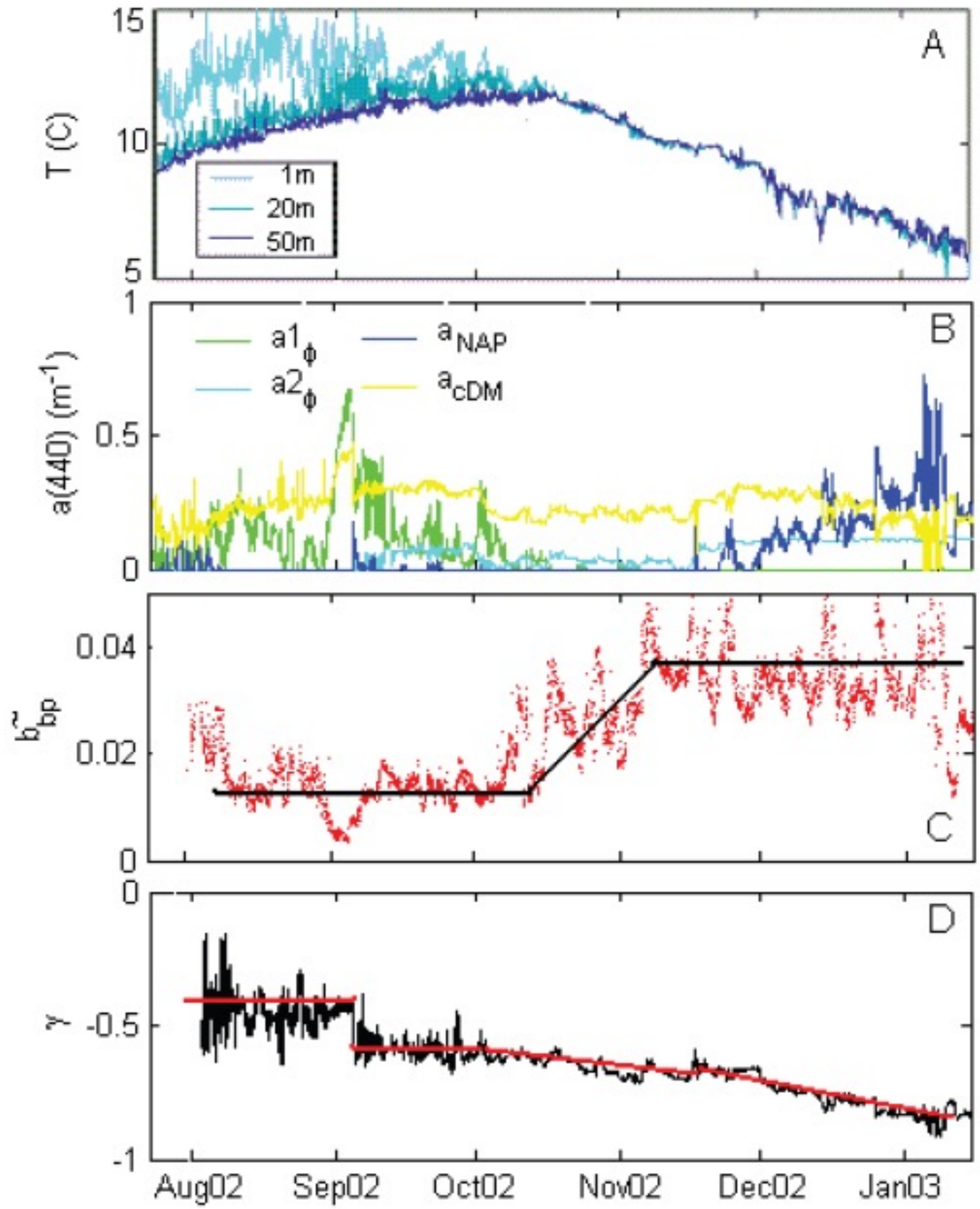


Boss et al., 2001

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

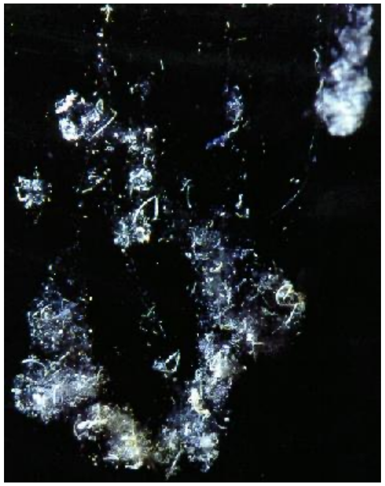
IOP data from z = 3 m

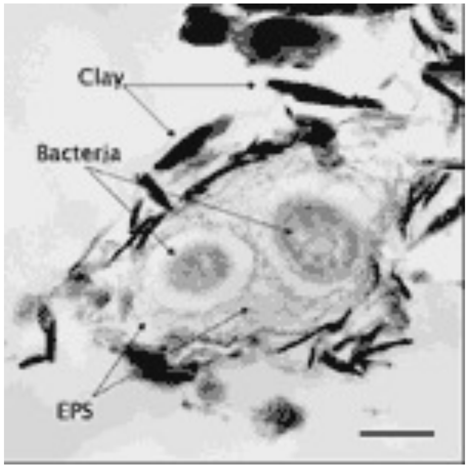
Phytoplankton type $a1_\phi$ is inferred to be high-light adapted, $a2_\phi$ is low-light adapted



Roesler and Boss, 2008, Ch. 5, Habwatch

How would you expect beam attenuation coefficients to compare between aggregates and the disaggregated primary particles (with mass concentration held constant)?





Aggregates

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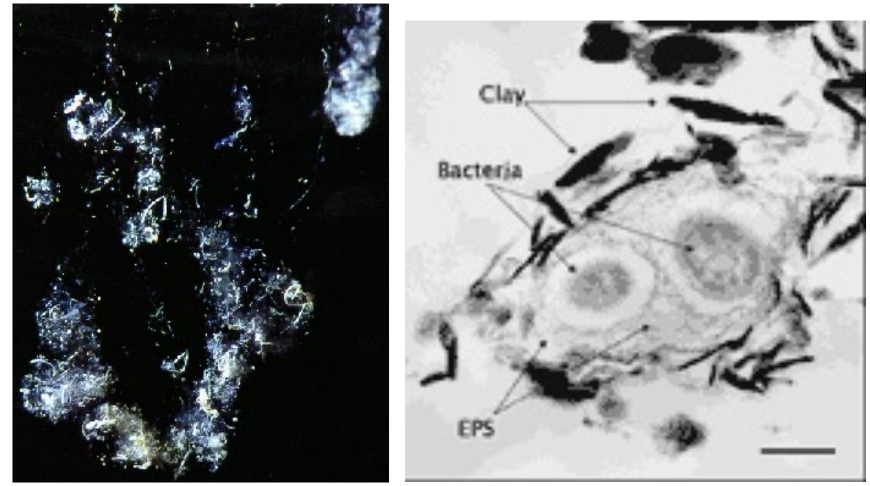

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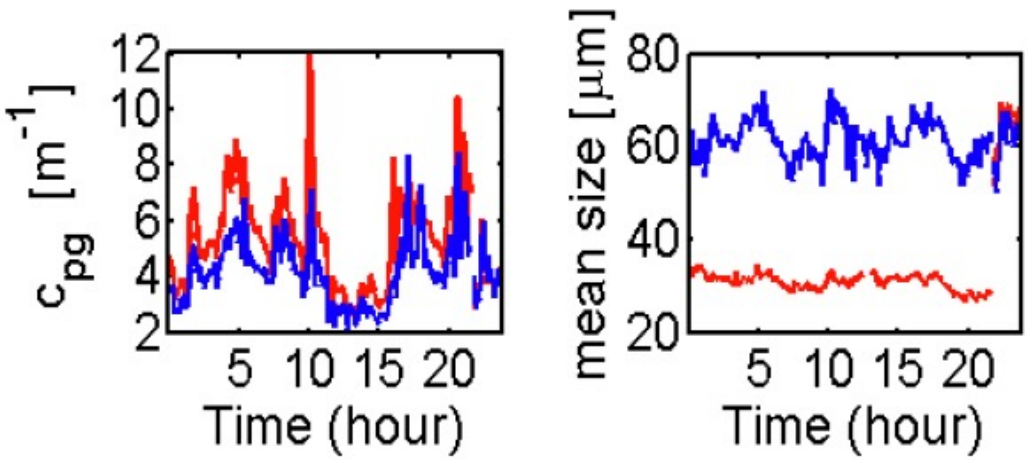

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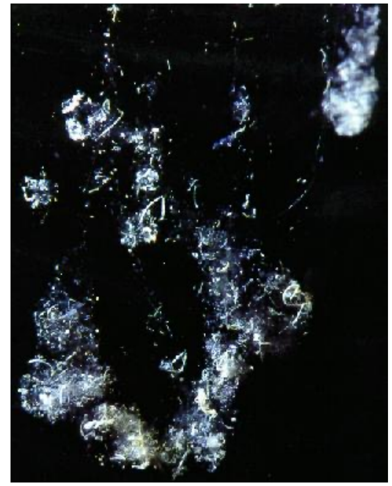

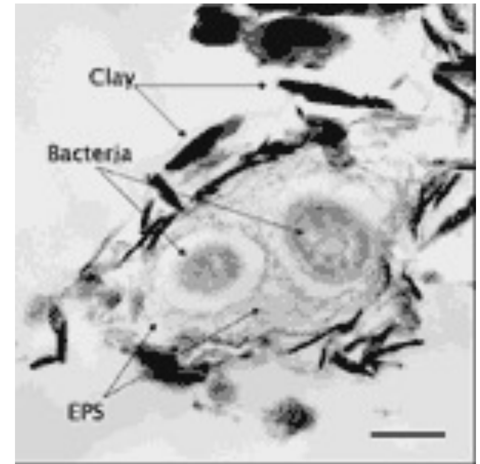

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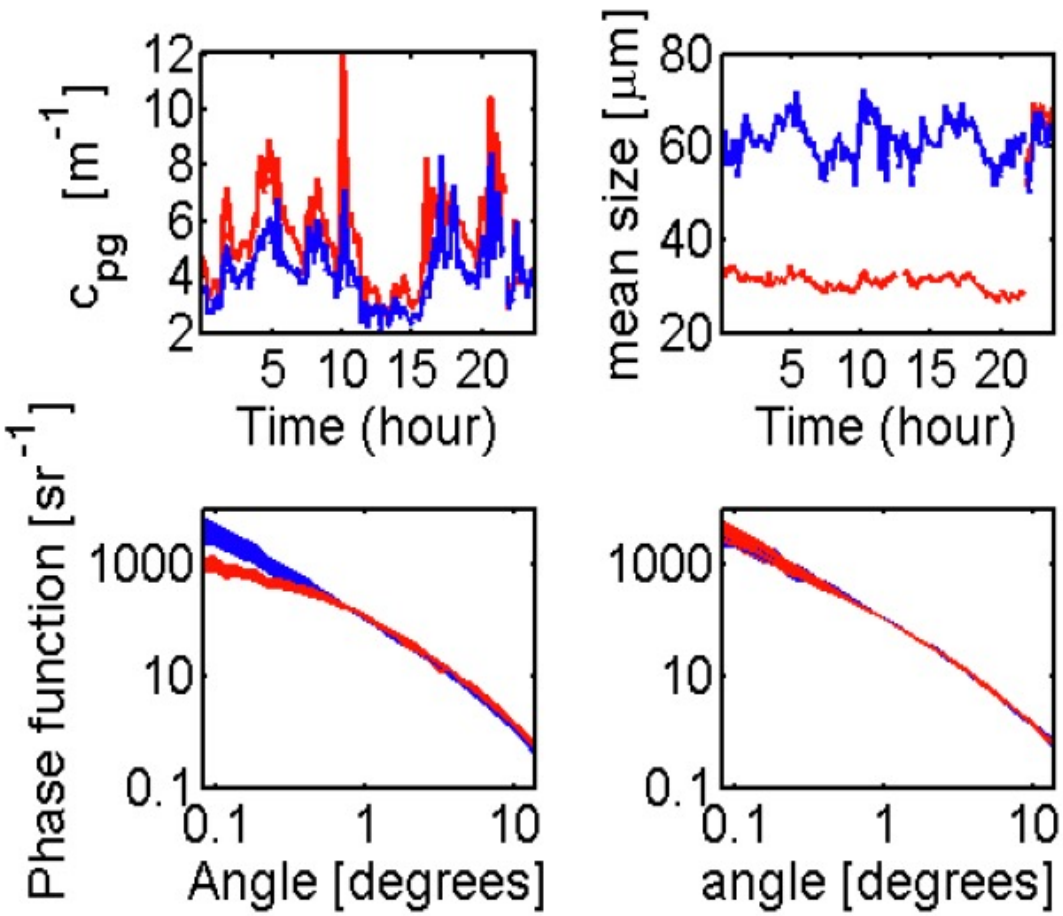
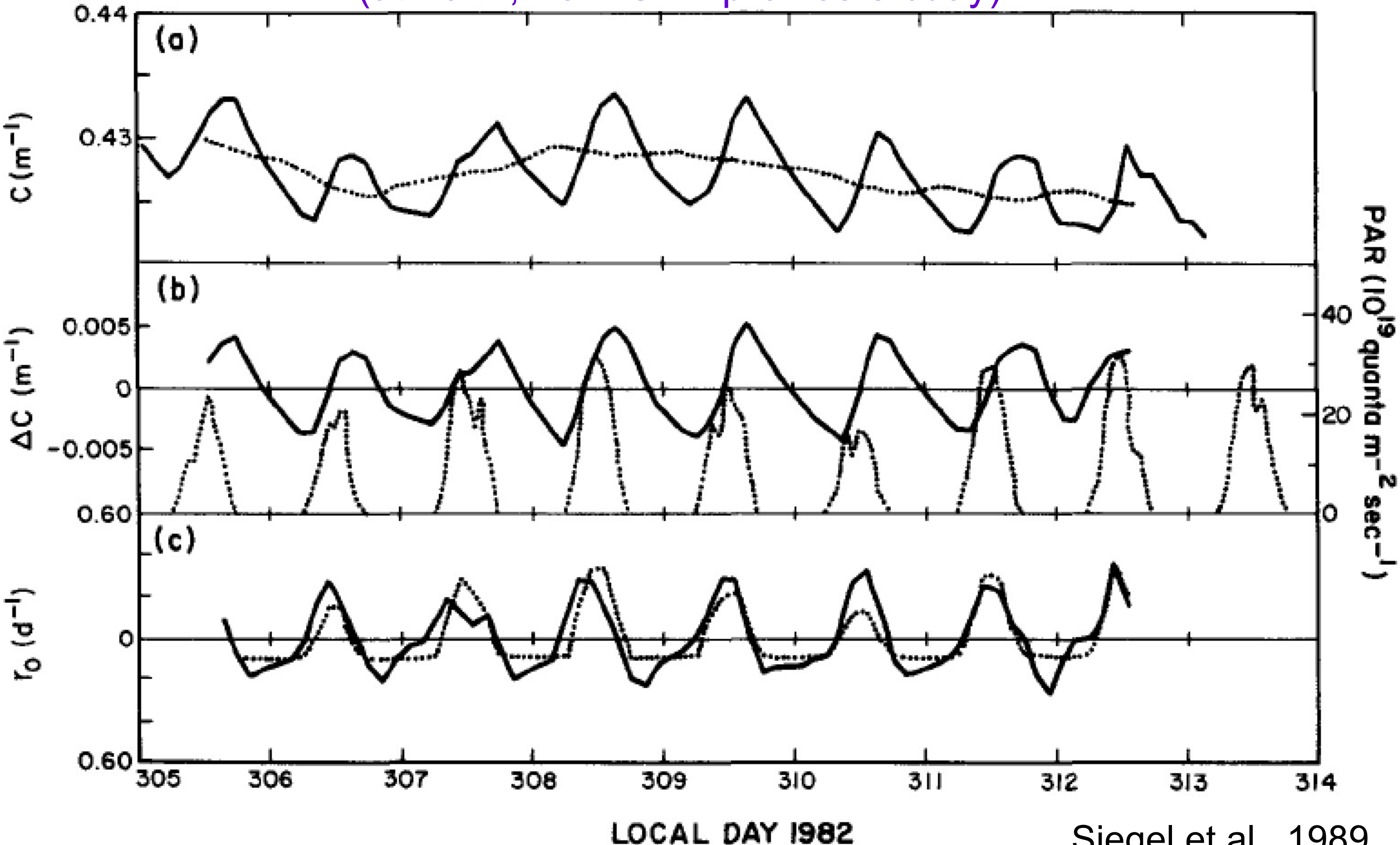


Boss et al., 2009, Slade et al., 2010, 2011

Diel cycles in beam attenuation

(at 20 m, from CTD profiles 8x/day)



Siegel et al., 1989

+relevant work by many others

Summary:

- Beam attenuation is a robust, relatively straightforward measurement with numerous applications

- ... but caveats to be aware of include acceptance angle effects, reference materials, dark signal removal