Lecture 3
IOPs: Absorption physics and absorbing materials

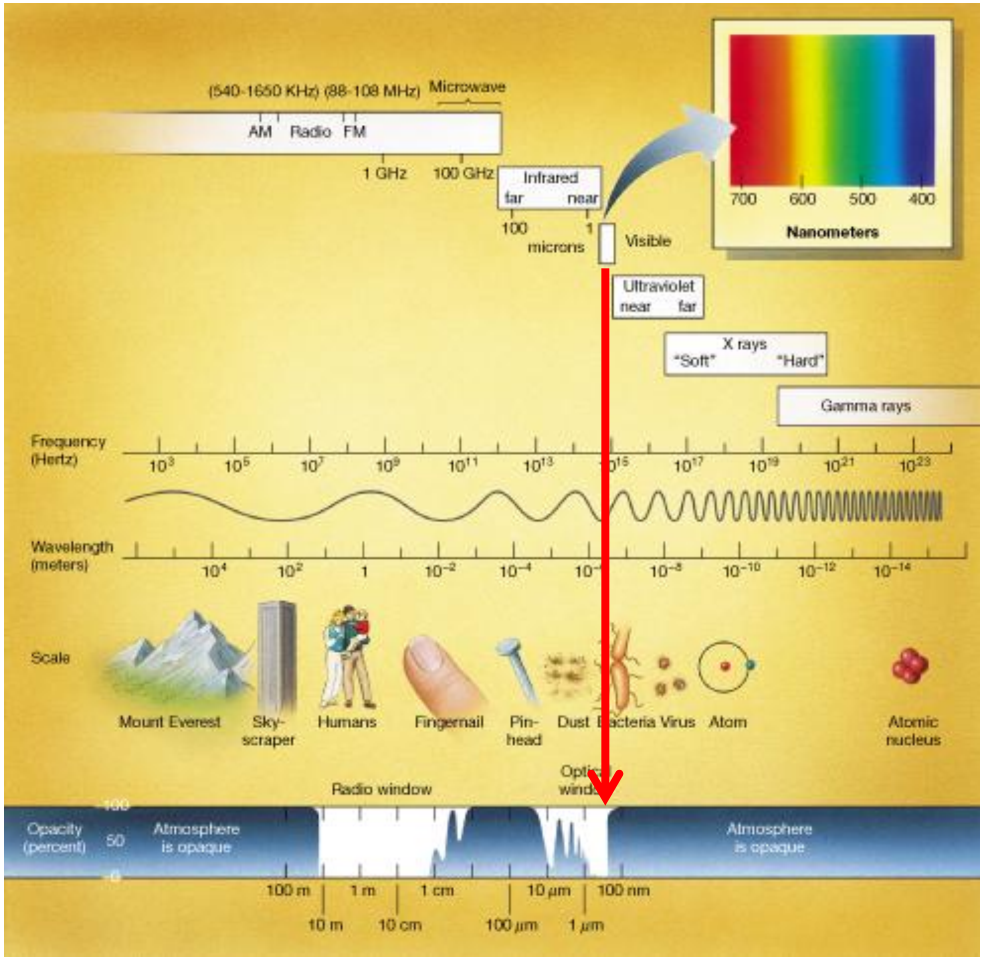
Collin Roesler
12 July 2011

Lecture Overview

- Overview of the electromagnetic spectrum
- What is absorption?
- Who are the absorbers?

Electromagnetic Spectrum

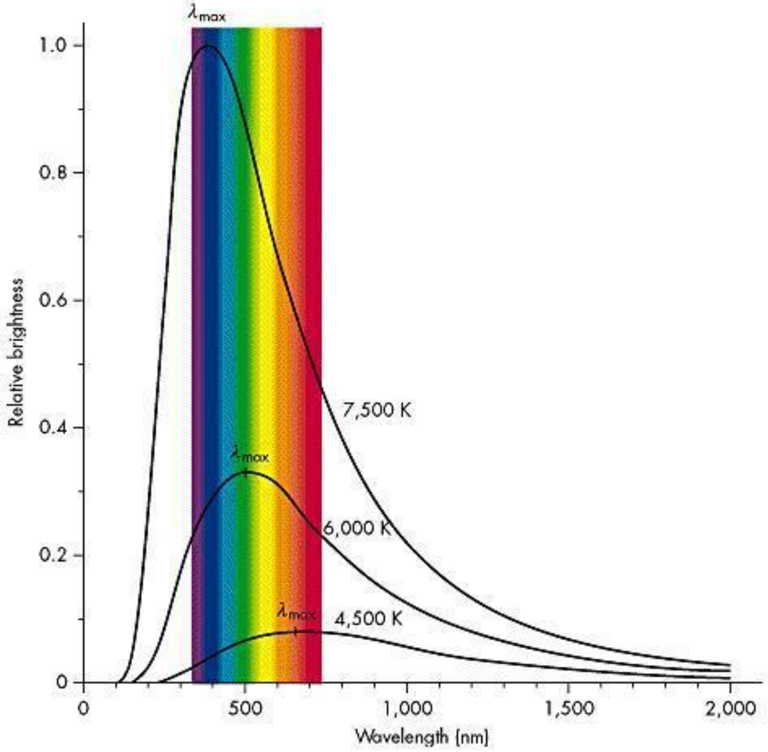
- Charged particles create electric fields (oscillation between +,-)
- When a charged particle moves, it creates a magnetic field
- The electromagnetic field oscillates as the energy propagates
- the range of oscillation frequencies is described by the EM spectrum



http://wps.prenhall.com/wps/media/objects/610/625137/Chaisson

Black body radiation

- Any object with a temperature >0 K emits electromagnetic radiation
- The spectrum of that emission depends upon the temperature (Planck's Law)
- As T ↑, emitted energy ↑ (Stefan-Boltzman's Law)
- As T ↑, the λ of maximal emission ↓ (Wein's Law)
- Energy contained in a packet of EM radiation (e.g. visible photon) ↓ with ↑ wavelength



http://aeon.physics.weber.edu/jca/PHSX1030/Images/blackbody.jpg

So the sun, at ~5800 K, emits primarily visible radiation (light), most of which penetrates the atmosphere

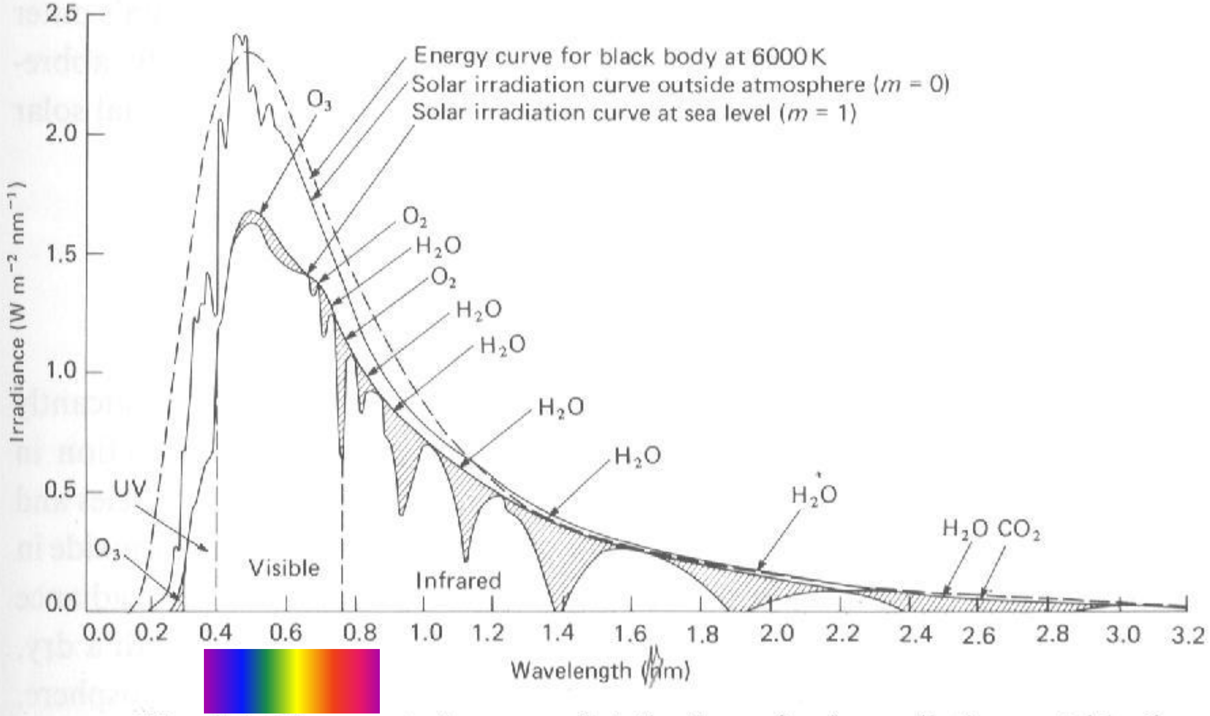
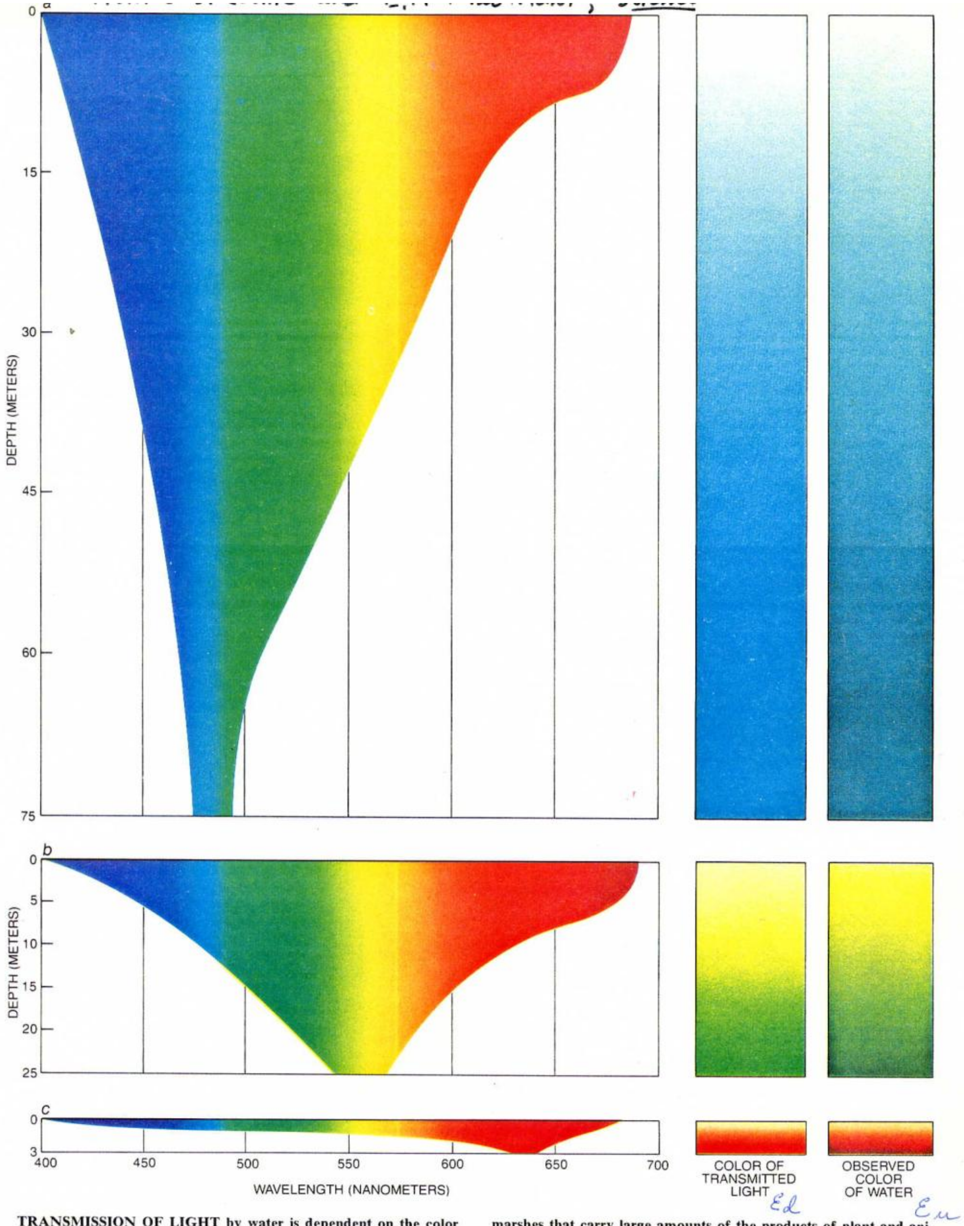


Fig. 2.1. The spectral energy distribution of solar radiation outside the atmosphere compared with that of a black body at 6000 K, and with that at sea level (zenith Sun). (By permission, from *Handbook of geophysics*, revised edition, U.S. Air Force, Macmillan, New York, 1960.)

Light Penetration



TRANSMISSION OF LIGHT by water is dependent on the color or wavelength of the light. In clear oceans and lakes (*a*) the light becomes increasingly monochromatic and blue as its path length increases. In fresh water that carries green organic matter (*b*) light at all wavelengths is absorbed more quickly than it is in clear water, but the light becomes greener with path length. In rivers, swamps and marshes that carry large amounts of the products of plant and animal decay (*c*) absorption is rapid and the spectral distribution of the light shifts to the red. Such waters are called black because the human eye is relatively insensitive to light at long wavelengths; a less anthropomorphic name would be infrared water. The depths given for the maximum penetration of light are typical, but they vary widely.

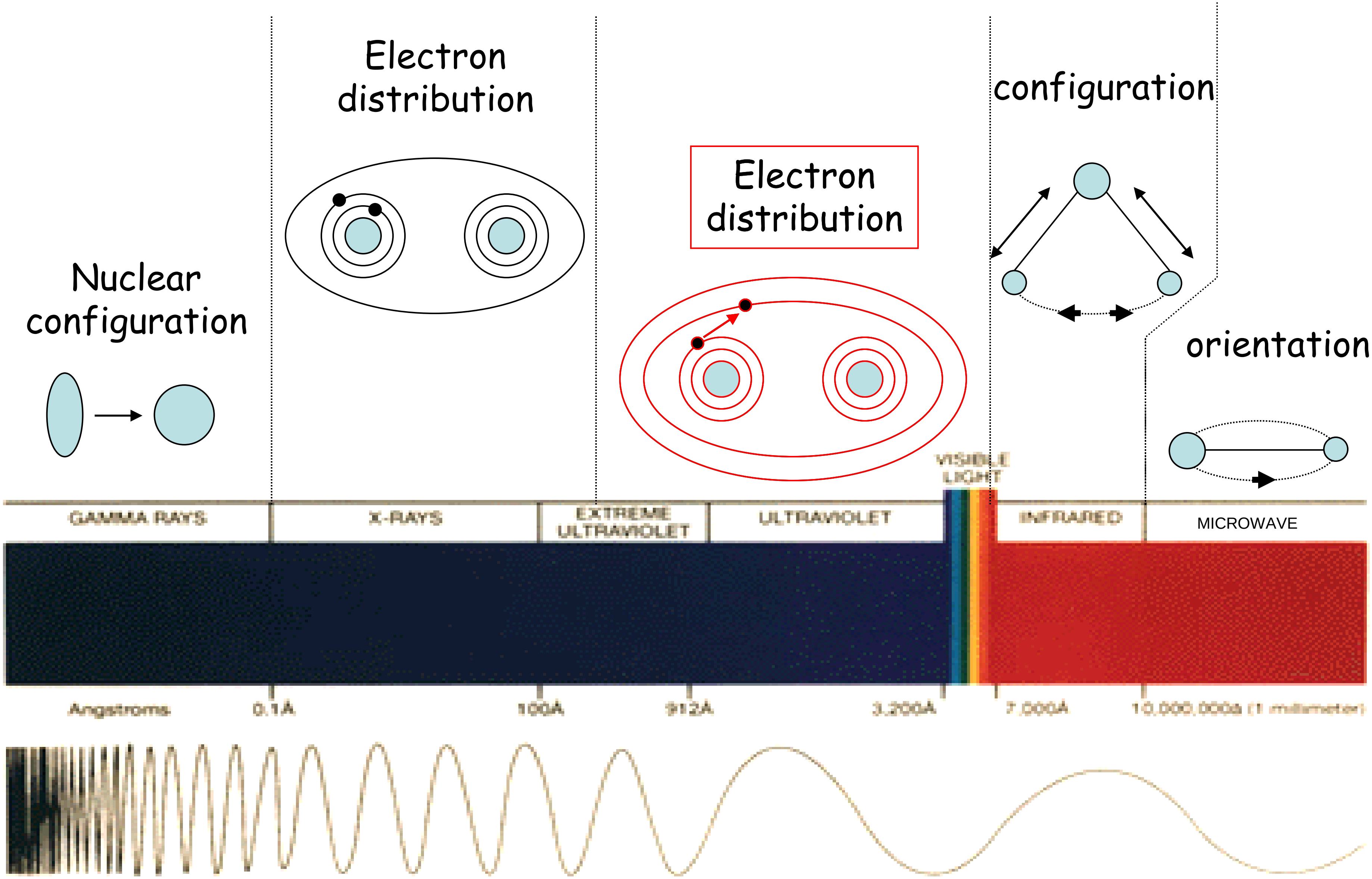
The visible radiation incident on the ocean surface penetrates spectrally to different depths depending upon water composition

in particular the composition of absorbing material

What is absorption?

- since electromagnetic radiation is energy propagation, when materials absorb radiation, they absorb energy
- what happens to the molecule depends upon the wavelength (frequency)

Interactions between energy and matter



Nuclear configuration

Electron distribution

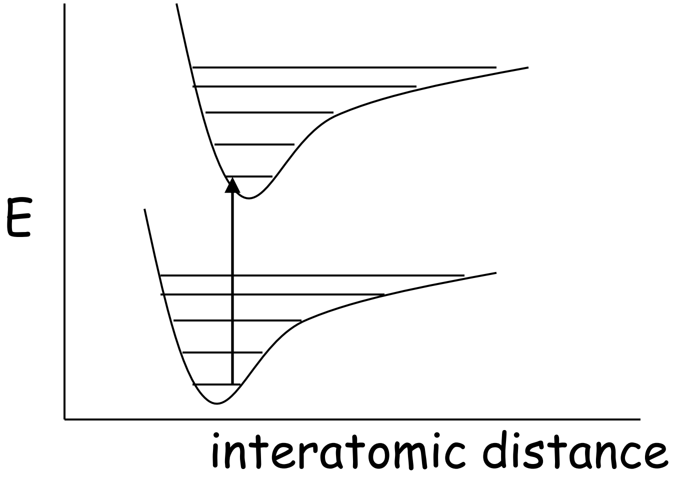
Electron distribution

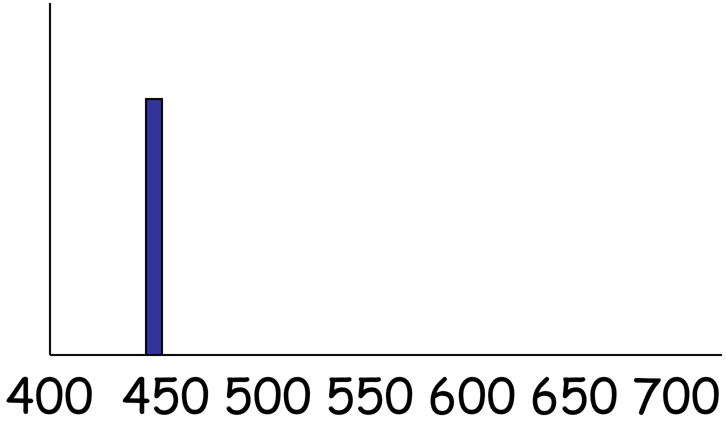
configuration

orientation

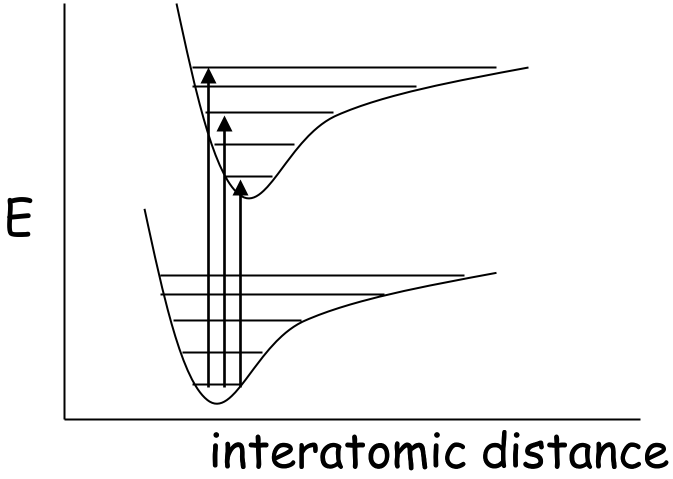
The amount of energy required to move an electron to another orbital shell is quantized

- The atom/molecule can **only** absorb visible radiation of this specific quantized energy or wavelength
- This determines the wavelength of the absorption peak

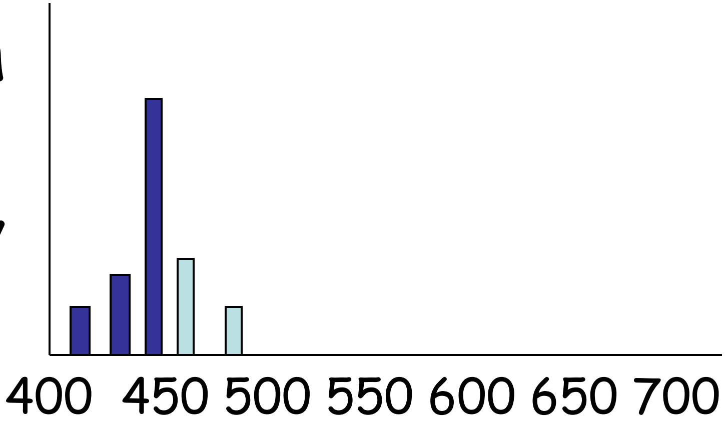




quantized energy states

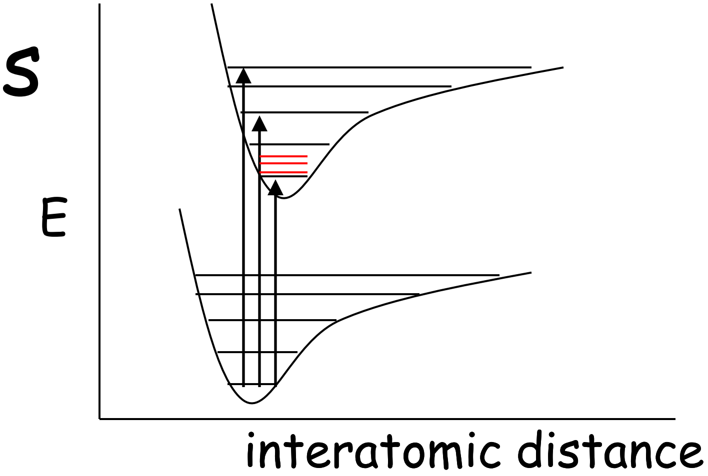


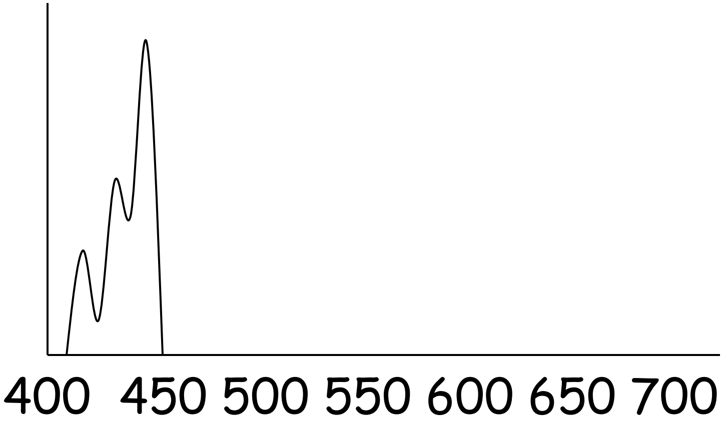
- Each orbital shell is associated with a series of higher excited states, which are also quantized
- These determine the wavelengths of the absorption side peaks which are higher (lower) energy but have a lower probability for absorption



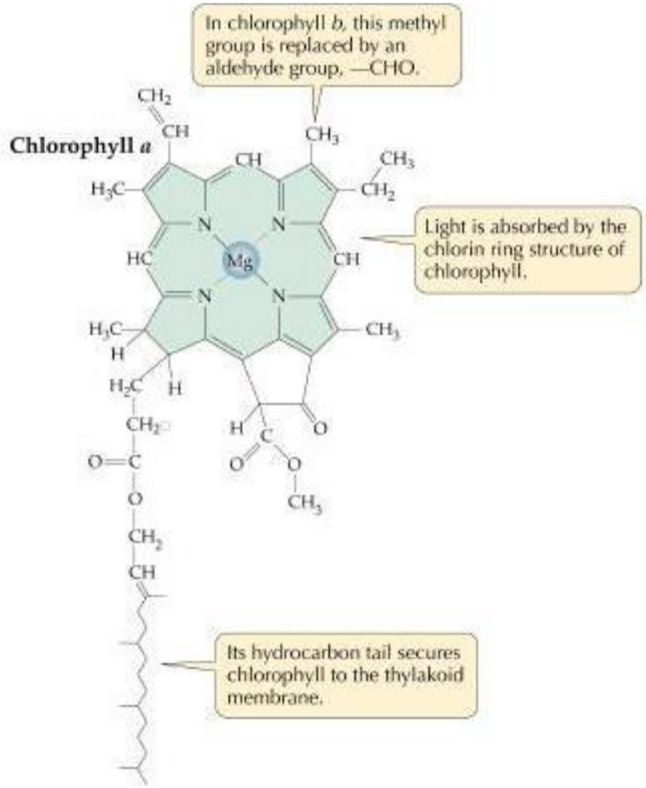
quantized vibrational states

- Each excited state, has vibrational and rotational states, also quantized
- These result in the smoothing of the absorption peaks





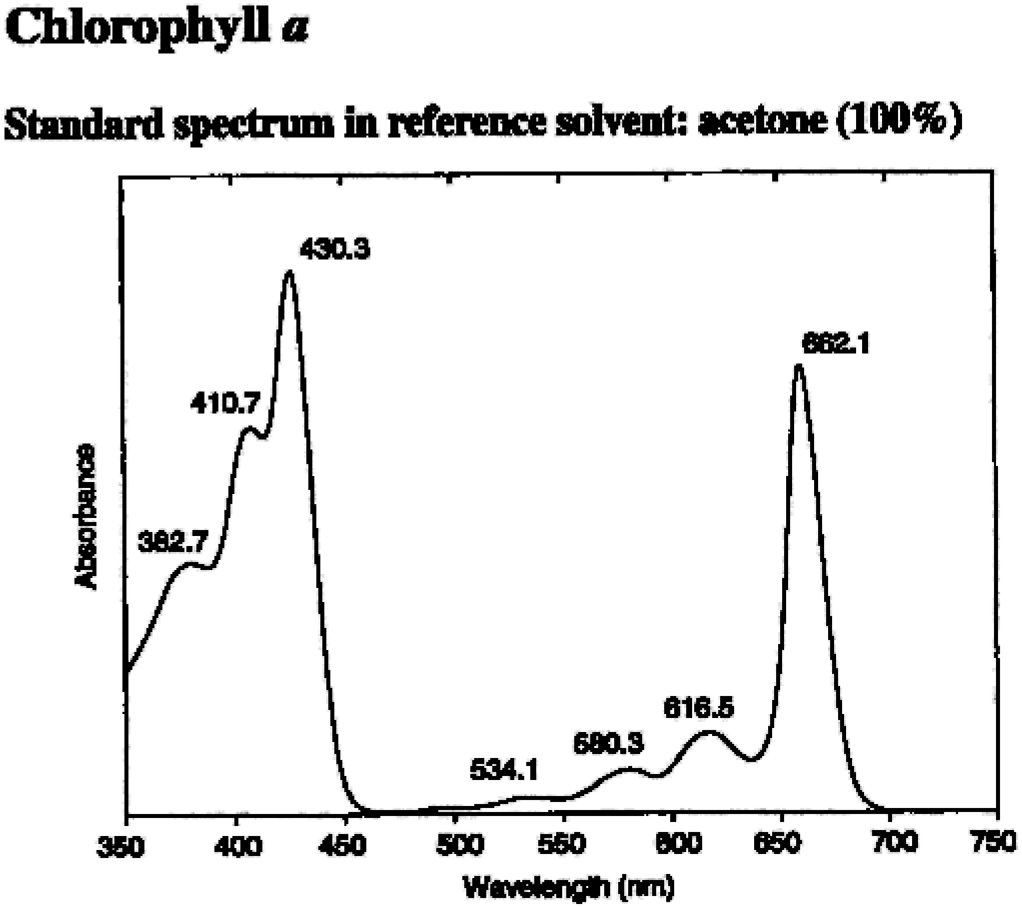
The chlorophyll a molecule has two higher energy orbital shells associated with the energy equivalent of a blue (443 nm) and a red (676 nm) photon



In chlorophyll *b*, this methyl group is replaced by an aldehyde group, —CHO.

Light is absorbed by the chlorin ring structure of chlorophyll.

Its hydrocarbon tail secures chlorophyll to the thylakoid membrane.



Chlorophyll *a*

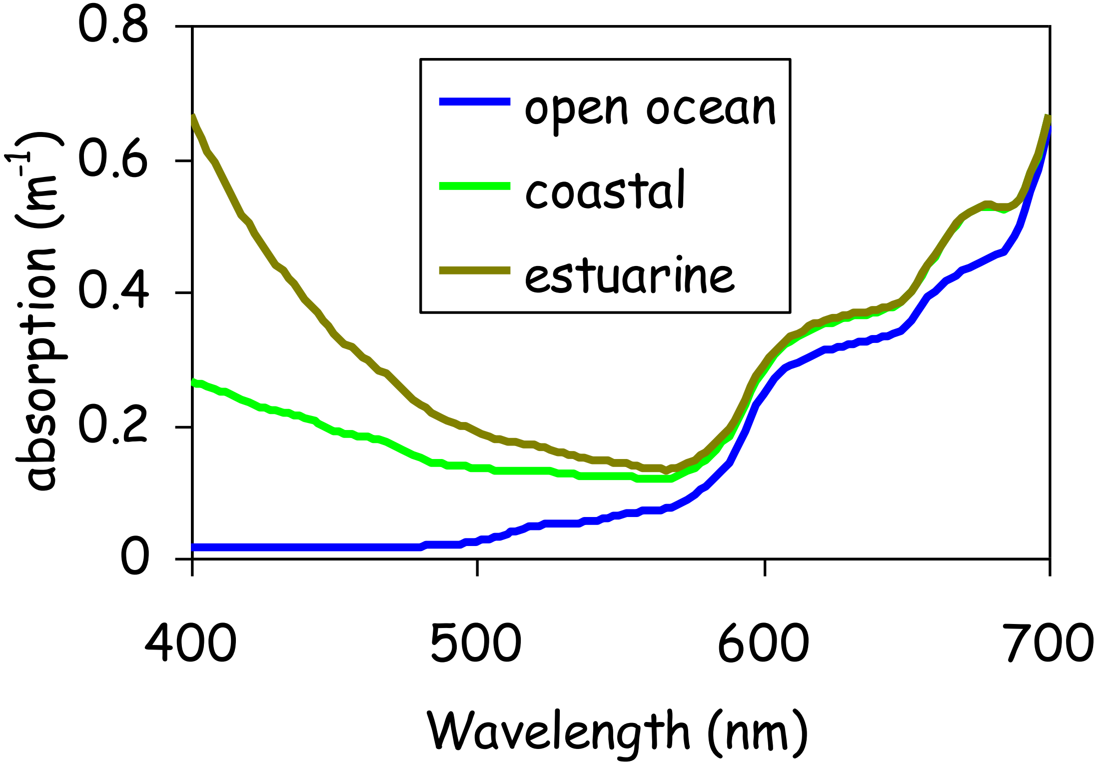
Standard spectrum in reference solvent: acetone (100%)

http://www.mie.utoronto.ca/labs

Now that we know the physics of absorption

Let's meet the main absorbers in the ocean

Example of absorption spectra for three environments



all have strong red absorption

but variable blue absorption

Absorbing matter

Ideally…

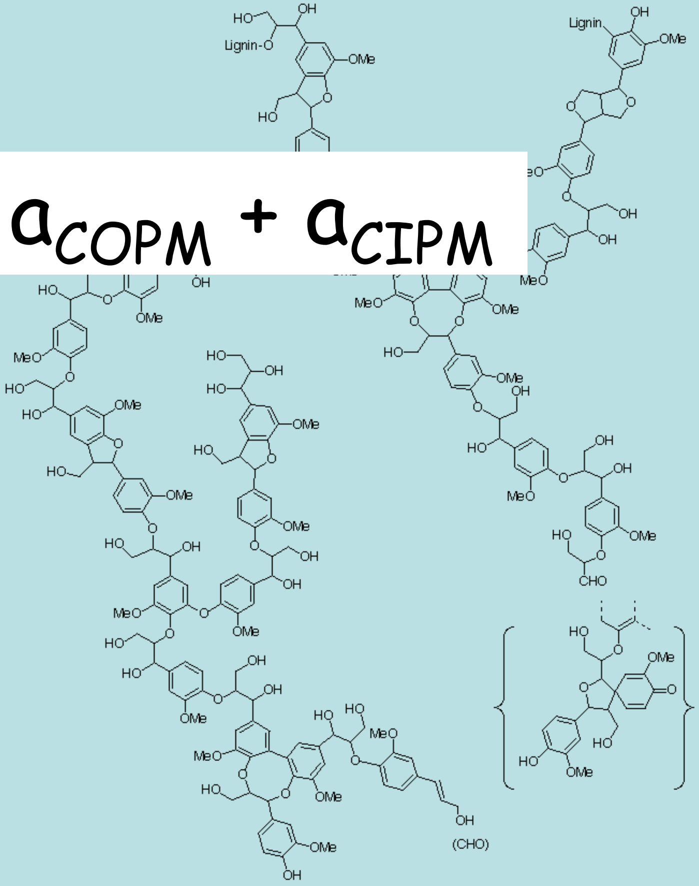
$$a_T = a_w + \Sigma a_{\text{dissolved compounds}} + \Sigma a_{\text{particles}}$$

And because of Beer's Law, the absorption coefficients are proportional to the concentration of absorbing matter, therefore absorption is a proxy for concentration, in some cases biomass…

Absorbing matter

Practically…

$$a_T = a_w + a_{CD(O)M} + a_\phi + a_{COPM} + a_{CIPM}$$



water
colored dissolved (organic) matter
phytoplankton (in vivo pigments)
colored organic particulate matter (not pigments)
colored inorganic particulate matter (minerals)

Absorbing Components: Water

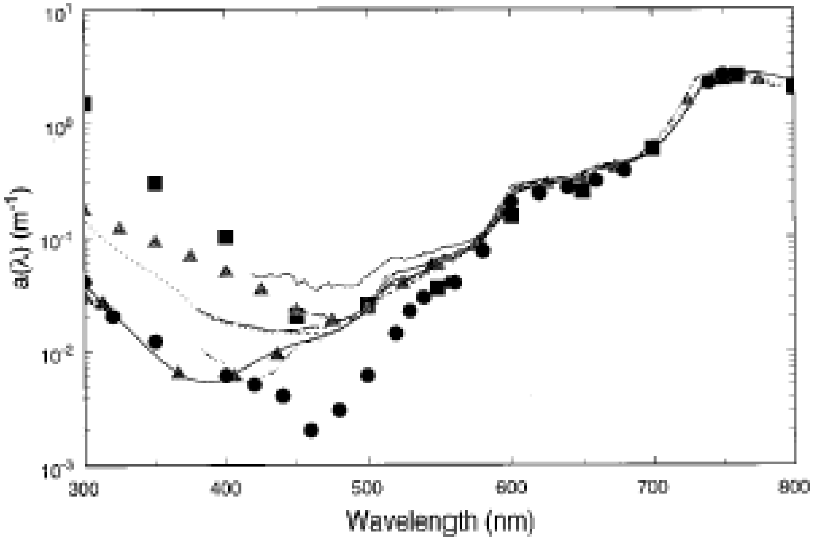


Fig. 1. Absorption coefficient of pure water as measured or compiled by several investigators.[1,2,11,18,19,21,26–33] The discrepancy in the estimated absorption coefficients is largest at short wavelengths where absorption by organic contaminants is significant. At wavelengths longer than 550 nm the standard deviation of the estimates is between 5 and 10% of the mean value.

W. Scott Pegau, Deric Gray, and J. Ronald V. Zaneveld

Absorption and attenuation of visible and near-infrared light in water: dependence on temperature and salinity

20 August 1997 / Vol. 36, No. 24 / APPLIED OPTICS

variations are methodological

Absorbing Components: Water

Temperature

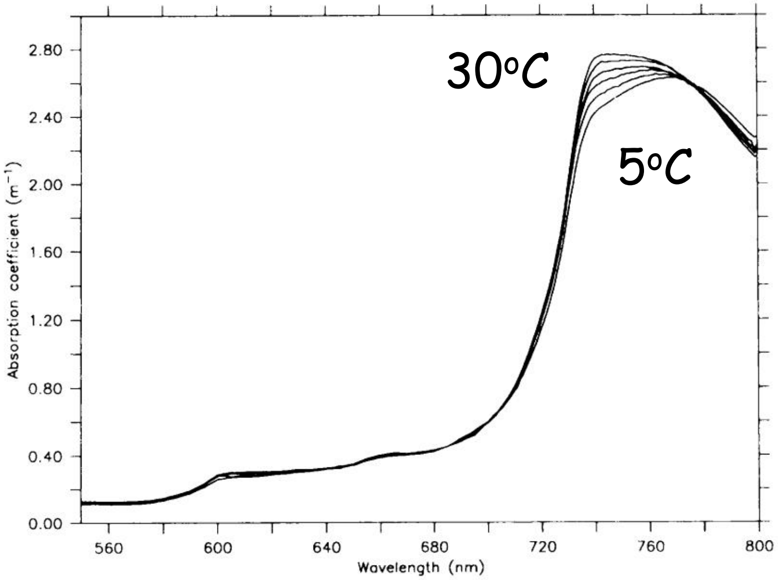
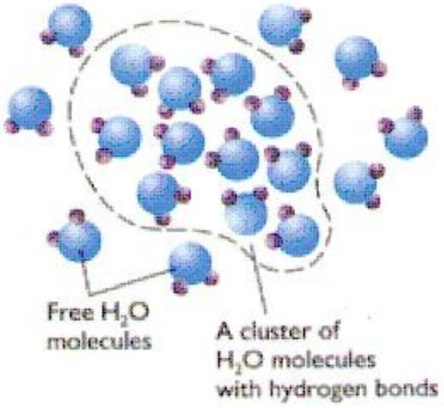
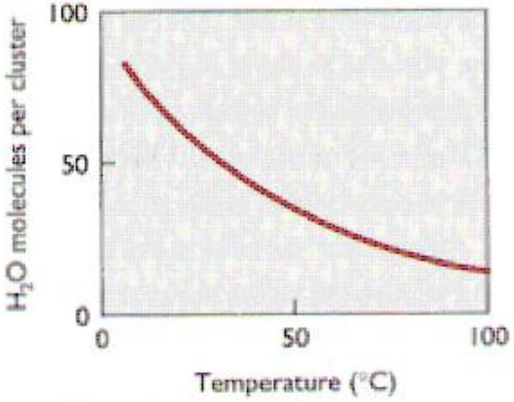


Fig. 3. Absorption coefficient from 550 to 800 nm adjusted at 685 nm to the value of Tam and Patel (1979). The curves represent absorption at temperatures of 5, 10, 15, 21, 25, and 30°C as read from bottom to top at 750 nm.

Pegau and Zaneveld 1993 Limnol Oceanogr.



(d) CLUSTERS OF WATER



(e) SIZE OF WATER CLUSTERS

natural variations

Absorbing Components: Water

Salinity

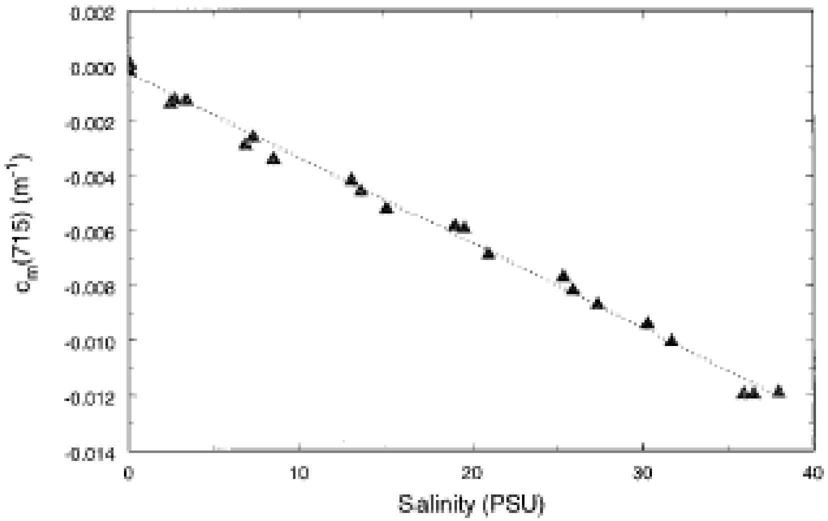
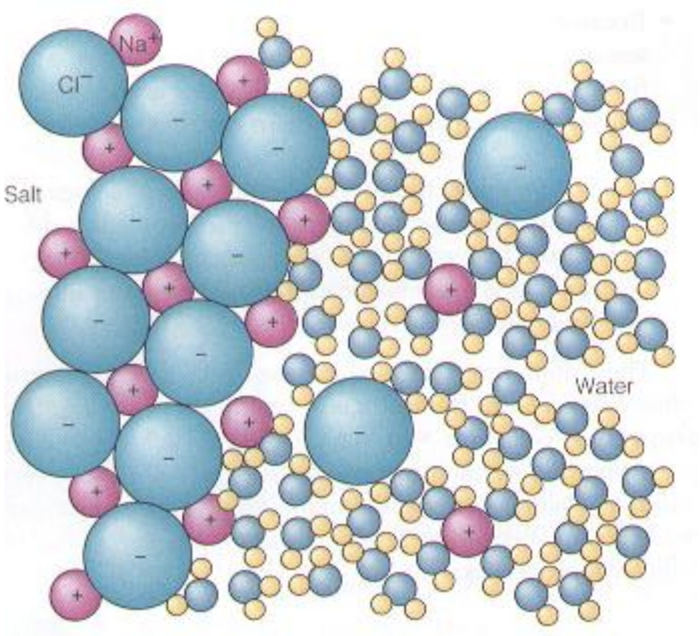
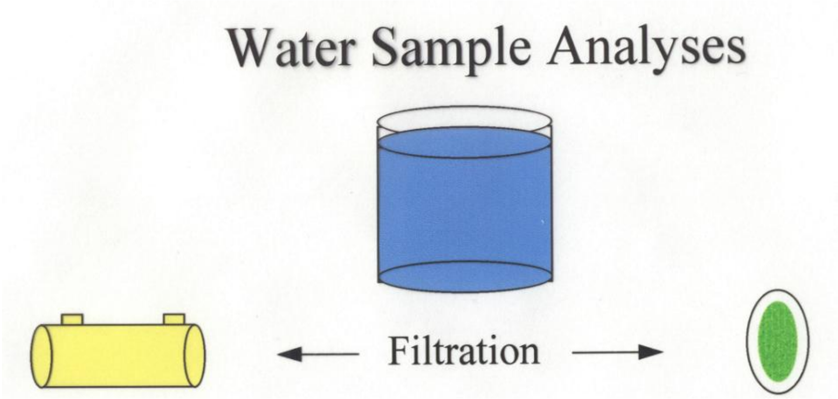


Fig. 6. Attenuation coefficient at 715 nm as a function of salinity. This figure illustrates the linear dependence of the attenuation coefficient on salinity. Pegau etal. 1997 Appl.Opt.



natural variations

Absorbing Components: Colored Dissolved (Organic) Matter



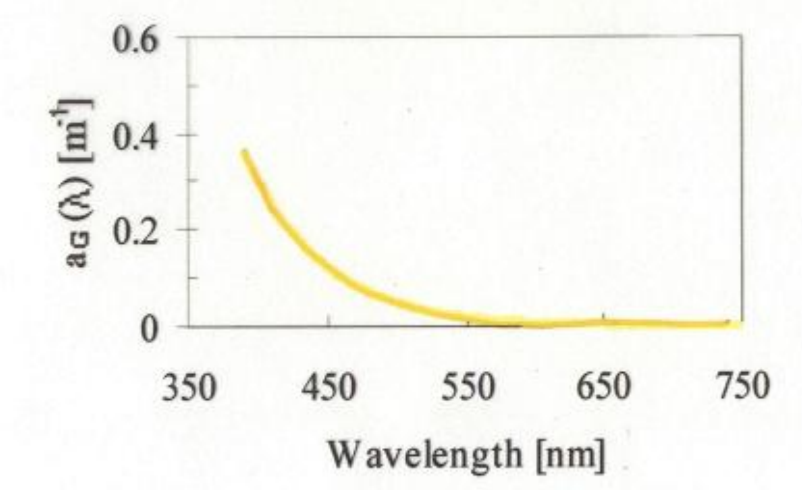
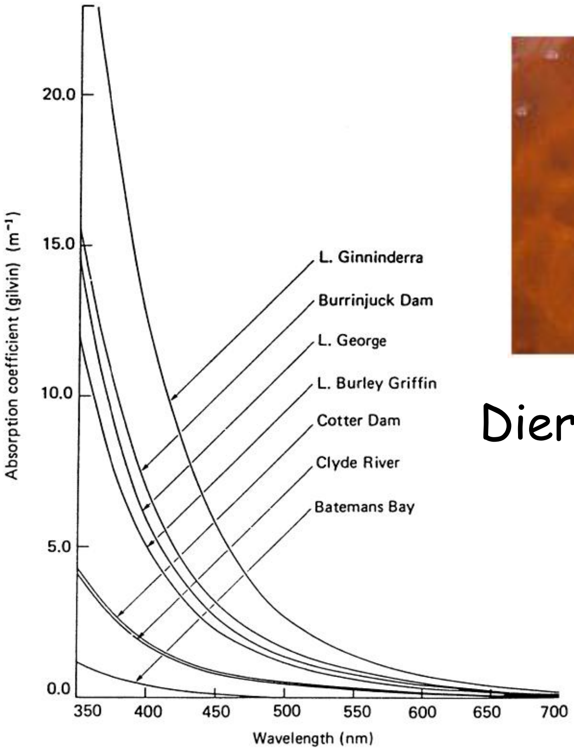
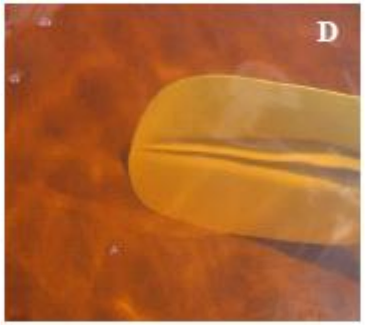


Fig. 3.5. Absorption spectra of soluble yellow material (gilvin) in various Australian natural waters (from Kirk, 1976*b*). The lowest curve (Batemans Bay, NSW) is for coastal sea water near the mouth of a river; the next curve (Clyde River, NSW) is for an estuary; the remainder are for inland water 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.



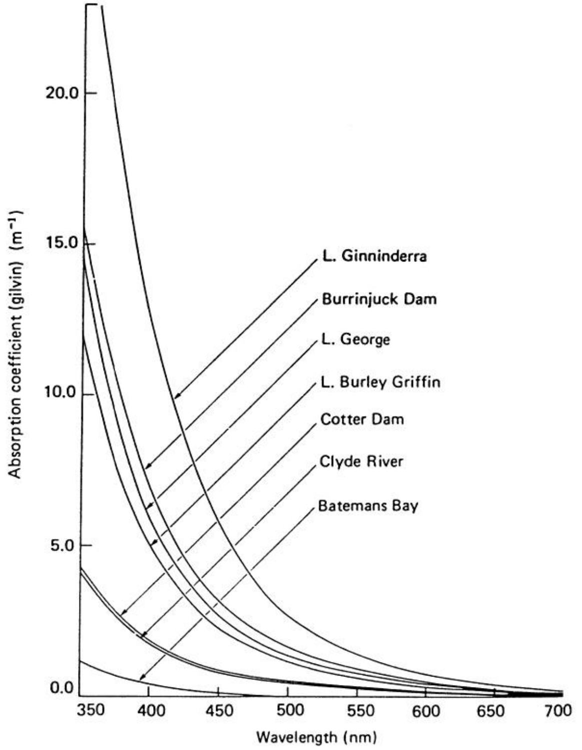
Kirk 1983



Dierssen et al. 2006

Absorbing Components: Colored Dissolved (Organic) Matter

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

$$a_{CDM}(\lambda) = a_{CDM}(\lambda_o)\exp(-S\,(\lambda-\lambda_o))$$

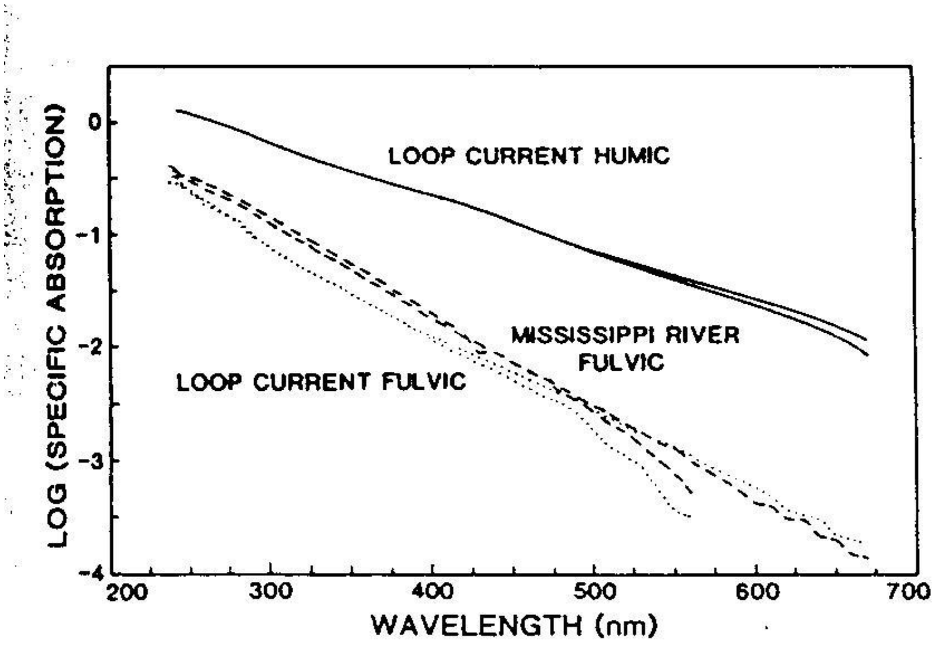
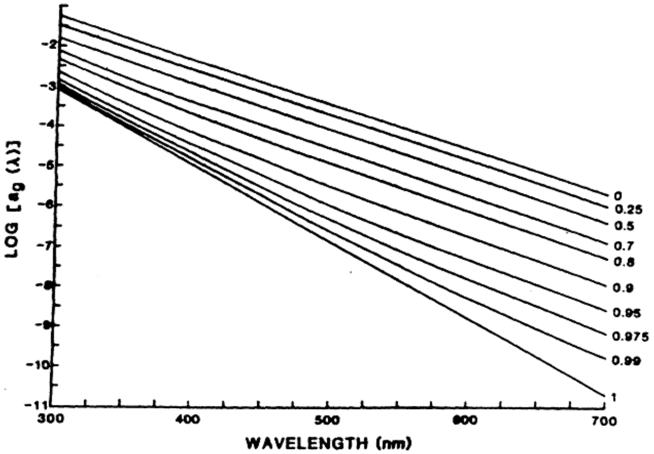


Fig. 1. Specific absorption curves vs. wavelength for marine humic acid and marine fulvic acid.

Carder et al. 1989 L&O

Absorbing Components:
Colored Dissolved (Organic) Matter

$$a_{CDM}(\lambda) = a_{CDM}(\lambda_o) \exp(-S\,(\lambda-\lambda_o))$$



S

0.01

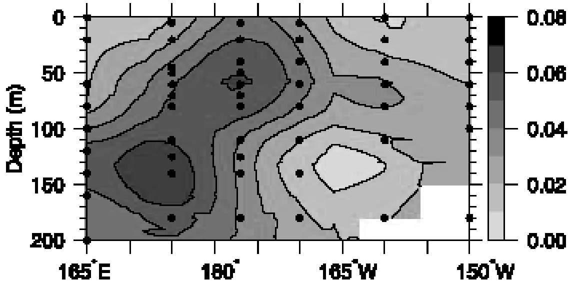
0.02

Fig. 3. Spectral variation of the absorption coefficient due to marine humus or Gelbstoff as a function of t fulvic acid fraction of Gelbstoff for $a^*_f = 0.00732\ m^2\ g^{-1}$, $a^*_h = 0.131\ m^2\ g^{-1}$, $B_f = 0.0186\ nm^{-1}$, and B $0.0110\ nm^{-1}$. The fulvic acid fraction is shown beside each curve.

Carder et al. 1989 L&O

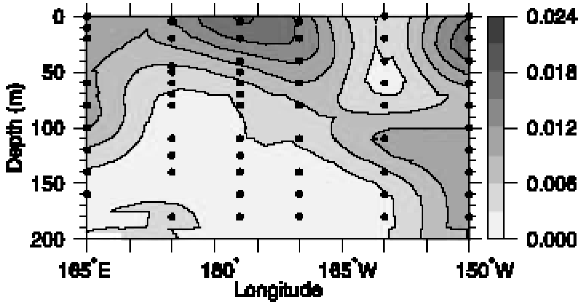
Equatorial Pacific

b. < 0.2 µm a_{CDOM} at 440 nm (m^{-1})



S=0.014

c. 0.2 to 0.7 µm a_{CDOM} at 440 nm (m^{-1})



S=0.011

Simeon et al. 2003 JGR

Absorbing Components: Colored Dissolved (Organic) Matter

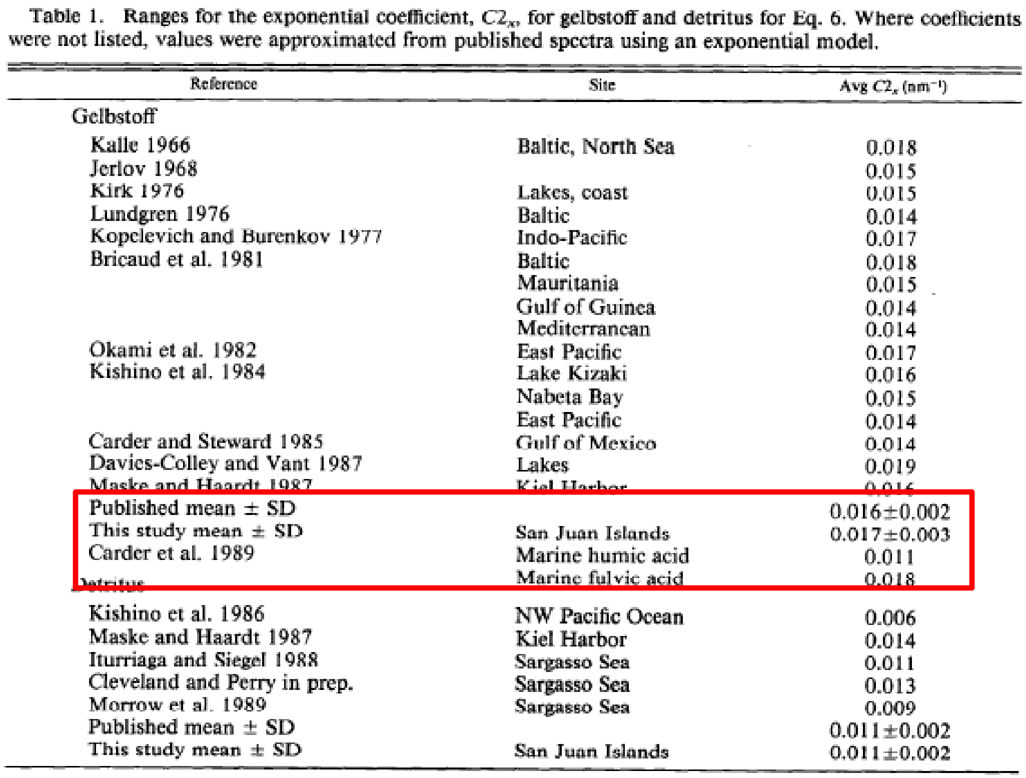
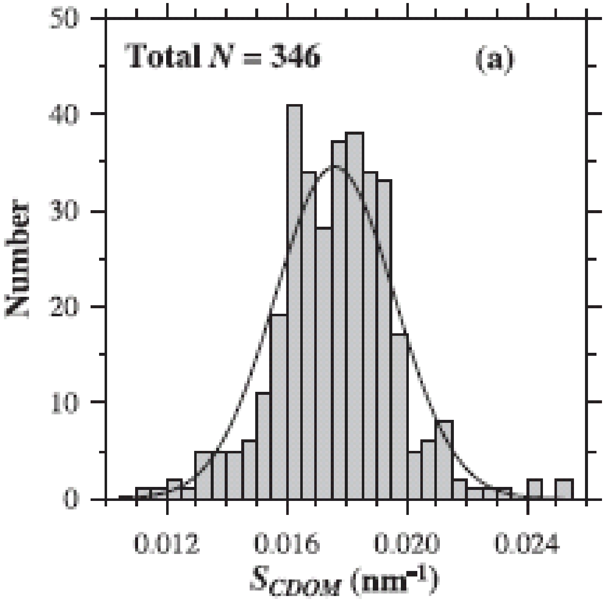


Table 1. Ranges for the exponential coefficient, $C2_x$, for gelbstoff and detritus for Eq. 6. Where coefficients were not listed, values were approximated from published spectra using an exponential model.

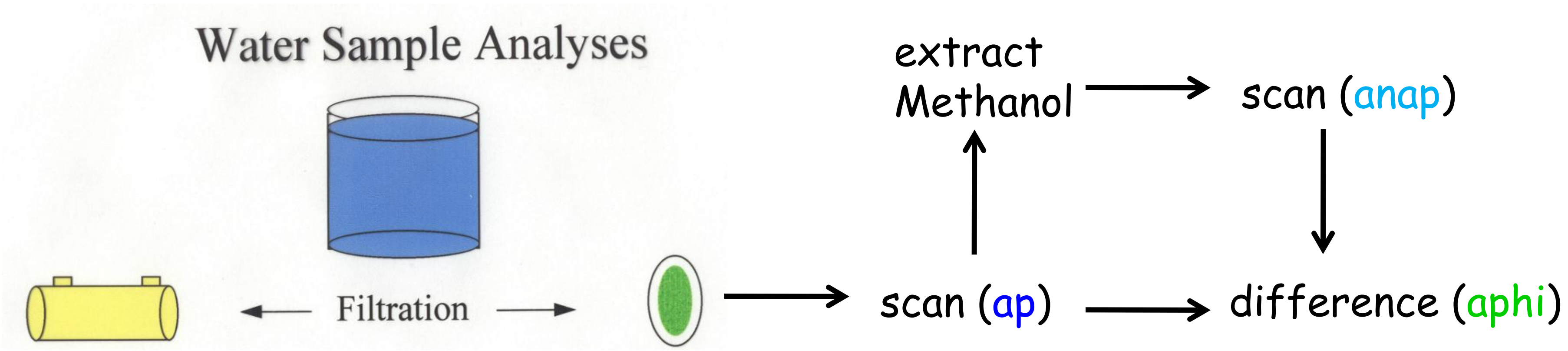
Reference	Site	Avg $C2_x$ (nm^{-1})
Gelbstoff		
Kalle 1966	Baltic, North Sea	0.018
Jerlov 1968		0.015
Kirk 1976	Lakes, coast	0.015
Lundgren 1976	Baltic	0.014
Kopelevich and Burenkov 1977	Indo-Pacific	0.017
Bricaud et al. 1981	Baltic	0.018
	Mauritania	0.015
	Gulf of Guinea	0.014
	Mediterranean	0.014
Okami et al. 1982	East Pacific	0.017
Kishino et al. 1984	Lake Kizaki	0.016
	Nabeta Bay	0.015
	East Pacific	0.014
Carder and Steward 1985	Gulf of Mexico	0.014
Davies-Colley and Vant 1987	Lakes	0.019
Maske and Haardt 1987	Kiel Harbor	0.016
Published mean ± SD		0.016±0.002
This study mean ± SD	San Juan Islands	0.017±0.003
Carder et al. 1989	Marine humic acid	0.011
	Marine fulvic acid	0.018
Detritus		
Kishino et al. 1986	NW Pacific Ocean	0.006
Maske and Haardt 1987	Kiel Harbor	0.014
Iturriaga and Siegel 1988	Sargasso Sea	0.011
Cleveland and Perry in prep.	Sargasso Sea	0.013
Morrow et al. 1989	Sargasso Sea	0.009
Published mean ± SD		0.011±0.002
This study mean ± SD	San Juan Islands	0.011±0.002

Roesler et al. 1989



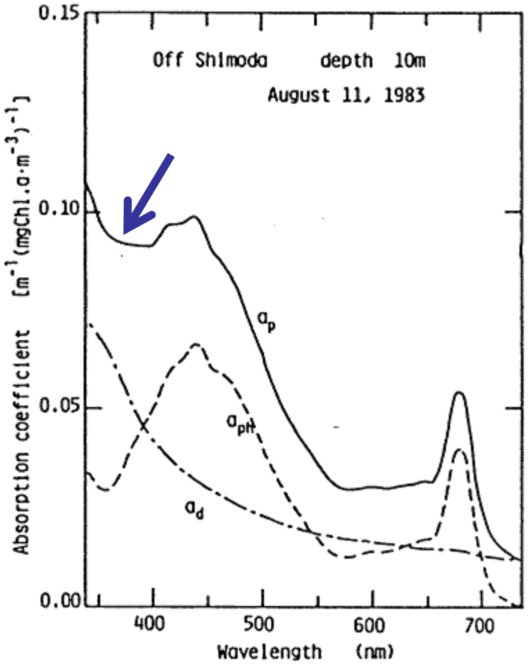
Babin et al. 2003

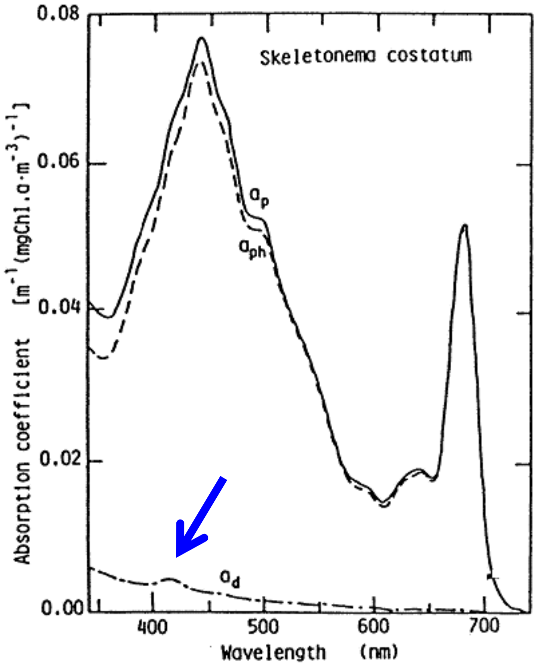
Absorbing Components: Particles



extract Methanol → scan (anap)

scan (ap) → difference (aphi)

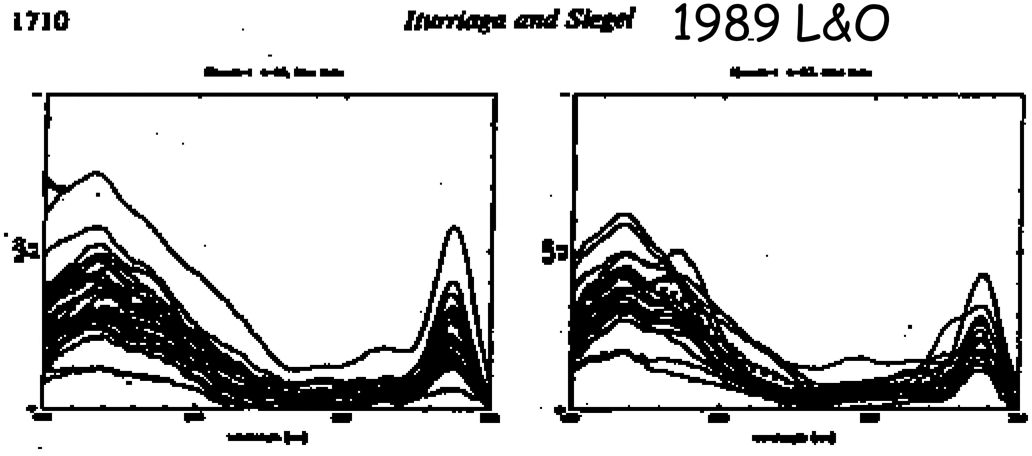




Kishino et al 1985

Absorbing Components: Phytoplankton

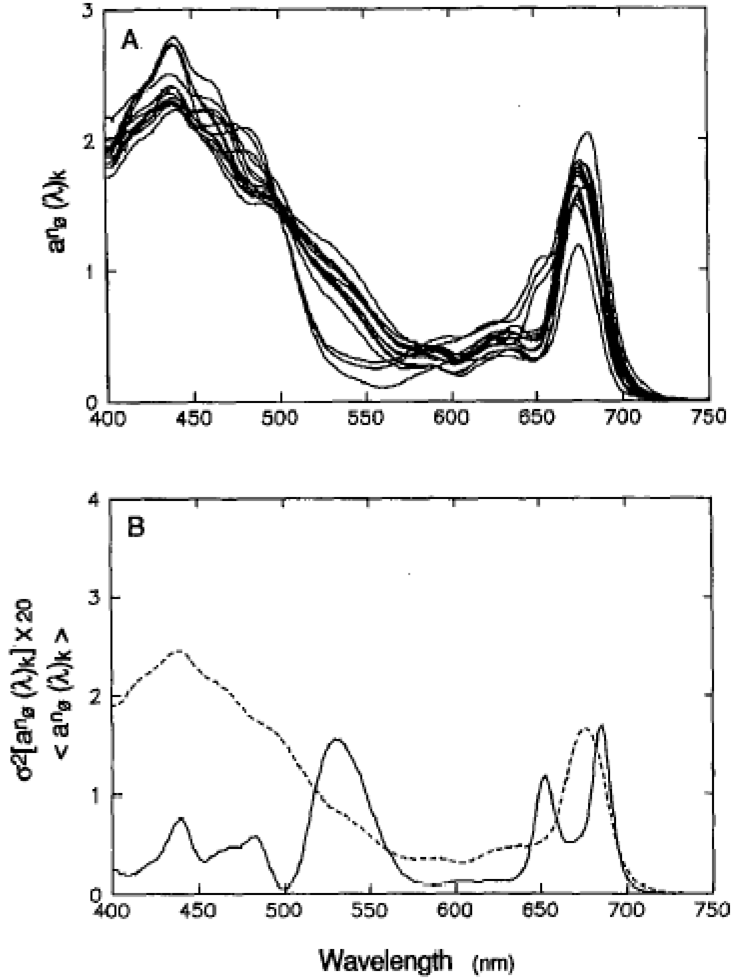
Individual cells, microphotometry



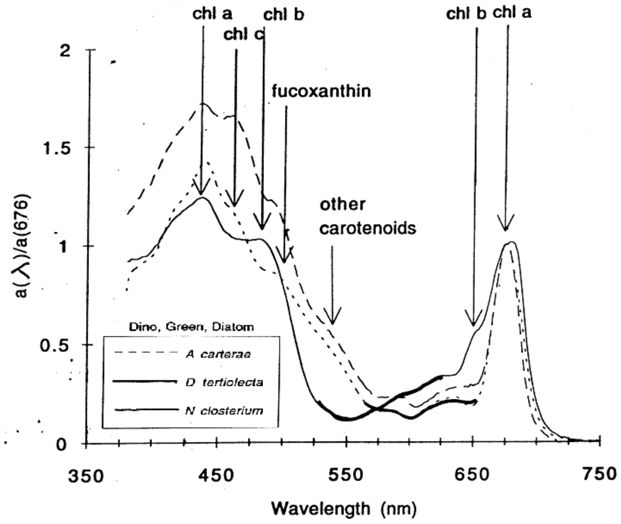
1989 L&O

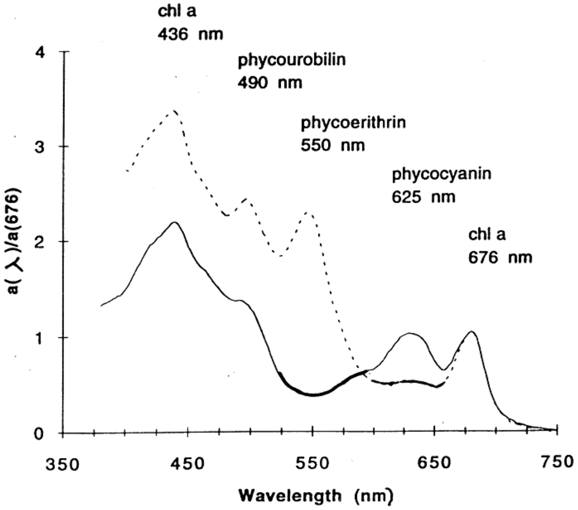
Absorbing Components: Phytoplankton

Species



Roesler et al. 1989 L&O





Absorbing Components: Phytoplankton

Pigment Packaging impact on absorption

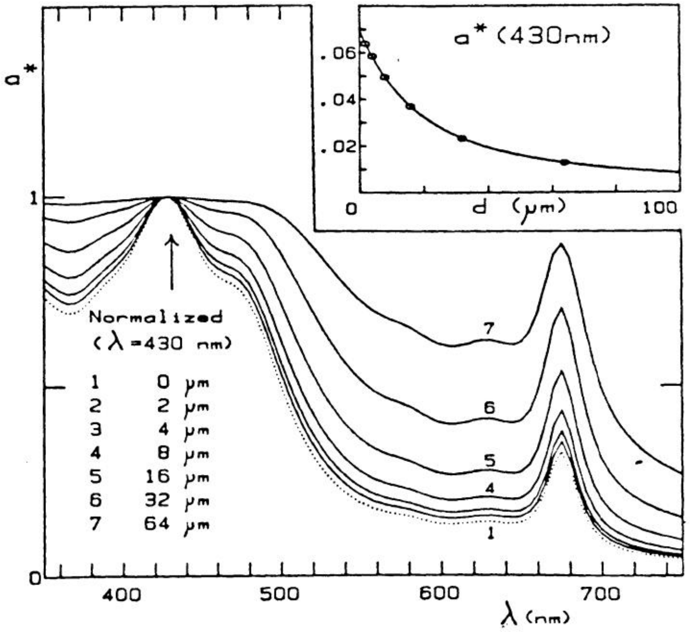
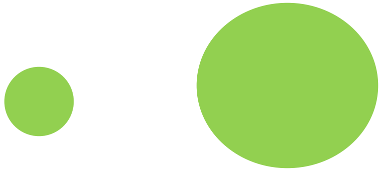


Fig. 2. Change in spectral absorption values with variable cell size (diameter, *d*, in μm) whereas the cell material forming the cells remains unchanged. The spectral absorption values of this material, somewhat arbitrarily adopted, are shown as the dotted curve. All curves are normalized, at $\lambda = 430$ nm, to evidence the progressive deformation. The variations with size of the specific absolute value at 430 nm ($m^2\ mg^{-1}$ Chl *a*) are shown in inset, under the same assumption of a constant absorption of the cell material ($a_{cm} = 2 \times 10^5\ m^{-1}$ at 430 nm) and with the additional assumption of a constant intracellular pigment concentration ($c_i = 2.86 \times 10^6$ mg Chl $a\ m^{-3}$).

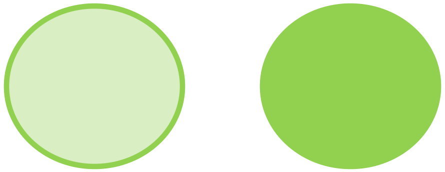
Morel and Bricaud 1981 DSR

(1) vary size, maintain constant intracellular pigment concentration



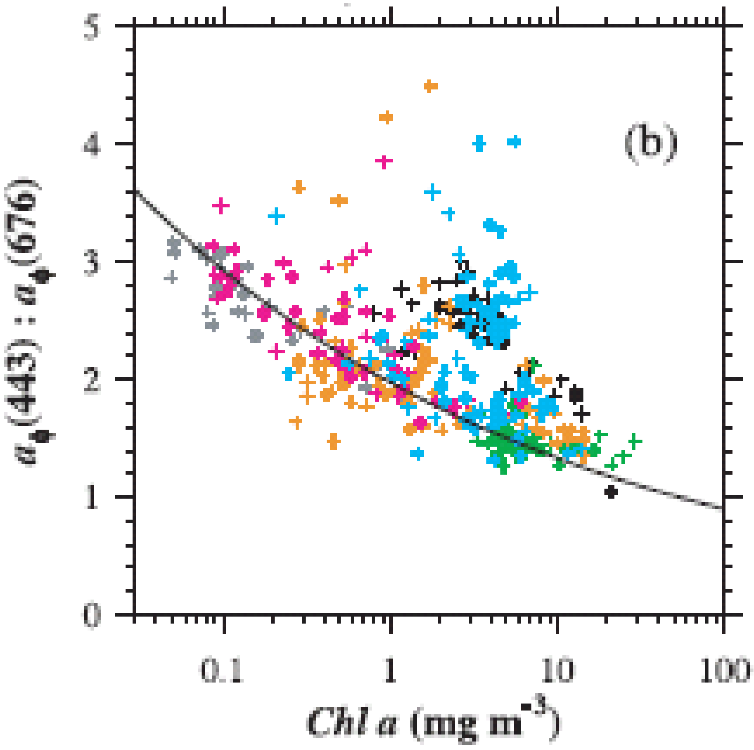
or

(2) maintain size, vary intracellular pigment concentration



Absorbing Components: Phytoplankton

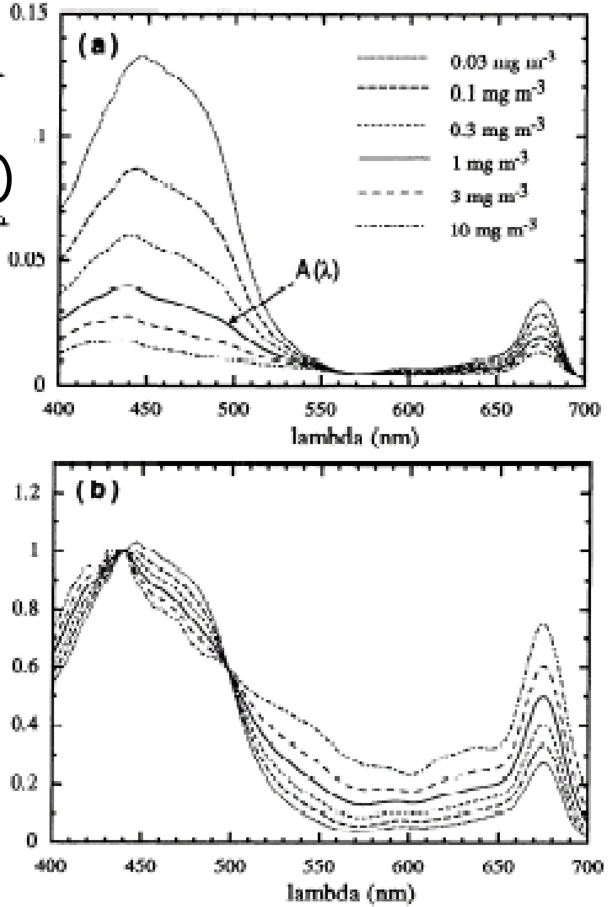
Babin et al. 2003



Bricaud et al. 1995

a*phi
(m^2/mg chl)

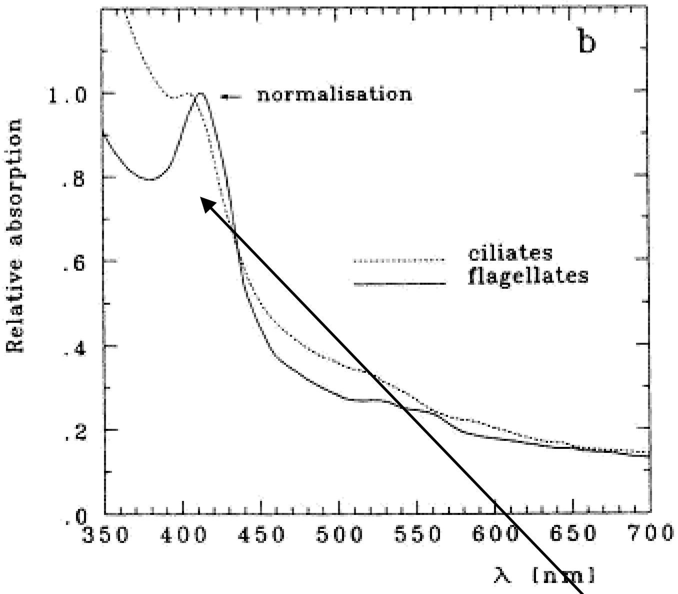
$\frac{\text{aphi}(\lambda)}{\text{aphi}(440)}$



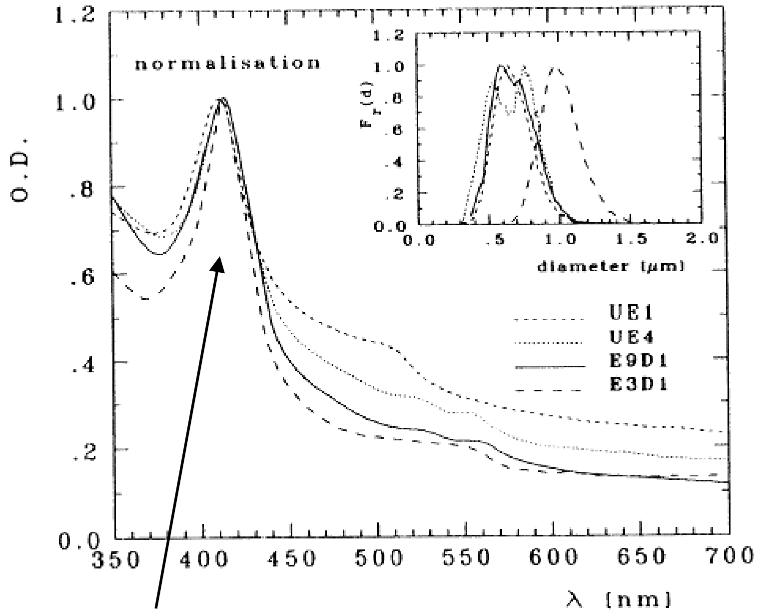
Global Relationships

Absorbing Components: other protists

ciliates and flagellates



heterotrophic bacteria

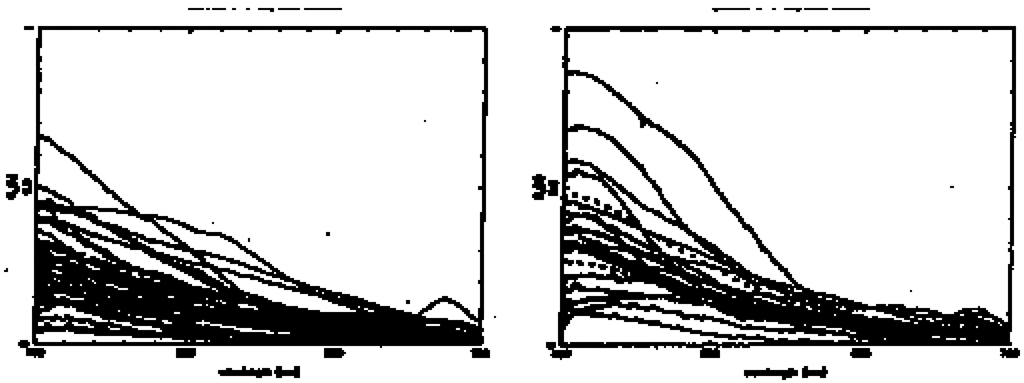


cytochrome 412

Morel and Ahn 1990 JMR

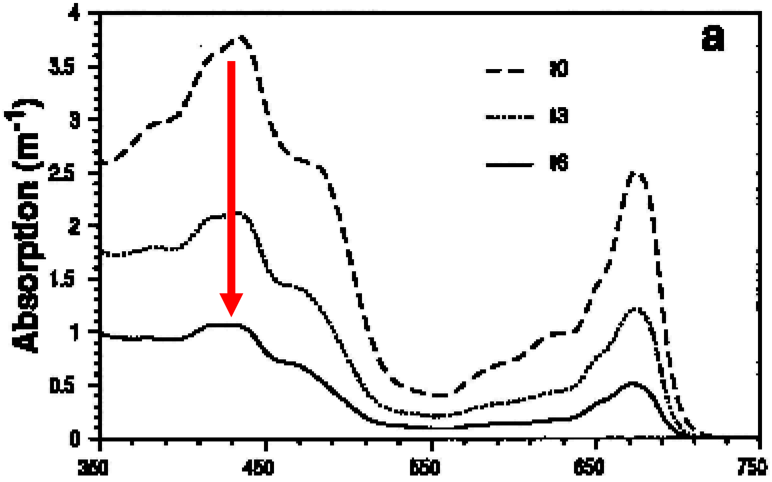
Absorbing Components:

Non-algal Particles →organic detrital particles



Iturriaga and Siegel 1989 L&O

Nelson & Robertson: Detrital spectral absorption 1993]
JMR



Absorbing Components:
Non-algal Particles

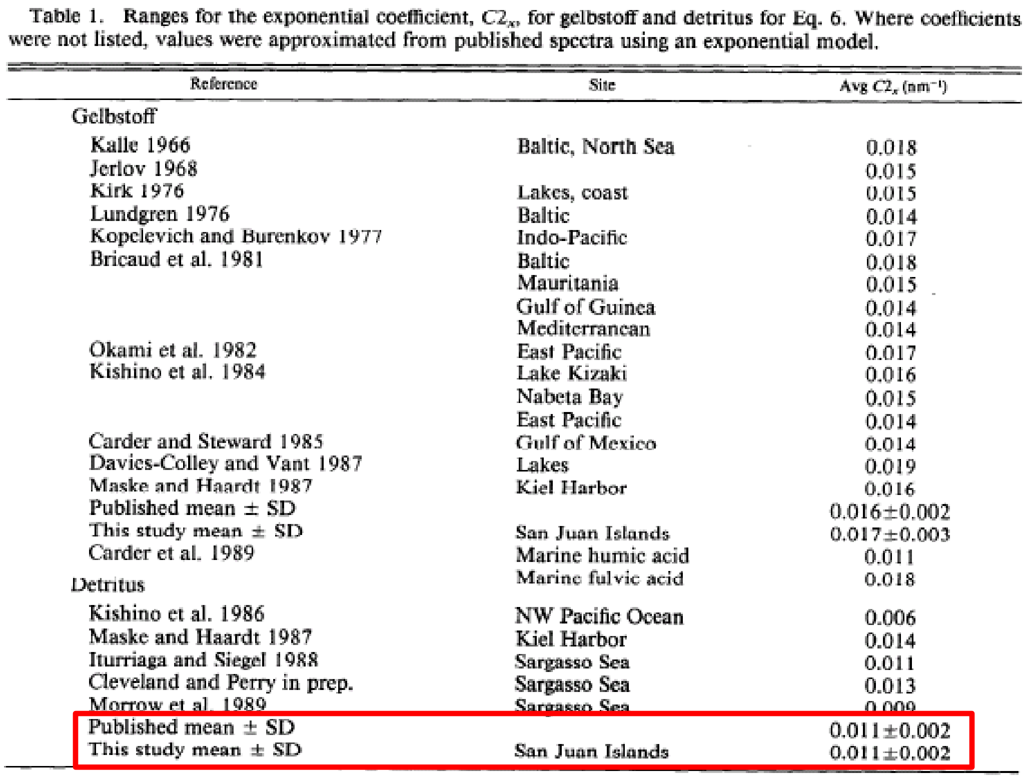
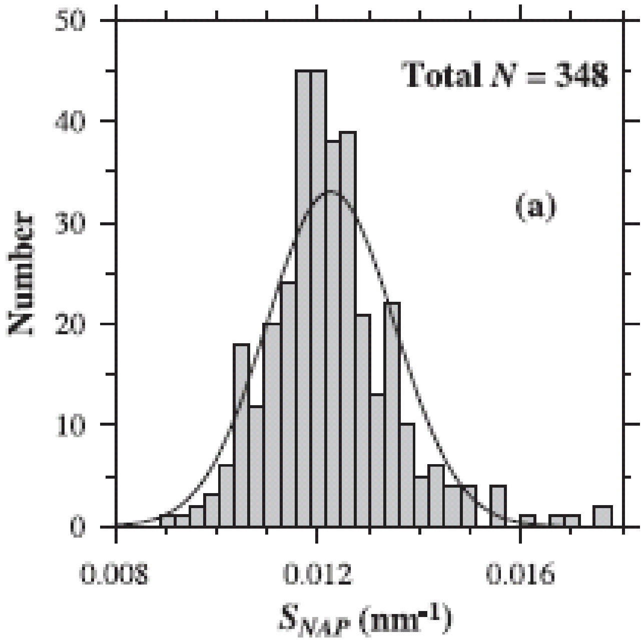


Table 1. Ranges for the exponential coefficient, $C2_x$, for gelbstoff and detritus for Eq. 6. Where coefficients were not listed, values were approximated from published spectra using an exponential model.

Reference	Site	Avg $C2_x$ (nm^{-1})
Gelbstoff		
Kalle 1966	Baltic, North Sea	0.018
Jerlov 1968		0.015
Kirk 1976	Lakes, coast	0.015
Lundgren 1976	Baltic	0.014
Kopelevich and Burenkov 1977	Indo-Pacific	0.017
Bricaud et al. 1981	Baltic	0.018
	Mauritania	0.015
	Gulf of Guinea	0.014
	Mediterranean	0.014
Okami et al. 1982	East Pacific	0.017
Kishino et al. 1984	Lake Kizaki	0.016
	Nabeta Bay	0.015
	East Pacific	0.014
Carder and Steward 1985	Gulf of Mexico	0.014
Davies-Colley and Vant 1987	Lakes	0.019
Maske and Haardt 1987	Kiel Harbor	0.016
Published mean ± SD		0.016±0.002
This study mean ± SD	San Juan Islands	0.017±0.003
Carder et al. 1989	Marine humic acid	0.011
	Marine fulvic acid	0.018
Detritus		
Kishino et al. 1986	NW Pacific Ocean	0.006
Maske and Haardt 1987	Kiel Harbor	0.014
Iturriaga and Siegel 1988	Sargasso Sea	0.011
Cleveland and Perry in prep.	Sargasso Sea	0.013
Morrow et al. 1989	Sargasso Sea	0.009
Published mean ± SD		0.011±0.002
This study mean ± SD	San Juan Islands	0.011±0.002



Roesler et al. 1989

Babin et al. 2003

Absorbing Components: non-algal particles

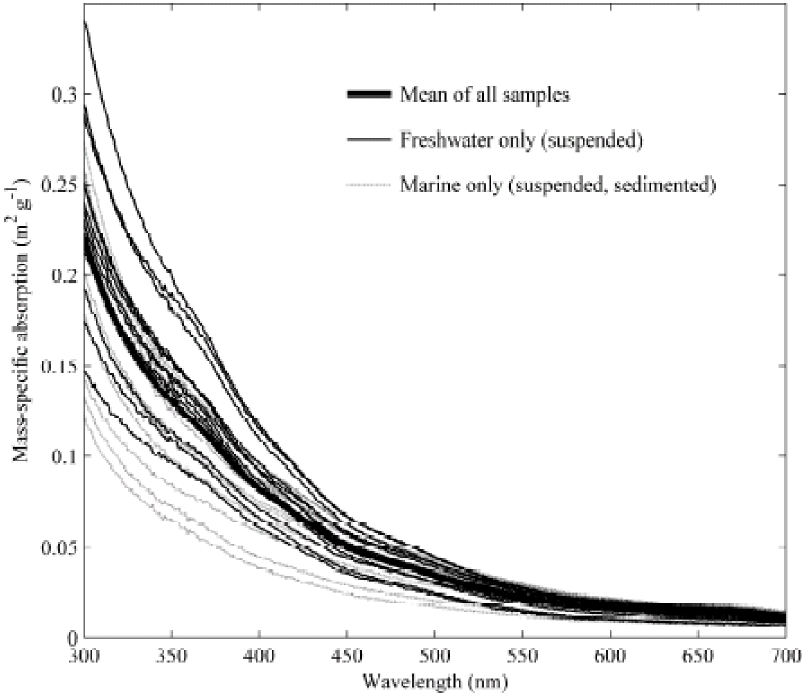


Figure 3.3. Mass-specific absorption spectra of all samples analyzed here (N = 25). Heavy black line shows the mean, thin solid lines show samples from freshwater sites on the Atchafalaya and Mississippi Rivers, and dashed lines show samples from marine sites at Freshwater Bayou and the Atchafalaya River delta. Marine samples include both sediments and suspended particulates; river samples are suspended particulates only.

iron oxide minerals

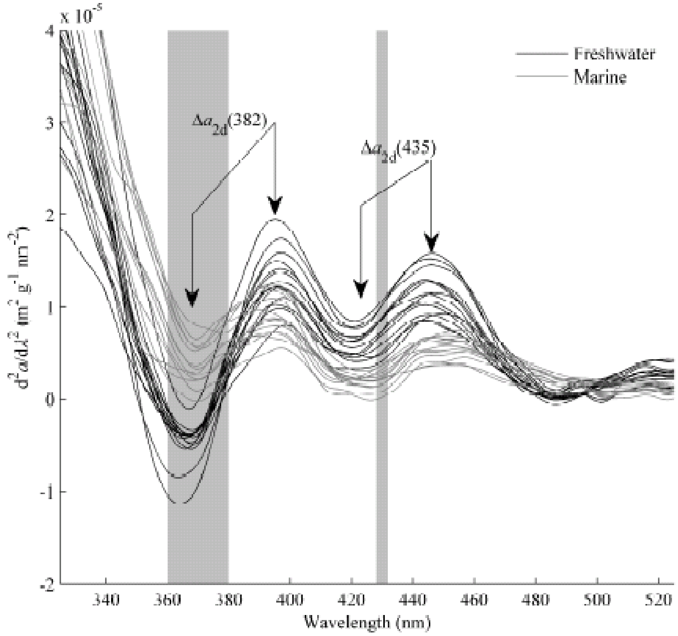


Figure 3.10. Second derivatives of mass-specific absorption spectra. Black lines denote freshwater samples and gray lines denote marine samples. Bracketed arrows labeled "$\Delta a_{2d}(382)$" and "$\Delta a_{2d}(435)$" show locations of second-derivative maxima and minima used to compute iron absorption peak heights plotted in Figure 3.11. Light gray vertical bars highlight approximate ranges for electronic transition bands of various iron oxide minerals (Sherman and Waite, 1985).

Estapa 2011

Absorbing Components: inorganic particles

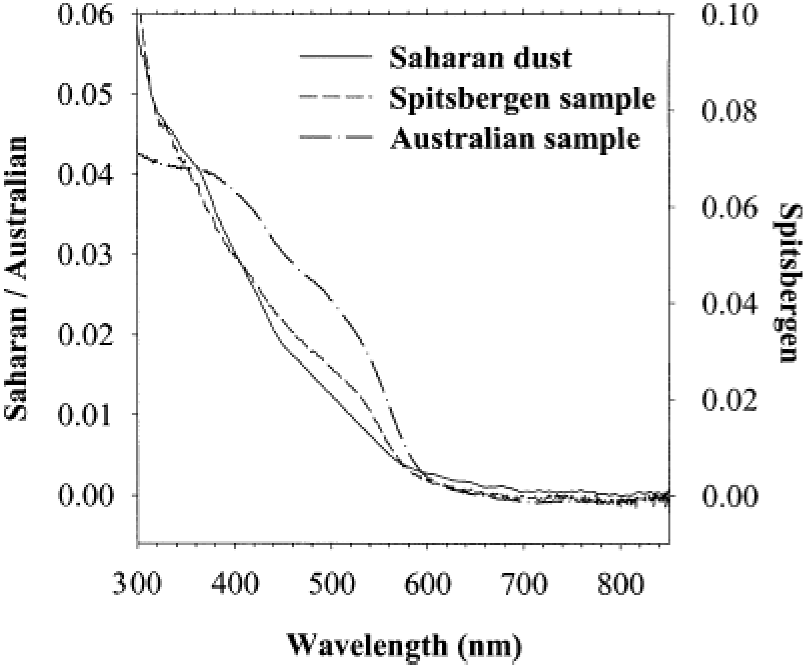


Fig. 5. Absorbance spectra of natural assemblages of mineral particles from three different environments.

Babin and Stramski 2003

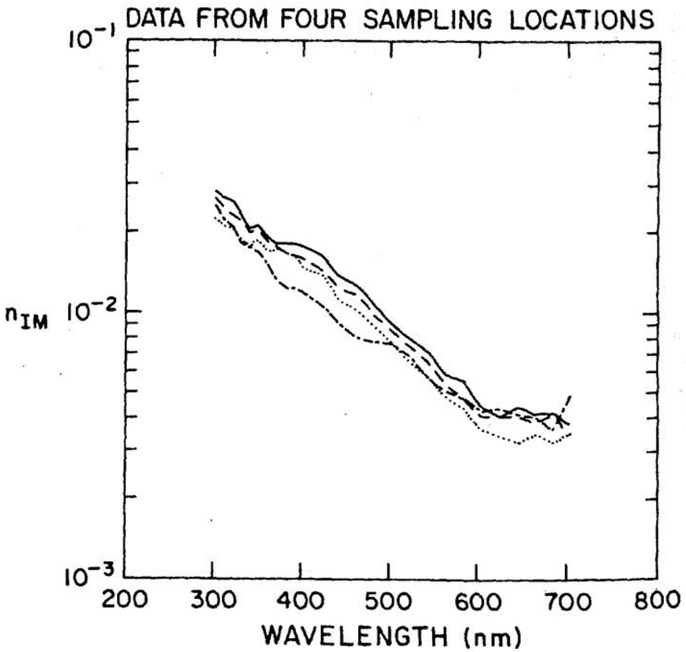
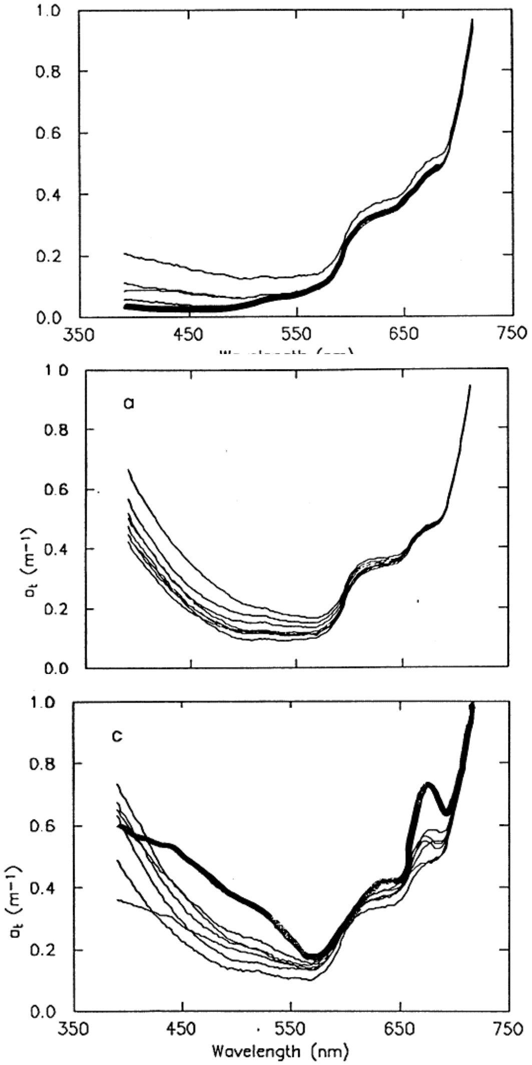
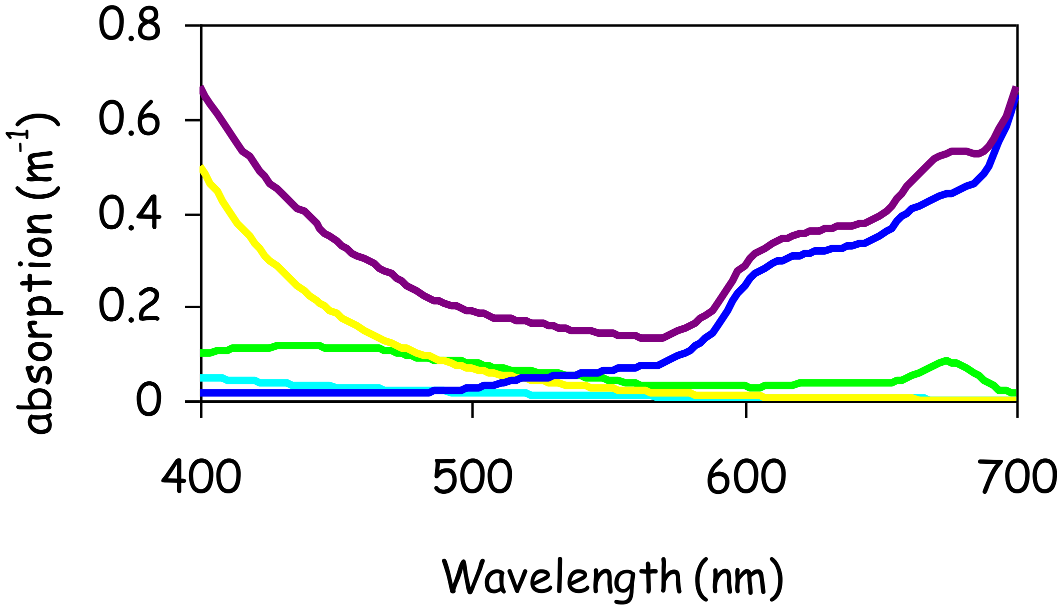


Fig. 8. Imaginary index of refraction for Saharan aerosols from each of the collection locations. The solid line represents the Tenerife sample; the dashed line, the *Meteor* sample; the dotted line, the Barbados sample; and the dashed-dotted line, the Sal Island sample.

Patterson et al. 1977 JGR

To model the impacts of absorbing constituents…add them up





which component dominates?

More on absorption

- Phytoplankton
  - next Lecture
- CDOM absorption methods
  - Beer's Law Lecture this afternoon
  - Lab today
- Particulate absorption methods
  - Lab Wednesday