An Introduction to Marine Optics

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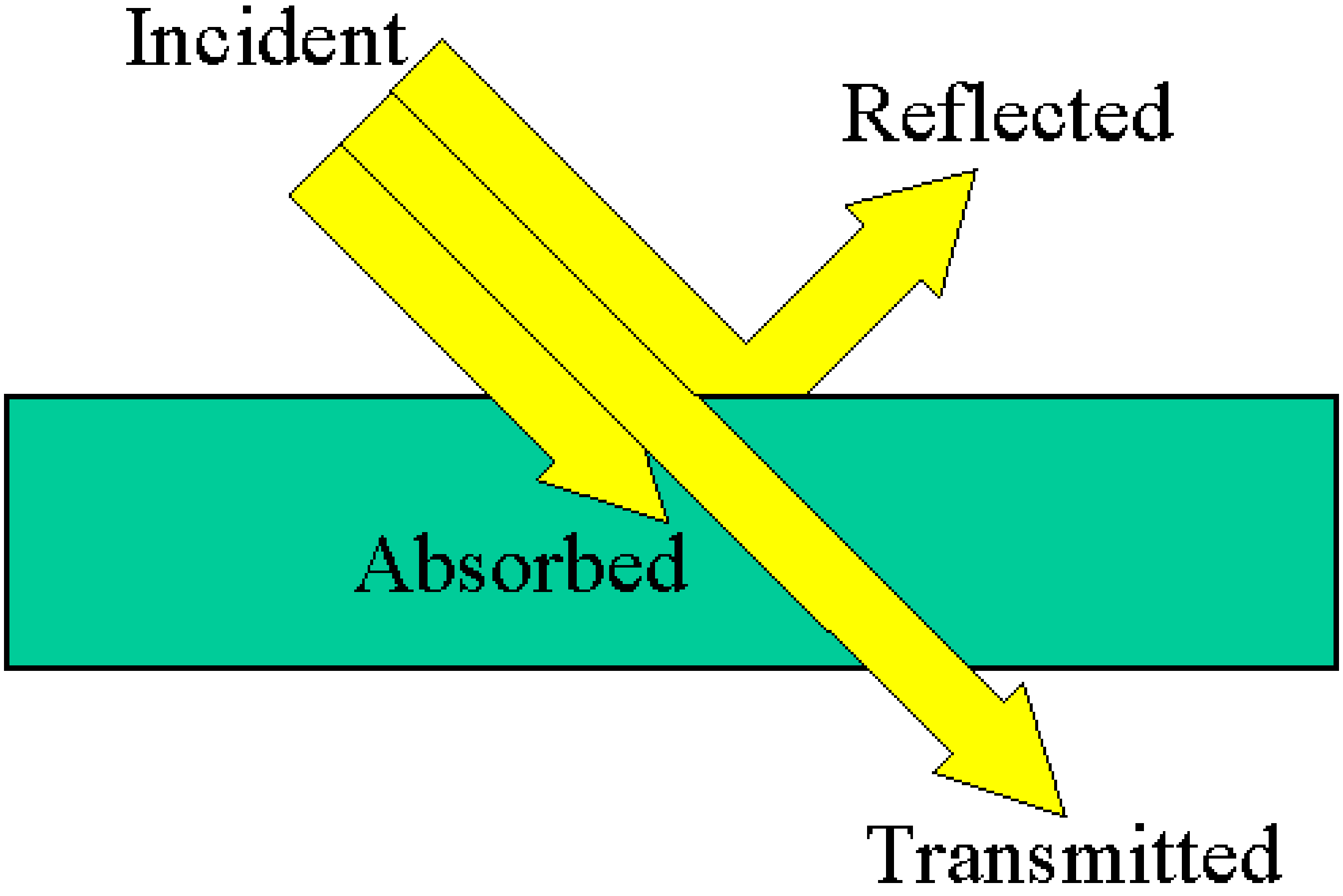
WHAT IS OCEAN COLOUR ?

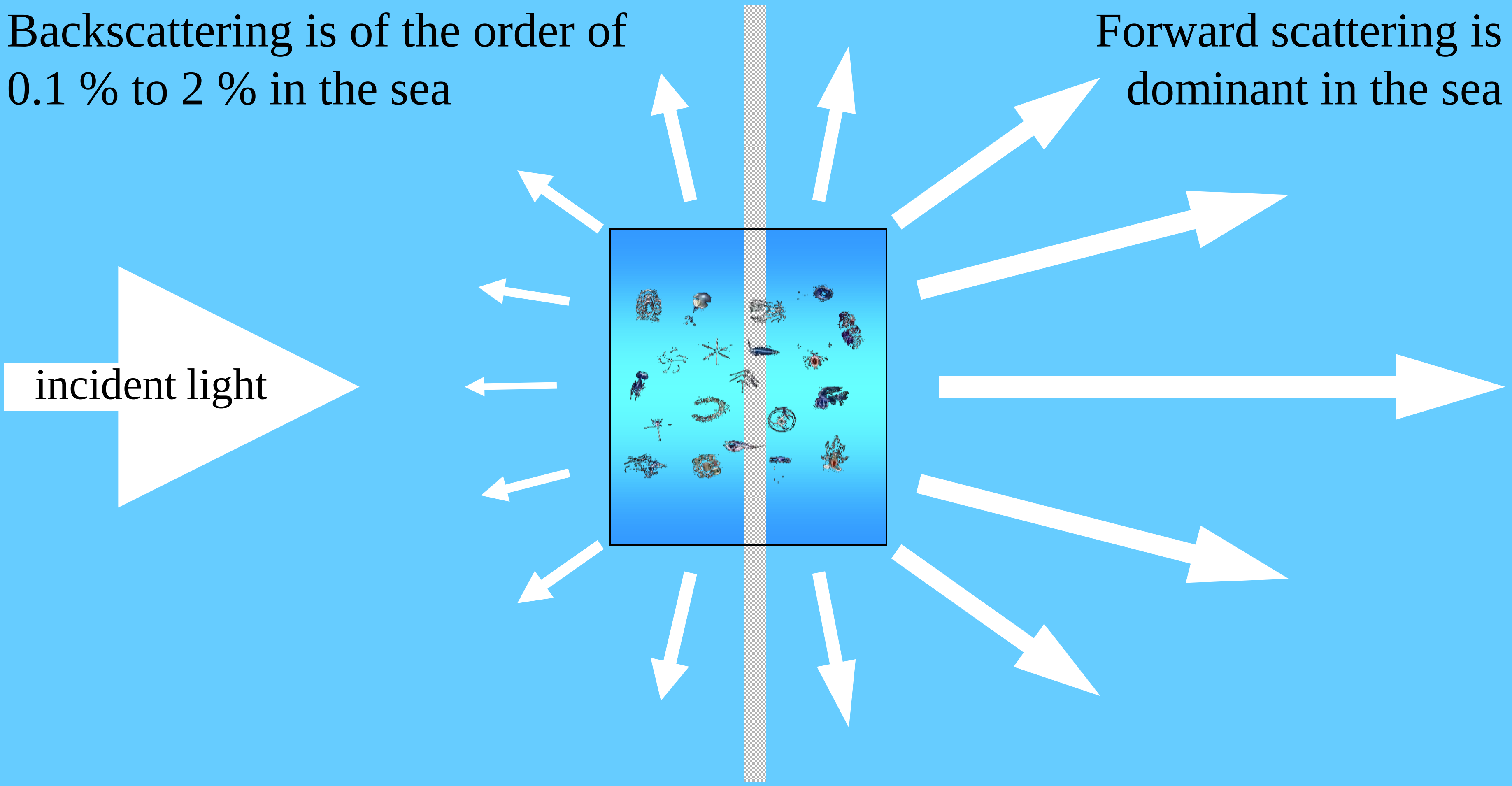
Colour of the ocean is BLUE in clear water but it changes due to :

- **Phytoplankton Patchiness**
- **Inorganic/Organic Matter**


Incident
Reflected
Absorbed
Transmitted

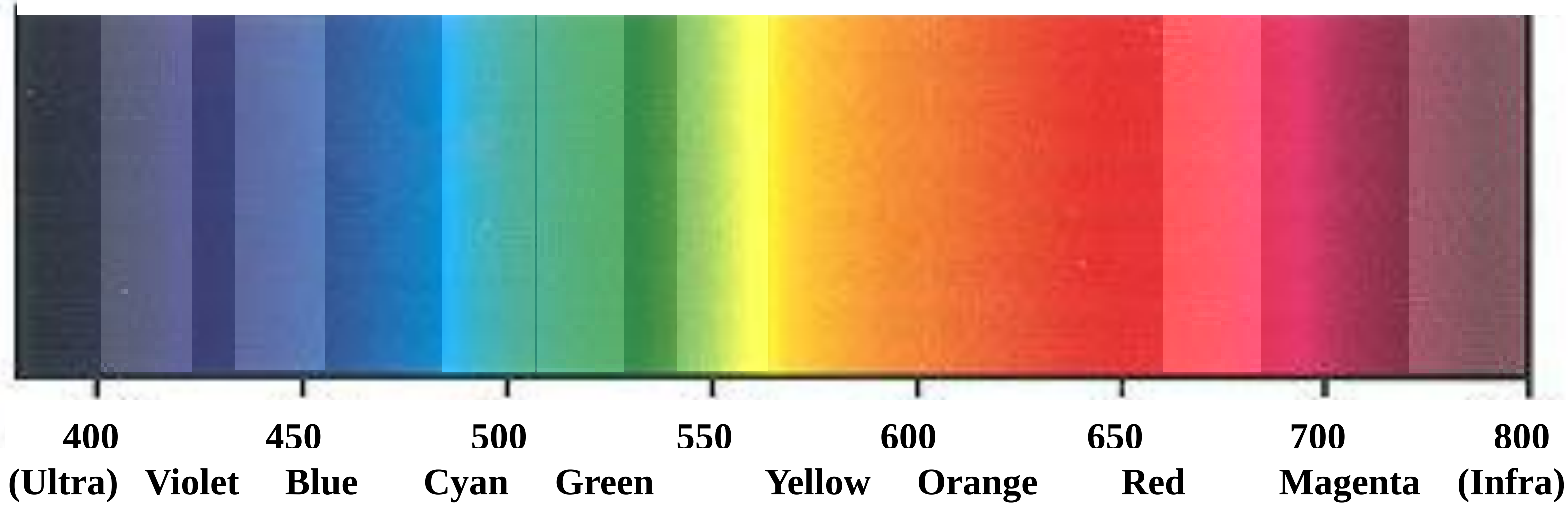
“There are only two things that can happen to photons within water: they can be absorbed or they can be scattered.”

Scattering is the change of direction of a photon



Absorption is the loss of a photon

THE VISIBLE SPECTRUM • wavelength in nanometers



Nature of light

EMR- Photons or quanta – A beam of light-continual stream of photons – very large number of photons travels at speed of 3 x10 8 m/s

In summer one sq meter of horizontal surface receives
About x10 21 quanta/ s of visible light

Each photon has a **λ** and **ν** related as **λ = c /ν,**
c is m/s, **ν is cycles/s, λ is in** meters.
Generally **I Remote Sensing λ** is in nanometers.

Energy ε = h ν = h c/λ
h is Planck constant 6.63 x10 –34 Js

Nature of light

A monochromatic radiant flux of Quanta (J/s) can be converted to Watts(W) i.e

quanta/s = 5.03 x radiant flux of wavelength x 1015

(it is not as simple to convert a photon of quanta to PAR because λ varies continuously)

Morel & Smith (1974) Q: W is 2.77 x10 18 quanta/s / w with in PAR(10%)

Refractive Index of air 1.00028. Vacuum 1.0

C in water is 2.25 x10 8 m/s as in air is 3.000 x10 8 m/s

PENETRATION OF LIGHT

$$I(z) = I(0)e^{-Kz}$$ non-spectral, uniform depth

$$I(z) = I(0)e^{-\int_0^z K(z')dz'}$$ non-spectral, Non uniform depth

$$I(z,\lambda) = I(0,\lambda)e^{-\int_0^z K(z',\lambda)dz'}$$ non-spectral, Non uniform depth

$$I(z) = \int_{\lambda=400}^{\lambda=700} I(0,\lambda)e^{-\int_0^z K(z',\lambda)dz'} d\lambda$$

Water Column Considerations

- The decay of incident light with depth is described by the downwelling diffuse attenuation coefficient - either spectrally with $K_d(\lambda)$ or broadband (400 nm - 700 nm) with $K_d(PAR)$

$$E_d(z) = E_d(0)\, e^{-K_d\, z} \qquad optical\ \ depth\ \zeta = K_d\ \ z$$

- Incident irradiance is therefore typically attenuated in an exponential manner

- The euphotic (well lit) zone is defined as being the layer within which $E_d(PAR)$ falls to within 1% of the subsurface value.

- ~ 90 % of water leaving radiance, or the satellite signal, emerges from the first optical depth or $1/K_d$

Optical Properties of the Sea

Inherent Optical Properties

"…depend only upon the substances comprising the aquatic medium and not on the geometric structure of the light fields…"

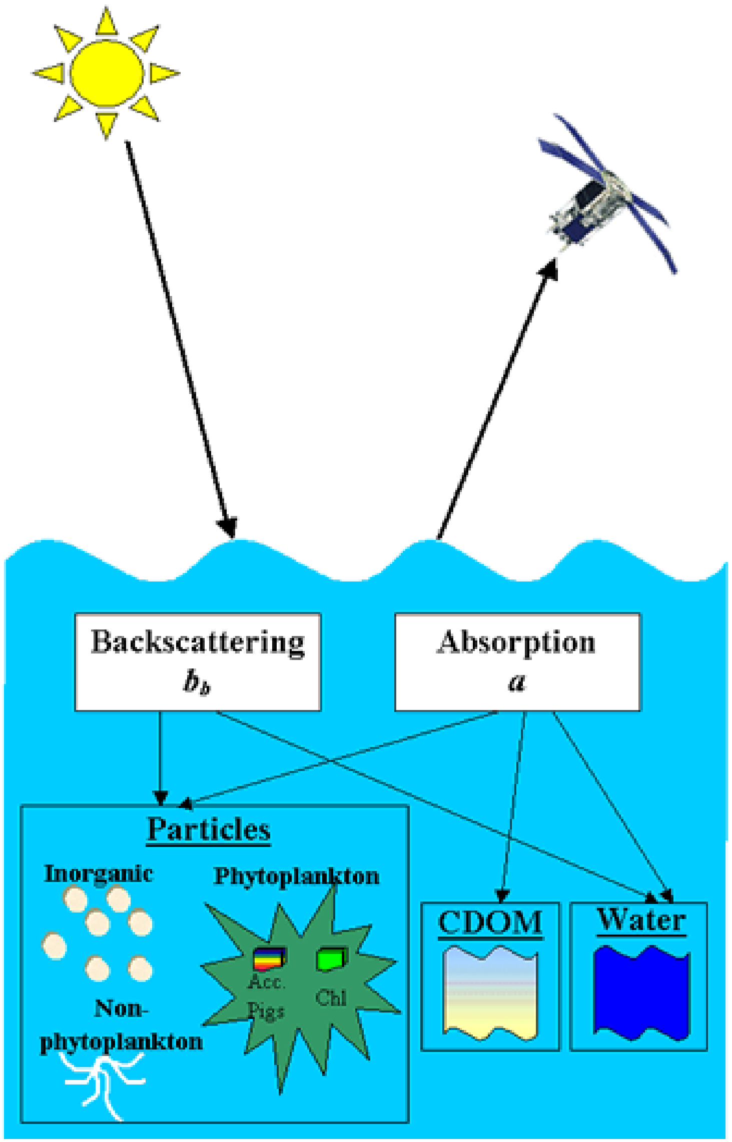
Absorption coefficient a [m^{-1}] Attenuation coefficient c [m^{-1}]
Scattering coefficient b [m^{-1}] Backscattering coefficient b_b [m^{-1}]
Volume scattering function $ß$ [$m^{-1}sr^{-1}$]

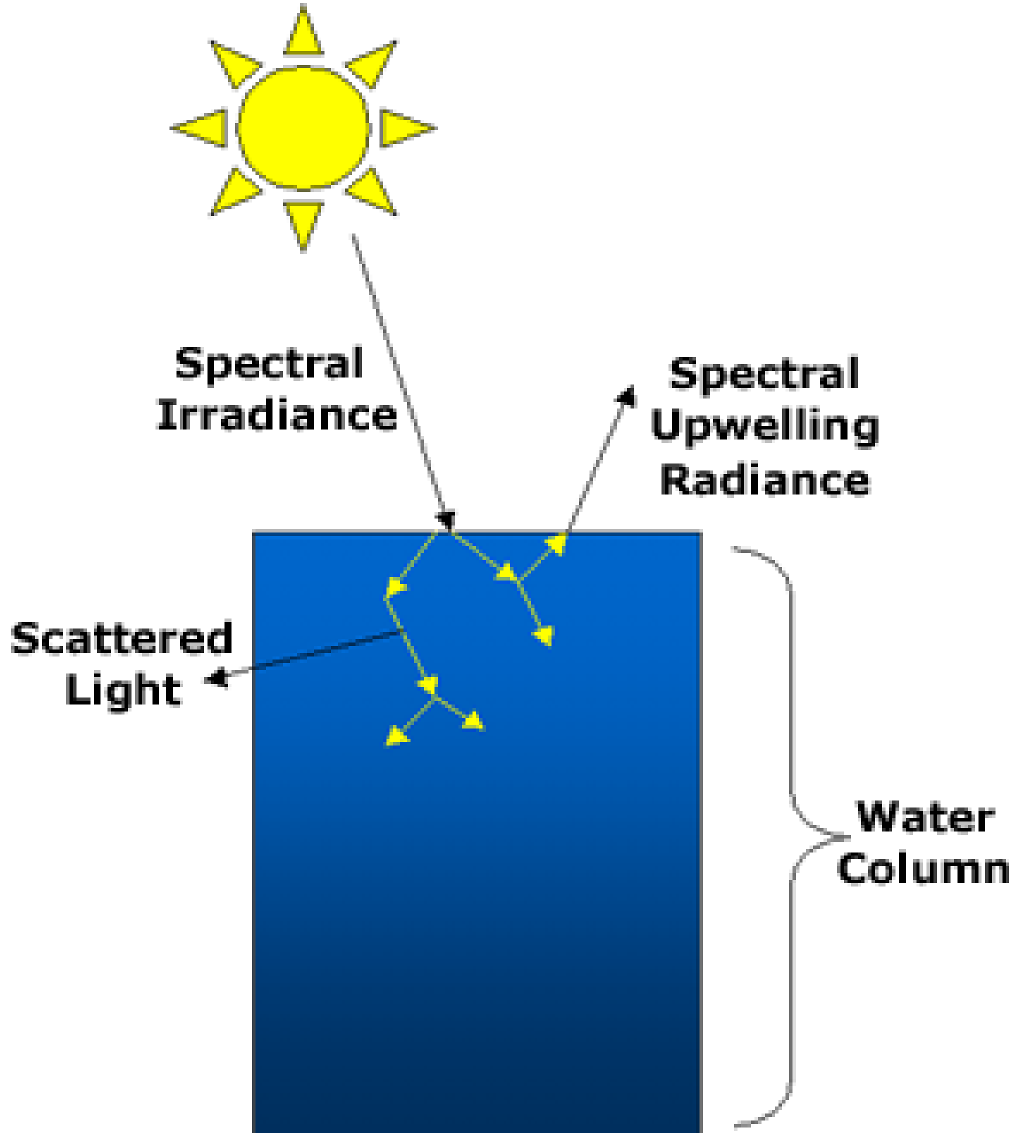
Apparent Optical Properties

Radiance L [$W\ m^{-2}\ sr^{-1}$]
Reflectance R
} ratio of these is or ocean colour
Irradiance E [$W\ m^{-2}$]
Diffuse attenuation coefficient K [m^{-1}]

All of the above are wavelength (λ) dependent

OCEAN OPTICS





The Absorbing and Scattering Constituents of Seawater

These can be separated into particulate and dissolved components

Major Components

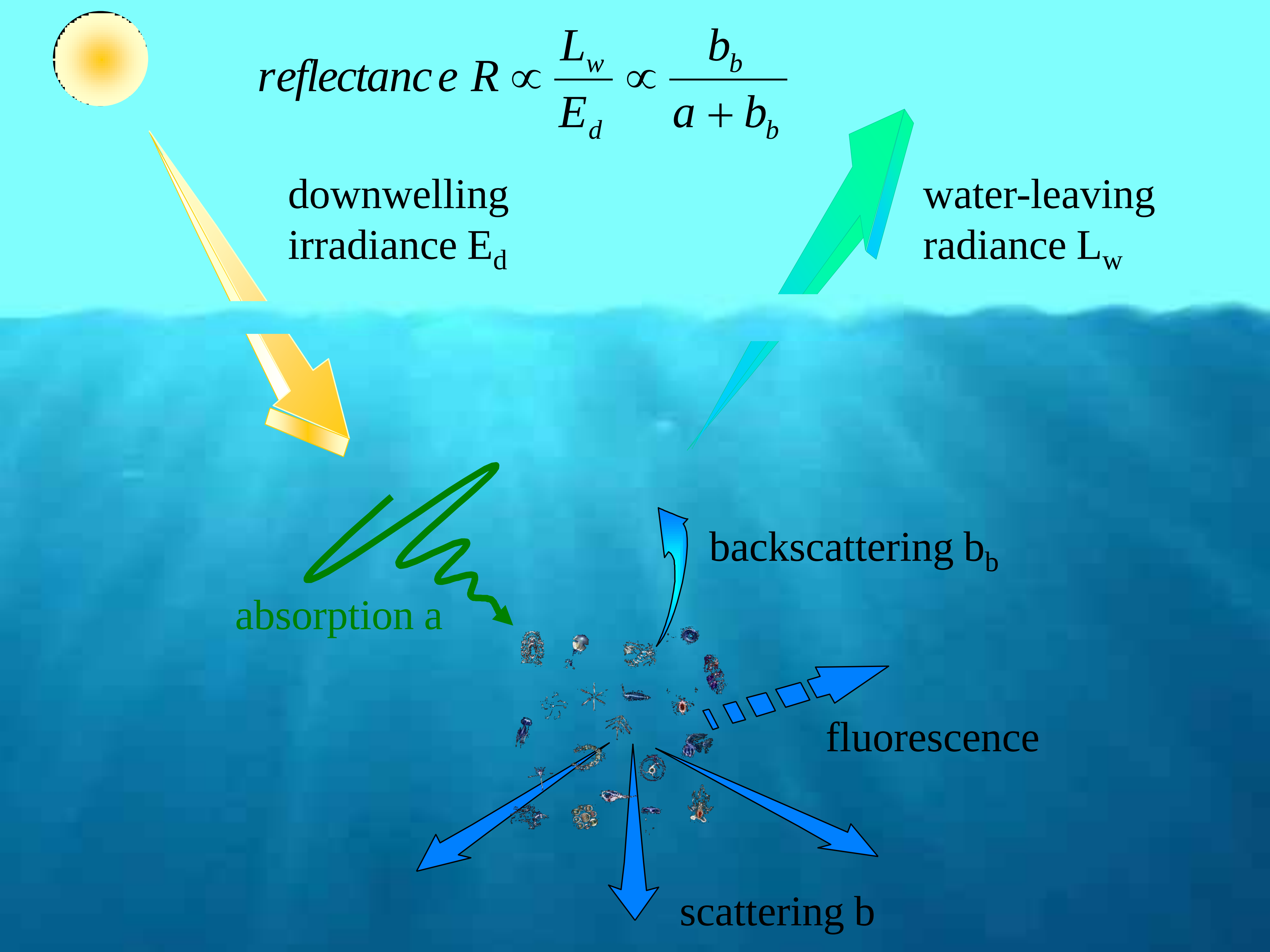
- The water itself
- Phytoplankton
- Gelbstoff or coloured dissolved organic material (CDOM)
- Other suspended particulate such as algal detritus and suspended sediment

Minor Components

- Bacteria
- Viruses
- Bubbles

The bulk optical properties of seawater can be treated cumulatively from an ocean colour perspective e.g.

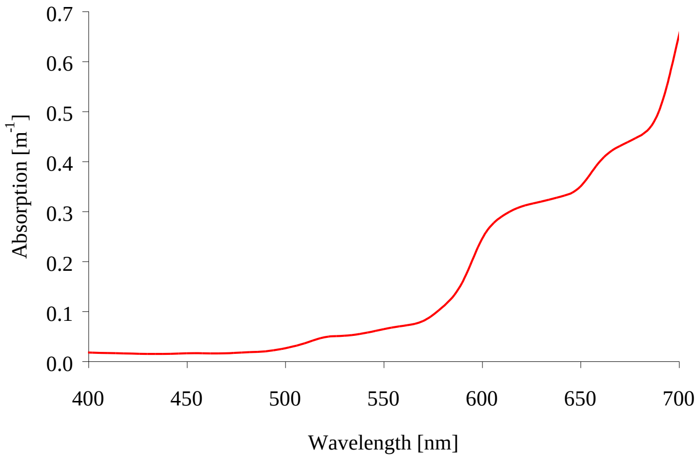
$$reflectance\ R = G\frac{b_b}{a+b_b} = G\frac{b_{b\,water} + b_{b\,plankton}}{a_{water} + a_{plankton} + a_{gelbstoff} + b_{b\,water} + b_{b\,plankton}}$$



$$reflectance\ R \propto \frac{L_w}{E_d} \propto \frac{b_b}{a+b_b}$$
downwelling
irradiance E_d
water-leaving
radiance L_w
backscattering b_b
absorption a
fluorescence
scattering b

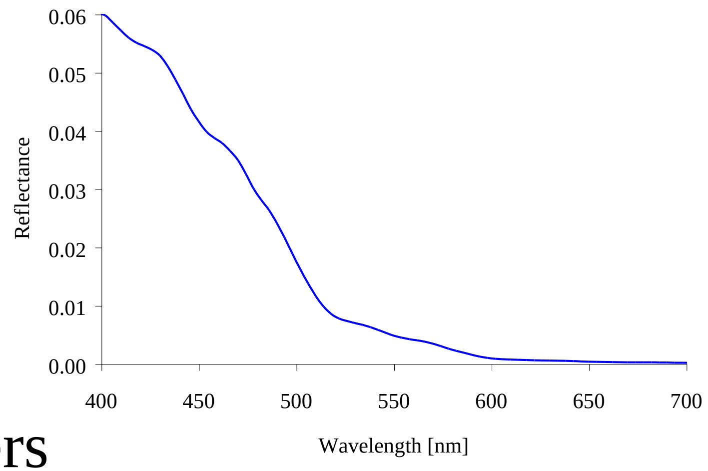
The Absorption and Backscattering of Water

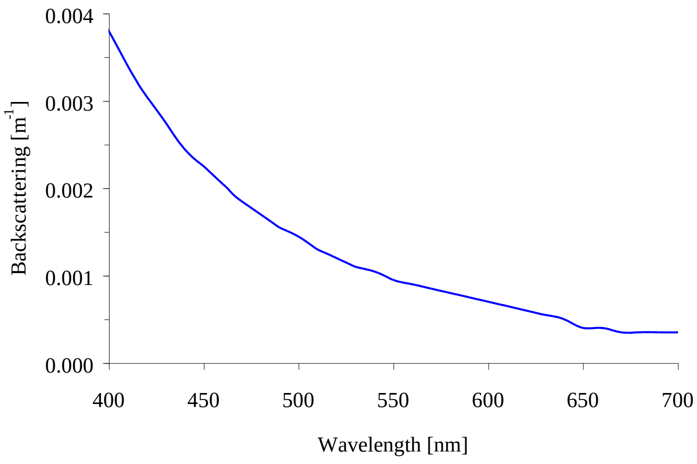
(or why water is blue)



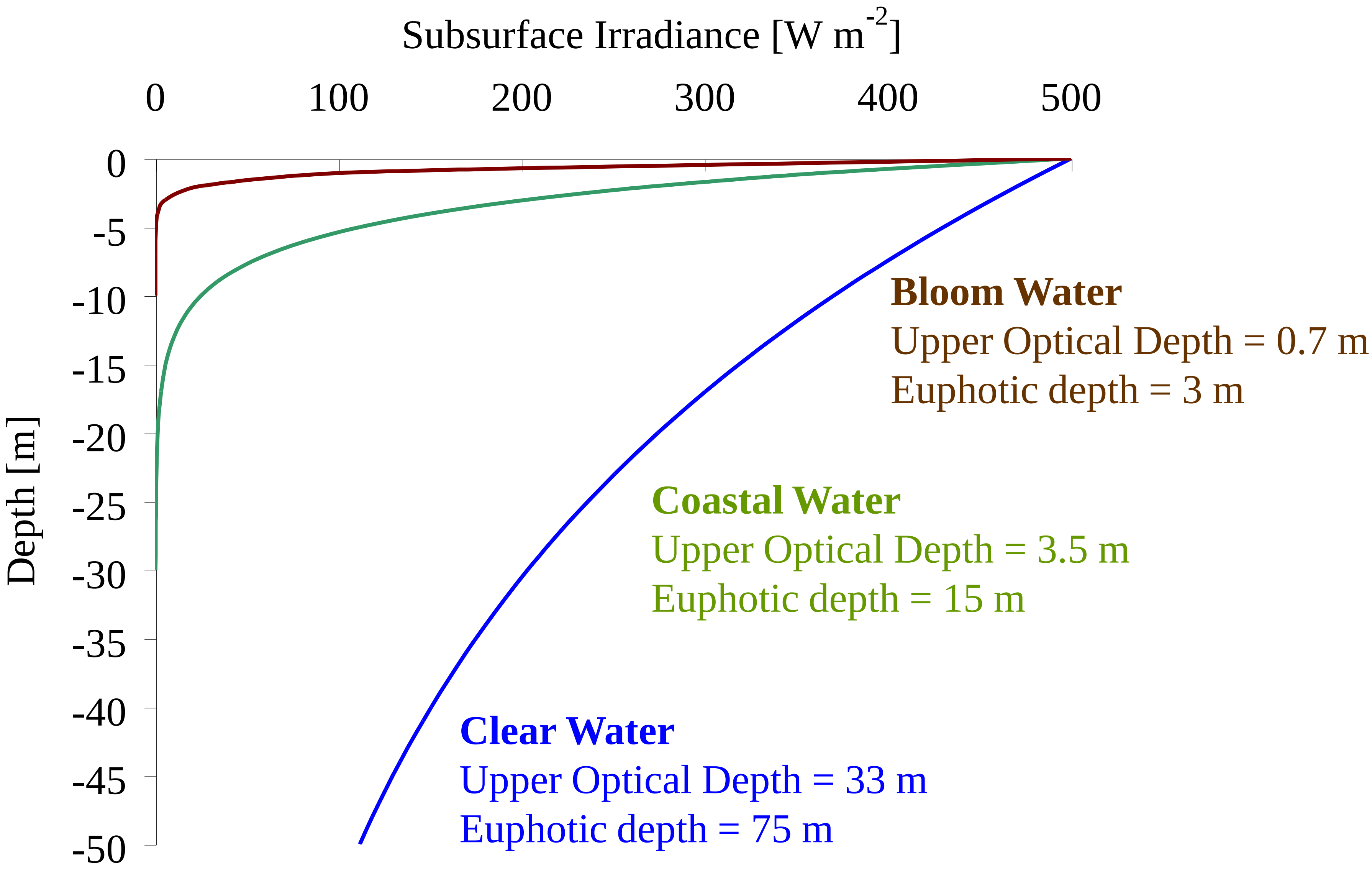
Water absorbs strongly in the red

$$R = 0.33 \frac{b_b}{a + b_b}$$





Water backscatters strongly in the blue


Subsurface Irradiance [W m-2]
0
100
200
300
400
500
0
-5
-10
-15
-20
-25
-30
-35
-40
-45
-50
Depth [m]
Bloom Water
Upper Optical Depth = 0.7 m
Euphotic depth = 3 m
Coastal Water
Upper Optical Depth = 3.5 m
Euphotic depth = 15 m
Clear Water
Upper Optical Depth = 33 m
Euphotic depth = 75 m

Reflectance (R) = Eu / Ed

$R(\lambda) = 0.33\, bb(\lambda) = /(a(\lambda) + \mathbf{bb}(\lambda\,))$

Kd= (1/z1-z2) Ln (Ed(1)/Ed(2))

1. Irradiance, radiance, and reflectance

Irradiance (E)

flux per unit surface area (W.m-2.nm-1)

Radiance (L)

flux per unit area and per unit solid angle (W.m-2.nm-1.sr-1)

Reflectance (R)

R=Eu/Ed (no dimension)

Remote Sensing Reflectance

Rrs=Lu/Ed (sr-1)

Optical properties of water

- **Apparent Optical properties**

  1. **Light intensity**
  2. **Light attenuation**
  3. **Reflectance**

- **Inherent Optical Properties**

  1. **Absorption**
  2. **Scattering**

CLASSIFICATION OF WATERS

CASE-1

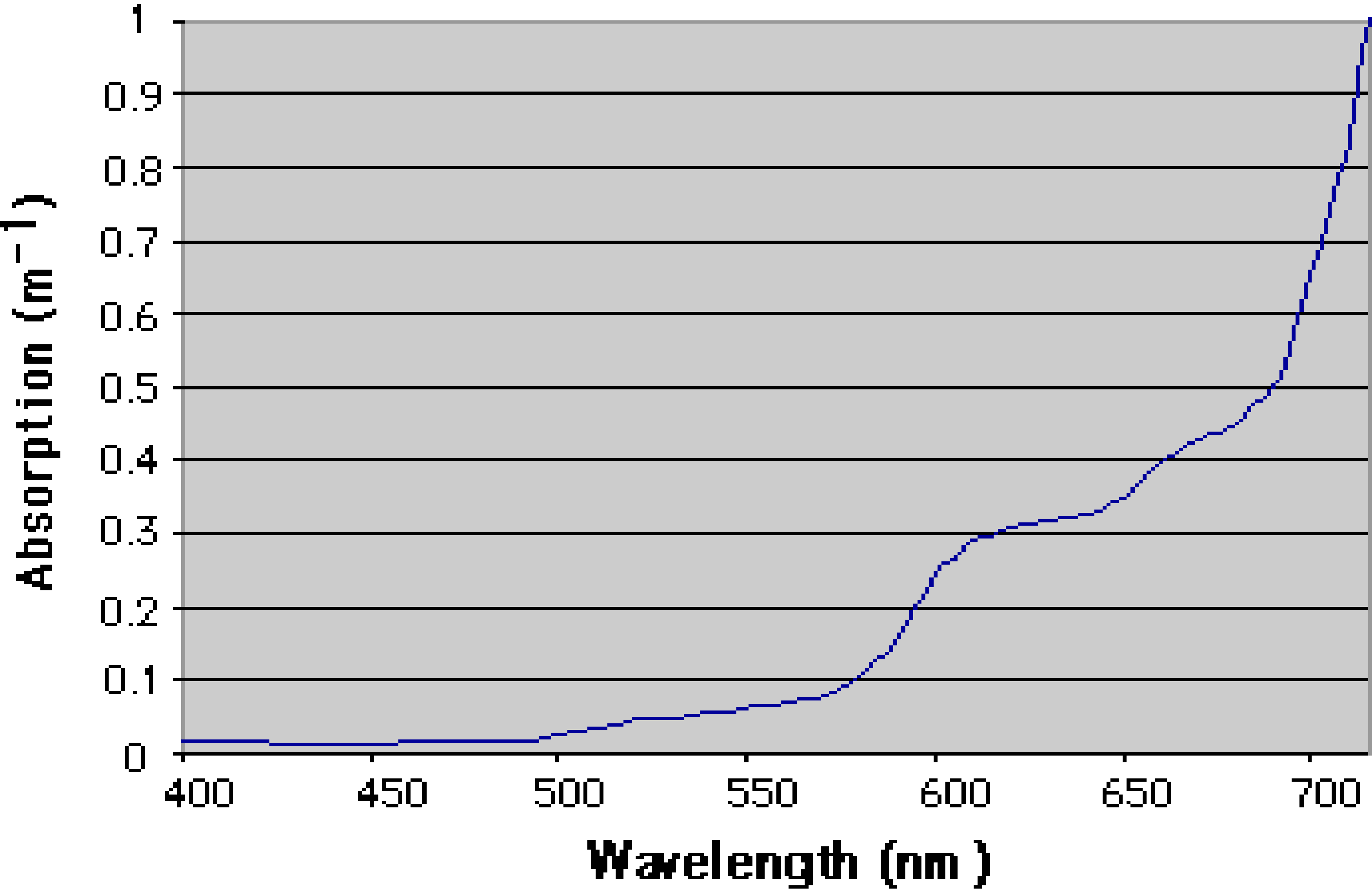
- **Dominance of Chlorophyll**

CASE-2

- **Dominance of Yellow substances**
- **Dominance of Suspended Sediment**

Constituent	Optical Result
Water it Self	Absorbs mainly red light, in the longer wavelengths. Weakly scattering
Colored dissolved Organic matter	Strongly absorbs light, mostly shorter wavelengths, especially blues. Scatter is negligible.
Phytoplankton	Strongly absorbing and scattering. Absorption is selective with peaks in the blue and red regions. Scatter is mainly directed forward.
Suspended particulate matter	Strongly scattering. Absorption characteristics depend upon composition of the particulate material.

Normal conditions



Primary Optical Measurements

- Incident Spectral Irradiance,Es
- Down welled Spectral Irradiance,Ed
- Up welled Spectral radiance,Lu

Derived Variables

- Water-Leaving Radiance,Lw
- Attenuation Coefficient Down welled Irradiance,K_{ed}
- Attenuation Coefficient Up welled radiance,K_{lu}
- Spectral Reflectance, R

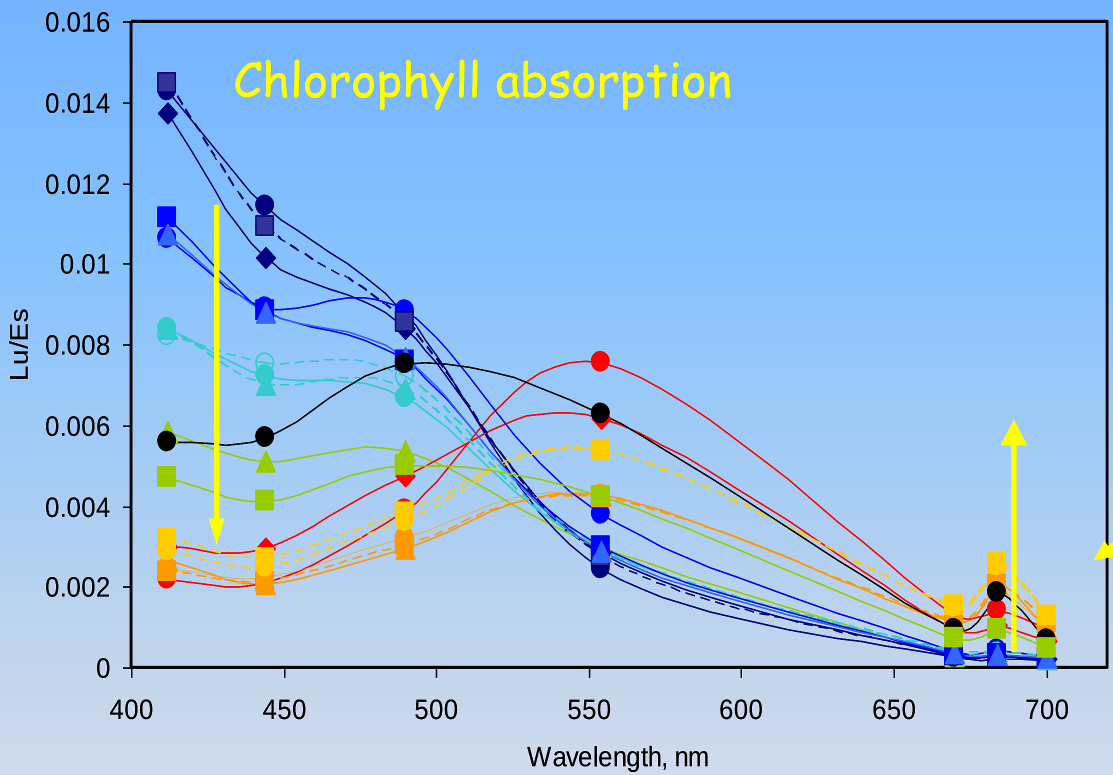
Ambient Properties

- **Sea and Sky state**
- **Wind Velocity**
- **Temperature and Salinity Profiles**
- **Secchi Depth**

Primary Biogeochemical Measurements

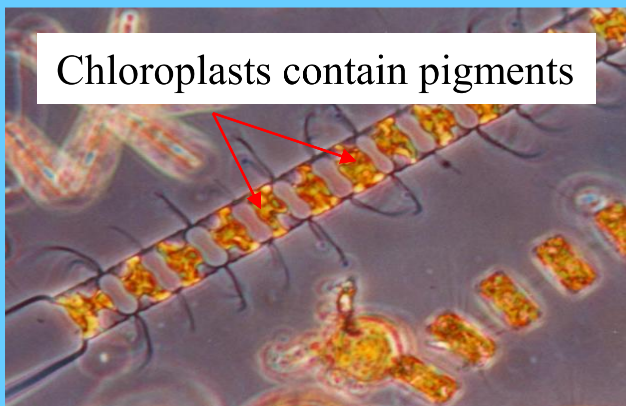
- **Phytoplankton Pigments**
- **Total Suspended Material**
- **Colored Dissolved Organic Material**

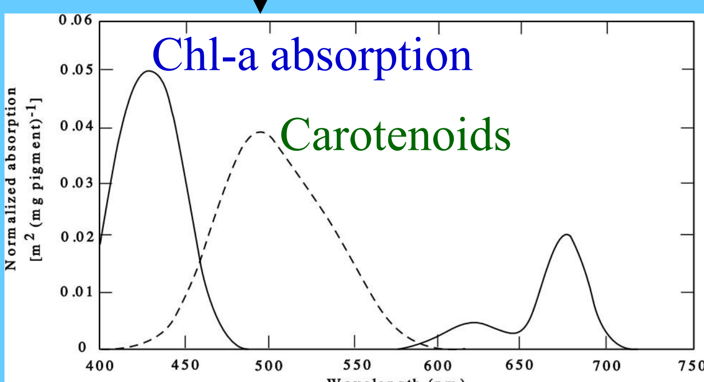
Fluorescence spectral signature

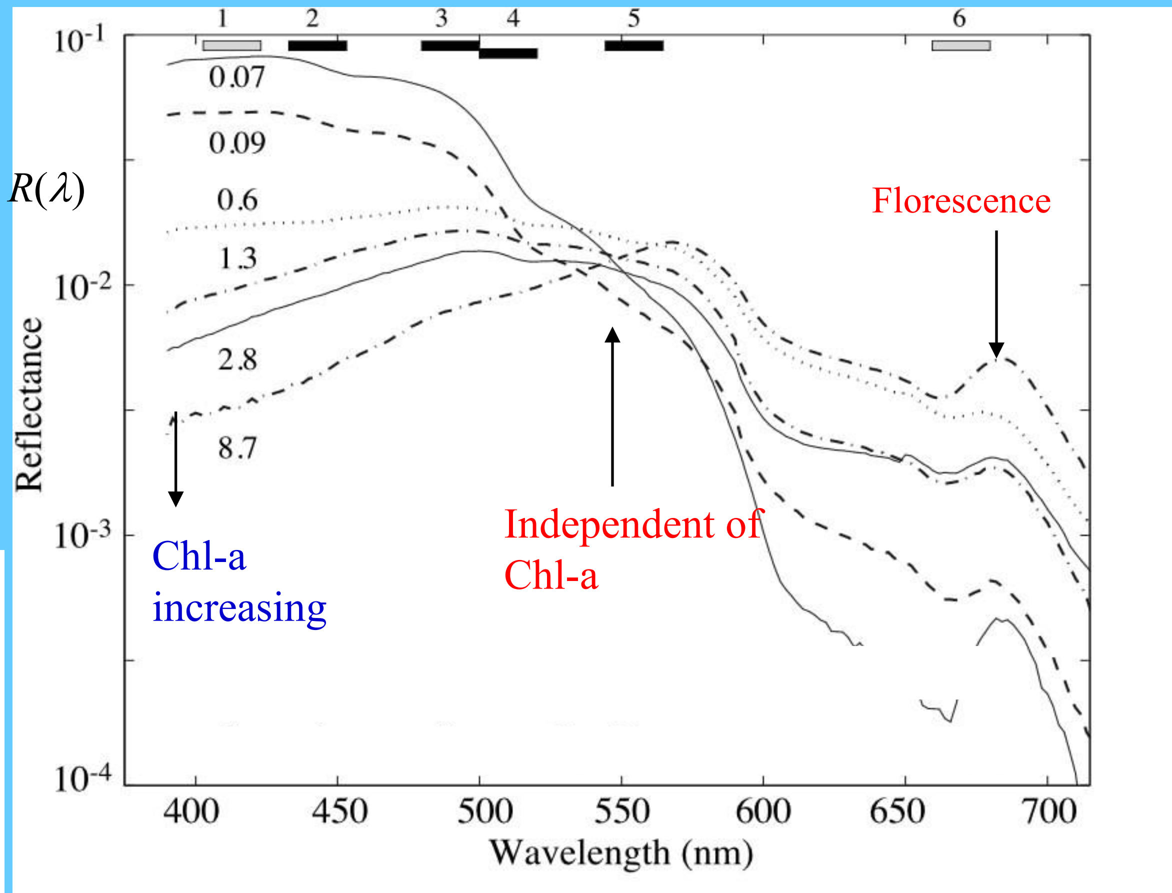


Increase in fluorescence

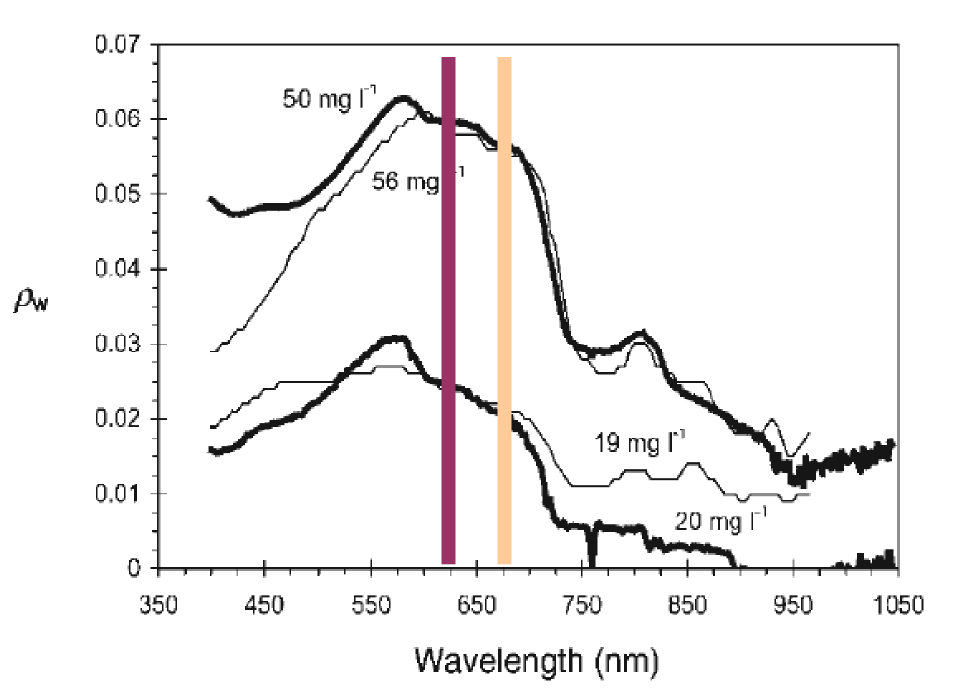
Detection of Phytoplankton Pigment using remote sensing

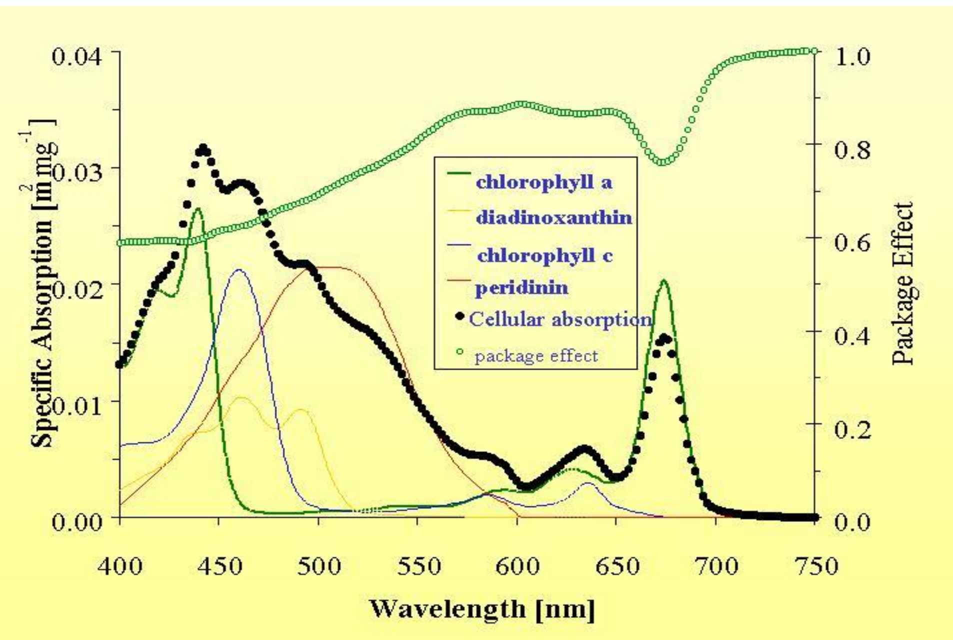


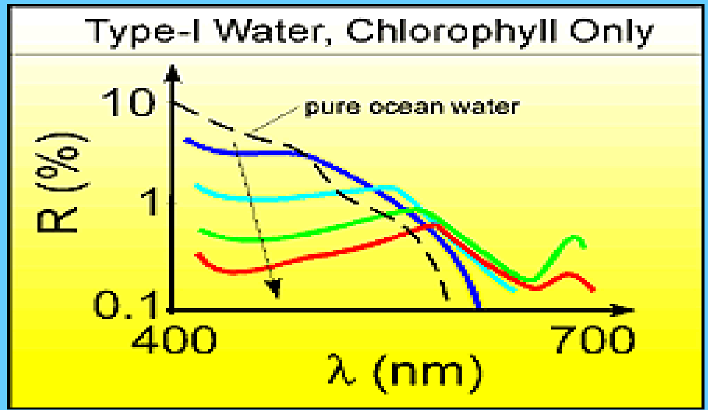


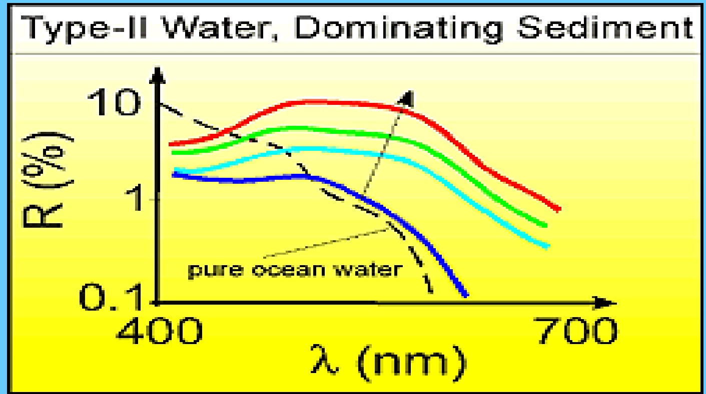


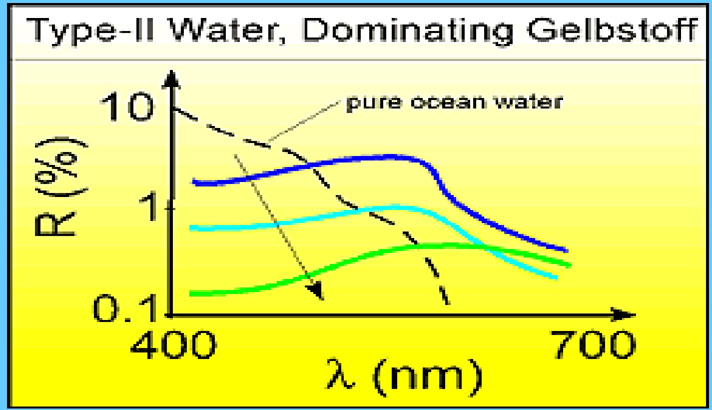
Spectral Curves for different water constituents









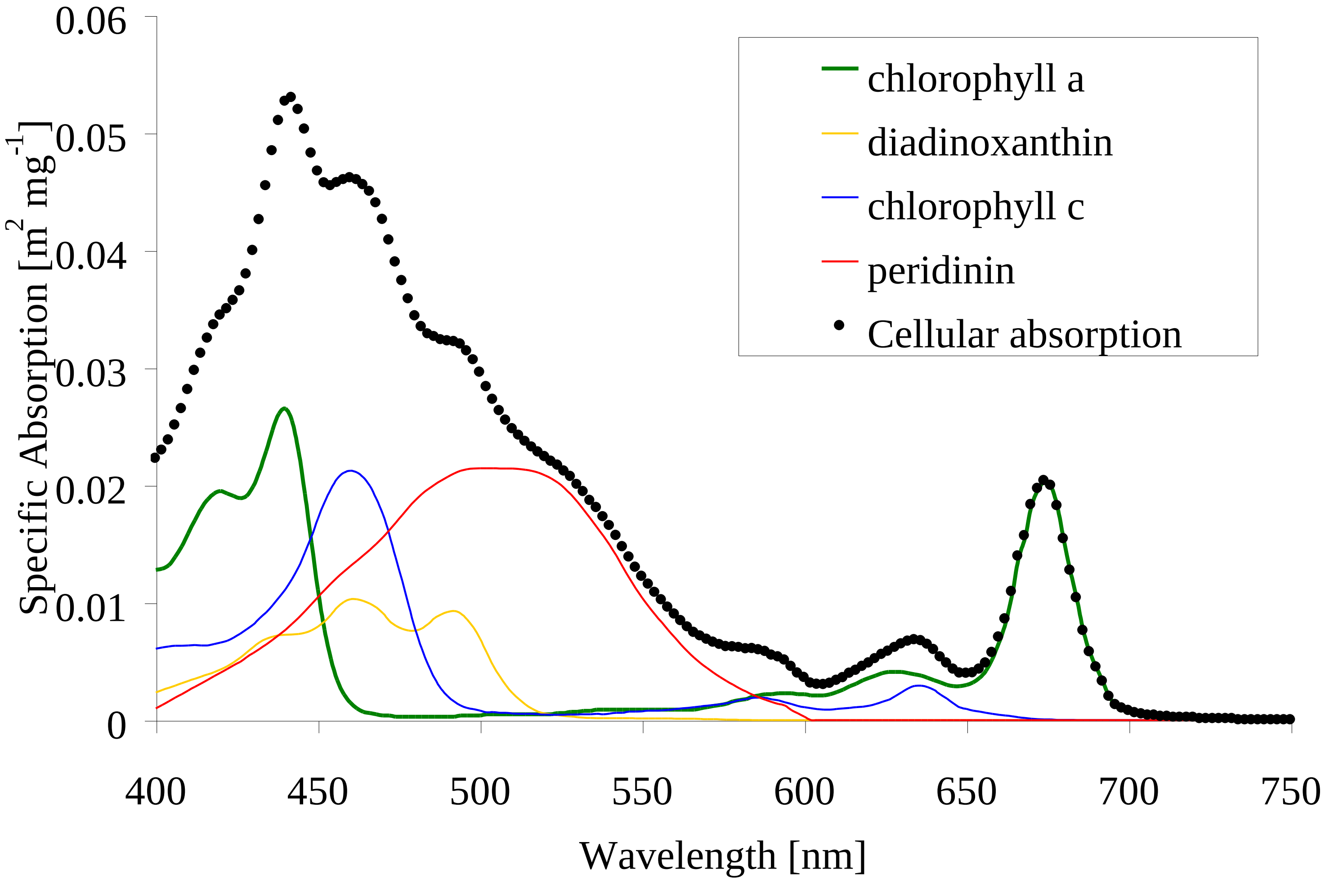


The Absorption and Backscattering of Phytoplankton

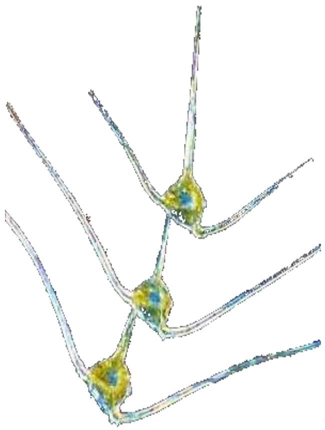
There is a great diversity of phytoplankton species in the world oceans. A typical litre of seawater is likely to contain hundreds of thousands of cells of many different species.

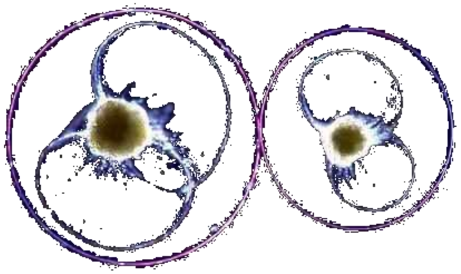
The optical properties of a phytoplankton assemblage will depend upon the following factors:

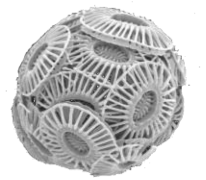
1. The variable presence and concentration of intracellular pigments.

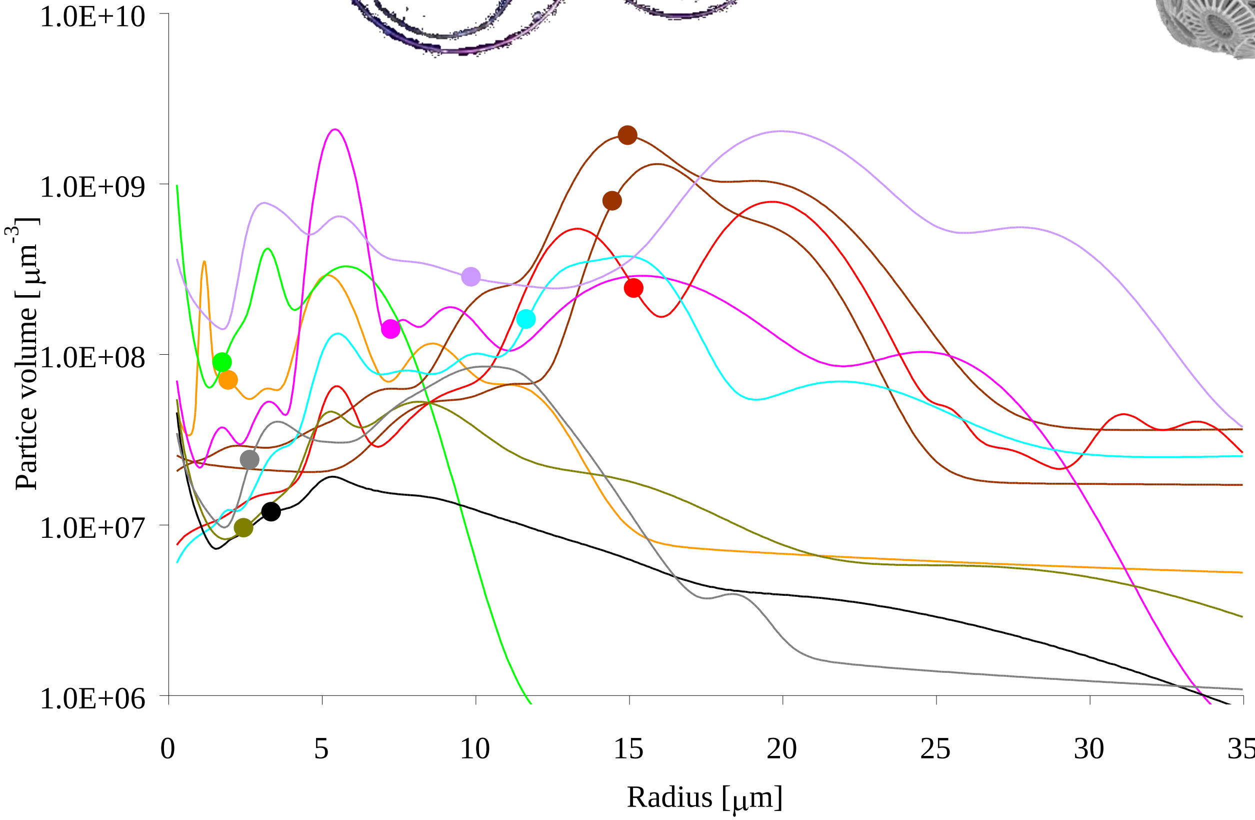


2. The size, shape and material structure of the cells



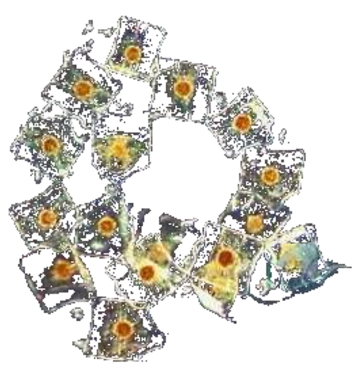






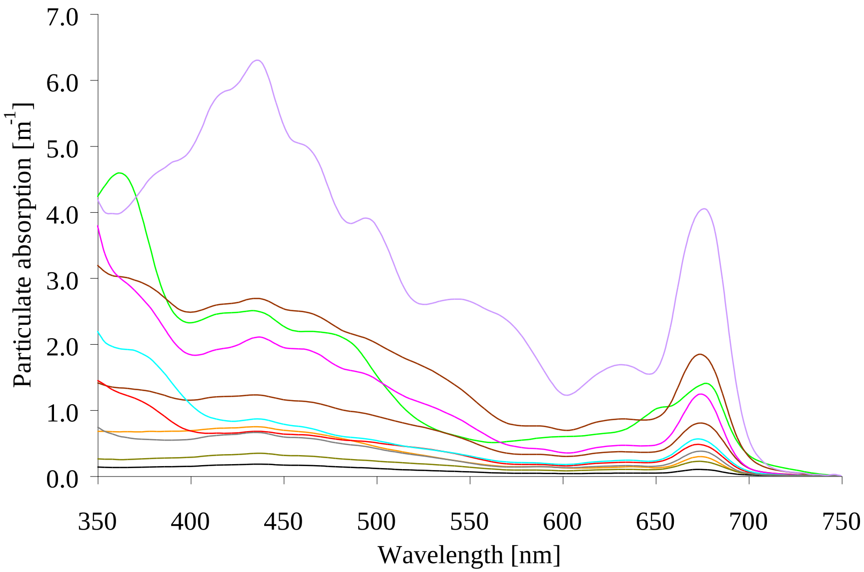
Dominant Species

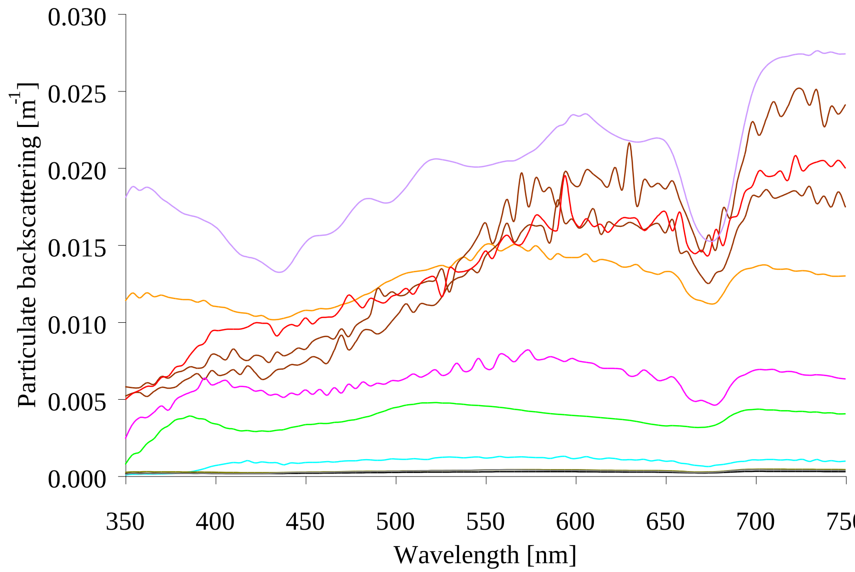
A. anophagefferens
Ceratium spp.
A. catenella, Ceratium spp.
West Coast Gymnodinium sp.
Dinophysis spp, Nitzchia spp.
Chlorophyte
Diatom
G. mikimotoi
Mixed
Mesodinium rubrum



The Absorption and Backscattering of Phytoplankton

Particulate absorption data, measured using a spectrophotometer, and particulate backscattering data, modelled using spherical particle models, from algal blooms.





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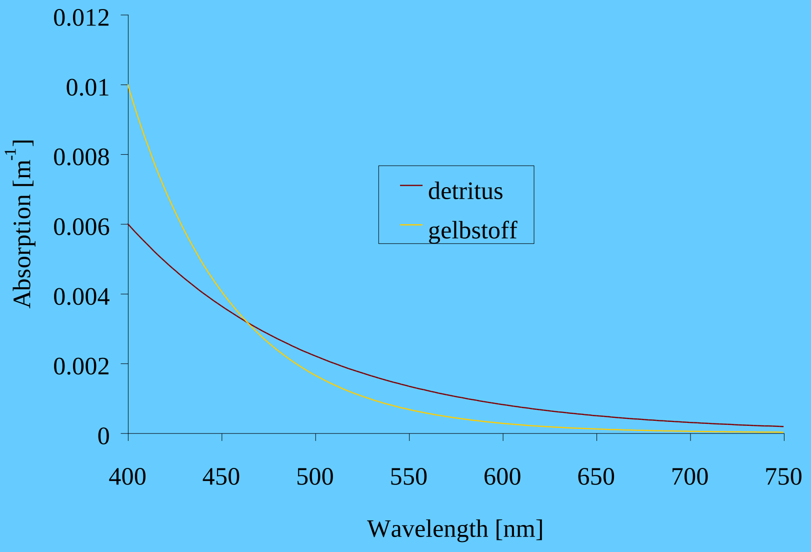
Dinophysis spp, Nitzchia spp.	Chlorophyte
Diatom	G. mikimotoi
Mixed	Mesodinium rubrum (b_b=x0.2)

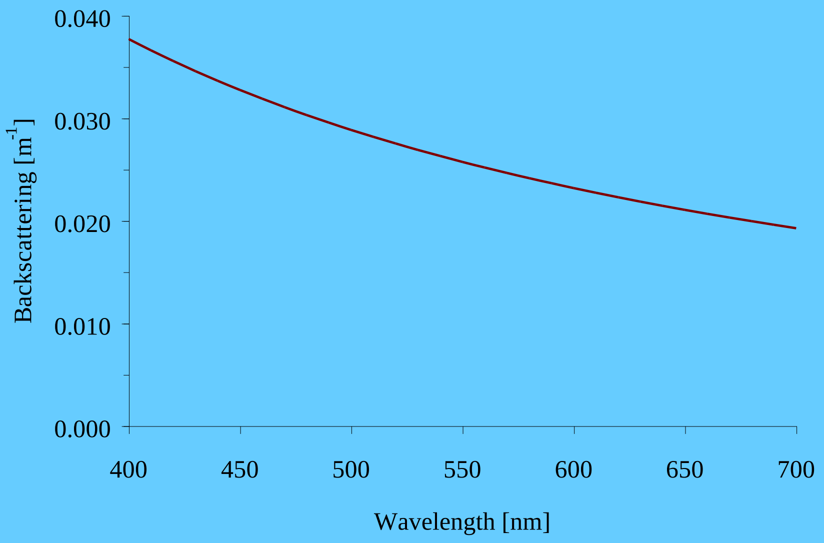
Gelbstoff, Detritus and Suspended Sediment

- Gelbstoff (coloured dissolved organic matter) and detritus (non algal biological particulate) are also typically present in seawater and must be considered in bio-optical models.

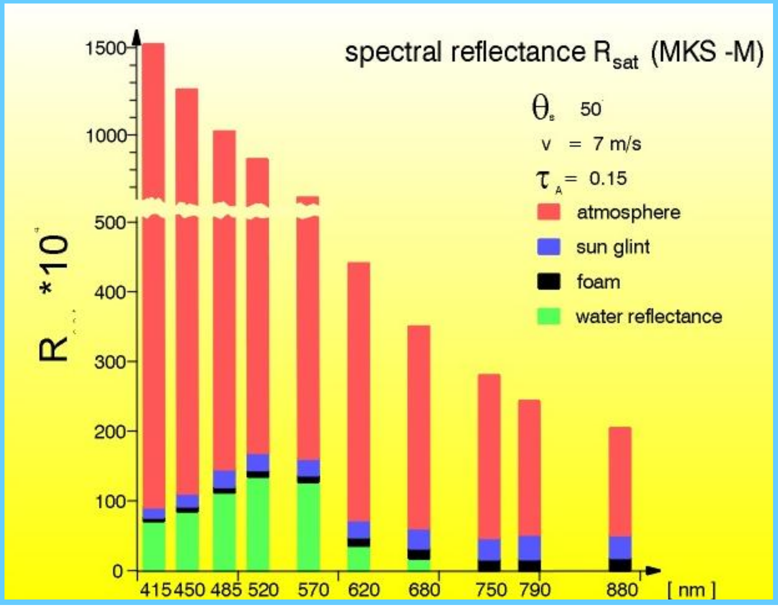
- Inorganic sediments are typically highly scattering with low absorption, and need to be considered on a case specific basis e.g. in areas of high river discharge or resuspension

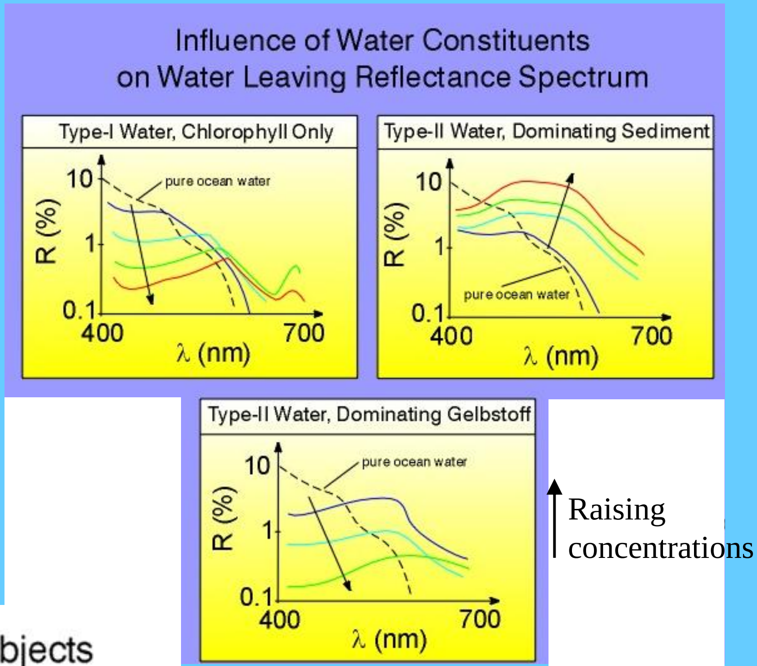


Typical exponential decay with wavelength of gelbstoff and detritus absorption



Modelled backscattering of quartz sediment at 1 mg m^{-3}





Spectral reflectance of different remote sensing objects

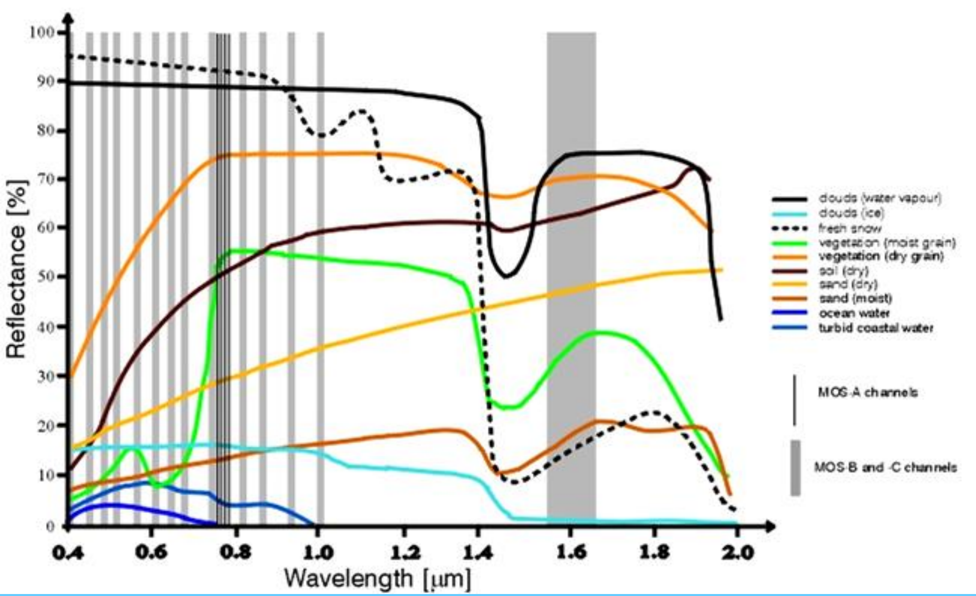
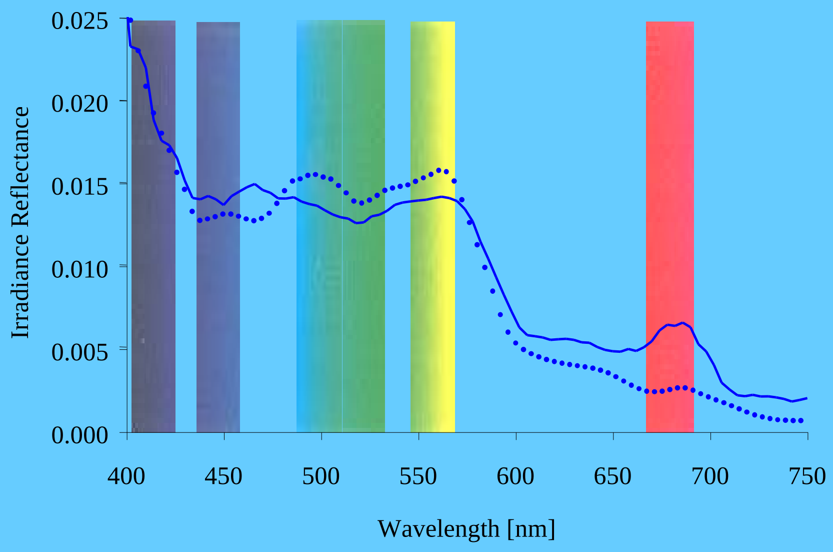


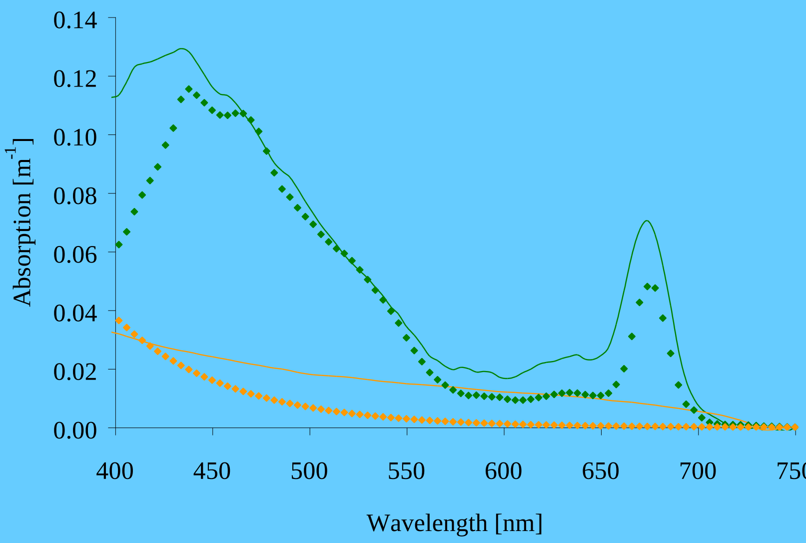
Table 4-2 Chlorophyll algorithms used in this study

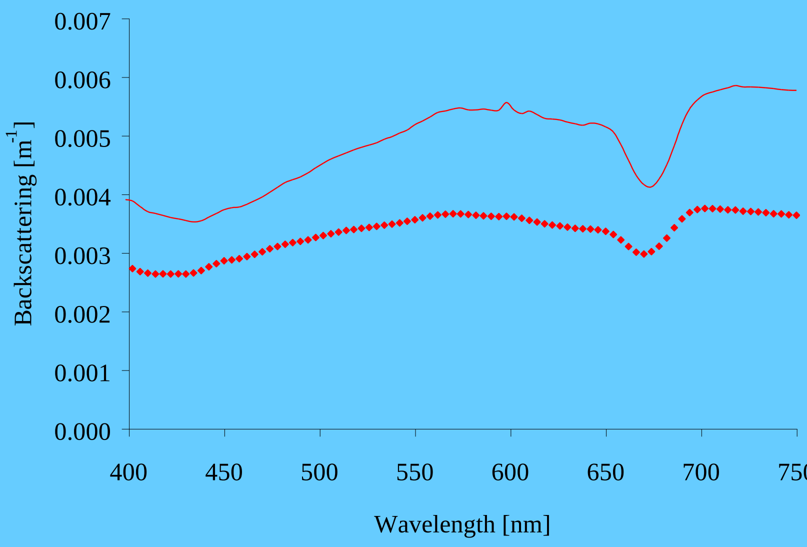
Algorithms	Type	Empirical equation	Band ratio (R)	Coefficients (a)
Aiken – C (Aiken *et. al.*, 1995)	Hyperbolic + power	$C_{21}= \exp(a_0+a_1\times\ln(R))$ $C_{23}=(R+a_2)/(a_3+a_4\times R)$ $C = C_{21}$; if $C<2$ mg m^{-3} then $C = C_{23}$	$L_W[N]490/L_W[N]555$	[0.745, -2.252]
OCTS – C (O'Reilly *et. al.*, 1998)	Power	$C = 10\wedge(a_0+a_1 \times R)$	log $((L_W[N]520+L_W[N]565)/L_W[N]490)$	[-0.55006, 3.497]
POLDER (Morel, 1988)	Cubic	$C = 10\wedge(a_0+a_1\times R+a_2\times R^2+a_3\times R^3)$	$\log(R_{rs}443/R_{rs}565)$	[0.438, -2.114, 0.916, -0.851]
Morel -3 (Morel, 1988)	Cubic	$C = 10\wedge(a_0+a_1\times R+a_2\times R^2+a_3\times R^3)$	$\log(R_{rs}443/R_{rs}565)$	[0.20766, -1.828, 0.75, -0.739]
OC2 V. 4 (O'Reilly *et. al.*, 2000)	Modified cubic	$C = 10\wedge(a_0+a_1\times R+a_2\times R^2+a_3\times R^3)+a_4$	$\mathrm{Log}(R_{rs}490/R_{rs}555)$	[0.319, -2.336, 0.879, -0.135, -0.071]
OC4 V. 4 (O'Reilly *et. al.*, 2000)	Modified cubic	$C = 10\wedge(a_0+a_1\times R+a_2\times R^2+a_3\times R^3)+a_4$	$\log(R_{rs}443>R_{rs}490>R_{rs}510/R_{rs}555)$	[0.366, -3.067, 1.93, 0.649, -0.532]
CZCS-pigment (Clark, 1997)	Modified cubic	$C = 10\wedge((a_0+a_1R+a_2\times R^2+a_3\times R^3+a_4)/e)$	log $(L_W[N]443/L_W[N]551)$	Coefficients when R> 0.7368 are: a = [-1.4443, 1.4947, -1.5283, -0.0433, 1] Coefficients when R<0.7368 are: a = [-5.0511, 2.8952, -0.5069, -0.1126, 1]

Analytical Reflectance Inversion Algorithm

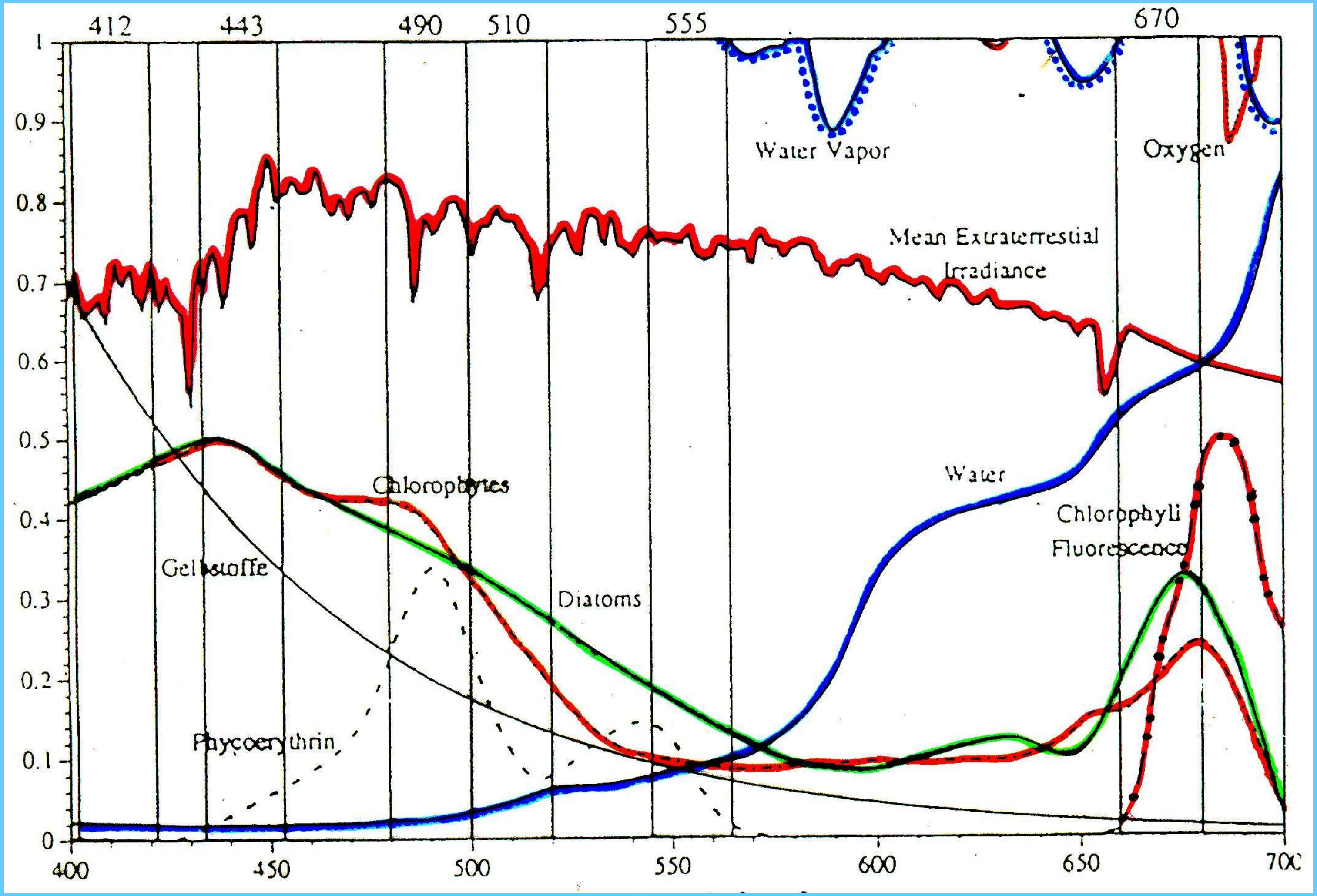
$$R = G \frac{b_{b\ water} + b_{b\ plankton}}{a_{water} + a_{plankton} + a_{gelbstoff} + b_{b\ water} + b_{b\ plankton}}$$







SPECTRAL SIGNATURES



RELATIVE ABSORPTION / TRANSMITTANCE

WAVELENGTH (NM)

- WATER VAPOUR
- MEAN EXTRATERRESTRIAL IRRADIANCE
- DIATOMS
- PHYCOERYTHRIN
- CHLOROPHYLL FLUORESCENCE
- OXYGEN
- CHLOROPHYTES
- GELBSTOFFS (YELLOW SUBSTANCE)
- WATER

NEED OF OCEAN COLOUR DATA

- ✓ Synoptic Scales of Pigments
- ✓ Marine Fisheries
- ✓ Primary Production
- ✓ Carbon Budgeting
- ✓ Small-Scale Processes
- ✓ River Plumes
- ✓ Phytoplankton Blooms
- ✓ Coastal Upwelling
- ✓ Coastal Bathymetry
- ✓ ENSO Monitoring
- ✓ Aerosol / Cloud optical properties
- ✓ Oils Spills / Ship wake studies

SENSOR REQUIREMENT

- ✓ More no. of spectral bands in visible region
- ✓ More no. of bands for atmospheric correction
- ✓ Narrow spectral band width
- ✓ S/N Ratio should be high
- ✓ High quantization levels
- ✓ Regular calibration of sensor
- ✓ Spatial resolution should be less than 1KM
- ✓ Observation time should be noon to avoid specular reflection and low level clouds

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REMOTE SENSING OF OCEAN COLOR

- ✓ Locates and enables monitoring of regions of high and low bio-activity.
- ✓ Food (phytoplankton associated with chlorophyll)
- ✓ Climate (phytoplankton possible CO_2 sink)
- ✓ Reveals ocean current structure and behavior.
- ✓ Seasonal influences
- ✓ River and Estuary influences
- ✓ Boundary currents
- ✓ Reveals Anthropogenic influences (pollution)
- ✓ Remote sensing reveals large and small scale structures that are very difficult to observe from the surface.

Requirement s for Retrieval of parameters from Ocean colour sensors

- **Atmospheric correction algorithm**
- **Normalized Water leaving Radiance (L_{wn})**
- **Global / Local Bio – optical algorithm**

Validation

- **Insitu Optical measurements**
- **Insitu oceanic parameters**
- **Measurements of Aerosols**

What is Bio-Optical algorithm ?

This is a empirical / semi-empirical.

NEED OF BIO-OPTICAL ALGORITHM

- **Estimation of ocean Bio-geochemical parameters using in-situ observed radiance field.**

- **Bio-optical algorithm is required to retrieve different Oceanic parameters using water leaving radiance derived from satellite Data incorporating reliable atmospheric correction models.**

Several algorithms are available operationally, but a regional Bio-optical algorithm is required for Indian waters.

DIFFERENT FUNCTIONAL / EMPERICAL ALGORITHMS

POWER

C13 = 10^(a0+ a1*R1) R1 = Log(Lwn443/Lwn550) Evans and Gordon 1994

HYPERBOLIC + POWER

C_21 = EXP(a0 + a1*Ln(R)) R = Lwn490/Lwn555
C_23 = (R +a2)/(a3 + a4*R) a = [0.464, -1.989, -5.29, 0.719, -4.23]

MULTIPLE REGRESSION

C+P=10^(a0 + a1*R1 + a2*R2) R1 = Log(Lwn443/Lwn520) R2 = Log(Lwn490/Lwn520)
a = [0.19535, -2.079, -3.497]

CUBIC

C=10^(a0 + a1*R + a2*R^2 + a3*R^3) R = Log(Rrs443/Rrs565)
a = [0.438, -2.114, 0.916, -0.851]

CUBIC POLYNOMIAL

C=10^(a0 + a1*R + a2*R^2 + a3*R^3) +a4 R = Log(Rrs490/Rrs555)
a = [0.341, -3.001, 2.811, -2.041, -0.040]

OC2 modified cubic Polynomial

$C=10^{(a0+a1*R+a2*R^2+a3*R^3)} + a4$

Where $R=\log(Rrs490/Rrs555)$

OC4 modified cubic Polynomial

$C=10^{(a0+a1*R+a2*R^2+a3*R^3)} + a4$

Where $R=\log((Rrs443>Rrs490>Rrs510)/Rrs555$

THANK YOU