Apparent and inherent optical properties in the ocean

Tomorrow: "Open questions in radiation transfer with a link to climate change"

9:30 Gathering and Coffee
9:50 Opening – Ilan Koren,
Environmental Sciences and Energy Research, WIS
10:00 Warren Wiscombe, NASA - Goddard Space Flight Center, USA
"What is the minimum ante for playing the radiation game in climate models?"
11:00 Alexander Marshak, NASA - Goddard Space Flight Center, USA
"From ICESat and MODIS to ARM; how radiative transfer helps to interpret satellite and ground-based measurements"
12:00 Lunch break
13:30 Emmanuel Boss, School of Marine Sciences, University of Maine, USA, "The backscattering enigma: what contributes to oceanic backscattering?"
14:30 Eli Tziperman, Department of Earth and Planetary Sciences, Harvard University, USA, "Dinosaur forecast: cloudy (warming of the high latitudes by a convective cloud feedback)"
15:30 Alex Kostinski, Department of Physics, Michigan Technological University, USA, "Extinction vs. Spatial distribution of Scatterers"

Review:

In a plane-parallel medium without internal sources for a given wavlength:

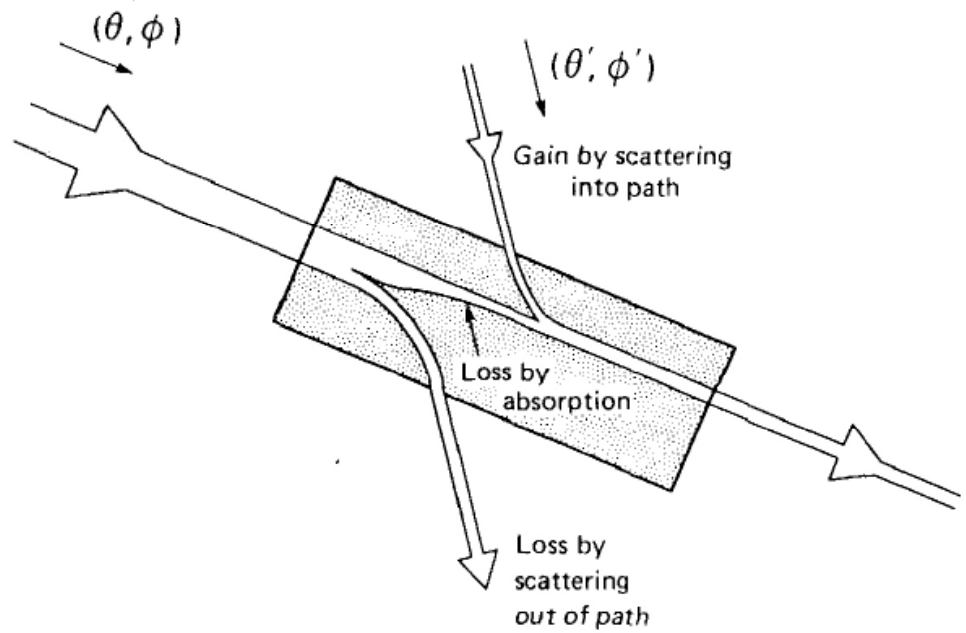
$$\cos\theta \, dL(\theta,\phi)/dz = - c(z) \, L(z,\theta.\phi) + \int_{4\pi} \beta(z,\theta,\phi;\theta',\phi') \, L(\theta',\phi') \, d\Omega'$$

Which we can rewrite as:

$$\mu dL(\theta,\phi)/dz = - c(z) \, L(z,\theta,\phi) + b(z) \int_{4\pi} \beta'(z,\theta,\phi;\theta',\phi') \, L(\theta',\phi') \, d\Omega'$$

$$\rightarrow \quad \mu dL(\theta,\phi)/d\tau = - L(\tau,\theta,\phi) + \omega_0(\tau) \int_{4\pi} \beta'(\tau,\theta,\phi;\theta',\phi') \, L(\theta',\phi') \, d\Omega'$$

→ media with the same ω_0 and boundary conditions will have the same radiance distribution at similar optical depth horizons.



Some things to note about transmission, optical depth and attenuation:

$$\tau_{12}\left(r_1 \rightarrow r_2\right) = \int_{r_1}^{r_2} c\,dr = \bar{c}(r_2 - r_1) = \bar{c}\Delta r$$

$$t(r_1 \rightarrow r_2) = e^{-\bar{c}\Delta r} = e^{-\tau_{12}}$$

$$\Rightarrow \tau_{1N} = \sum_{i=1}^{N-1} \tau_{i,i+1}$$

Demo (Petty): effect of dilution on τ

$$\Rightarrow t_{1N} = \prod_{i=1}^{N-1} t_{i,i+1} = e^{-\sum_{i=1}^{N-1} \tau_{i,i+1}}$$

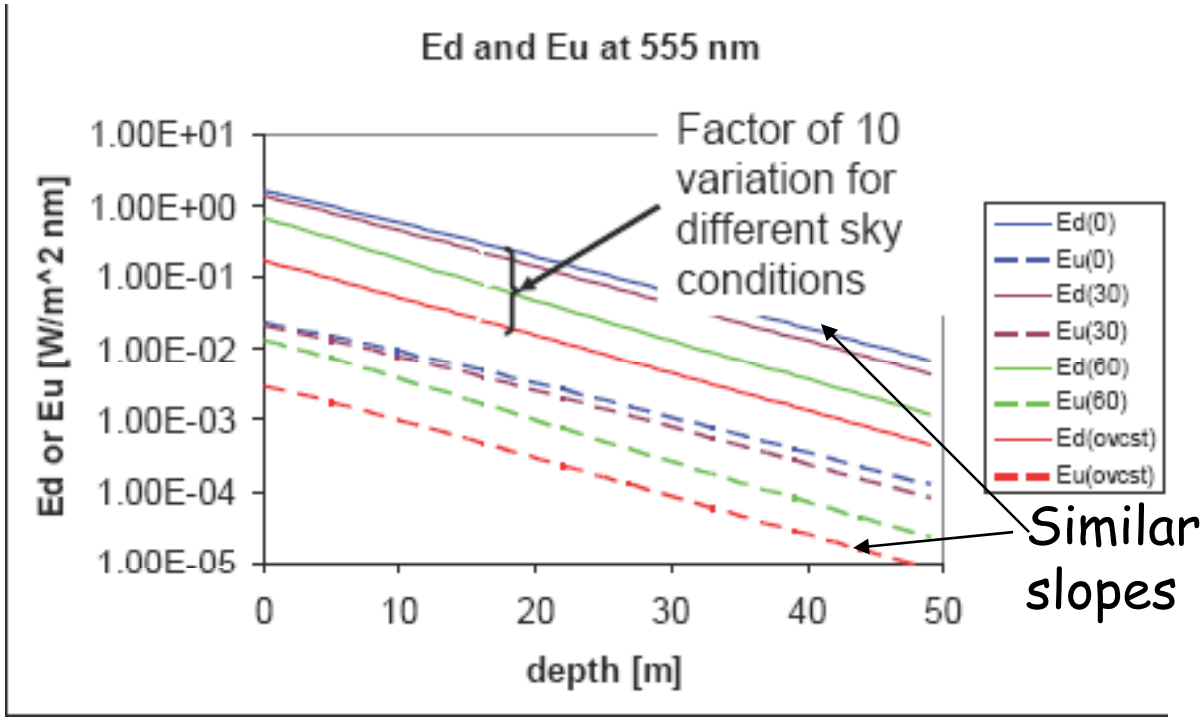
Apparent Optical Properties

usually: ratios of radiometric properties (L, E, etc') or normalized depth derivatives of radiometric properties.

Why AOPs?

- IOPs are not always easy to measure.
- Radiometric properties depends strongly on sky conditions.

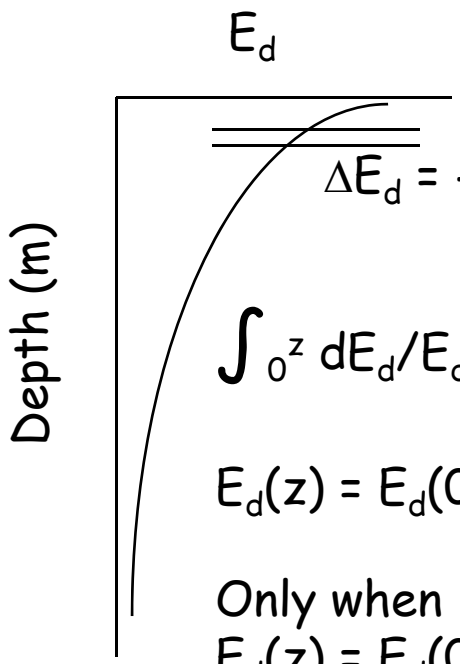
→ Relatively insensitive OPs



Mobley, 2004: Hydrolight runs with 1 mgchl./m^3, with sun at 0, 30, 60° in clear skies and overcast skies.

Apparent Optical Properties: ratios of radiometric quantities

Diffuse Attenuation, K (m^{-1})



$$\Delta E_d = -E_d K_d \Delta z$$

$$\int_0^z dE_d/E_d = \int_0^z K_d(z)\, dz$$

$$E_d(z) = E_d(0)\, e^{-\int Kd(z)\, dz}$$

Only when K_d is not depth dependent

$$E_d(z) = E_d(0)\, e^{-Kd\, z}$$

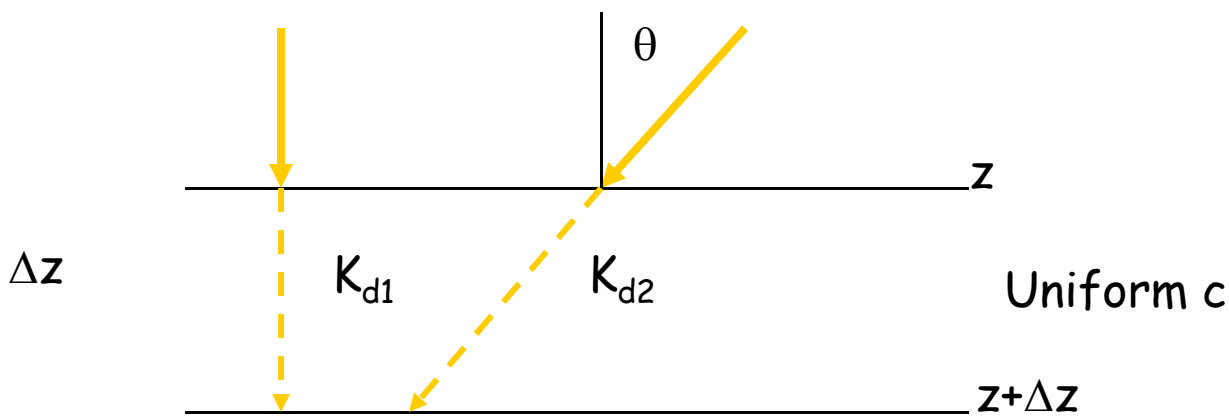
Table 3.2. Terms, units, and symbols for apparent optical properties.

Quantity	SI units	Recommended symbol	Historic symbol
distribution function	dimensionless	D	D
average cosine of light field	dimensionless	$\bar{\mu}$	$D = 1/\bar{\mu}$
of downwelling light	dimensionless	$\bar{\mu}_d$	$D(-) = 1/\bar{\mu}_d$
of upwelling light	dimensionless	$\bar{\mu}_u$	$D(+) = 1/\bar{\mu}_u$
irradiance reflectance	dimensionless	R	$R(-)$
remote sensing reflectance	sr^{-1}	R_{rs}	—
(vertical) diffuse attenuation coefficients (K-functions):			
of radiance $L(z;,\theta,\phi)$	m^{-1}	$K(\theta,\phi)$	$K(\theta,\phi)$
of downward irradiance $E_d(z)$	m^{-1}	K_d	$K(-)$
of upward irradiance $E_u(z)$	m^{-1}	K_u	$K(+)$
of downward scalar irradiance $E_{od}(z)$	m^{-1}	K_{od}	$k(-)$
of upward scalar irradiance $E_{ou}(z)$	m^{-1}	K_{ou}	$k(+)$
of total scalar irradiance $E_o(z)$	m^{-1}	K_o	k
of PAR(z)	m^{-1}	K_{PAR}	—

Apparent Optical Properties

Diffuse attenuation, K (m^{-1}):

Note that c and K are very different because K depends
Upon the properties of the solar source



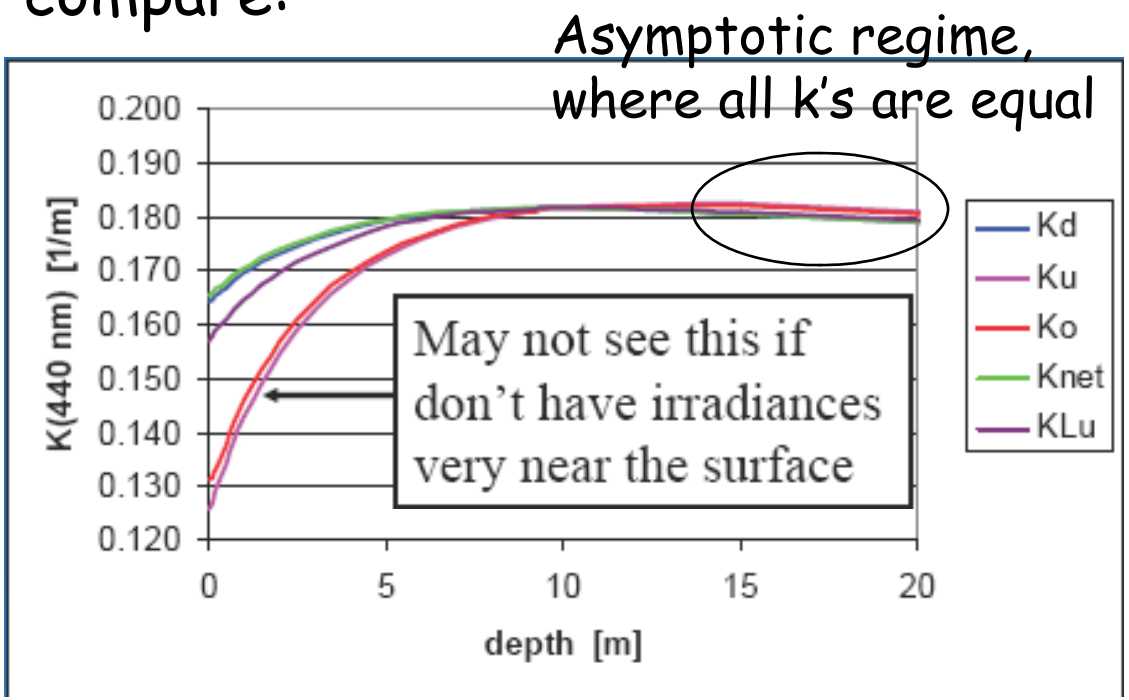
K_d describes the loss of E_d from z to z+Δz,
but the pathlength traveled is r = Δz/cos θ

$K_{d2} > K_{d1}$

$K_d < c$

Apparent Optical Properties: diffuse attenuation coefficients

How do different attenuation compare:



Mobley, 2004, Hydrolight with 2mgChl./m^3

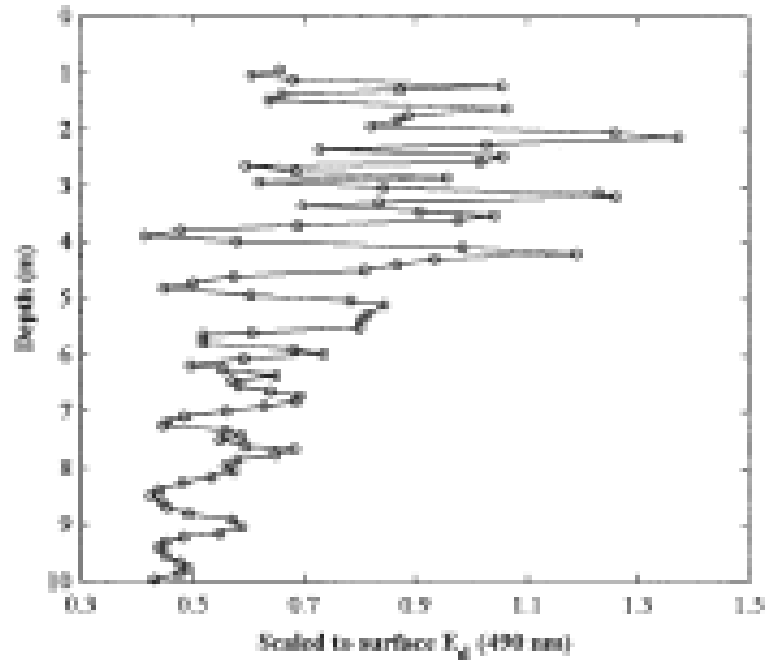
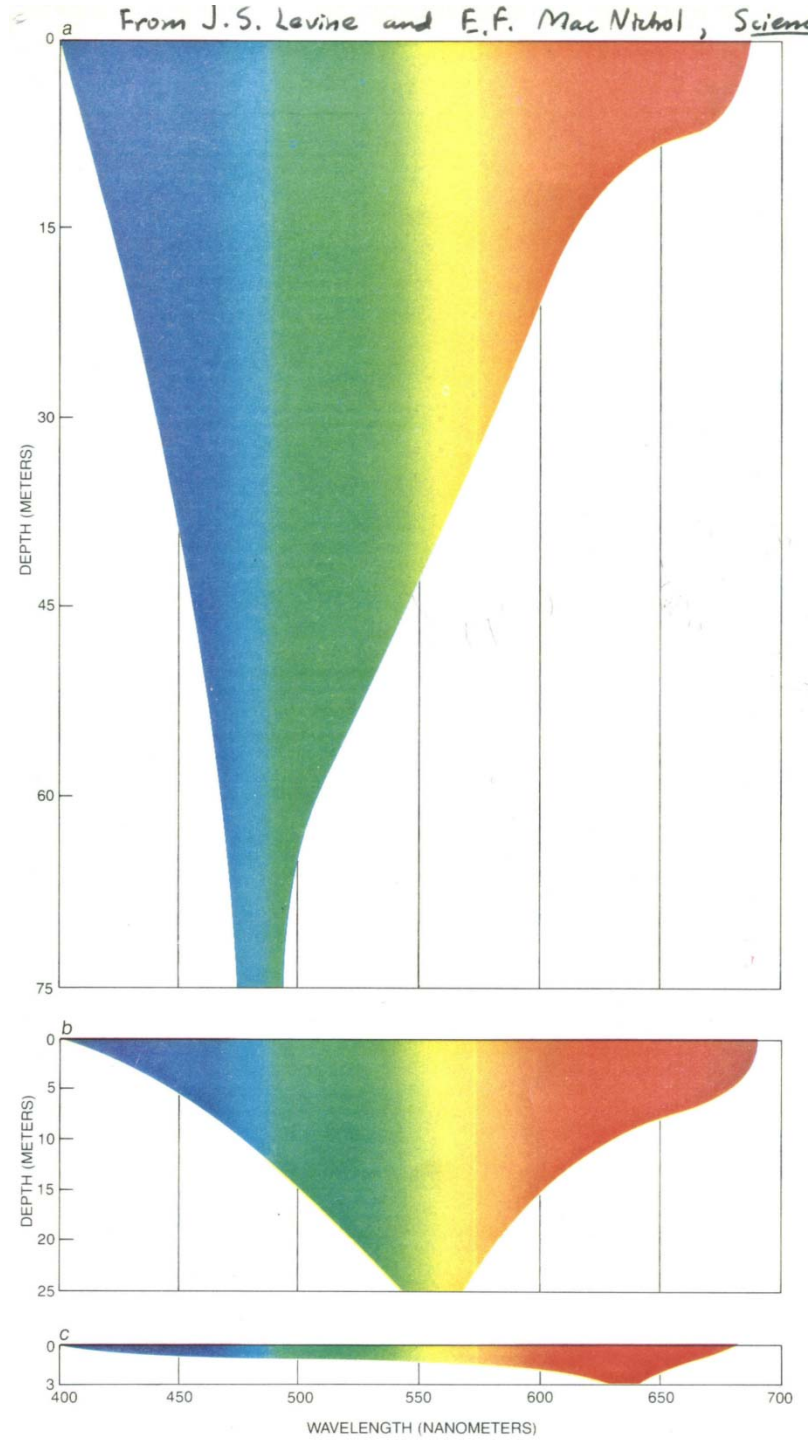


Fig. 1. Irradiance profile taken off the Oregon coast, September 1997, with a Satlantic irradiance profiler. The profiler drops at approximately 0.8 m/s and samples at 8 Hz. Conditions were calm.

Zaneveld et al., 2001.

Changes in spectral light penetration with depth for different water bodies.

What causes the difference?



Apparent Optical Properties

Average cosines describe the angular distribution of the light field:

$\mu_d = E_d/E_{od}$

$\mu_u = E_u/E_{ou}$

$\bar{\mu} = \vec{E}/E_o$

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Apparent Optical Properties

Average cosines describe the angular distribution of the light field:

$\mu_d = E_d/E_{od}$

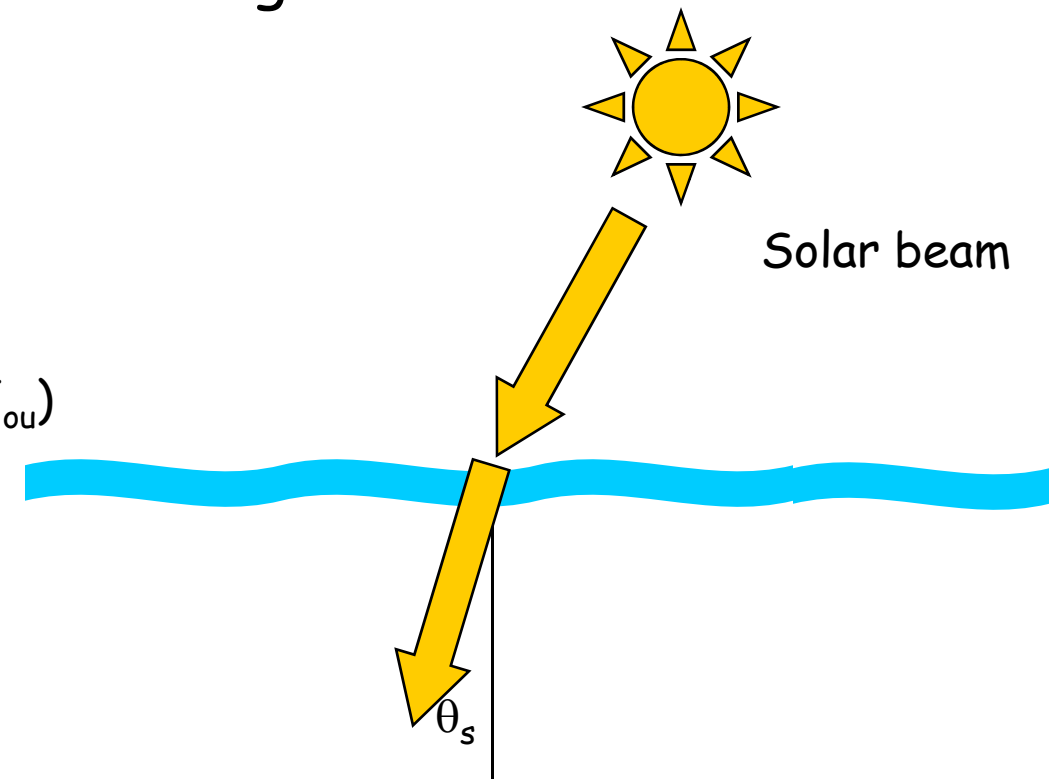
$\mu_u = E_u/E_{ou}$

$\bar{\mu} = \vec{E}/E_o = (E_d - E_u)/(E_{od} + E_{ou})$

$\mu_d = \cos\theta_s$

$\mu_u = 0$

$\bar{\mu} = \cos\theta_s$



Apparent Optical Properties

Average cosines describe the angular distribution of the light field

$\mu_d = E_d/E_{od}$

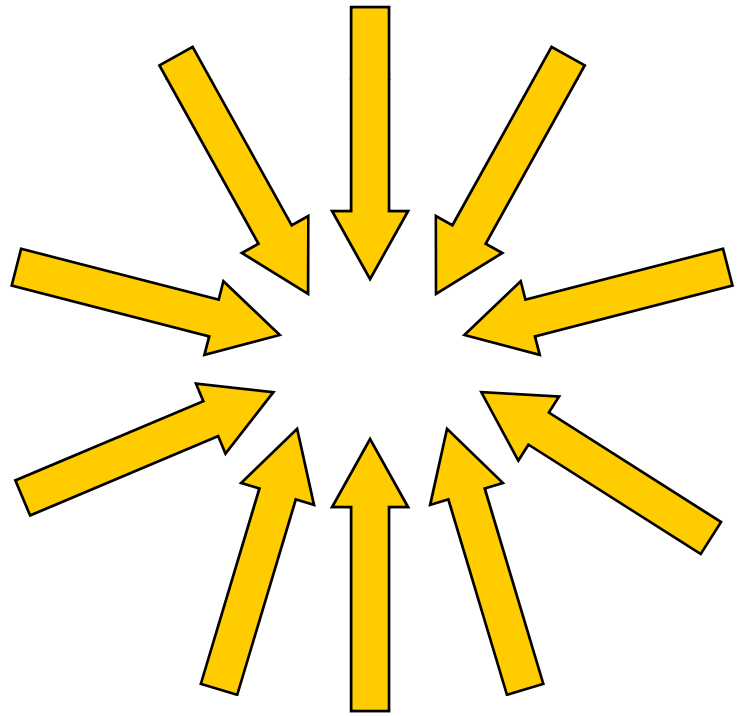
$\mu_u = E_u/E_{ou}$

$\bar{\mu} = \vec{E}/E_o = (E_d-E_u)/(E_{od}+E_{ou})$

$\mu_d = \frac{1}{2}$ $(\theta=60^o)$

$\mu_u = -\frac{1}{2}$ $(\theta=120^o)$

$\bar{\mu} = 0$



Isotropic light field

Average cosines

Observed Ranges

$\mu_d = E_d/E_{od}$

$\mu_u = E_u/E_{ou}$

$\bar{\mu} = \vec{E}/E_o$

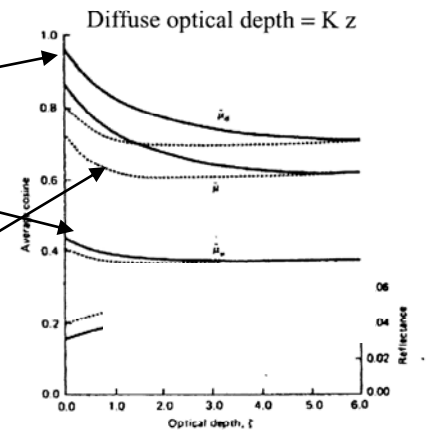


Fig. 6.14. Variation of average cosines for downwelling ($\bar{\mu}_d$), upwelling ($\bar{\mu}_u$) and total ($\bar{\mu}$) flux, and irradiance reflectance (R) with optical depth ($\zeta = K_d z$) in water with $b/a = 5$. Data obtained by Monte Carlo calculation. (Vertically incident light ——. Light incident at 45° ------.)

Rank in magnitude of $\bar{\mu}$, $\bar{\mu}_d$, $\bar{\mu}_u$

$\bar{\mu}_d > \bar{\mu} > \bar{\mu}_u$

Variations with z?

Why does μ_d vary More than μ_u?

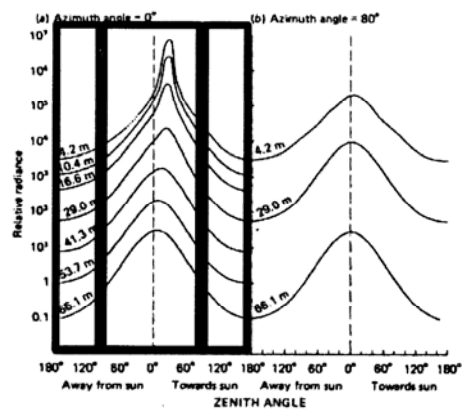
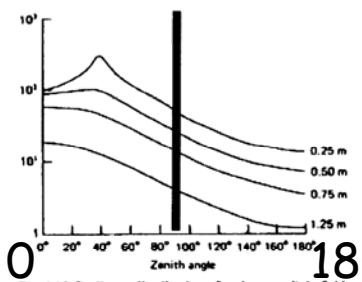


Fig. 6.11. Radiance distribution of underwater light field at different depths. Plotted from measurements at 480 nm made by Tyler (1960) in Lake Pend Oreille, USA, with solar altitude 56.6°, scattering coefficient 0.285 m⁻¹ and absorption coefficient 0.117 m⁻¹. (a) Radiance distribution in the plane of the Sun. (b) Radiance distribution in a plane nearly at right angles to the Sun.



0.25m

1.25m

0 180

Fig. 6.13. Radiance distribution of underwater light field averaged over al azimuth angles in a turbid lake. Radiance values for total PAR in Lak Burley Griffin, Australia, were obtained by Monte Carlo calculation usin the method of Kirk (1981a, 1981c) on the basis of the measured absorp tion and scattering properties (absorption spectrum – Fig. 3.9b; scatterin coefficient – 15.0 m⁻¹; solar elevation – 32°).

$b=15m^{-1}, \theta=32$

Radiance distribution with depth

Average cosines

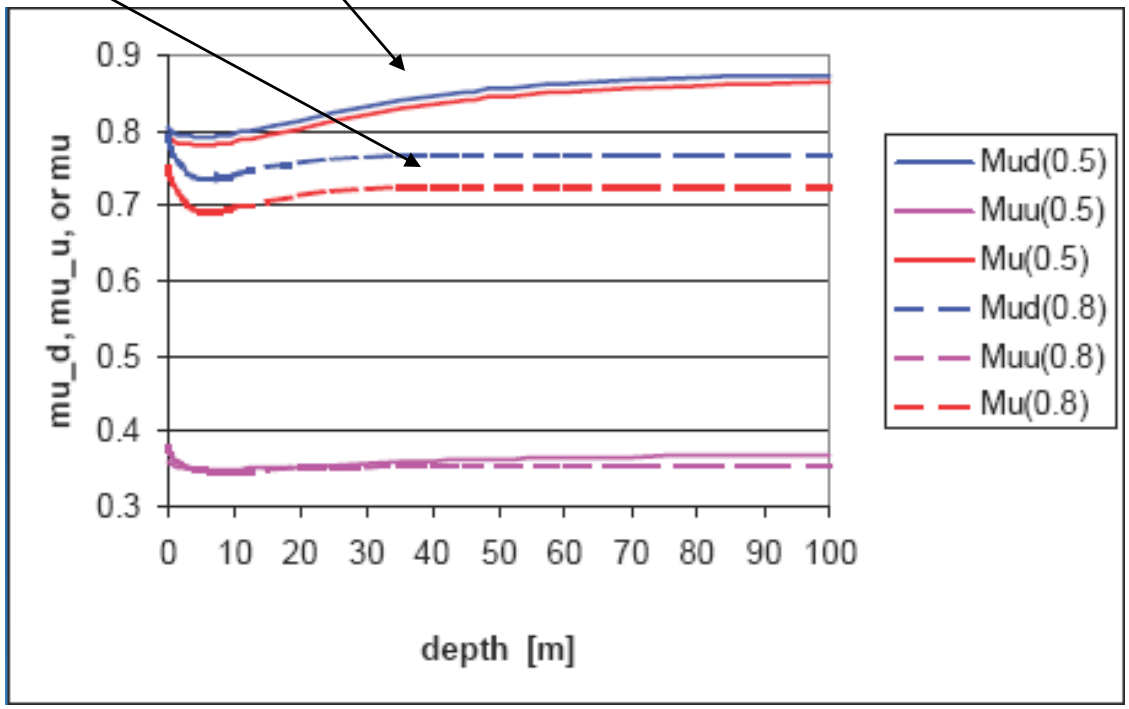
The more scattering → the faster is asymptotic attained

The more absorbing → the more collimated

$\mu_d = E_d/E_{od}$

$\mu_u = E_u/E_{ou}$

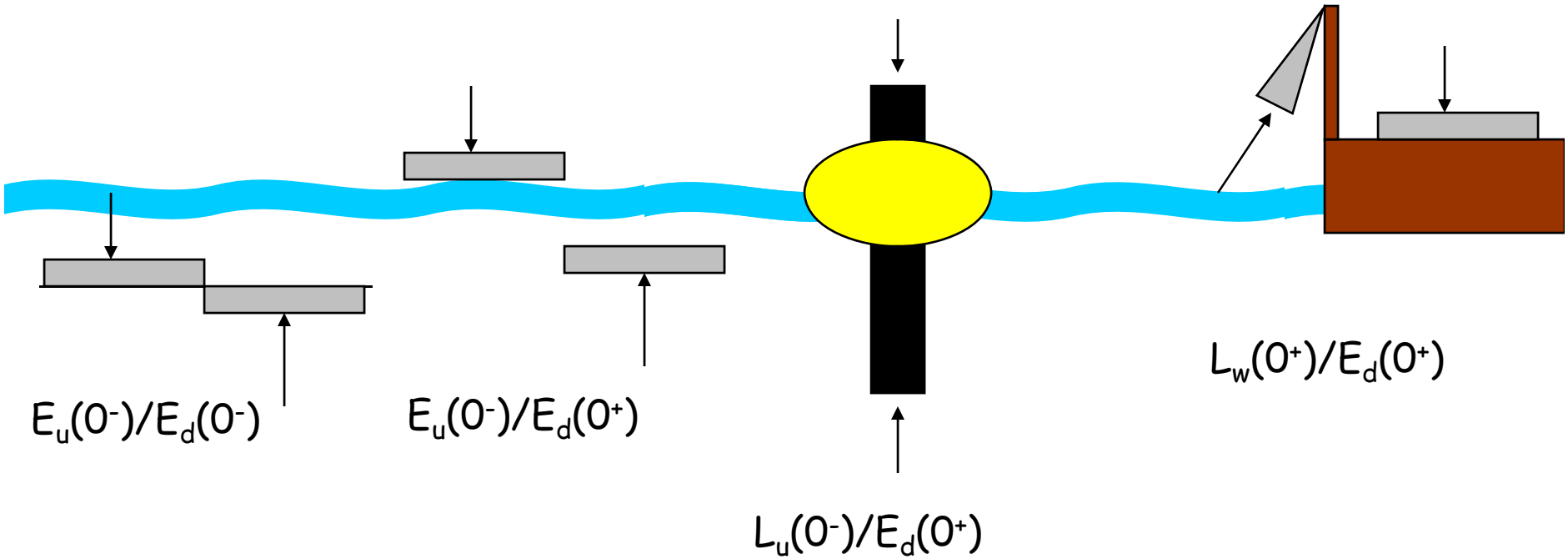
$\overline{\mu} = \vec{E}/E_o$

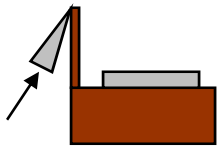


Mobley, 2004, Hydrolight with b=a (b/c=0.5) & b=4a (b/c=0.8).

Apparent Optical Properties

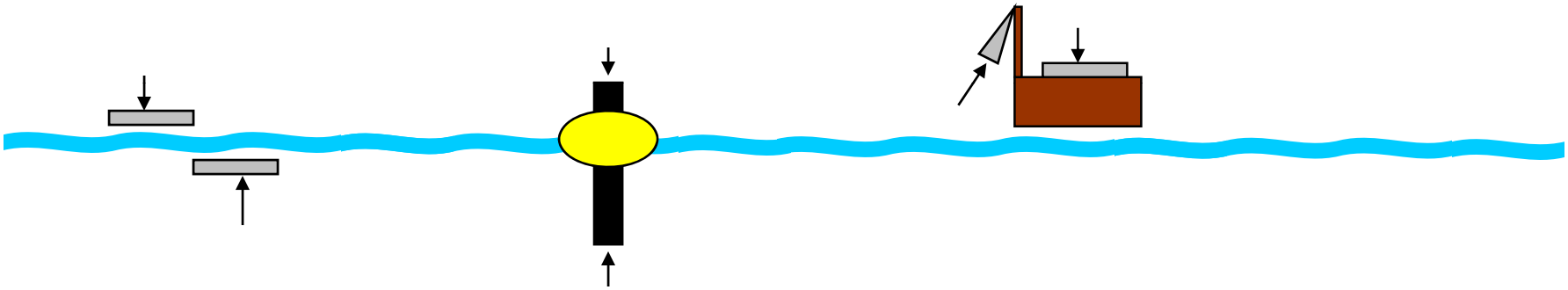
Reflectance ratios (upward to downward):

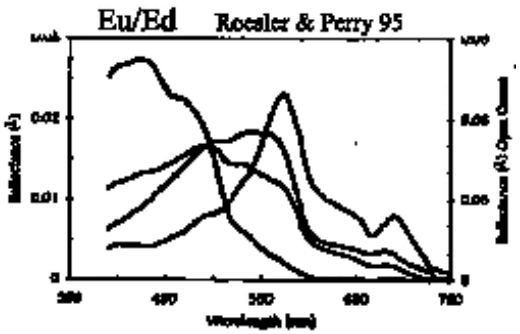


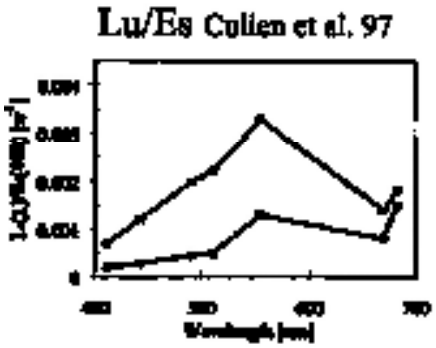


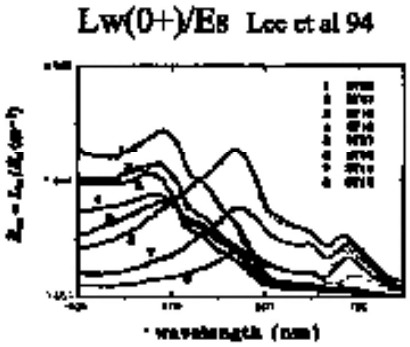
Apparent Optical Properties

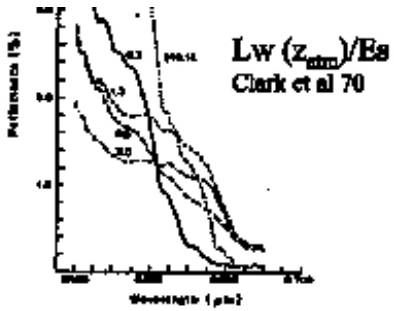
Reflectance ratios (upward to downward)









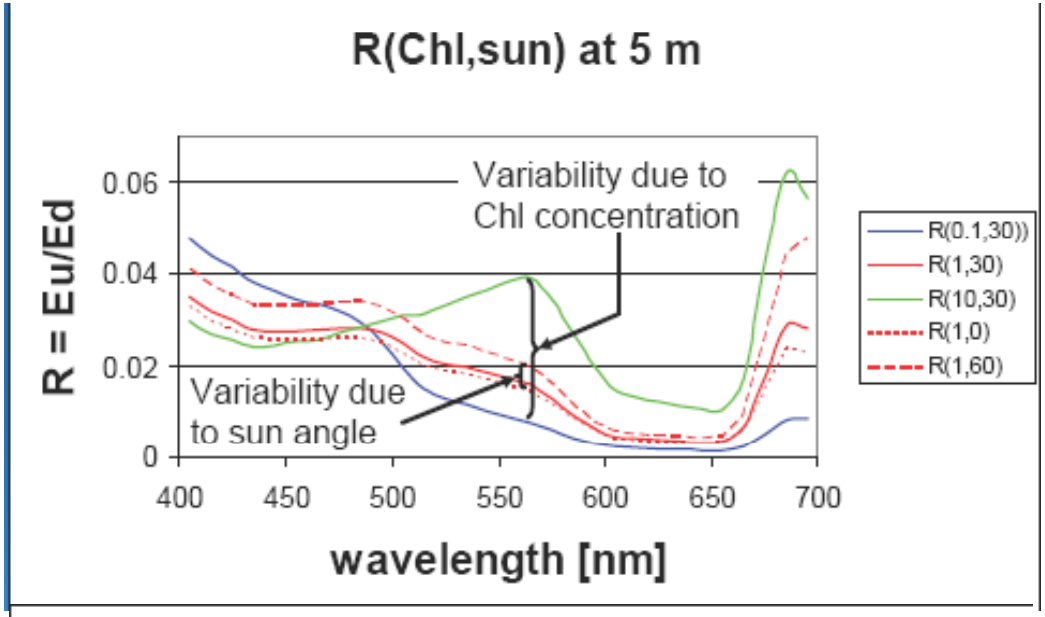


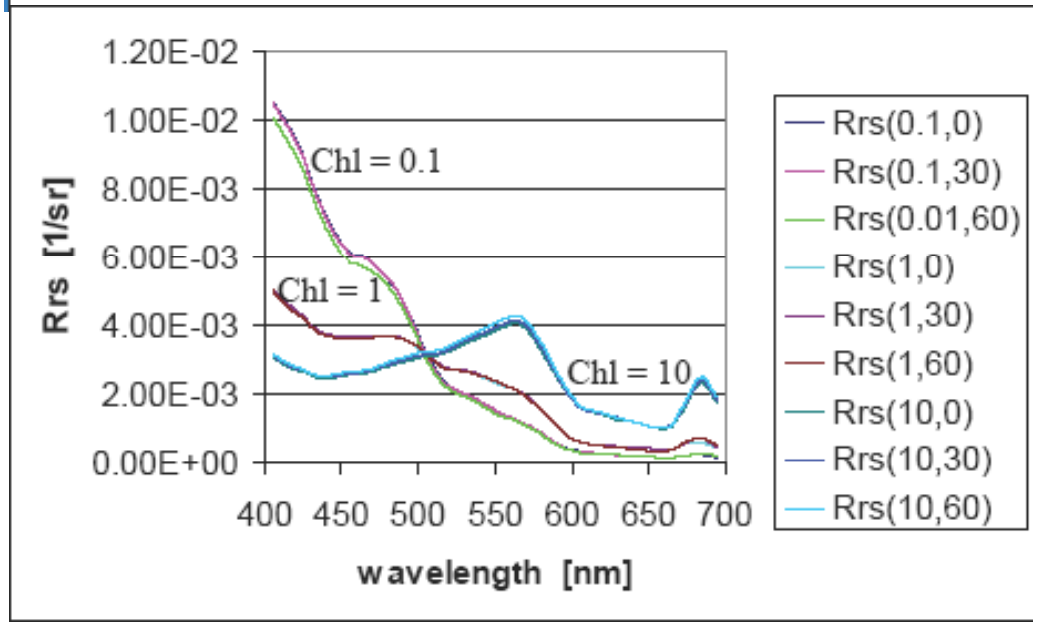
Sample spectra

Not all reflectances are equally good:

Mobley, 2004, Hydrolight with chl.=0.1,1,10 and sun angle, 0, 30 & 60°

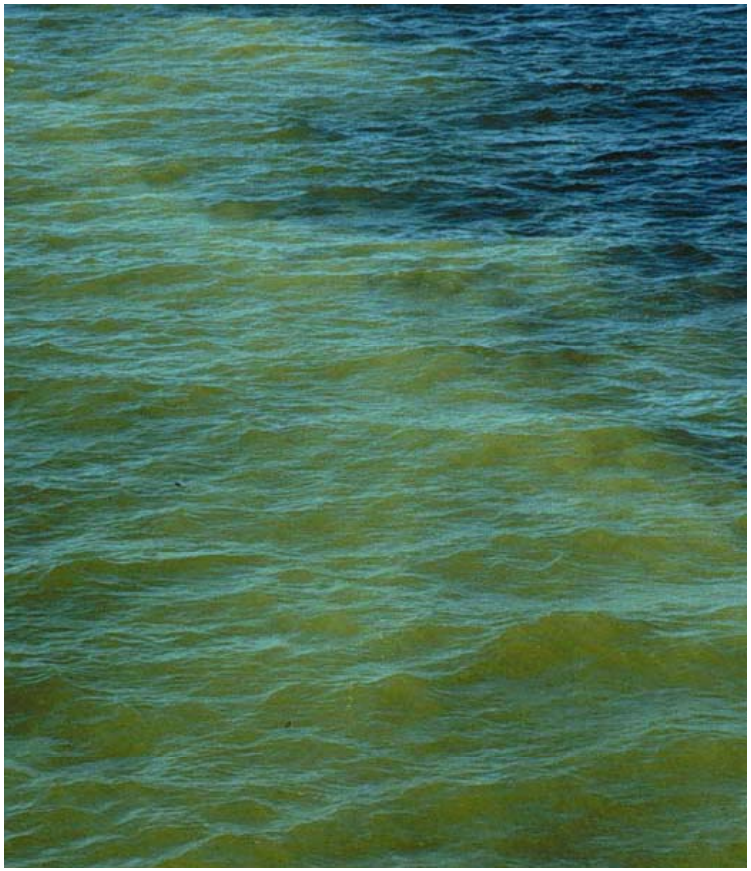
Rrs is less dependent on sun angle compared to R, a better AOP.





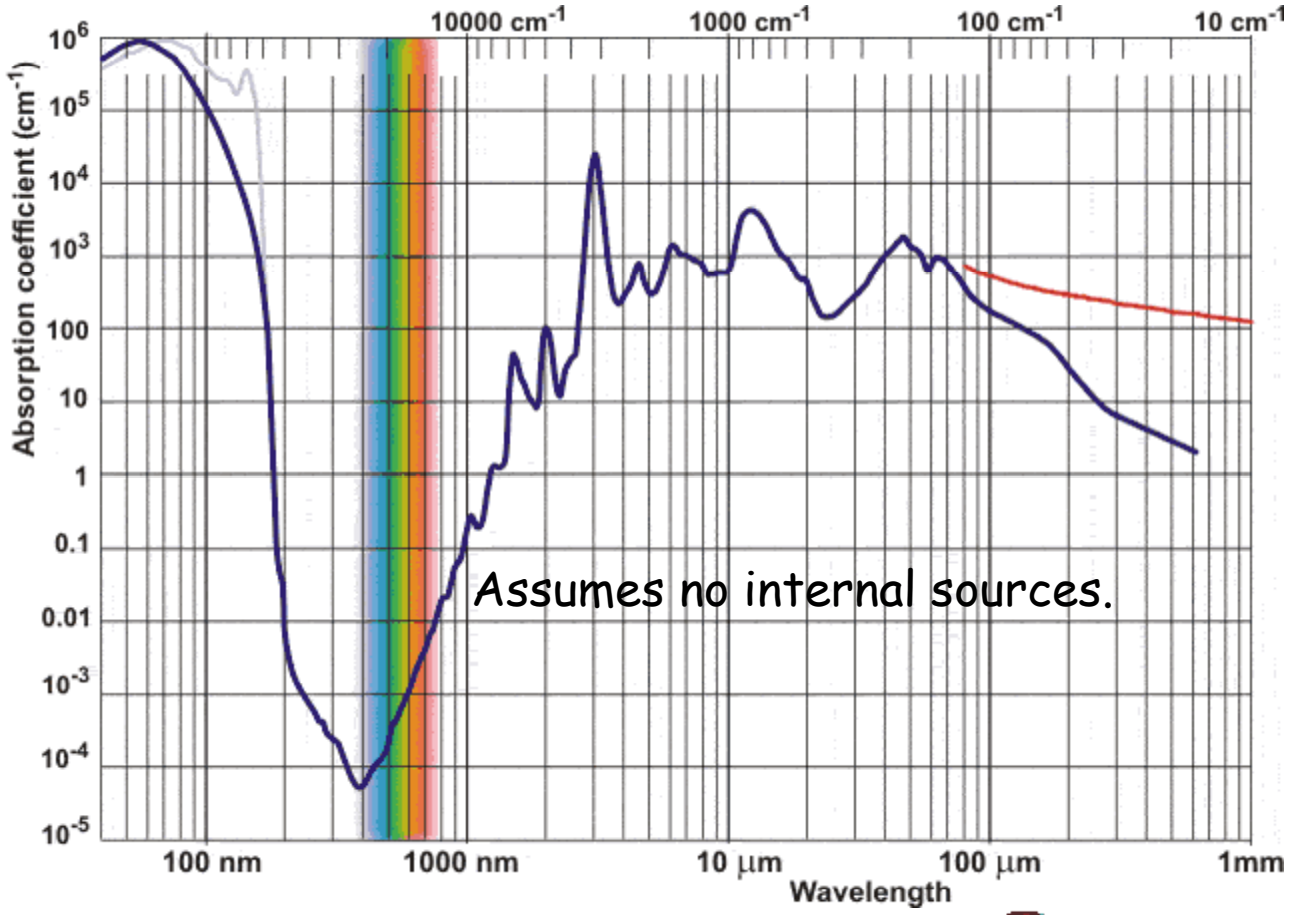
Absorbers and scatterers in ocean/lakes

- Water
- Phytoplankton
- Non-algal organic particles (CPOM)
- Dissolved organic matter (CDOM)
- Inorganic mineral particles (CPIM)



Note: most available information is in the visible (400-700nm). Why?

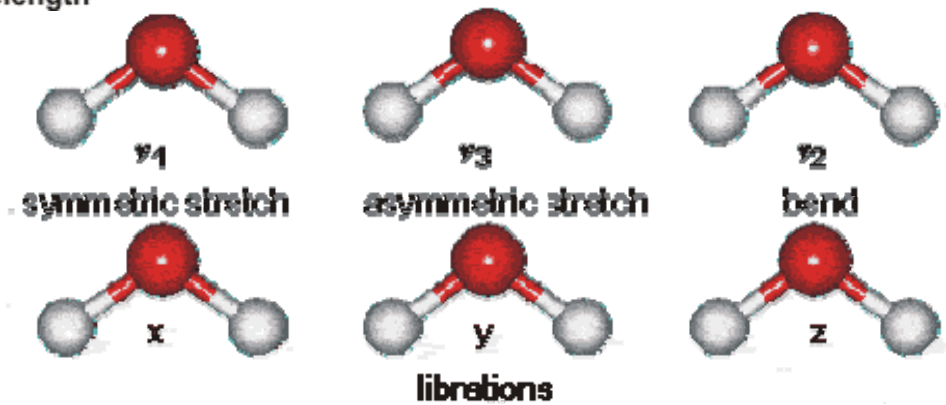
Absorption by (liquid and frozen) water:



Features:

- Extremly complex
- Variety of vibrational modes
- Combination possible

http://omlc.ogi.edu/spectra/water/index.html
& http://www.lsbu.ac.uk/water/vibrat.html



It's not really the molecules

- Density inhomogeneities

Water clusters

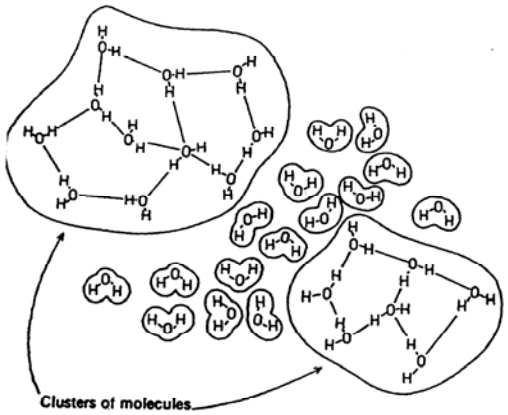


Fig. 2.2.4. The Frank–Wen cluster model of liquid water (adaptation taken from Nemethy an Scheraga, 1962, with permission of the American Institute of Physics; see also Horne, 1969)

... of molecules are hydrogen-bonded,

Unlike Rayleigh

$\sim \lambda^{-4.32}$ (Morel, 1974)

Water clusters with salt

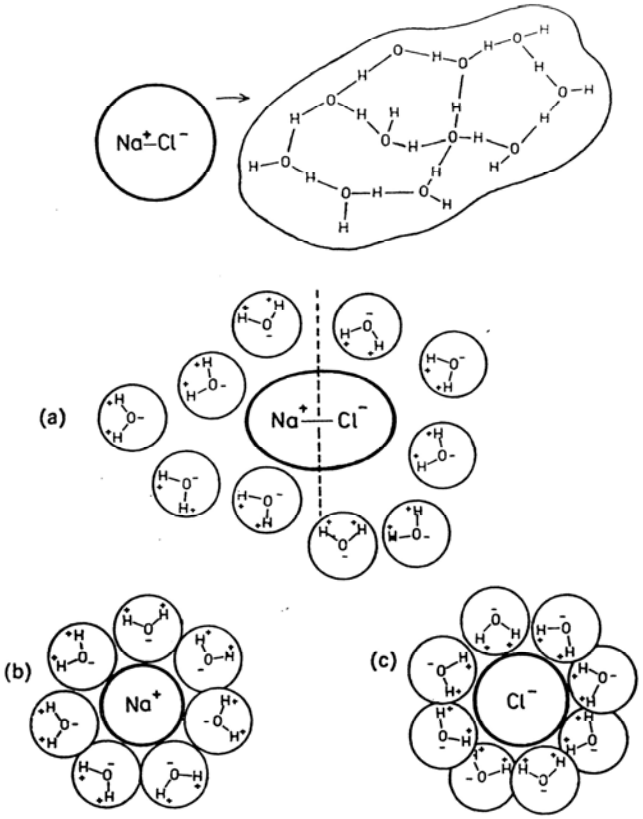
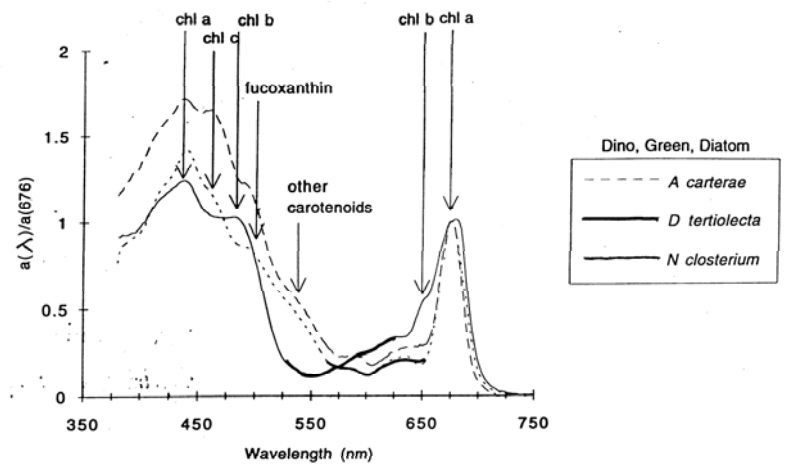
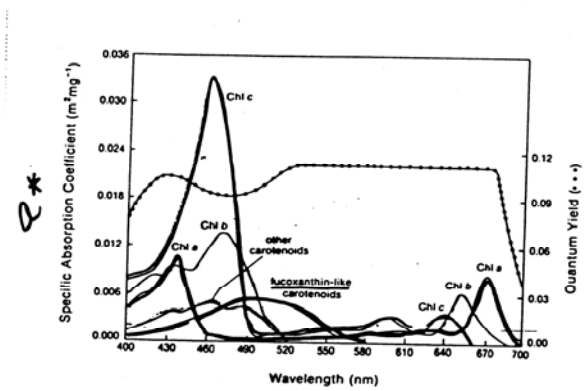


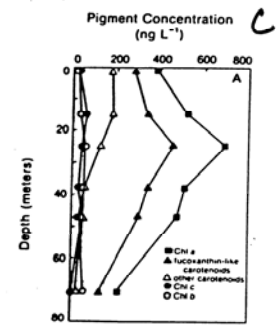
Fig. 2.3.1. The dissociation of a salt ion in water (a) and the formation of ion aggregates (b) and (c).

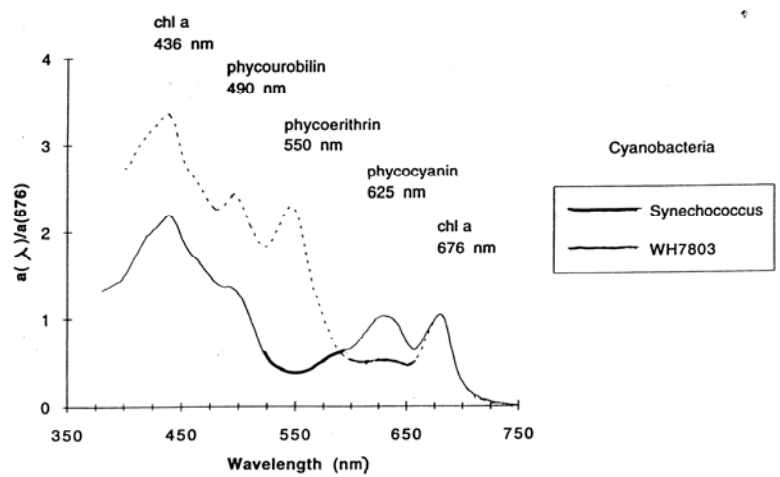
Phytoplankton

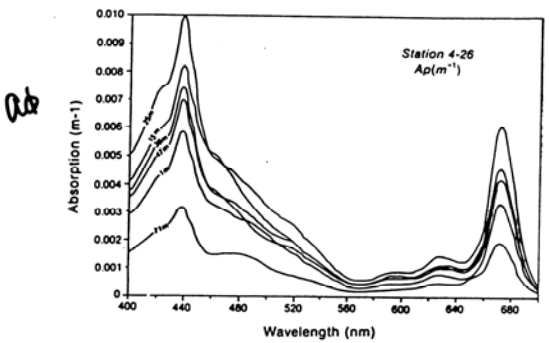
Phytoplankton





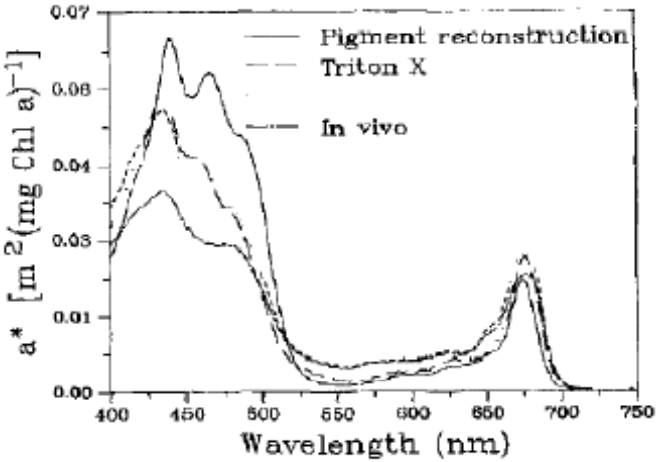




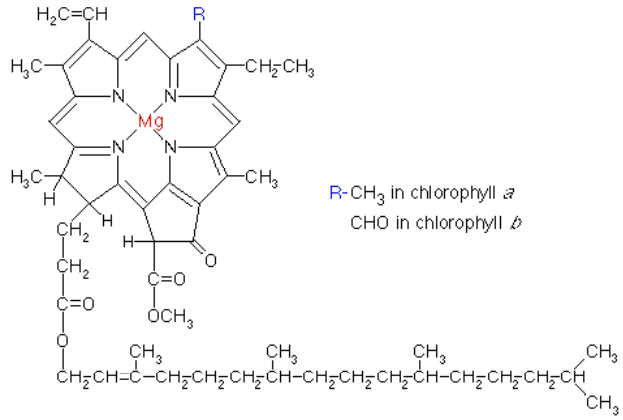


Bidigare et al 1991

Phytoplankton vs Chlorophyll



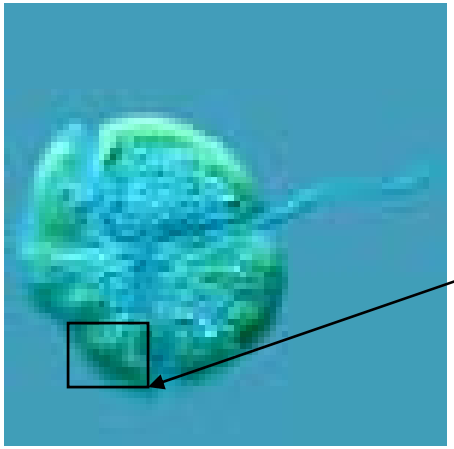
Sosik & Mitchell 1991

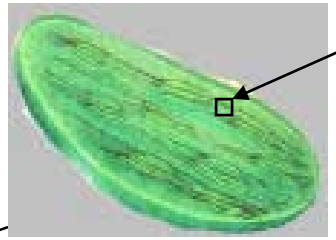


The structure of chlorophyll

http://chaitanya1.wordpress.com/2007/07/09/strawberries/

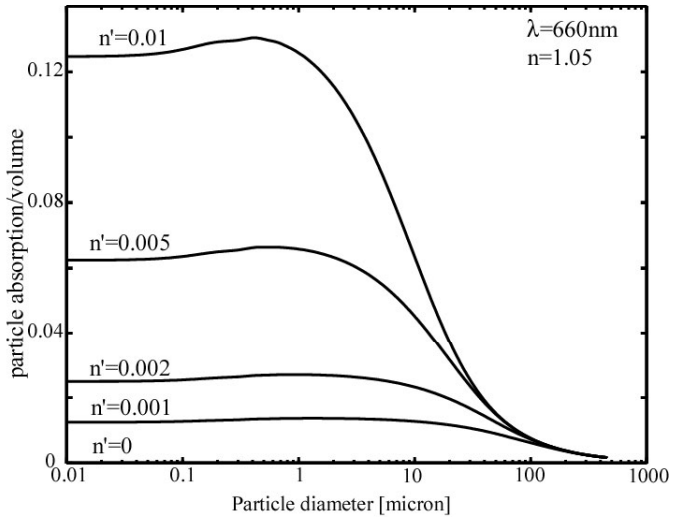
chlorophyll





chloroplast

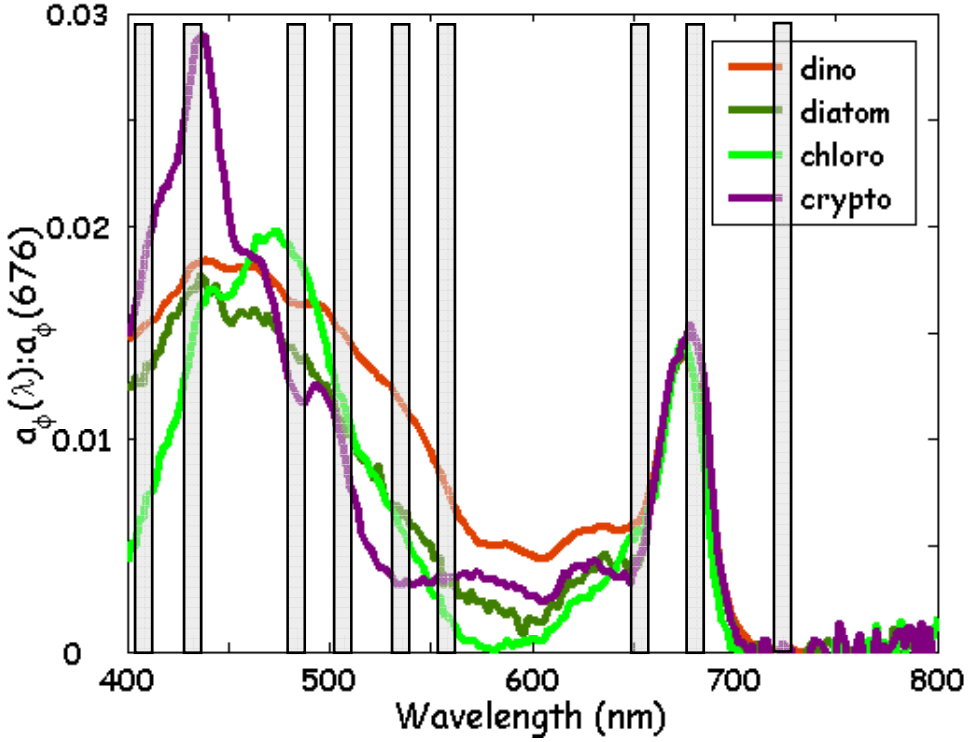
cell

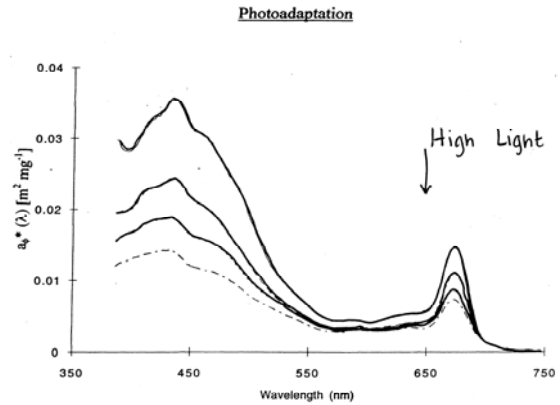


Packaging: *a*/[chl] is function of size and [chl]
Duysens (1956)

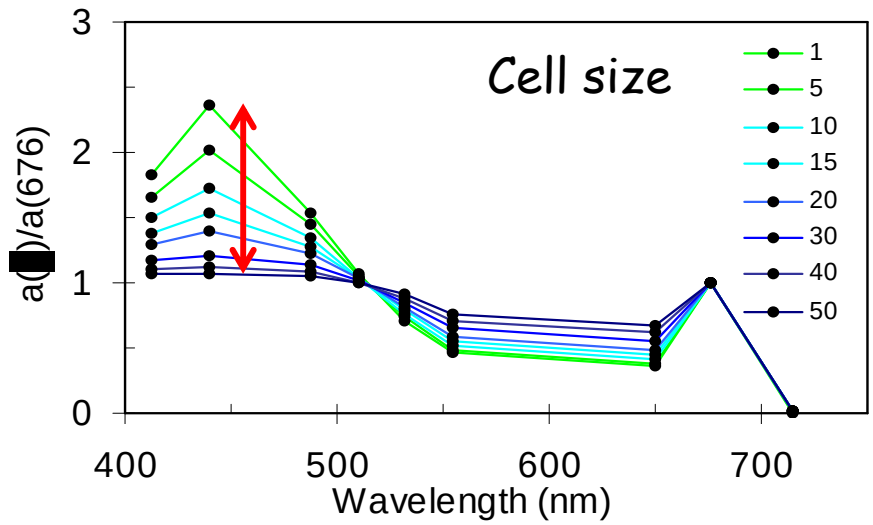
Phytoplankton

Species-specific pigment composition





The efficiency of absorption per chlorophyll molecule



(Morel and Bricaud 1981)

Model for attenuation and scattering:

$$b_{b,p}(\lambda) = b_{b,p}(\lambda_0)\left(\frac{\lambda}{\lambda_0}\right)^{-\gamma}$$

IOPs of phytoplankton (Bricaud et al., 1983, L&O):

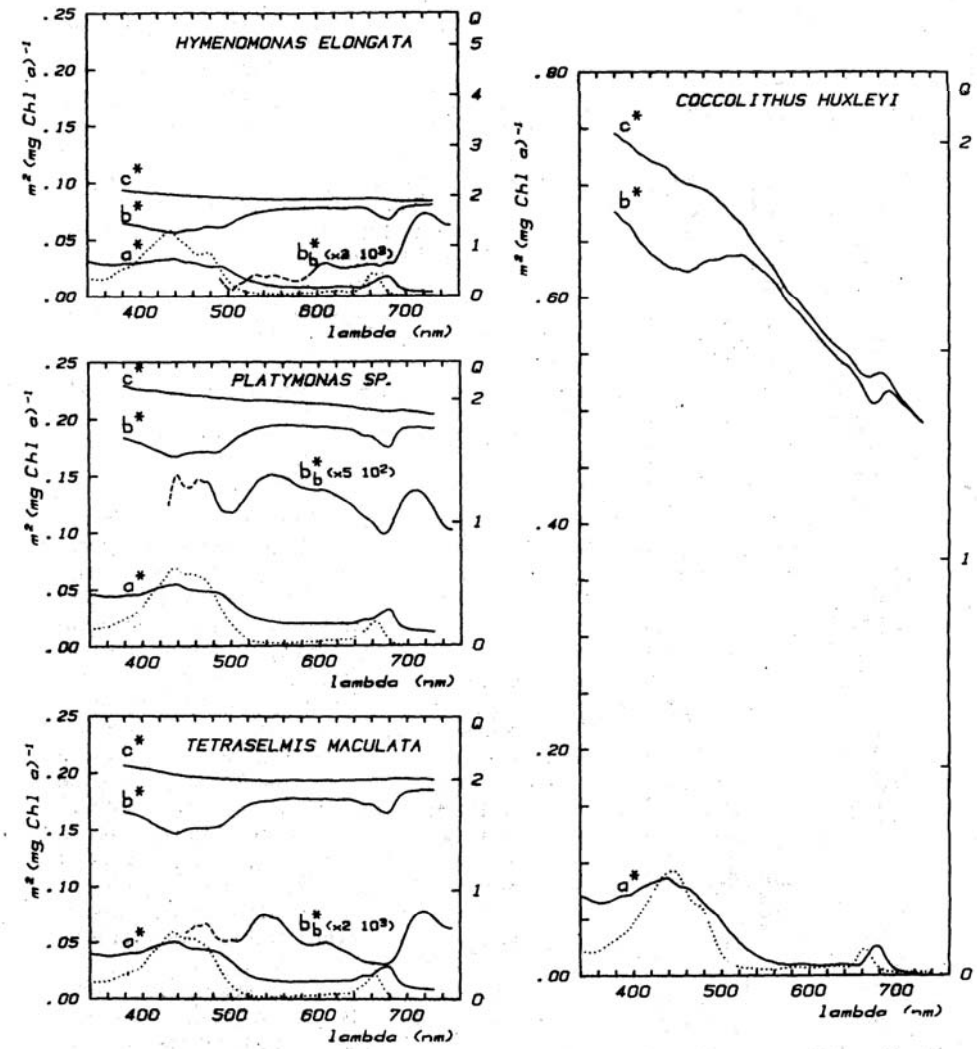
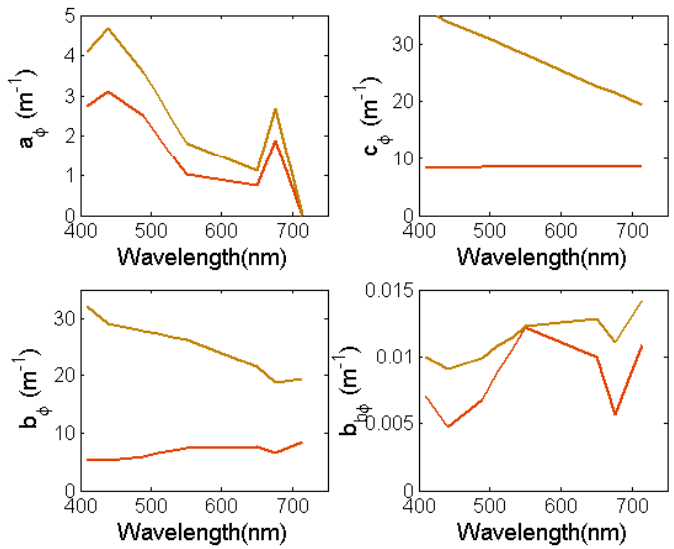


Fig. 5. Specific spectral values of absorption (a^*), attenuation (c^*), total scattering (b^*), and backscattering (b_b^*) determined on four algal species and normalized to unit (Chl *a* + Pheo *a*) concentration (1 mg·m^{-3}) (the parts of the b_b^* curves plotted as dashed lines correspond to a signal-to-noise ratio <10). The spectral values of absorption by the corresponding acetone solution of extracted pigments are also given with the same normalization (dotted lines). Right scales—corresponding values of efficiency factors for absorption (Q_a), attenuation (Q_c), total scattering (Q_b), and backscattering (Q_{bb}). Spectral values of b_b^* are not shown for *C. huxleyi*. A previously published curve (fig. 4: Morel and Bricaud 1981*b*) has been discarded because later microscopic examination showed contamination of that culture. The present data are from an uncontaminated culture and deal only with a^*, b^*, and c^*.

Optical properties and HABs:

- Phyto. blooms



Roesler and Etheridge, 2002

Prorocentrum micans (27μm) Photo M. Keller

Aureococcus anafragefferens (3μm) Photo S. Etheridge

Non-algal organic particles

Heterotrophic Ciliates, Flagellates, and bacteria

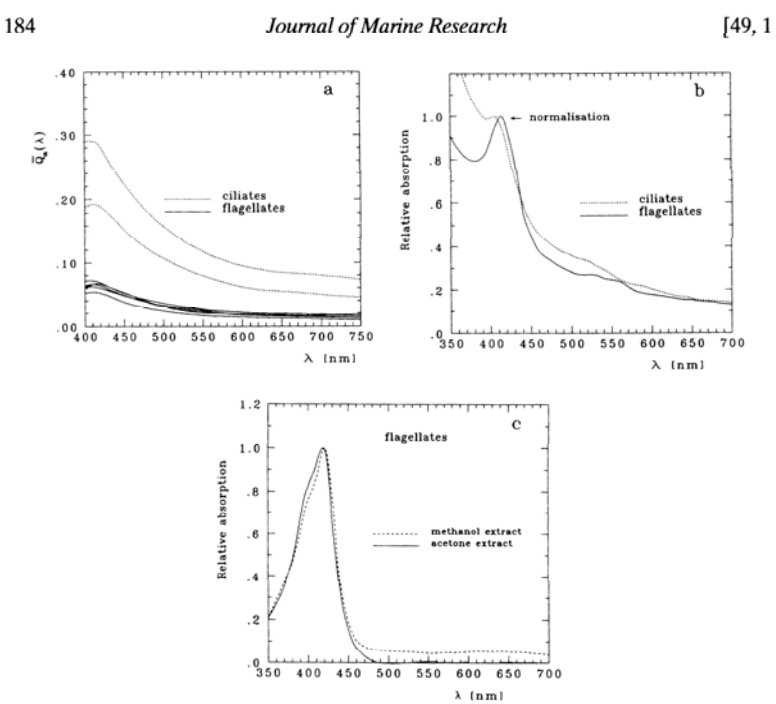


Figure 2. (a) Efficiency factor for absorption as function of wavelength for ciliates and flagellates. (b) Spectral absorption values, normalized by their maximum near 415 nm, when measurements are carried out with cells collected onto a GF/F; (c) absorption spectra (normalized as above) of acetonic and methanol extracts for flagellates only.

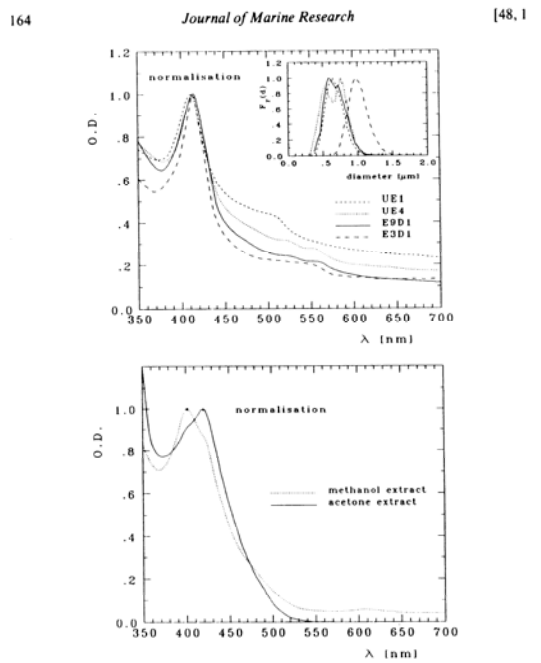


Figure 7. Spectral values of the optical density determined after having collected bacteria on a GF/F filter. The spectra are normalized with respect to their maximum at 412–415 nm (a). The corresponding size distribution functions for these four populations are shown in insert. Absorption spectra (normalized as above) of acetonic and methanol extracts (b).

Detritus

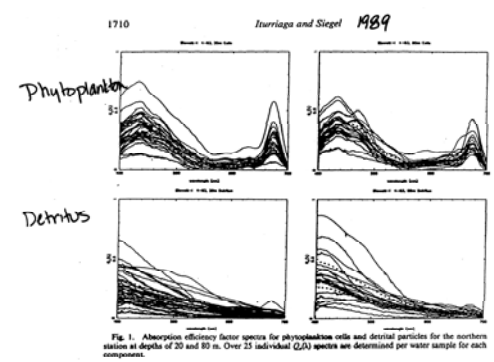


Fig. 1. Absorption efficiency factor spectra for phytoplankton cells and detrital particles for the northern station at depths of 20 and 80 m. Over 25 individual $Q_a(\lambda)$ spectra are determined per water sample for each component.

absorption of individual particles
→ microphotometry

Iturriaga and Siegel 1989

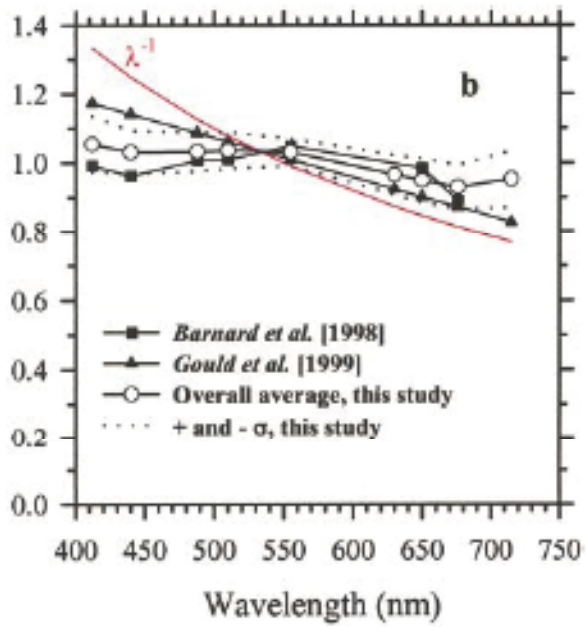
Ahn and Morel

$$a_{CPOM}(l) = a_{CPOM}(400)*\exp(-S_{CPOM}(\lambda-400))$$

$$S_{CPOM} = 0.007 \text{ to } 0.011$$

Scattering:

Average spectral shape:



Phytoplankton:

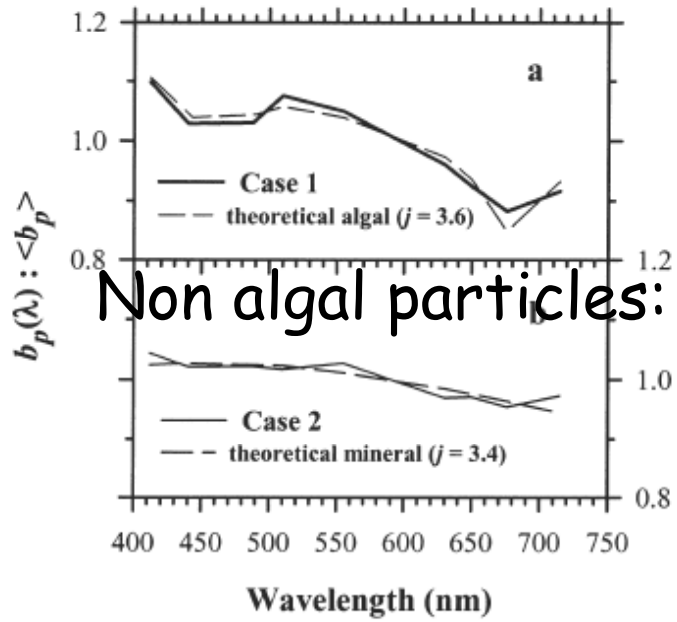


Fig. 11. The observed average spectra of the $b_p(\lambda):\langle b_p\rangle$ ratio for (a) case 1 and (b) case 2 waters (*see also Fig. 3*). The calculated spectra for typical pure phytoplankton and pure mineral particles are also shown.

Non algal particles:

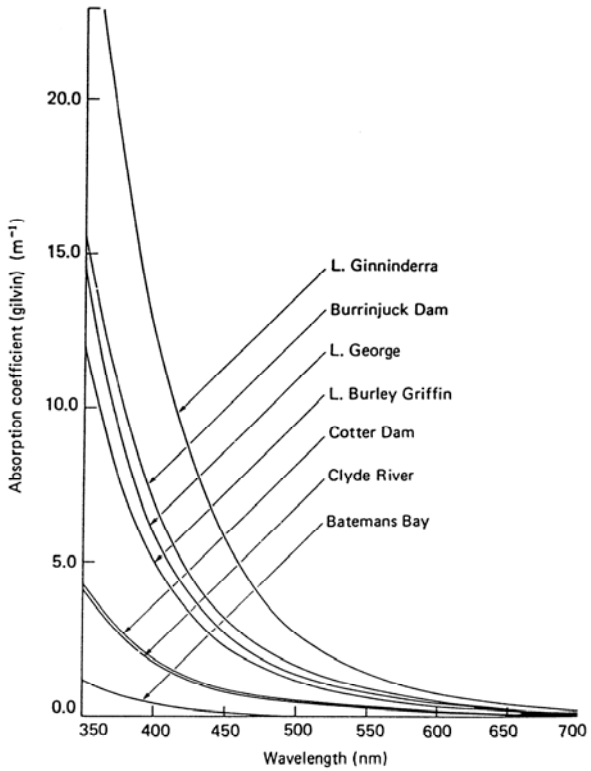
From Babin et al., 2003

CDOM: chromophoric "dissolved" organic matter

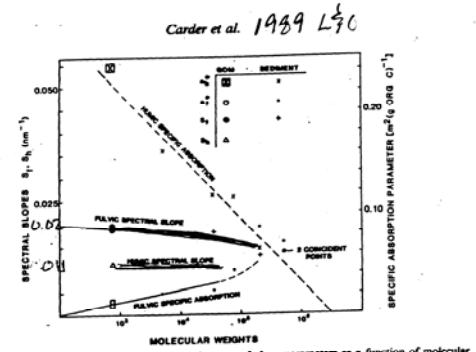
$a_{CDOM}(l) = a_{CDOM}(400)*\exp(-S_{CDOM}(\lambda-400))$

$S_{CdOM} = 0.011$ to 0.022

Fig. 3.5. Absorption spectra of soluble yellow material (gilvin) in various Australian natural waters (from Kirk, 1976*b*). The lowest curve (Batemans Bay, NSW) is for coastal sea water near the mouth of a river; the next curve (Clyde River, NSW) is for an estuary; the remainder are for inland water bodies in the southern tablelands of New South Wales/Australian Capital Territory. The ordinate scale corresponds to the true *in situ* absorption coefficient due to gilvin.



Kirk 1983



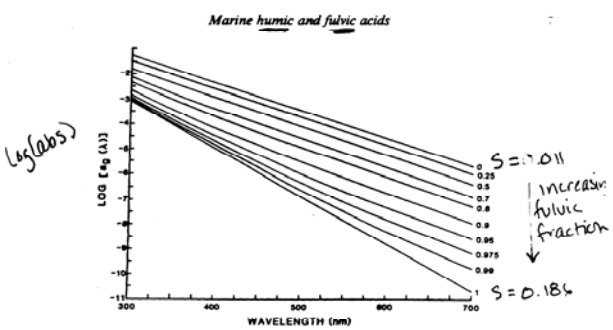
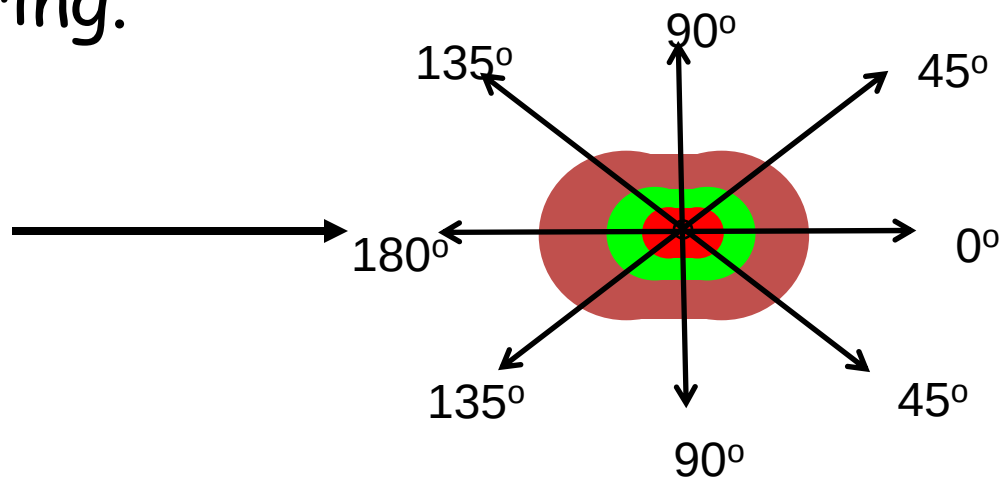


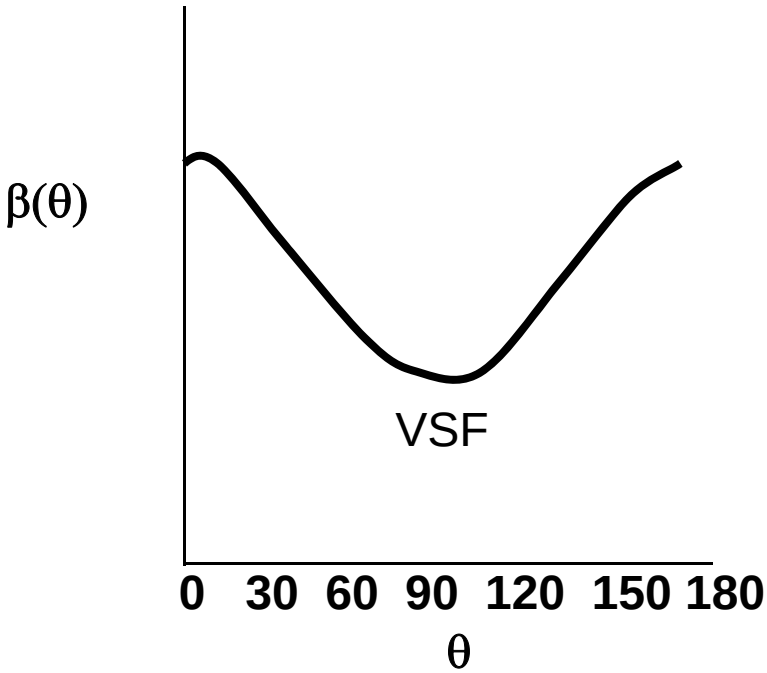
Fig. 3. Spectral variation of the absorption coefficient due to marine humus or Gelbstoff as a function of the fulvic acid fraction of Gelbstoff for $a^*_f = 0.00732$ m² g⁻¹, $a^*_h = 0.131$ m² g⁻¹, $B_f = 0.0186$ nm⁻¹, and $B_h = 0.0110$ nm⁻¹. The fulvic acid fraction is shown beside each curve.

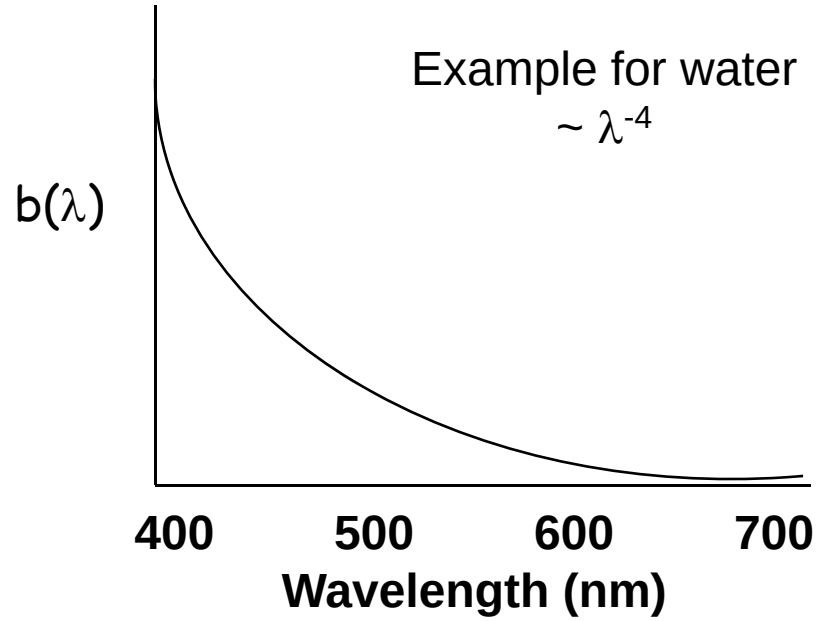
Carder et al. 1989

CDOM/Colloids scattering.

Mostly negligible in the ocean



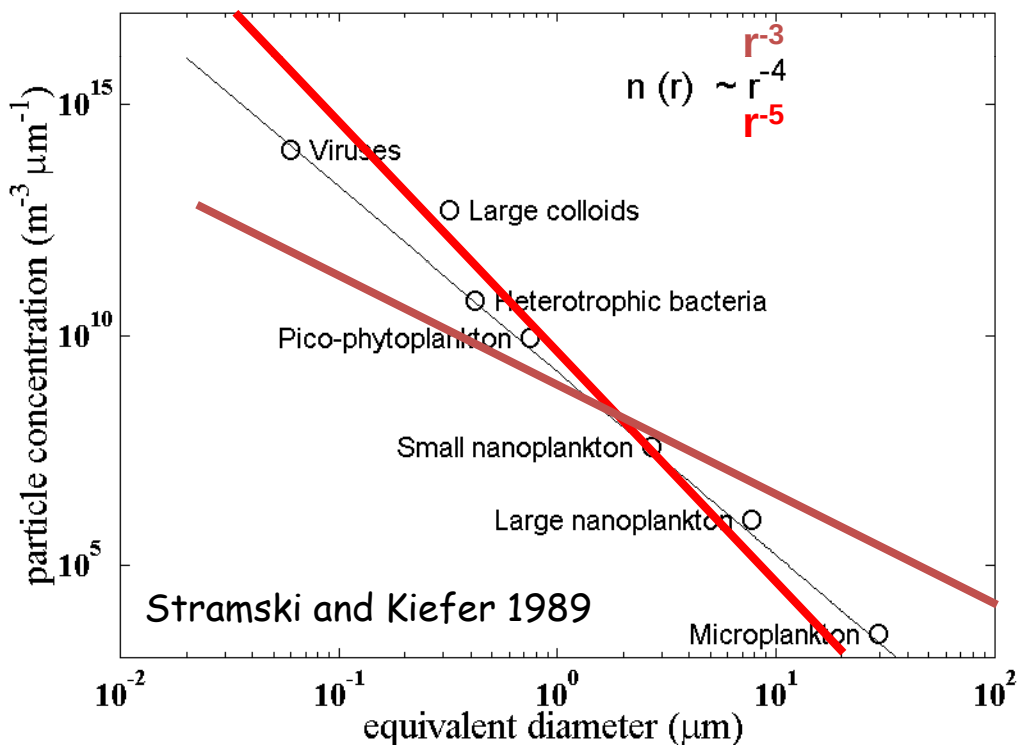




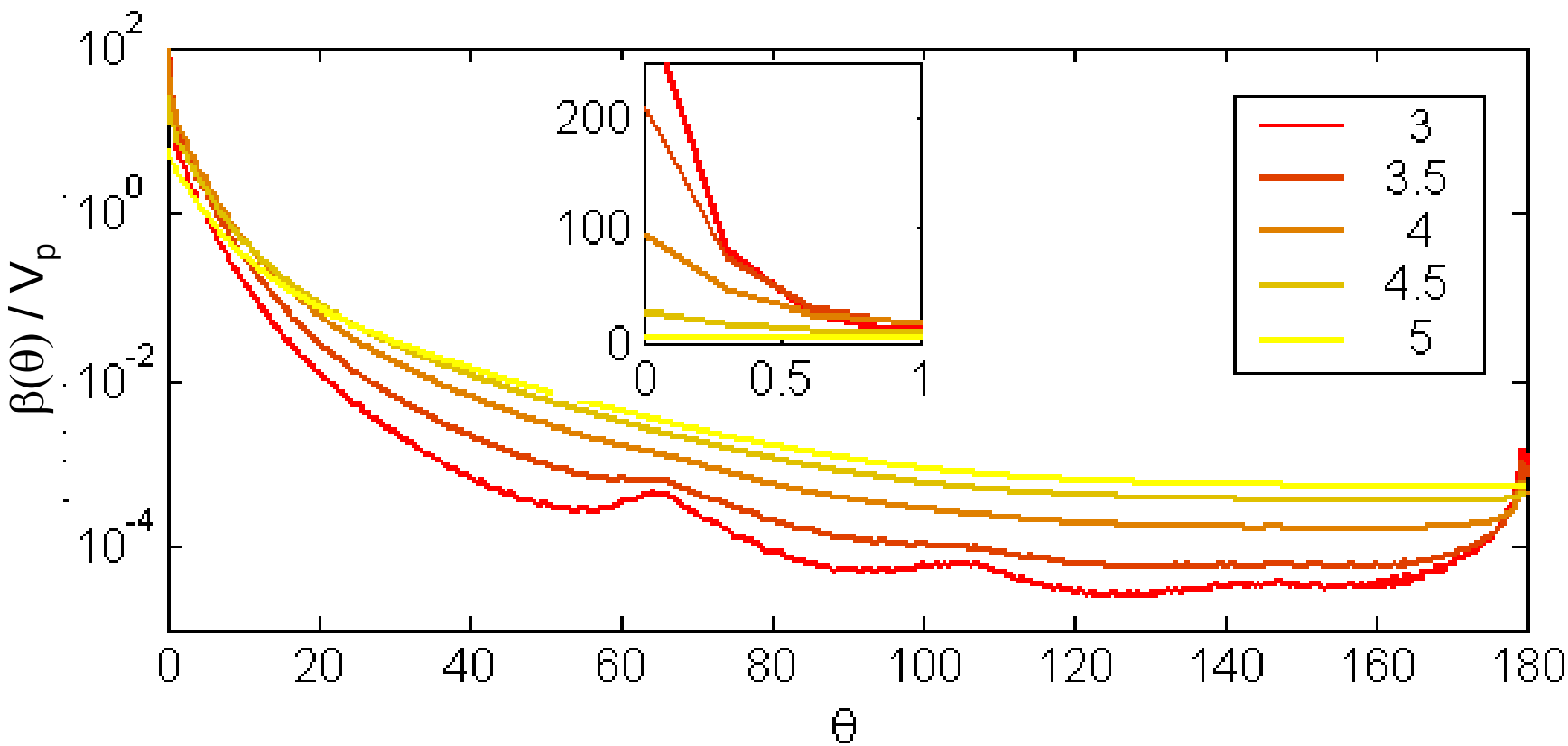
Similar results for viruses (Balch et al. 2000)

$\beta(\theta)$ response to particle size distribution

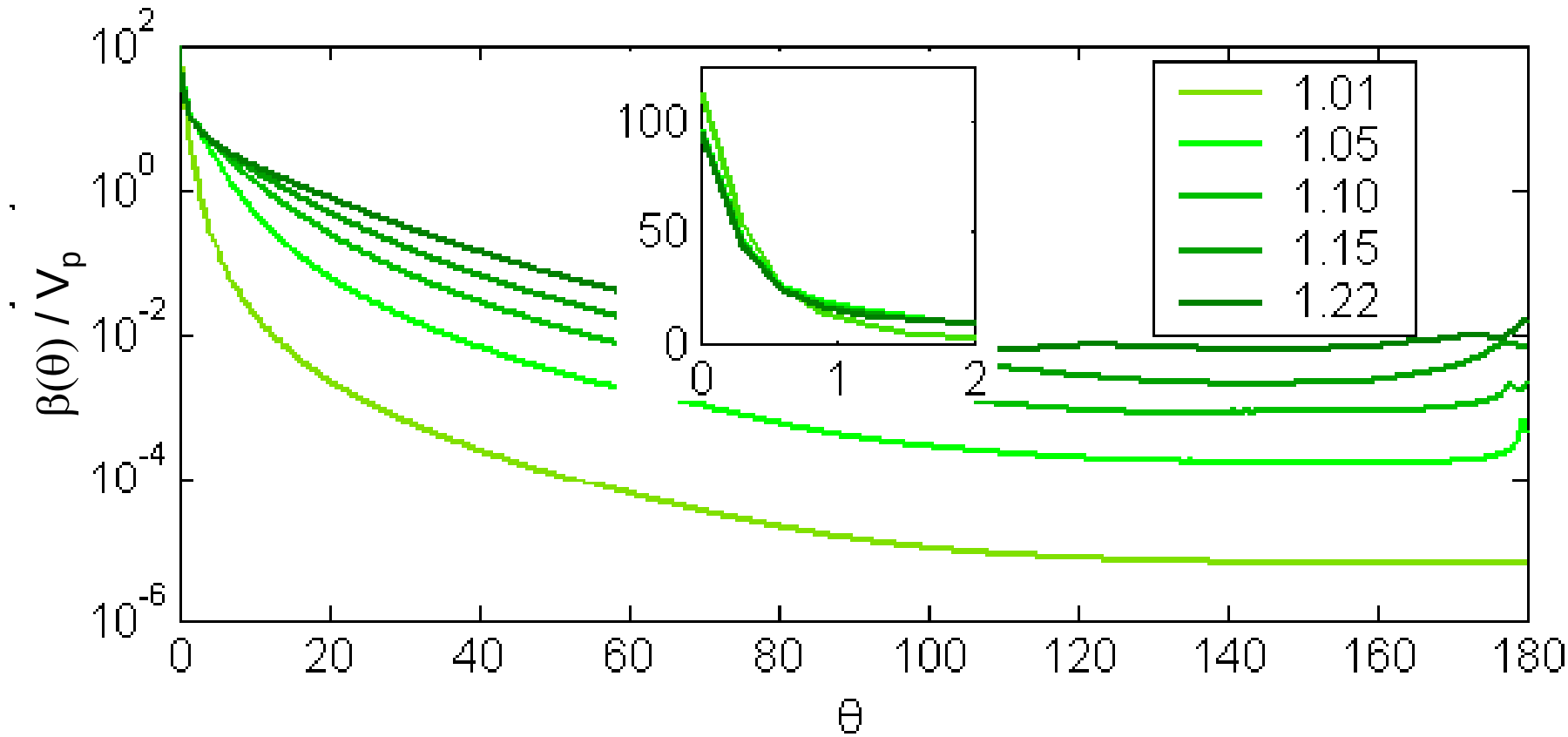
First let's talk about particle size distributions



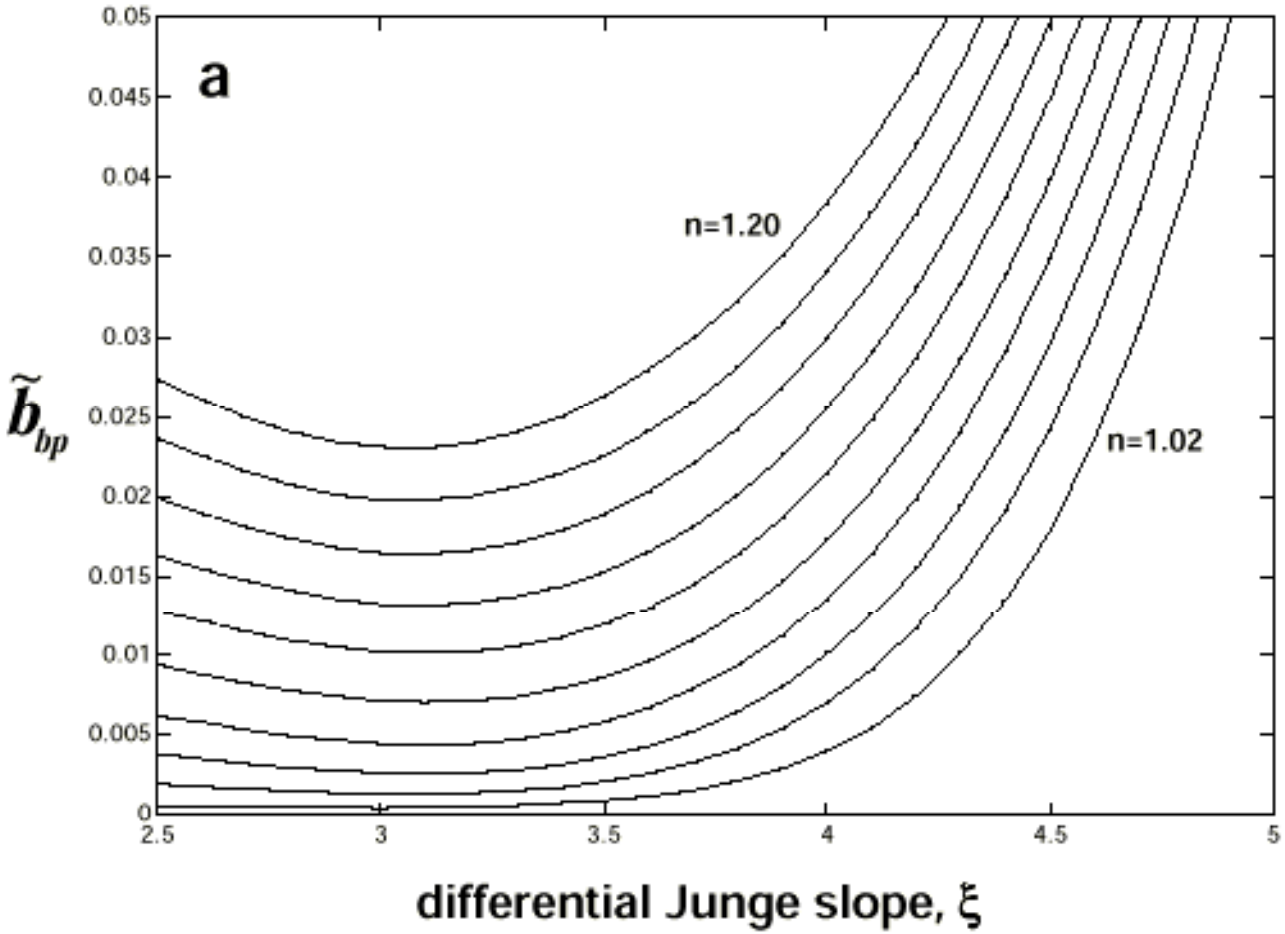
$\beta(\theta)$ and response to particle size distribution



β(θ) response to index of refraction



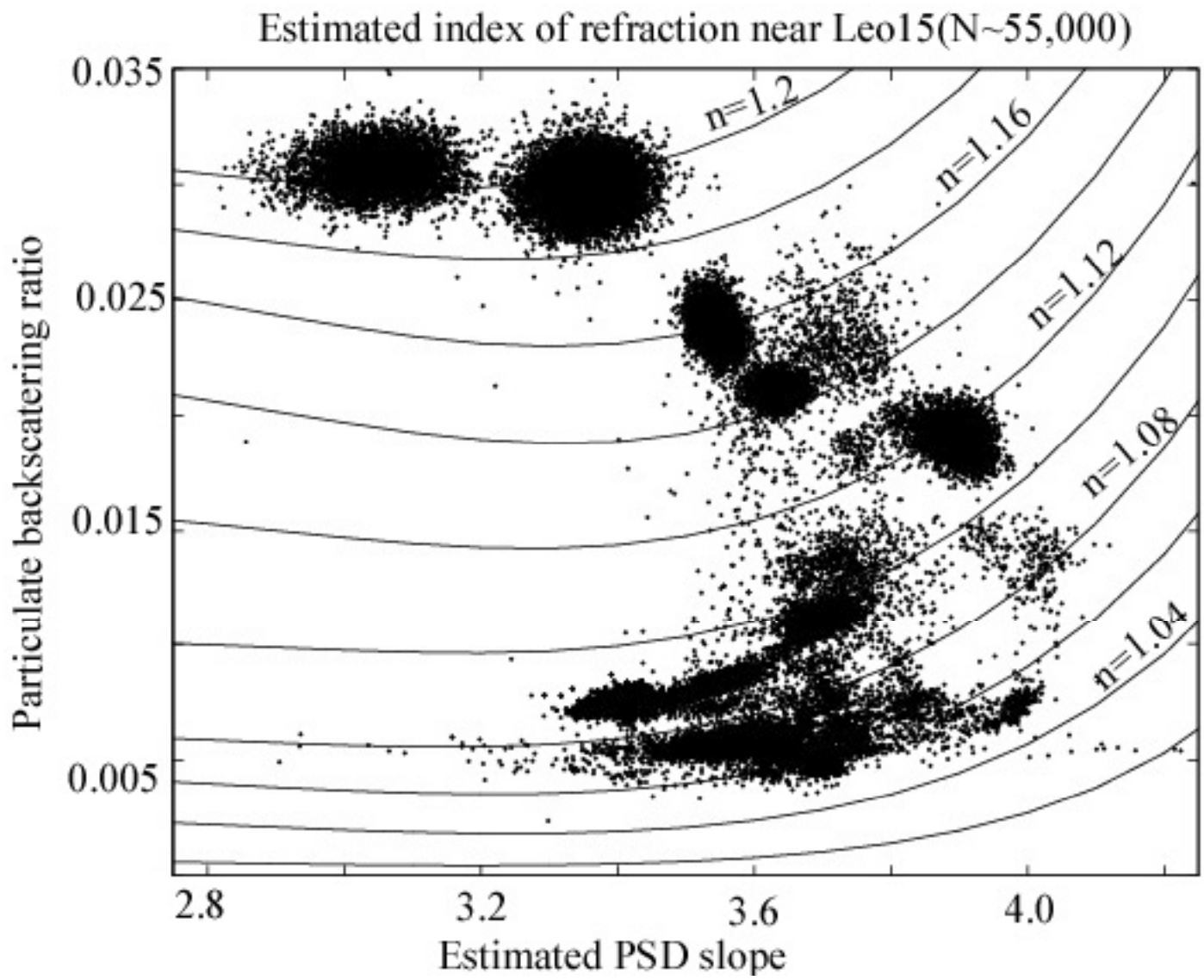
Theoretical dependence of the backscattering ratio $\left(\tilde{b}_{bp} \equiv b_{bp}/b_p\right)$ on index of refraction (n) and size (ξ):



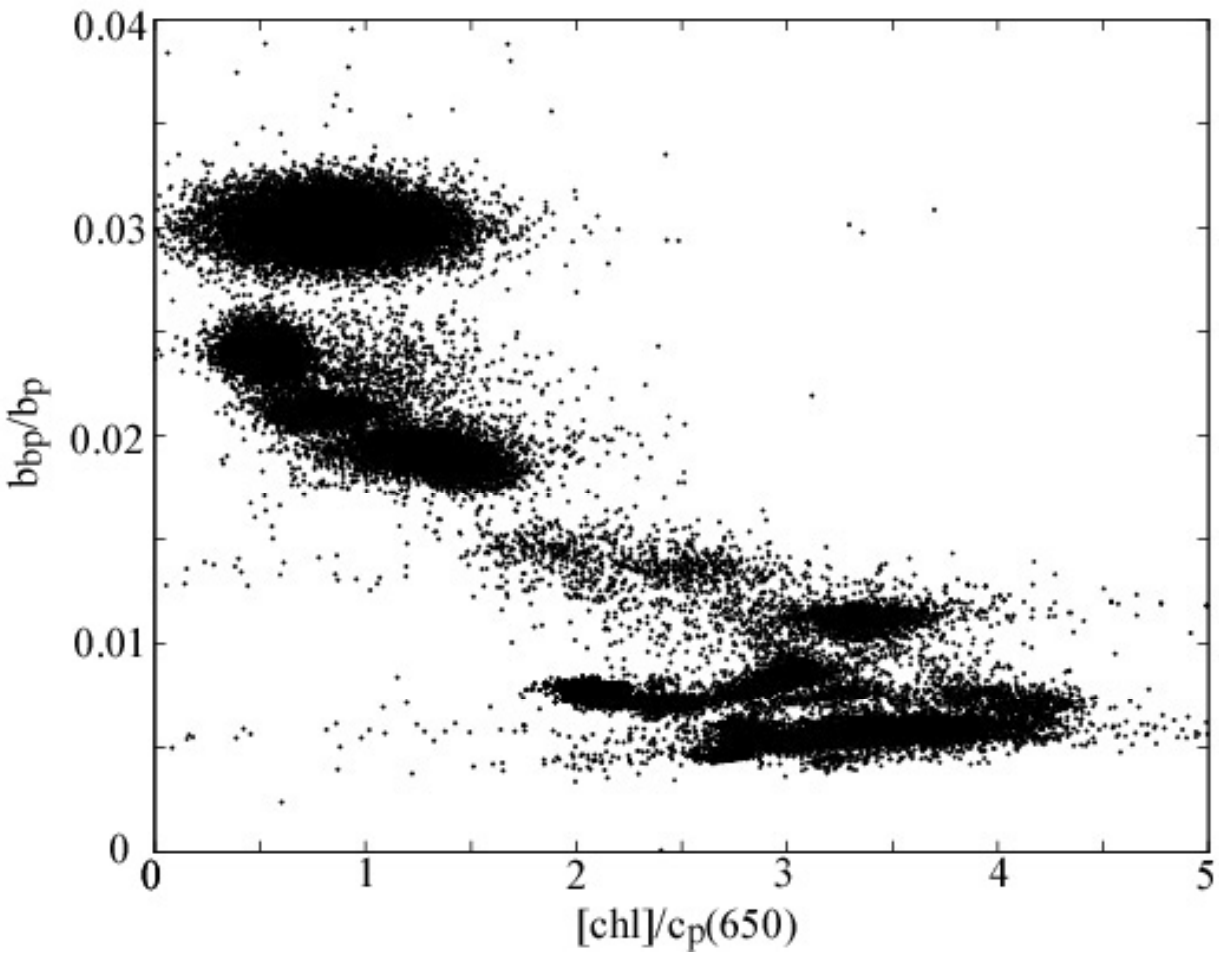
Twardowski et al., 2001

Backscattering ratio (55,000 observations from NJ shelf): consistent with theoretical prediction.

Varies from: phytoplankt on → inorganic particles.



Backscattering ratio relates to the relative concentration of phytoplankton and particulate material:



Beware of photoaclimation!

Inelastic scattering:

$$F(\lambda) = F_w(\lambda) + F_{dissolved}(\lambda) + F_{pigments}(\lambda)$$

Over all fluorescence is much weaker than absorption: O(1%) of absorbed photon fluoresce. Important in the clearest waters and water rich in phytoplankton (New paper, Behrenfeld et al., 2009 in Biogeosciences).

F_w- Raman Scattering (no consensus, Mobley, 1994). About $0.1b_w$.

F_d-Less well known. Variable shape and quantum yield.

F_p-known, but depend on pigment composition (chlorophylls, phycobillins). Variable quantum yield depend on physiology. F_{chl} line height is a product of MODIS.

Conclusions

- The dominant components in the ocean have characteristic absorption and scattering coefficients
- We use the optical coefficients as proxies for the component so as to determine concentration and composition (another lecture)
- While we measure bulk optical properties, there are methodological and modeling approaches to separate the constituents (another lecture)