Introduction to Marine optics
Ocean Optics

K .H. Rao
National Remote Sensing Centre, ISRO
Balanagar, Hyderabad-500037
rao_kh@nrsc.gov.in rao_kh@yahoo.com

Introduction

- The life on this planet is directly related to the energy supplied by the sun. The pyramid of life starts with the absorption of a fraction of this energy and its conversion from electromagnetic to chemical energy (photosynthesis) and its subsequent storage into biomass (primary production).

- The study of energy propagation to the planet is called geophysical optics - two categories, meteorologic optics (energy and atmosphere) and hydrologic optics (Preisendorfer, 1976).

- Most of solar energy striking the earth falls into two broad bands of the electromagnetic spectrum, visible energy (approximately 400 to 700 nm) and infrared energy (700 nm to 100 µm).

- The study of ocean optics has been primarily concerned with propagation of visible energy, i.e. light.

- Photosynthesis is driven by energy within the visible light spectrum, which has sufficient energy per photon to induce photochemistry.

- Phytoplankton accumulations impact the color and clarity of the water column, there is a direct link between the ocean optics and ocean ecology. (Yentsch and Phinney, 1989).

- Growth of Phytoplankton and accumulation, the total light absorption increases, reducing the total light flux to deeper levels.

- Photochemical conversion of visible energy to biomass is a negative biological feedback, creating instabilities for the future growth rate of the phytoplankton.

- Ocean optics and physical processes are linked to the radiative heating of solar radiation absorbed by the ocean water mixture(pure water + particulate and dissolved matter).

Penetrative Radiation and Upper Ocean Heating

- Solar radiation penetrating the atmosphere has a spectral distribution, i.e. each wavelength contains a varying fraction of the total downwelling energy.

- The distribution of radiative heating in the water column is dependent on both the spectra of incoming light and spectrum of optical properties of the water column.

- The solar that penetrates the ocean surface, the vast majority (> 99%) of infrared is absorbed within the first 1.5 m of the water column.

- In the visible part of the spectrum, the depth of penetration varies dramatically with the optical characteristics of the water.

- The radiation absorbed in the upper ocean is converted to heat and its depth-distribution is determined by the transmission function, T(λ,z).

- Although Ed(0-), the surface downwelling irradiance just above the sea surface, is routinely obtained locally from ships and buoys during oceanographic experiments, and can be obtained globally from satellite remote sensing products.

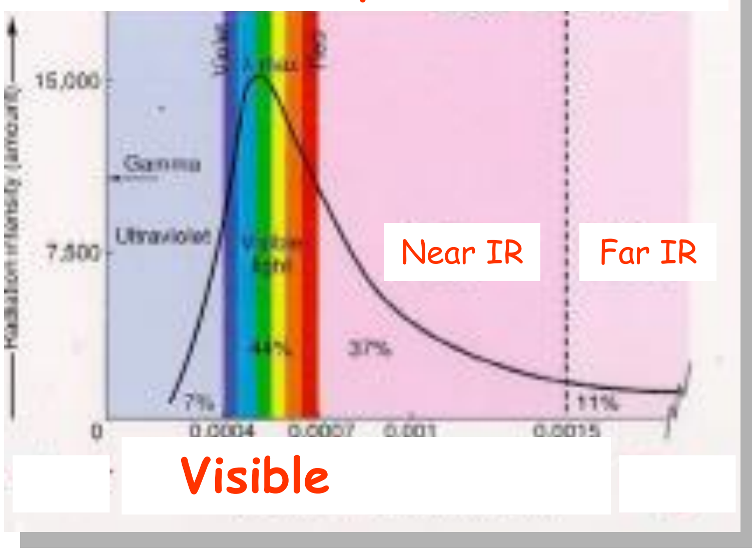
- T is not routinely measured. Instead, various parameterizations are used to account for the expected depth dependence of T for discrete wavelength bands.

- For most water types, variability in T is primarily due to phytoplankton pigments, the most ubiquitous of which is chlorophyll a, and this chlorophyll concentration can be used as the basis for a T parameterization.

Sun spectrum

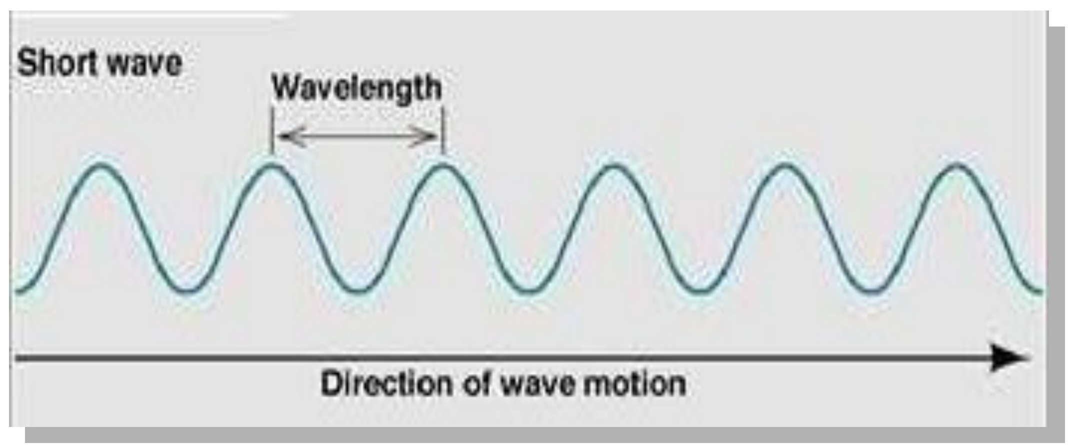
Recall: Each body with some temperature emits radiation. We feel the radiation emitted from our bodies as heat.
This law applies to all objects in the Universe.

Solar spectrum

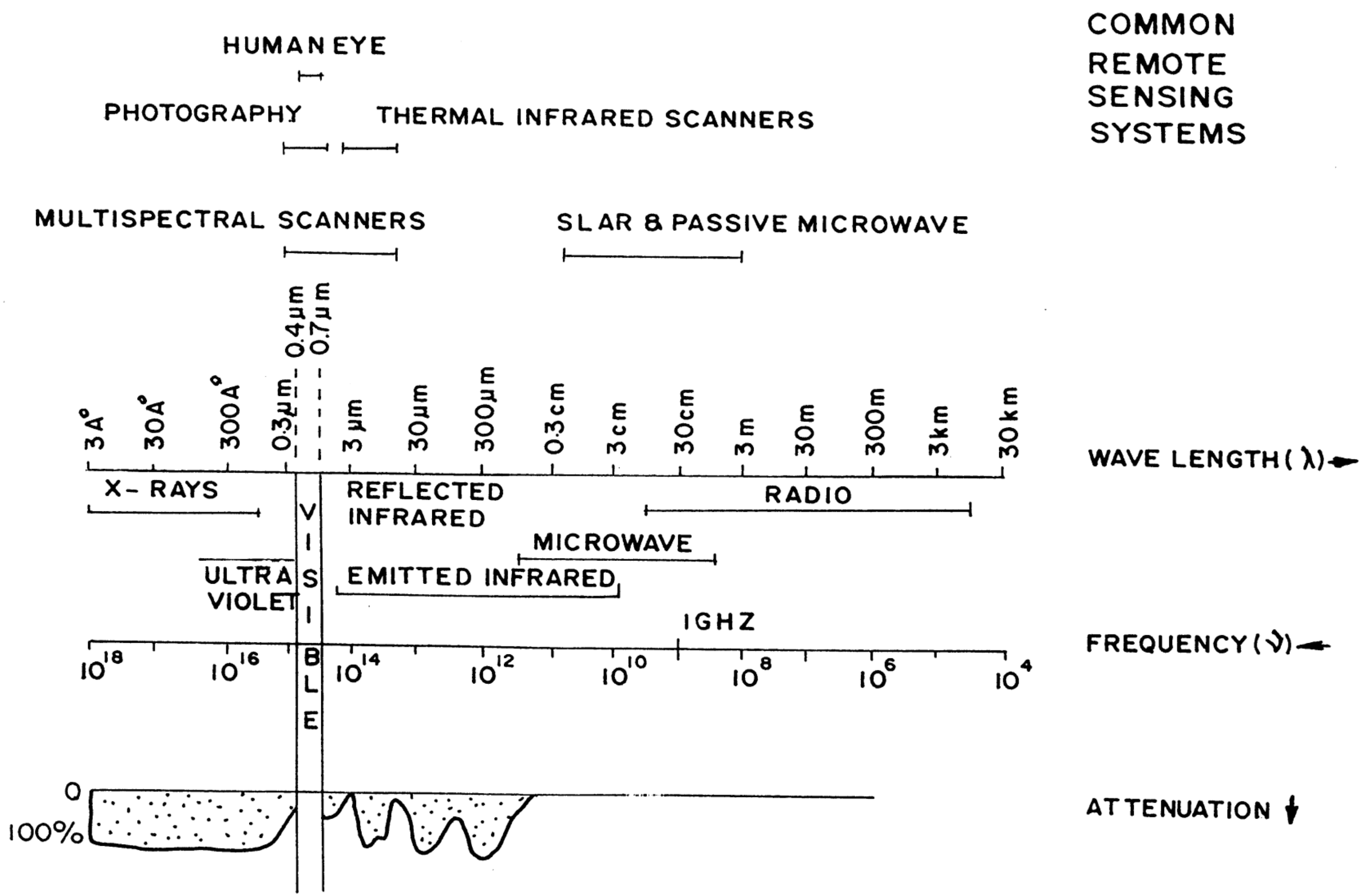


The Sun emission peaks in the visible range.

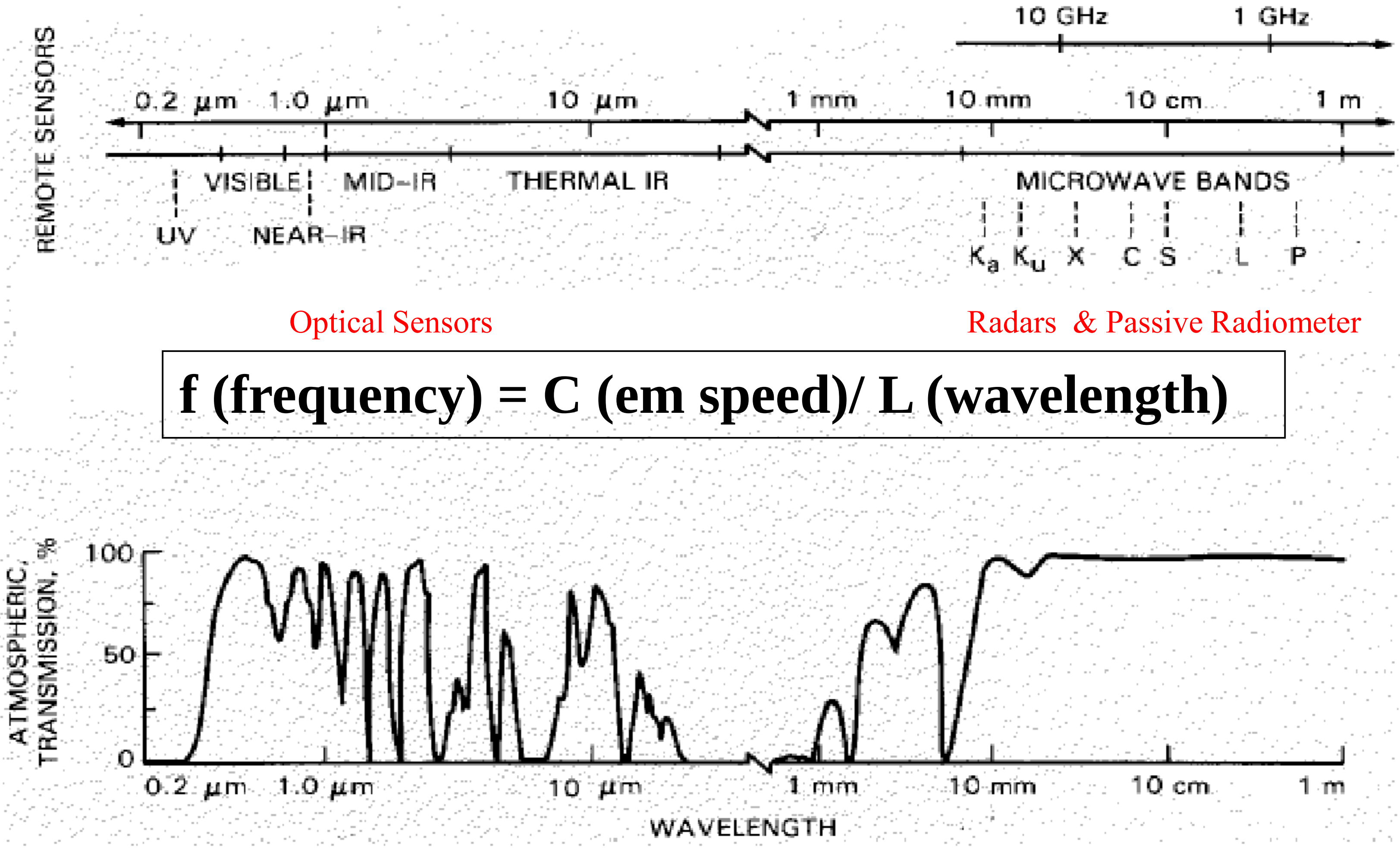
The sun is a celestial body with a temperature of 6000 ºC. Objects with such high temperature emit energy at the short wavelengths of the electromagnetic spectrum visualized as:



Electromagnetic Spectrum (after curran, 1988)



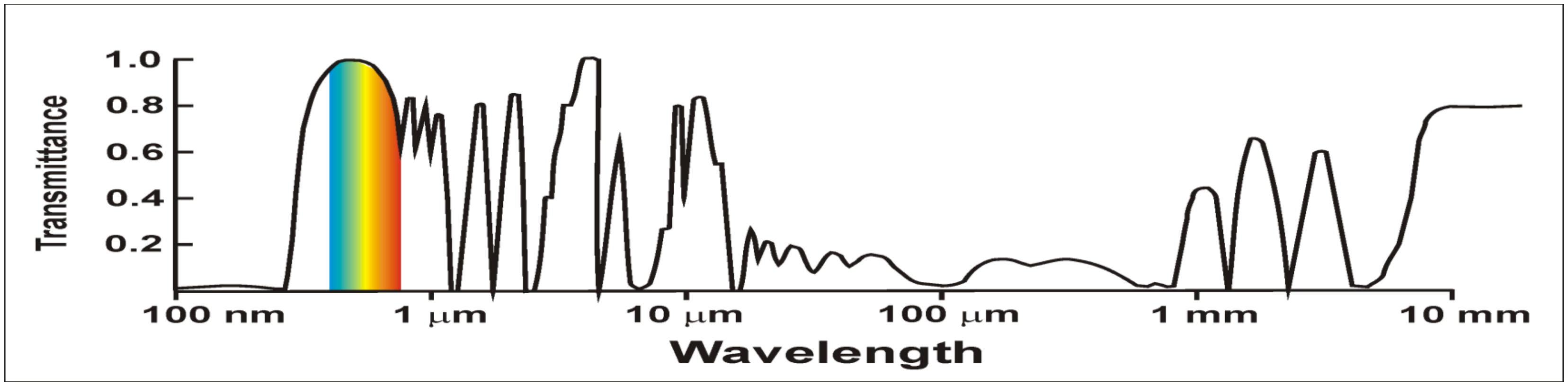
Overview of satellite sensor classes

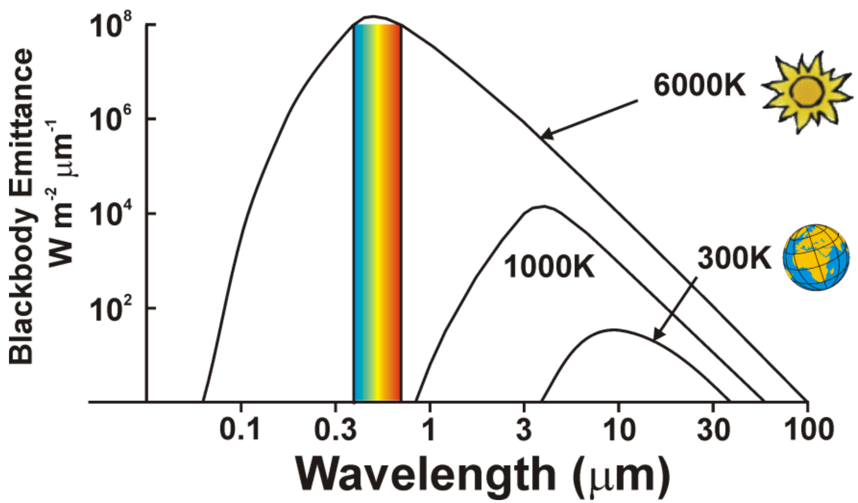


f (frequency) = C (em speed)/ L (wavelength)

The Electromagnetic Spectrum

Visible wavelength "ocean color" sensors





These sensors operate in the visible part of the electromagnetic spectrum, measuring electromagnetic radiation emitted by the sun and reflected by land and ocean surface.

Under water light field

- Human eye sensitive: ***400-700nm.***

- EMR is in indivisible units: photons/quanta

- Speed of light **$3x10^8$ m/s**(continuum of photons)

- In day light (bright summer)1 Sq meter of sea surface receives **10^{21}quanta/s** of visible light

- Relation of $\lambda = c/\nu$ **c** in meters, λ in meters, ν in cycles/s

- Energy :$\varepsilon = hc / \nu$ $h = 6.63 \times 10^{-34}$ Js

Photon of energy for a given wavelength

$\varepsilon = (1988/\lambda)\ 10^{-19}$ J

energy is in Watts or Js

Radiation flux in (Φ) in **W conversion to quanta/s**

$q/s = 5.03 \times \Phi \times \lambda \times 10^{15}$ For a given wavelength band conversion from quanta to W is difficult.

for 400-700 nm (Q: W) or W to q/s is

2.77×10^{18} q/s/w (2-5% accuracy) (Morel & Smith 1974)

Refractive Index

Light travels slowly in any media to vacuum

Light velocity in media

= **light in vacuum/ Refractive index of medium**

RI of air = 1.00028 (assumed as 1)

RI of water = 1.33 (natural water). Varies with T, S and λ

C in water = 2. 25x 10^8 m/s.

Frequency remains but λ diminishes in proportion to velocity

Properties of radiation field

- IAPSO defined the definitions
- Zenith angle(θ): Angle between light beam to upward vertical
- Azimuth angle(ϕ) = Angle between vertical plane incorporating the light beam to some other vertical plane (to vertical plane of Sun)
- Nadir angle: Angle between a given light beam to the downward vertical

- Radiant flux : Φ rate of flow of radiant energy in W (J/s) or in quanta/s
- Radiant Intensity: I flux per unit solid angle in specified direction. An infinitesimal cone in given direction / the element of a solid angle.
- $I = d\Phi / dw$ in W or in (quanta/s) / steradian
- Radiance : L radiant flux per unit solid angle per unit Area of a plane Right angles to the direction of flow . Function of Direction (zenith and Azimuth angles)

$$L(\theta, \phi): = d^2\Phi / d A \cos(\theta)\, dw,$$

- Irradiance : $E = d\Phi / dA$ (at point of source)W/m2
- Downward irradiance &upwardirradiance(E_d&E_u)
- Radiance in the given direction is defined by θ,ϕ
- The projected area of the element is ds cos θ,
- Corresponding angle is $d\omega$.
- Radiant flux on the element of surface within the solid angle $d\omega$
- is $L(\theta,\phi)\, dS \cos\theta\, d\omega$

The total irradiance at any point in the surface with respect to solid angle over the whole upper hemisphere is

$$Ed = \int_{2\pi} L(\theta,\phi)\, dS \cos\theta\, d\omega$$

$$Eu = -\int_{2\pi} L(\theta,\phi)\, dS \cos\theta\, d\omega$$

(cosθ is negative between 90-180 degree)

Scalar Irradiance Eo is the integral of the radiance distribution at a point over all directions about that point

$$Eo = \int_{4\pi} L(\theta,\phi)\, d\omega$$

Down ward scalar irradiance $Eod = \int_{2\pi} L(\theta,\phi)\, d\omega$

Upward scalar irradiance $Eou = -\int_{2\pi} L(\theta,\phi)\, d\omega$ (w/m2) or (w/m2/nm)

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

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

Spectral, Non uniform depth

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

LIGHT PENETRATION OCEANIC WATERS

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

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

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

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

$$\Rightarrow \overline{K}(z) = \frac{dI(z)}{dz}$$

$$K(\lambda) = K_W(\lambda) + K_B(B,\lambda)$$ where B=Chlorophyll Biomass

- **Irradiance Reflectance R**
- **Reflectance (R) = Eu / Ed   R = 0.33 bb/a**
- **Reflectance R (λ, z) = Eu(λ, z)/ Ed(λ, z),   R = 0.33 bb/a**

Irradiance decreases with depth approximately exponential manner, where R increases

Vertical attenuation coefficient is defined as

- **Downward irradiance = - d/dz (ln Ed) = - (1/ Ed) d Ed / dz**

$$Kd= (1/z1-z2) \ Ln\ (Ed(z1)/Ed(z2))$$

- **Upward irradiance Ku= = - d/dz (ln Eu) = - (1/ Eu) d Eu / dz**

$$Ku= (1/z1-z2) \ Ln\ (Ed(z1)/Ed(z2))$$

Net downward irradiance= Kn = - d ln (Ed-Eu) / dz

- **Optical depth : $\zeta = K_d z$,   Attenuation length = (1/K)**

Assume B $\Rightarrow$ independent of depth

$\Rightarrow$ K(λ) independent of depth

$$I(z,\lambda) = I(0,\lambda)e^{-K(\lambda)z}$$

$$\int_{400}^{700} I(z,\lambda)\,d\lambda = I(z)$$

$$\overline{K}(z) = \frac{-dI(z)}{dz}$$

I (0, λ, t) where t = time,

t = 0 at sunrise

= D/2 at noon

where D = Day length

Light transmission model for the atmosphere Bird (1983)

B (z)

$$\Downarrow$$

$$I(z,\lambda,t)$$

$$\Downarrow$$

$$\int I(z,\lambda,t)d\lambda$$

$$\Downarrow$$

K(z,t)

If $B \Rightarrow B(z)$

$$I(z,\lambda) = I(0,\lambda)e^{-\int_0^z B(z')K^*(\lambda)+K_W(\lambda)dz'}$$

$$\int I(z) = \int I(z,\lambda)d\lambda$$

$$\overline{K}(z) = \frac{-dI(z)}{dz} \Rightarrow I(z,t) = I(z-1)e^{-\overline{K}(z)dz}$$

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*
Irradiance *E* [W m^{-2}]
Diffuse attenuation coefficient *K* [m^{-1}]

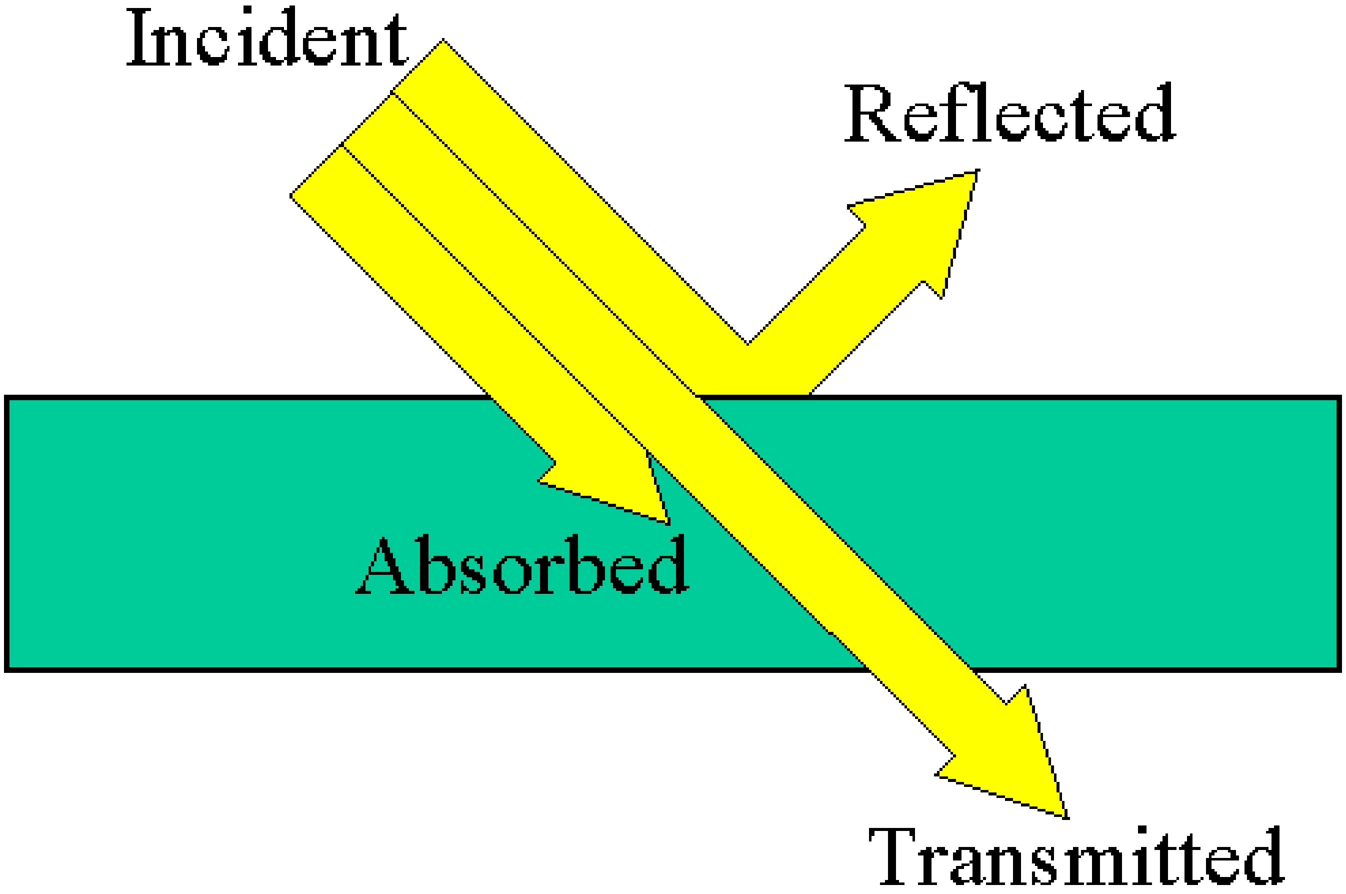
} ratio of these is or ocean colour

All of the above are wavelength (λ) dependent

WHAT IS OCEAN COLOUR ?

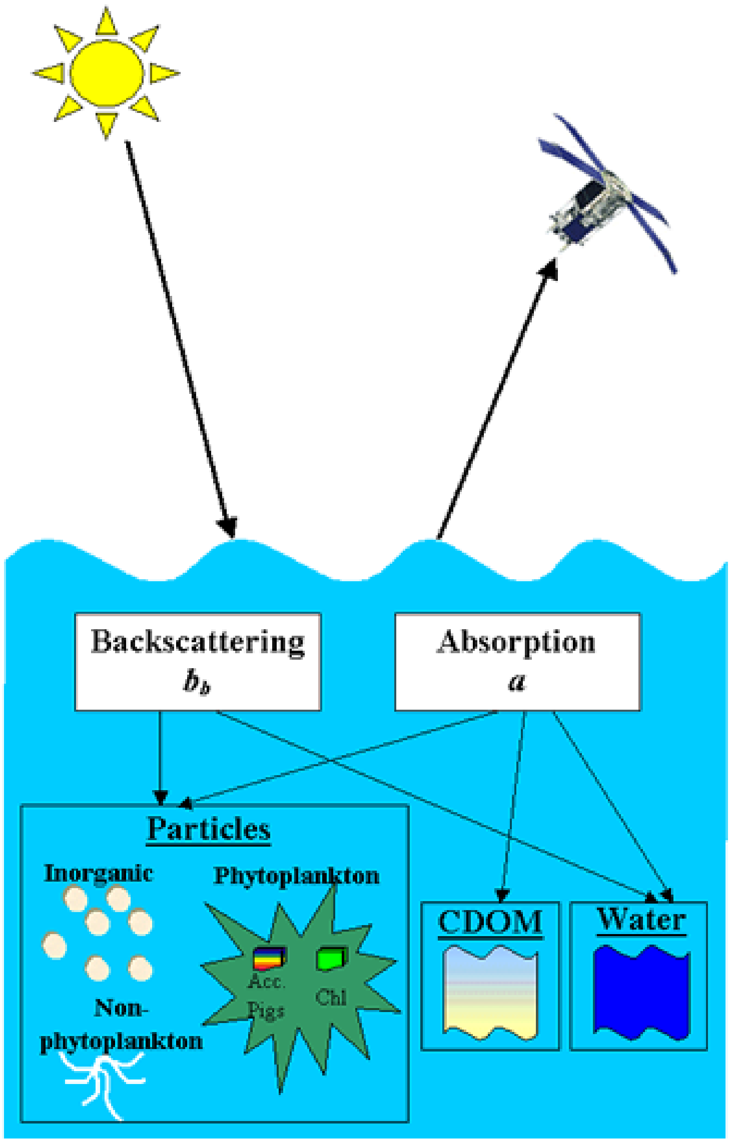
Colour of the ocean is BLUE in clear water but it changes due to :

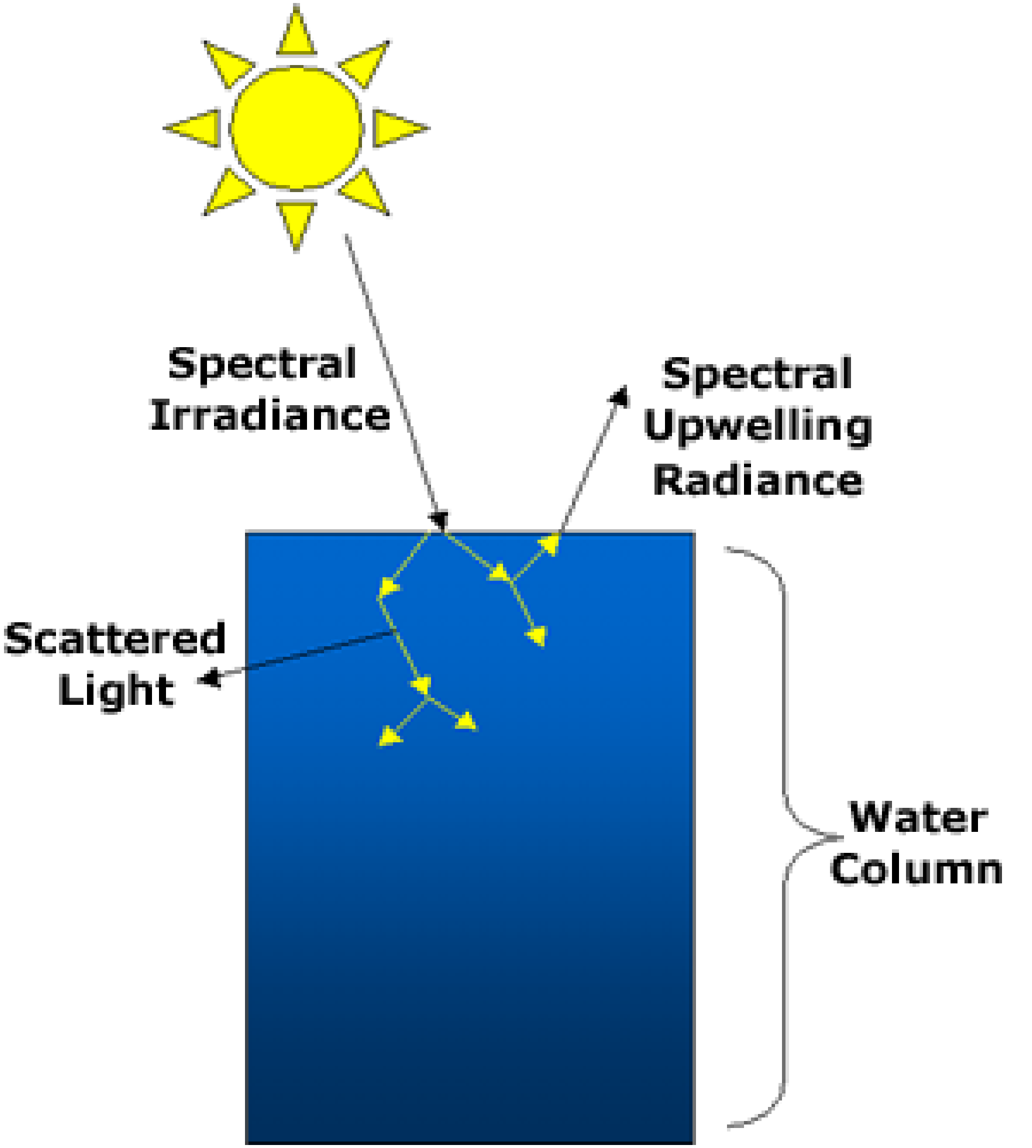
- **Phytoplankton Patchiness**
- **Inorganic/Organic Matter**


Incident
Reflected
Absorbed
Transmitted

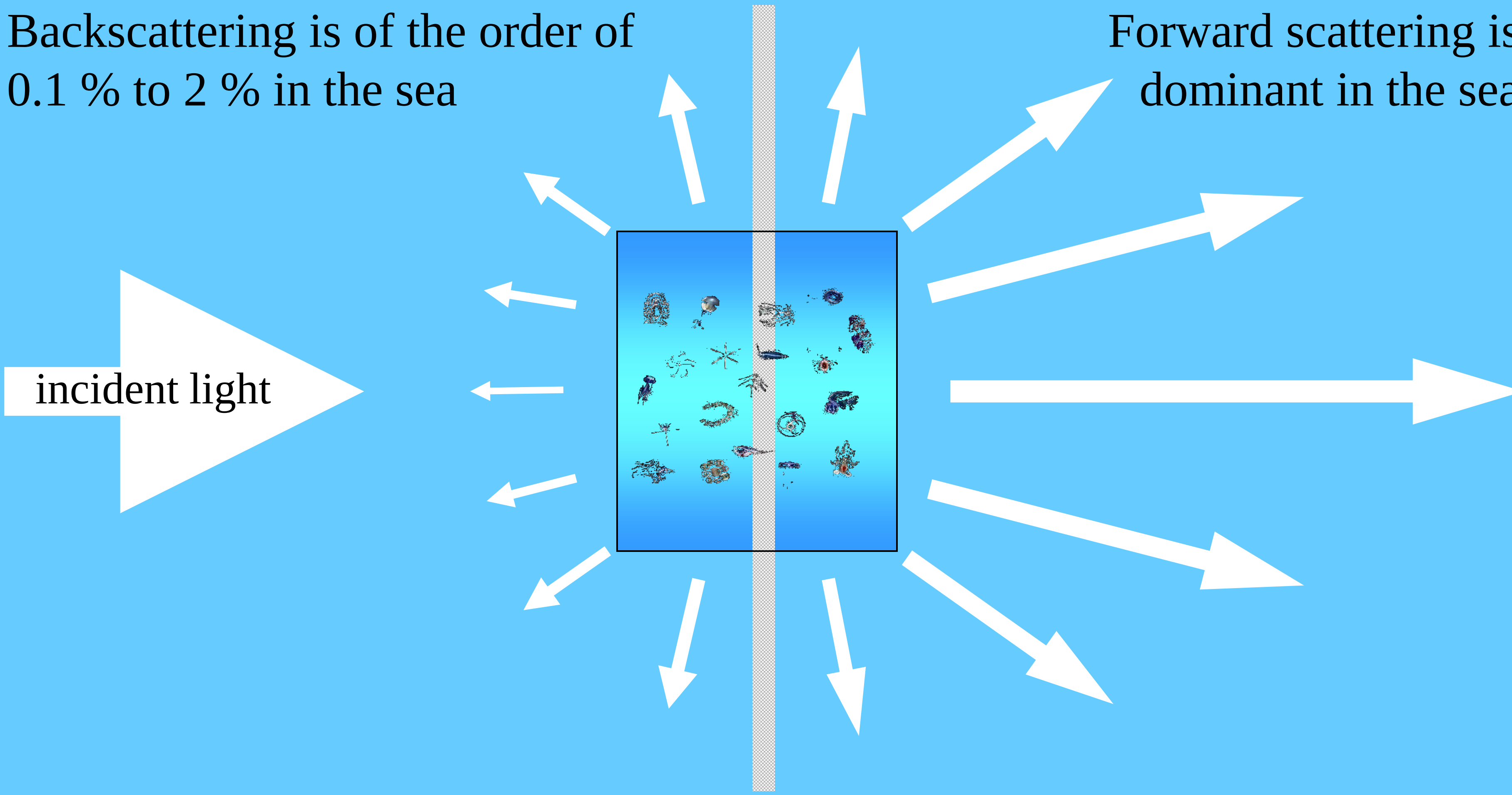
"There are only two things that can happen to photons within water: they can be absorbed or they can be scattered."

OCEAN OPTICS



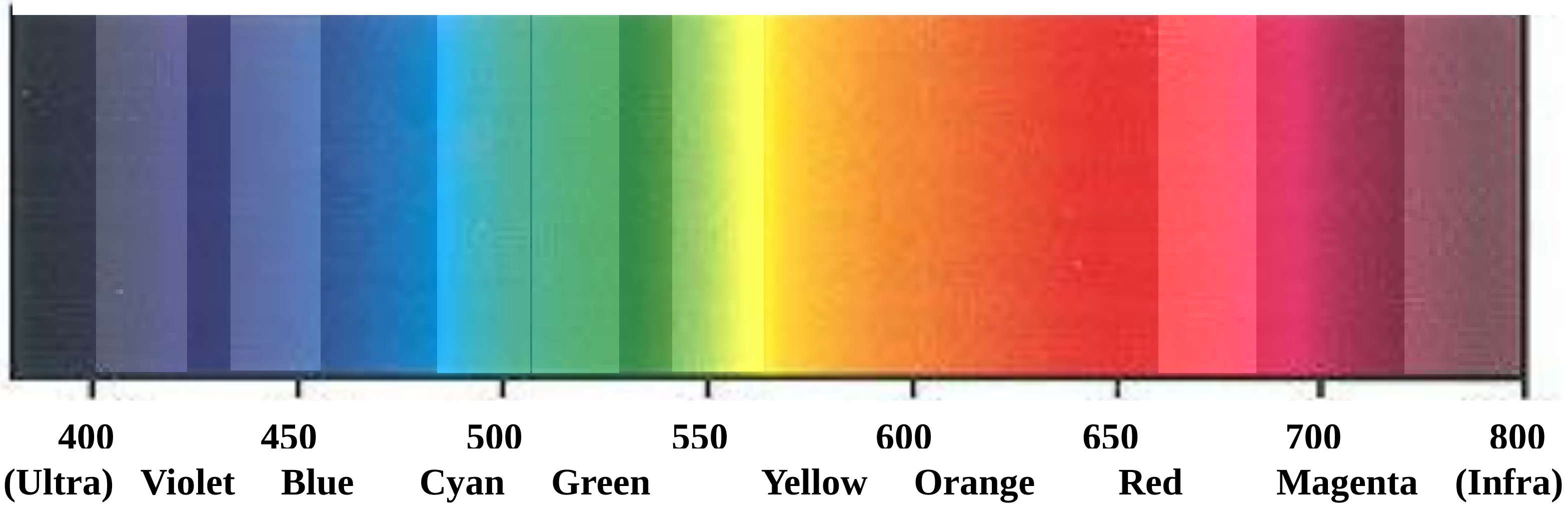


Scattering is the change of direction of a photon



Absorption is the loss of a photon

THE VISIBLE SPECTRUM • wavelength in nanometers



The Absorbing and Scattering Constituents of Seawater

These can be separated into particulate and dissolved components

Major Components

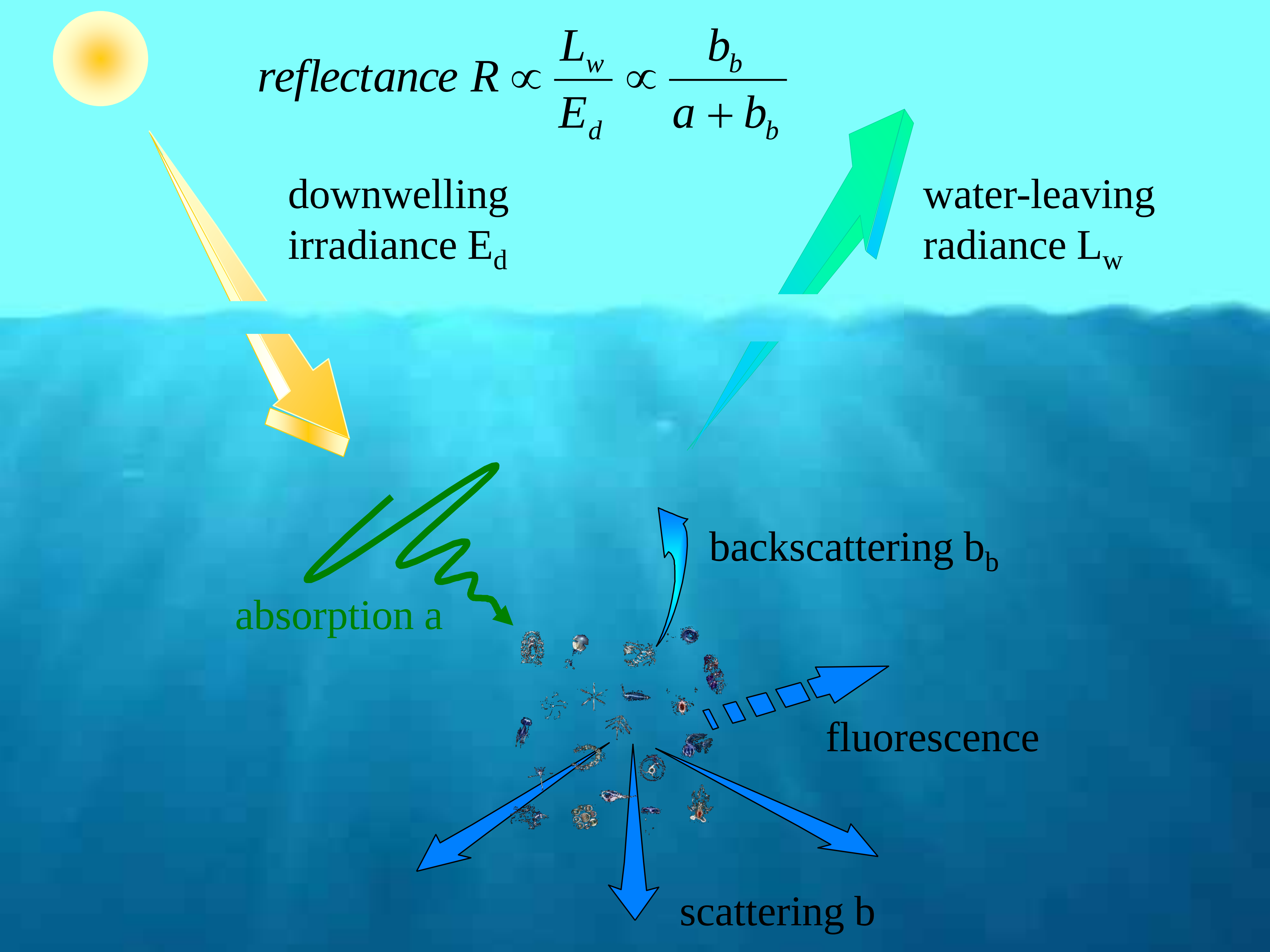
- The water itself
- Phytoplankton
- Gelbstoff or coloured dissolved organic material (CDOM)
- Other suspended particulate such as algal detritus and suspended sediment

Minor Components

- Bacteria
- Viruses
- Bubbles

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

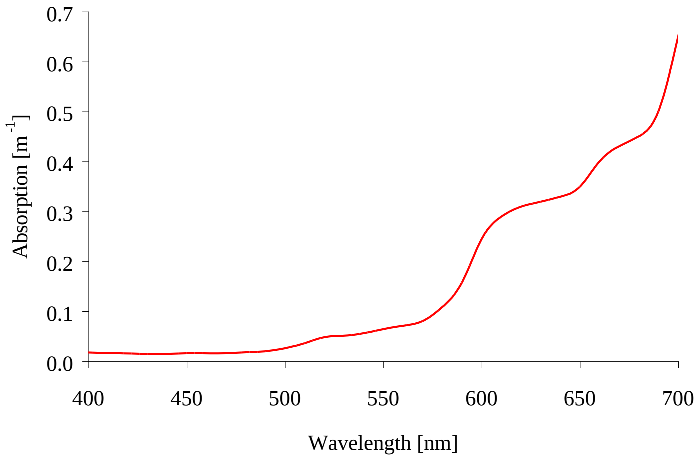
$$reflectance\ R = G\frac{b_b}{a + b_b} = G\frac{b_{b\ water} + b_{b\ plankton}}{a_{water} + a_{plankton} + a_{gelbstoff} + b_{b\ water} + b_{b\ plankton}}$$



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

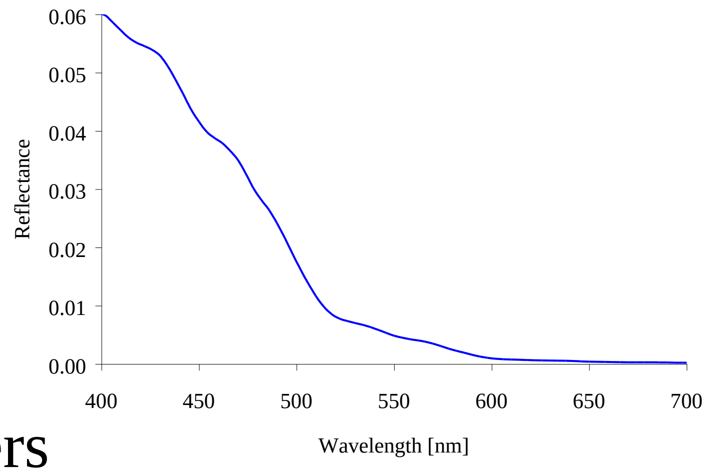
The Absorption and Backscattering of Water

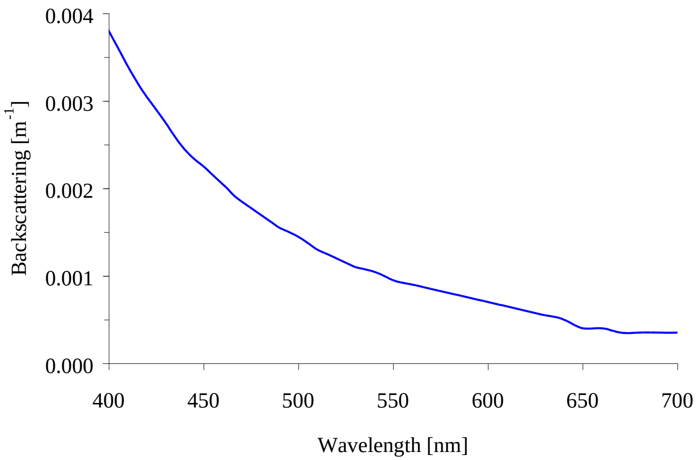
(or why water is blue)



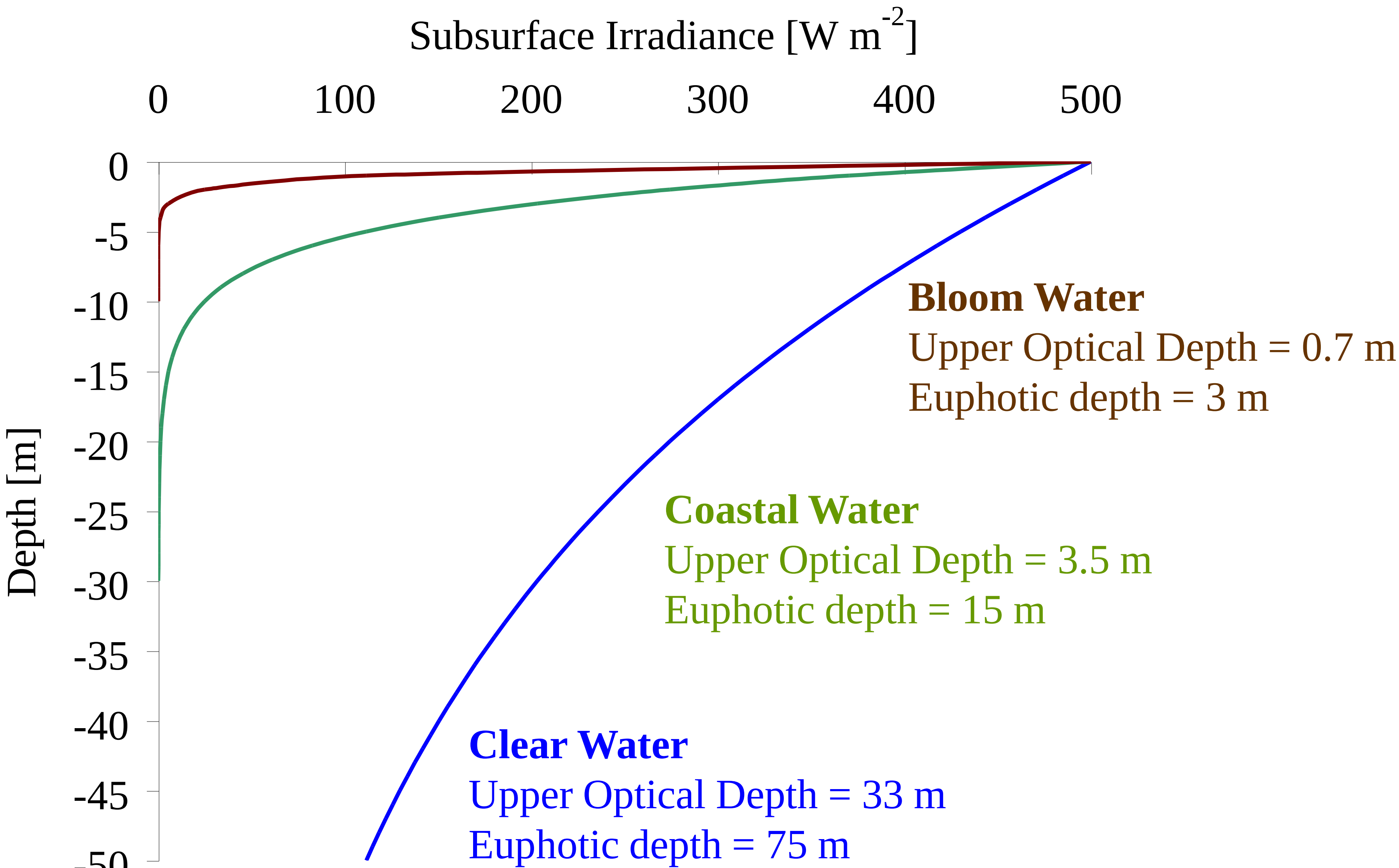
Water absorbs strongly in the red

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





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

$$\text{Reflectance (R)} = Eu / Ed$$

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

$$Kd = (1/z1\text{-}z2)\ Ln\ (Ed(1)/Ed(2))$$

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

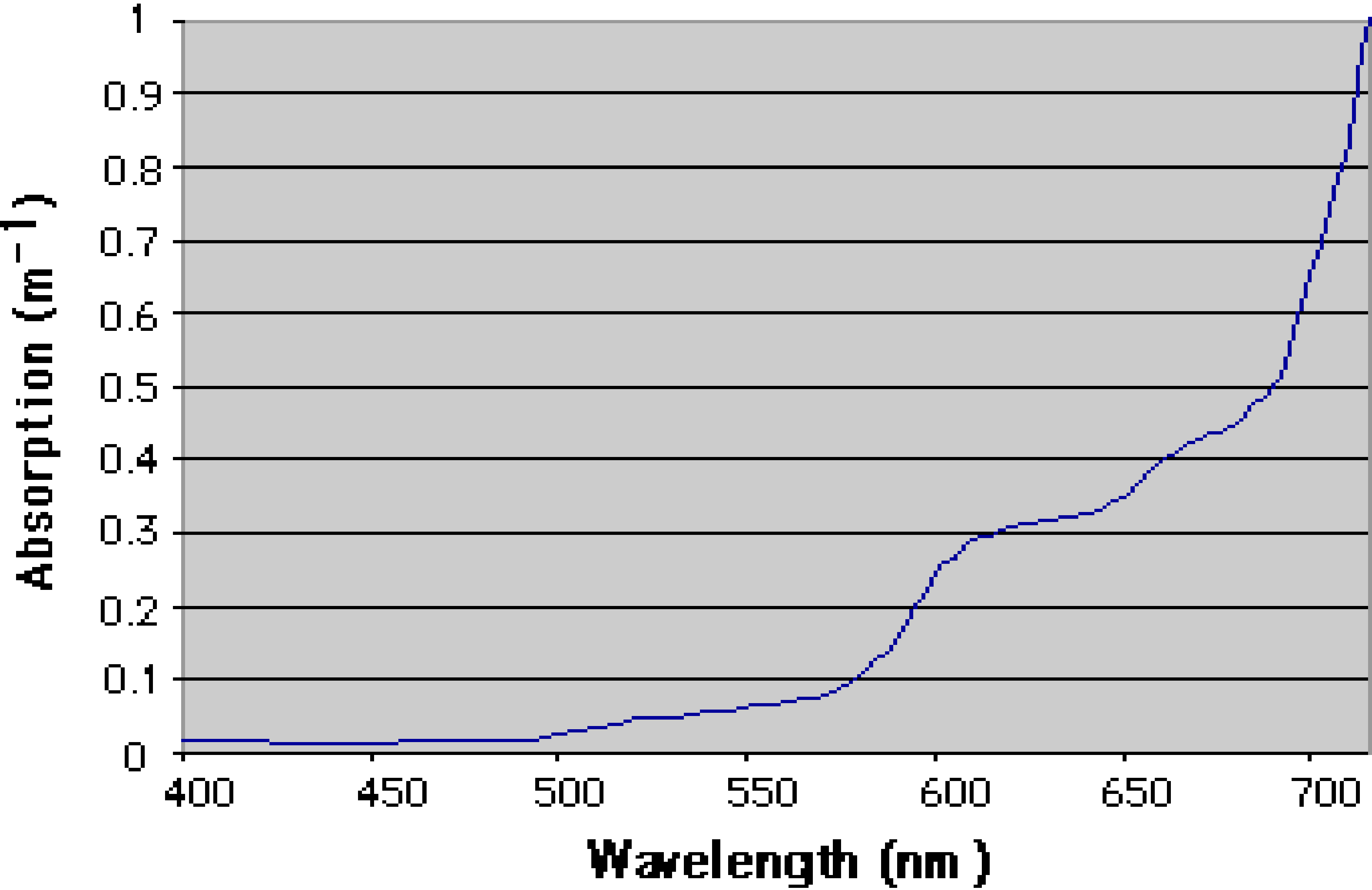
- Dominance of Chlorophyll

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

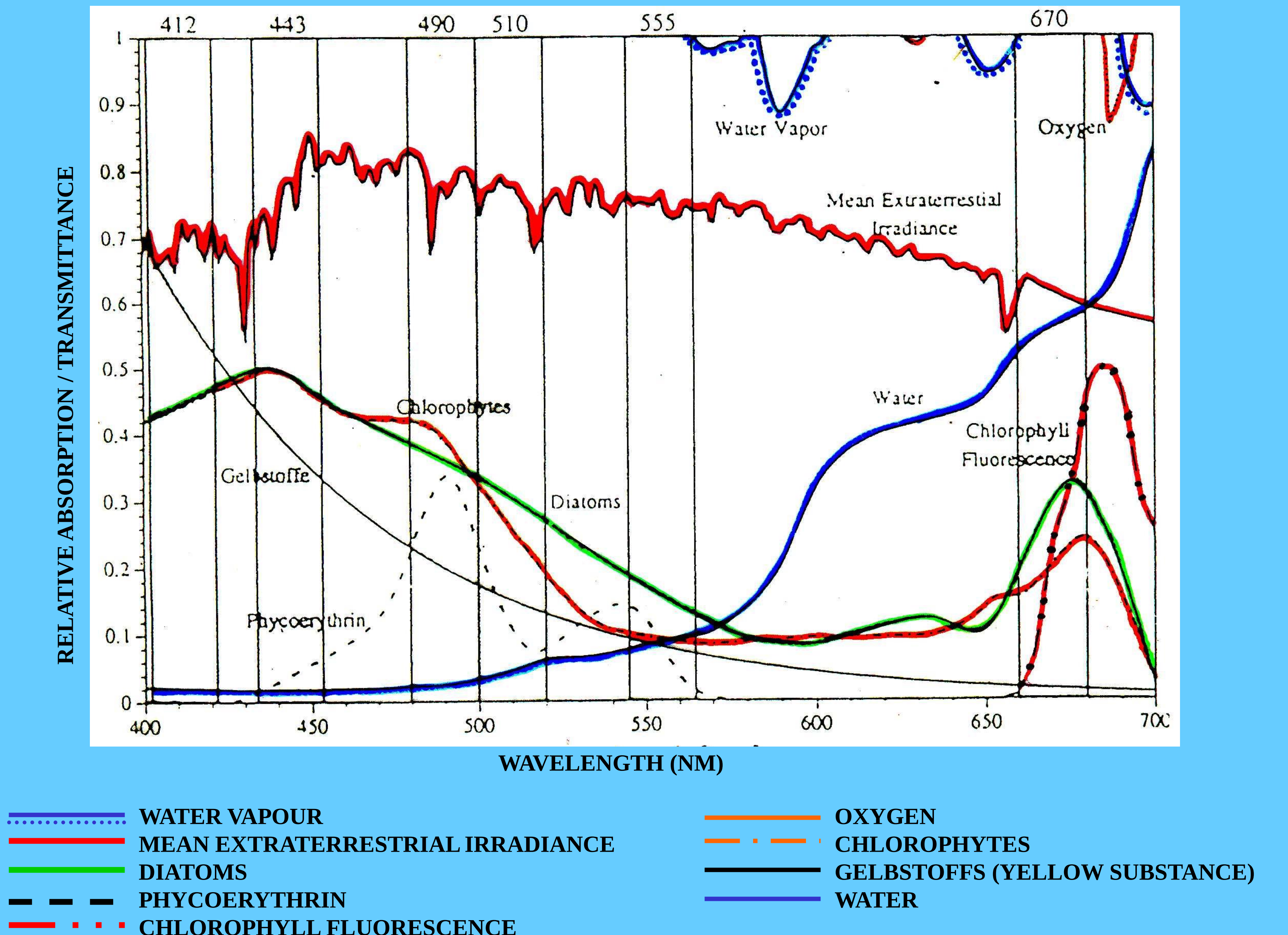
Ambient Properties

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

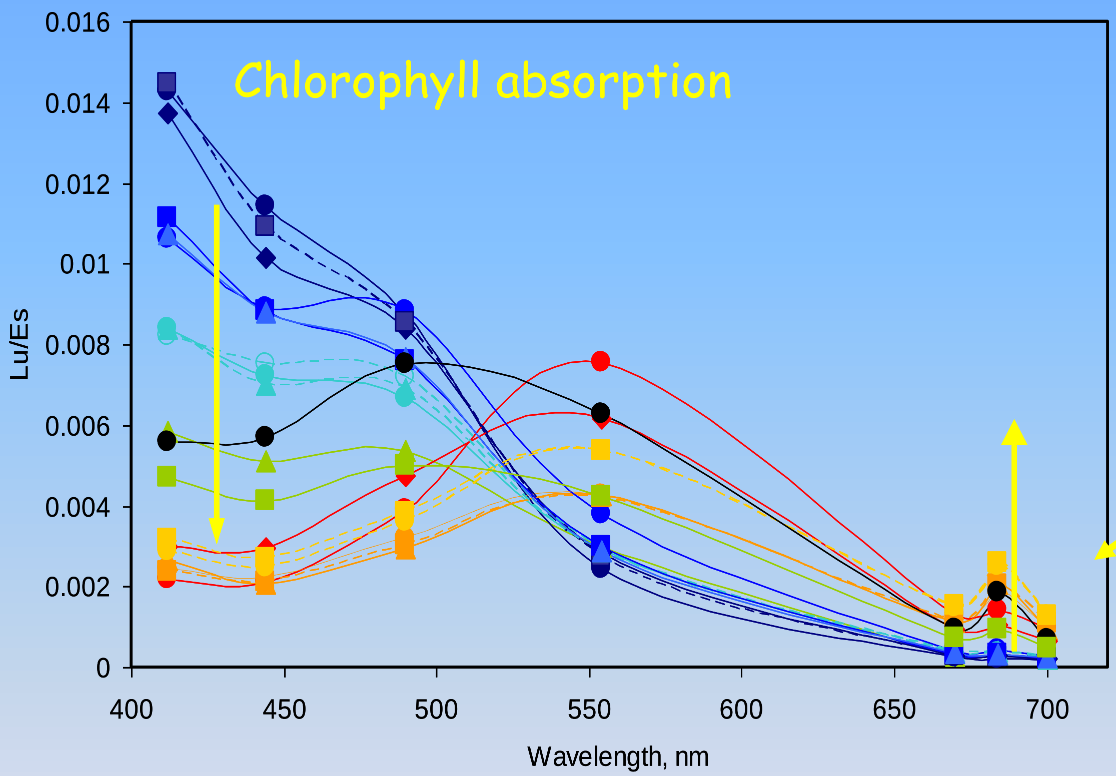
Primary Biogeochemical Measurements

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

SPECTRAL SIGNATURES

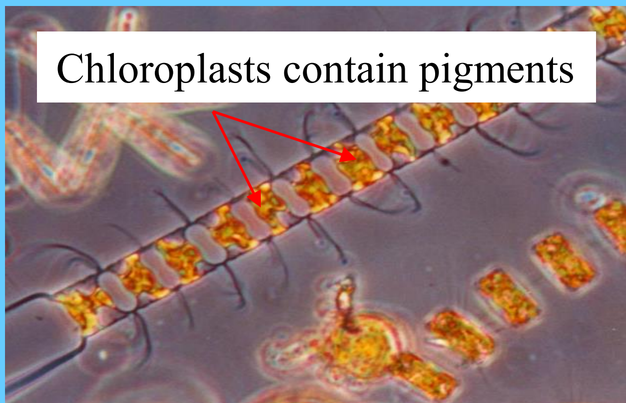


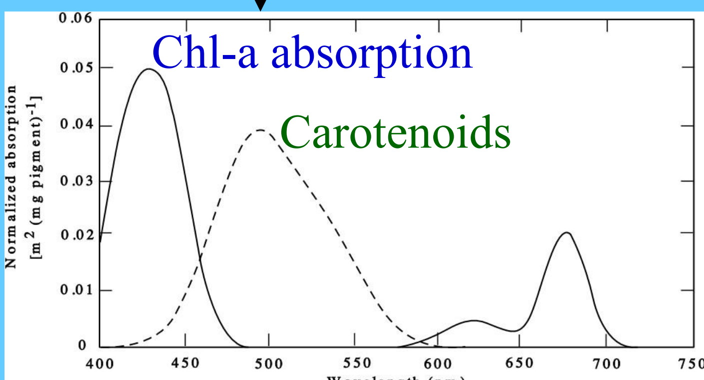
Fluorescence spectral signature

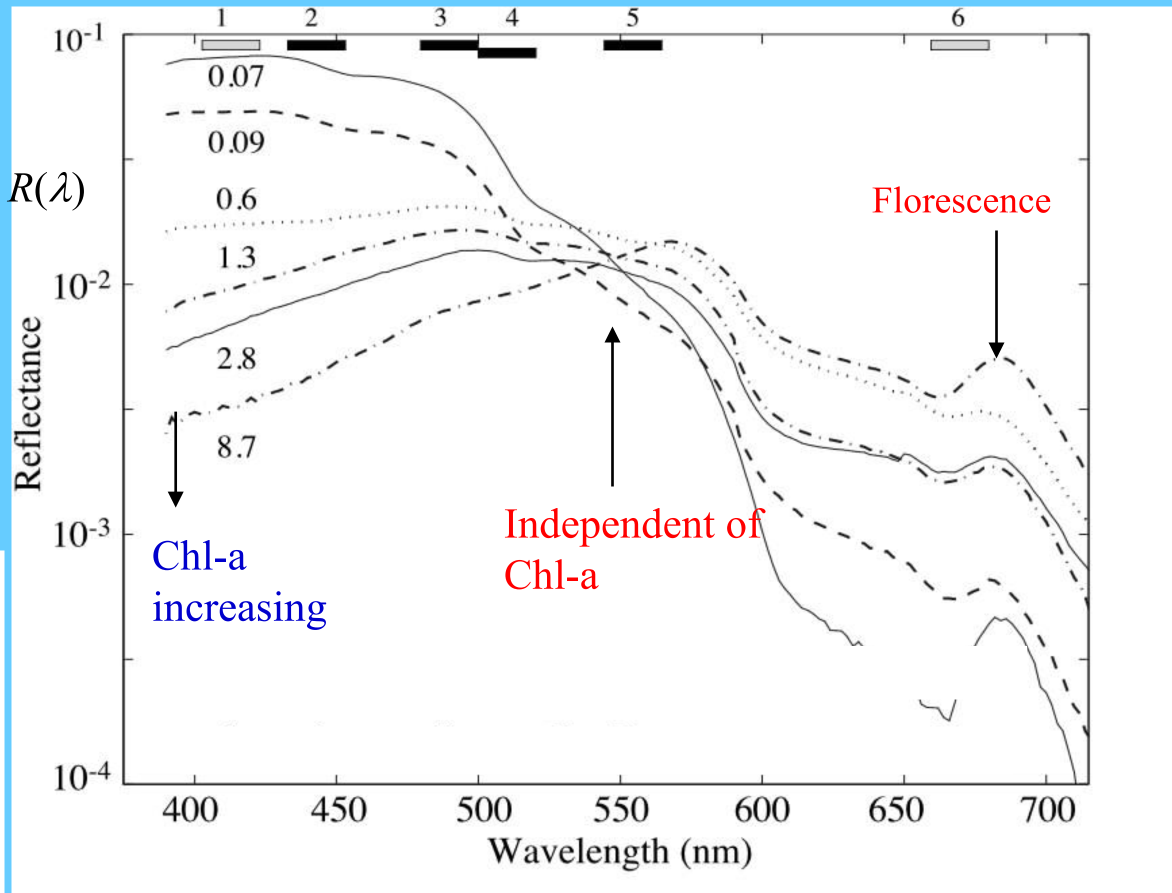


Increase in fluorescence

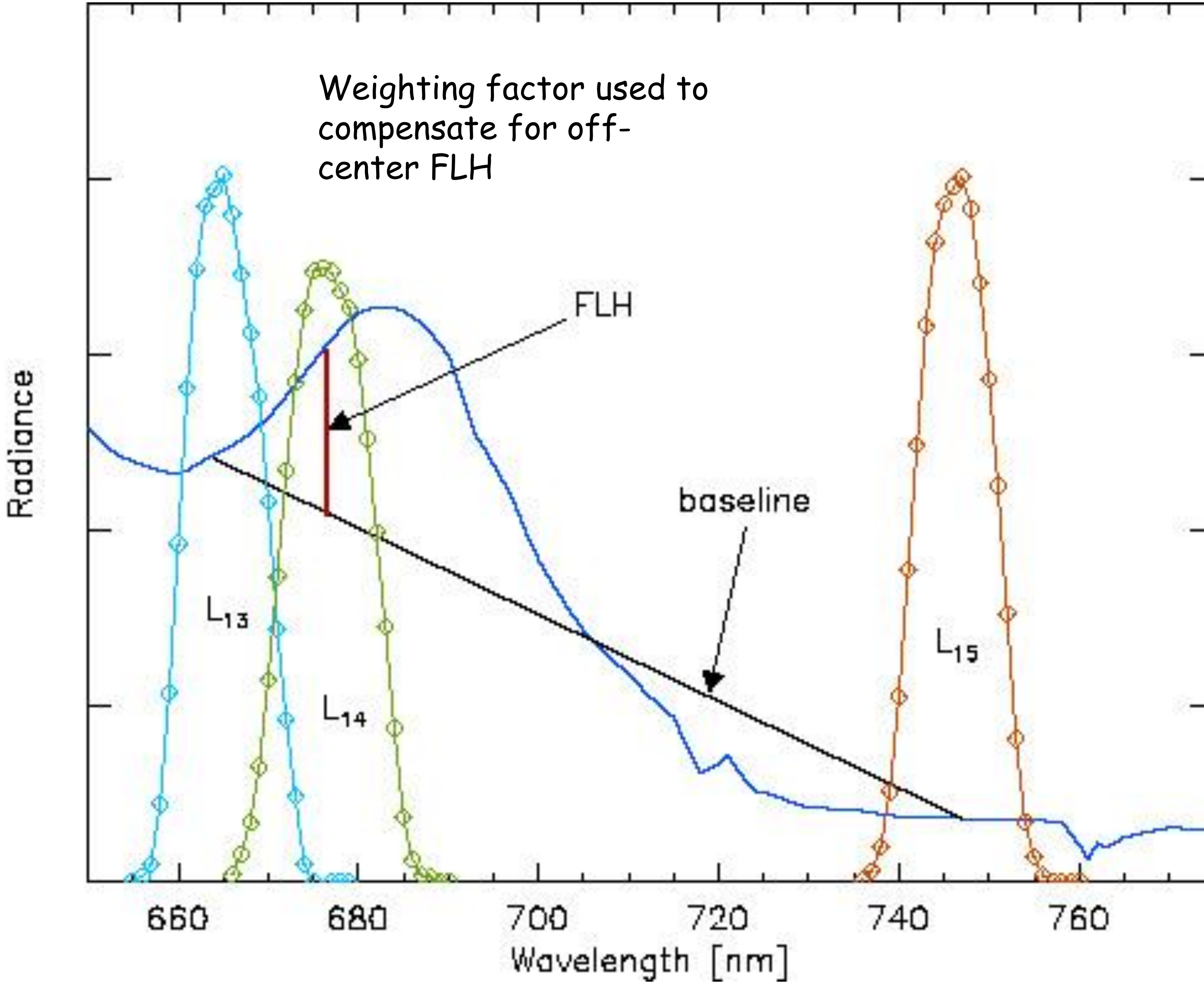
Detection of Phytoplankton Pigment using remote sensing



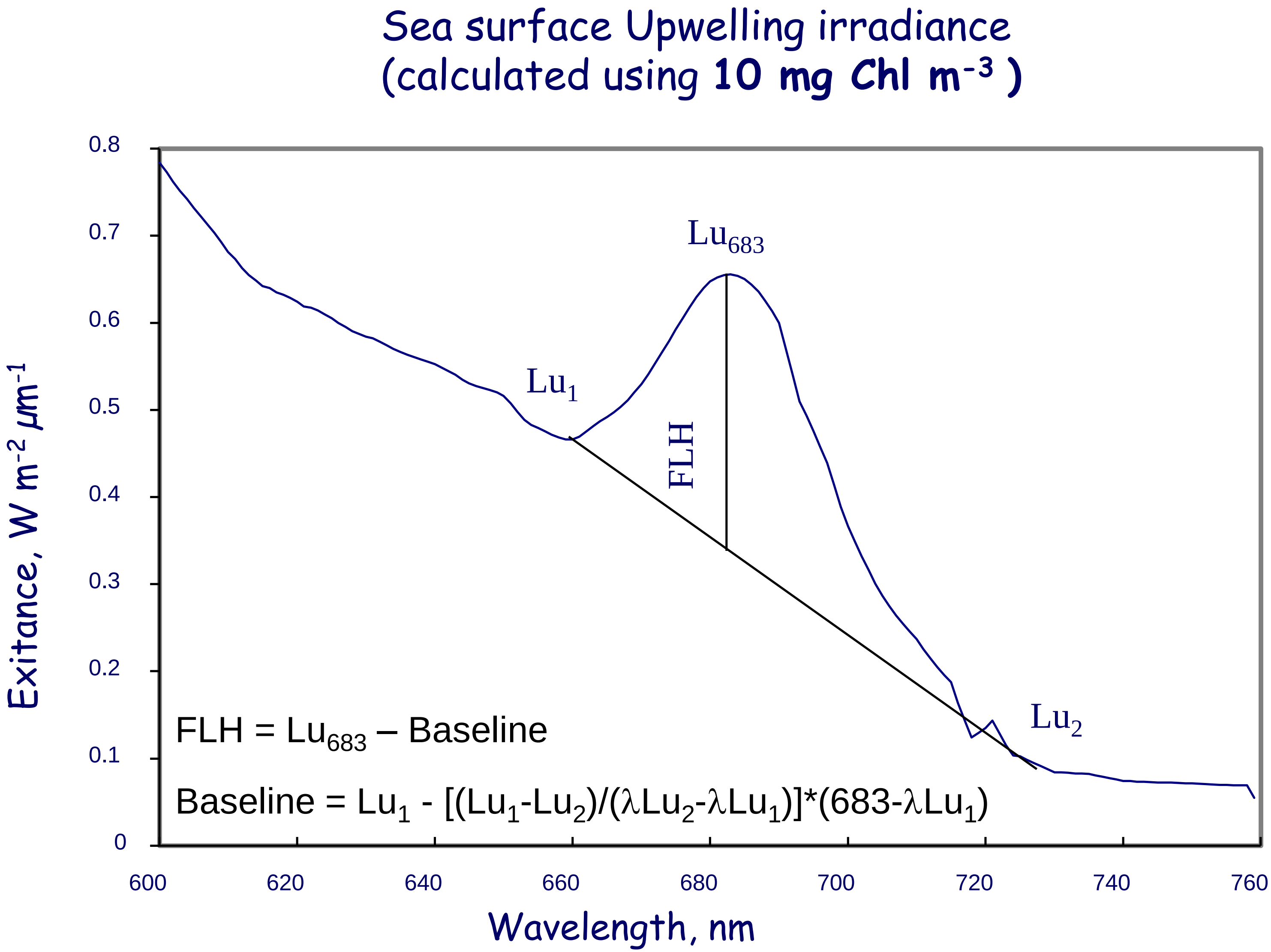




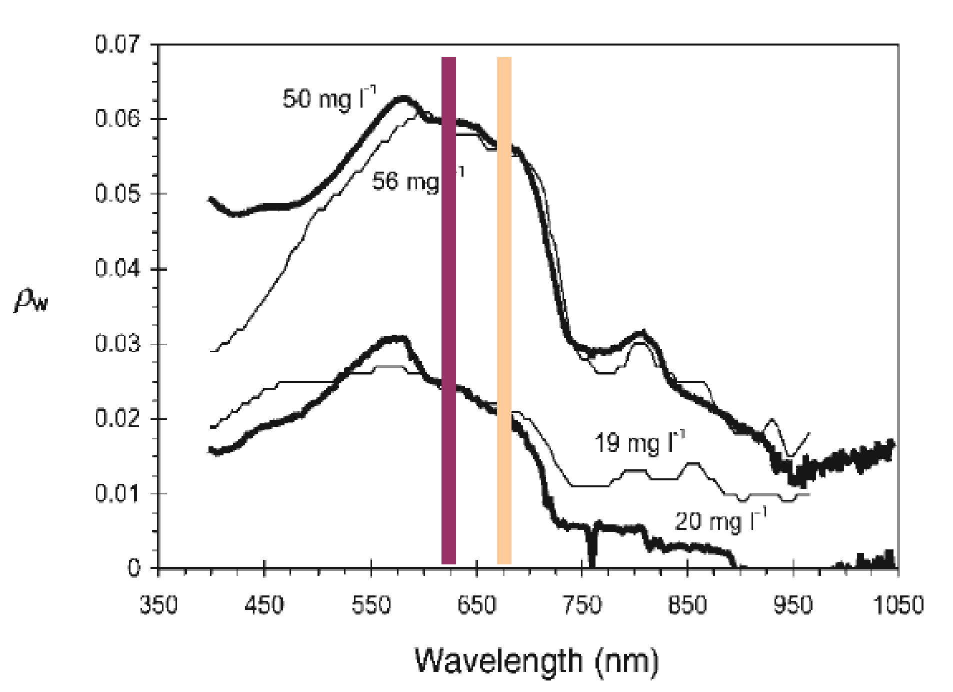
MODIS FLH bands: avoid oxygen absorbance at 687 nm

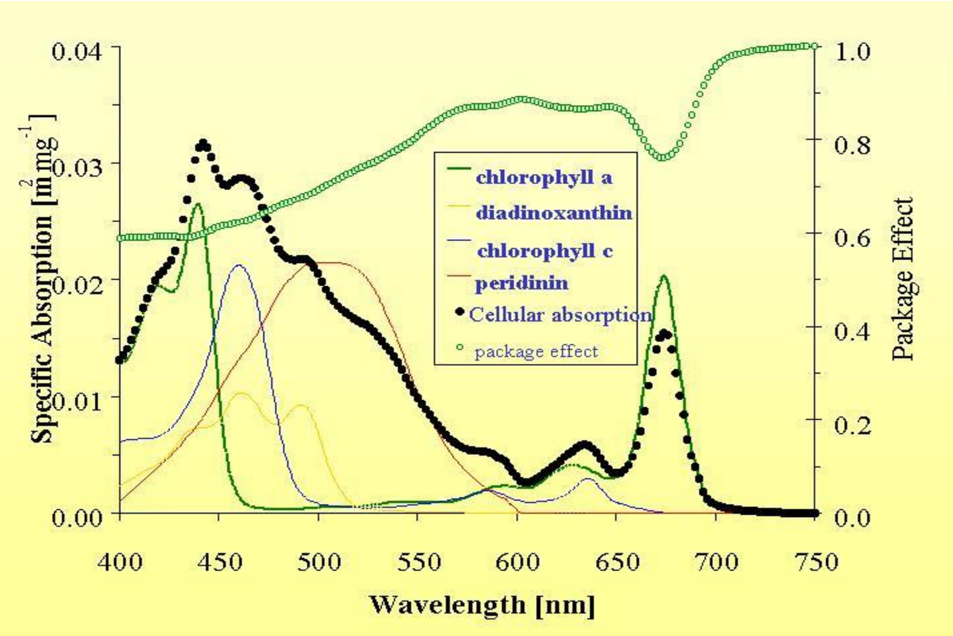


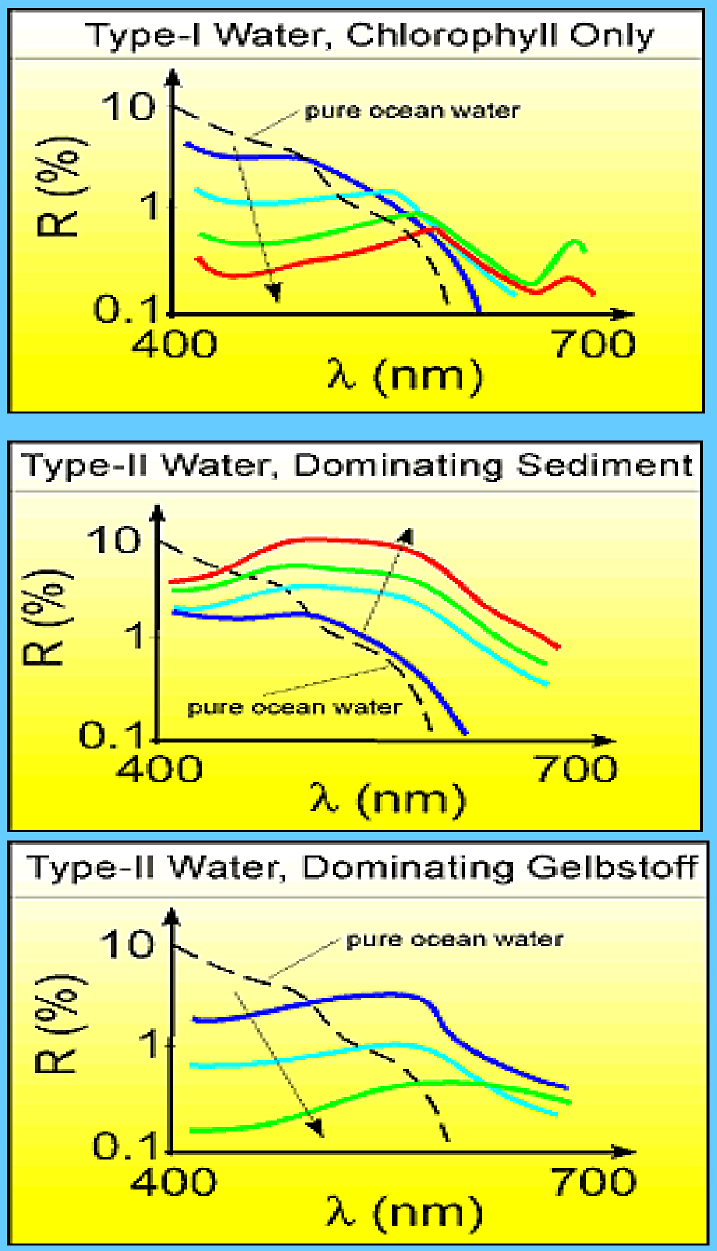
Calculation of Chl fluorescence : Using Fluorescence Line Height



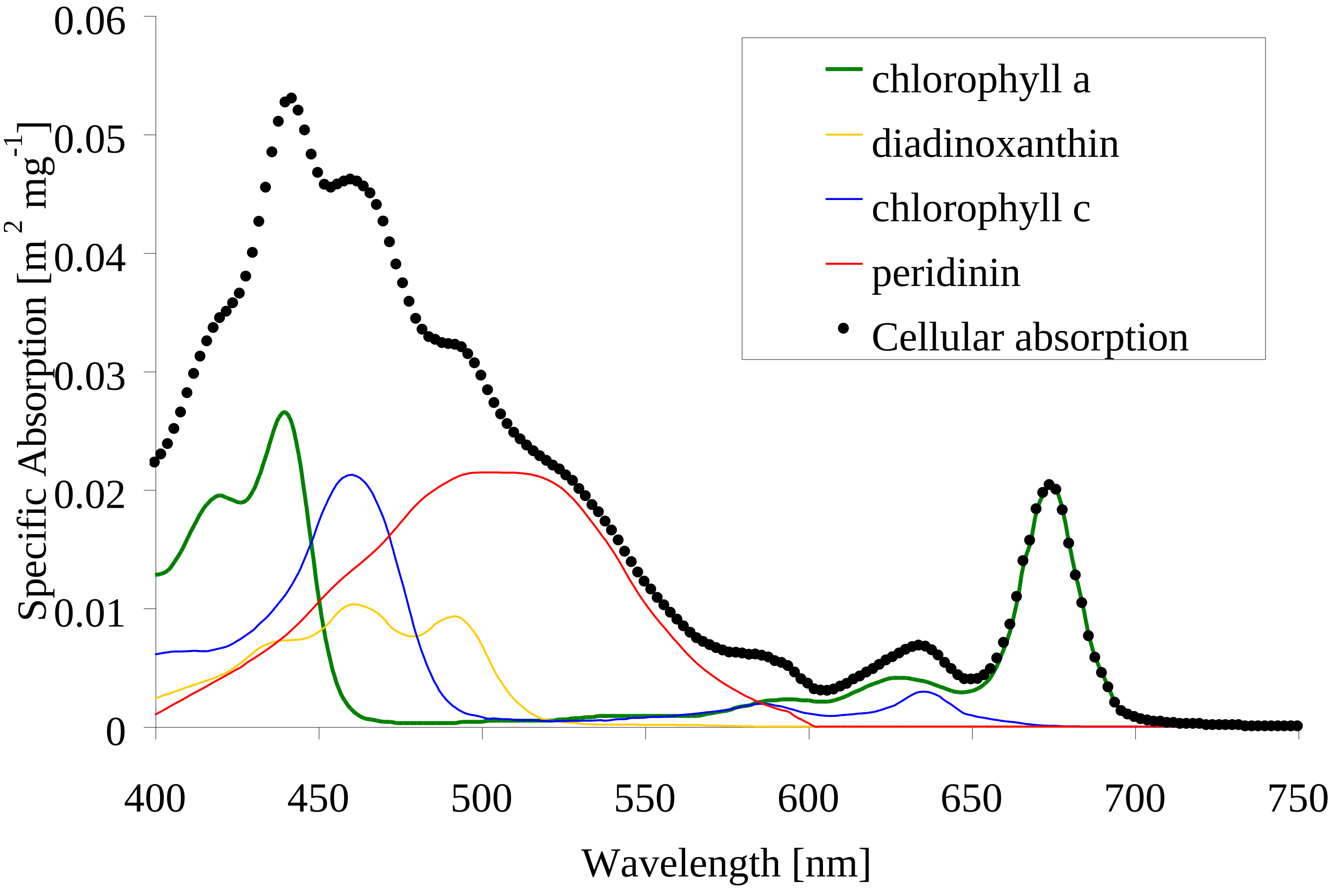
Spectral Curves for different water constituents



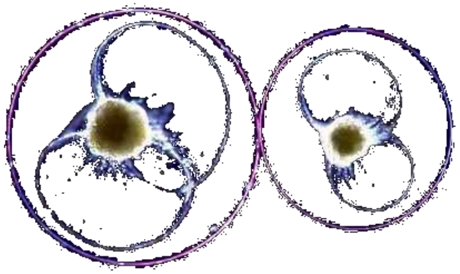


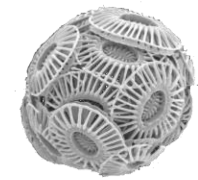


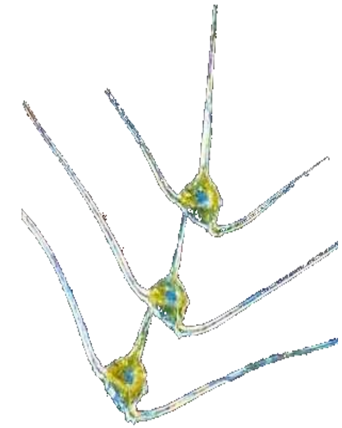
1. The variable presence and concentration of intracellular pigments.

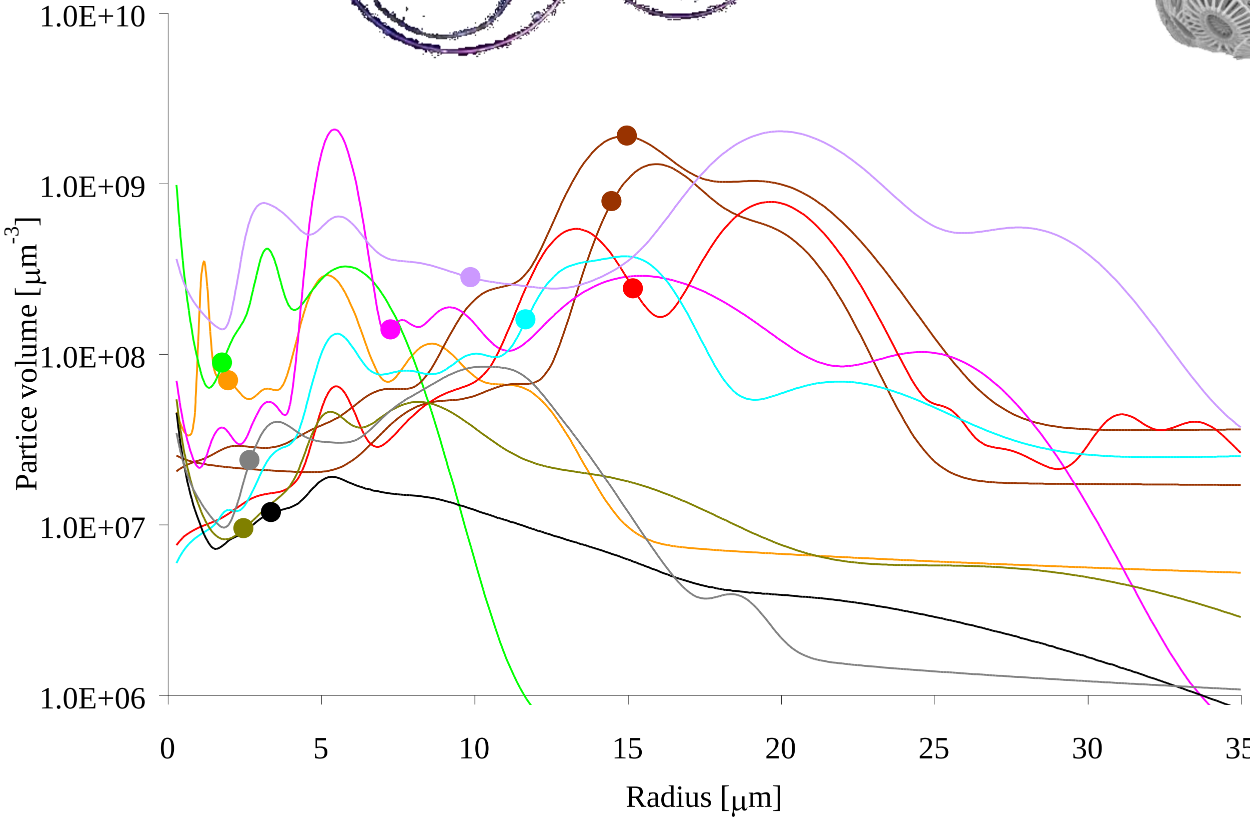


2. The size, shape and material structure of the cells







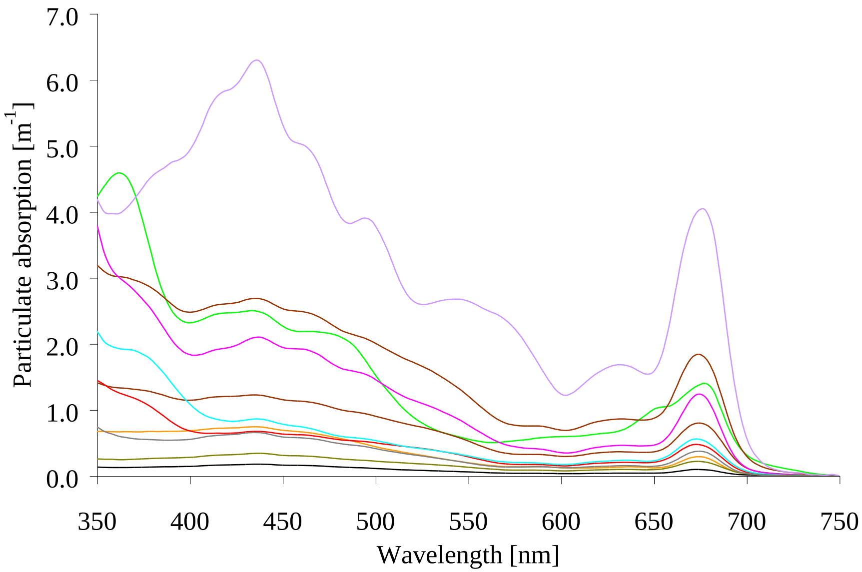


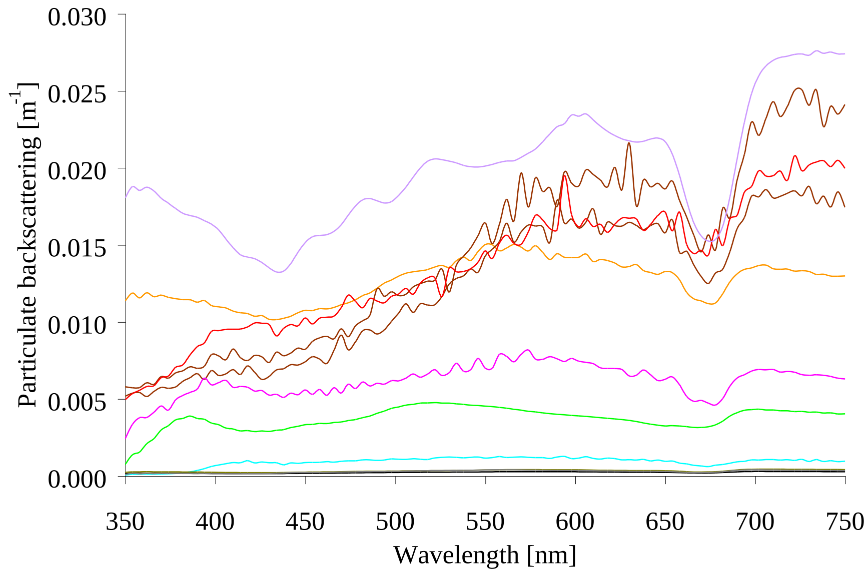
Dominant Species

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.





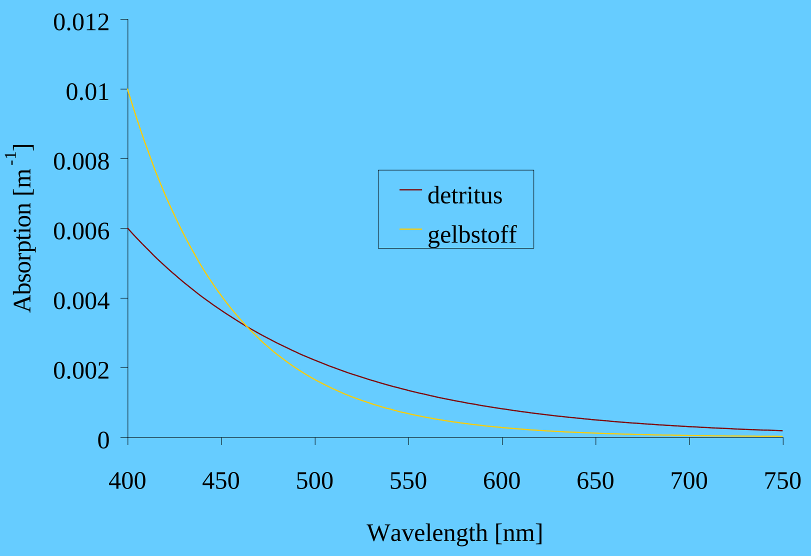
Dominant Species

A. anophagefferens	Ceratium spp.
A. catenella, Ceratium spp.	West Coast Gymnodinium sp.
Dinophysis spp, Nitzchia spp.	Chlorophyte
Diatom	G. mikimotoi
Mixed	Mesodinium rubrum (b_b=x0.2)

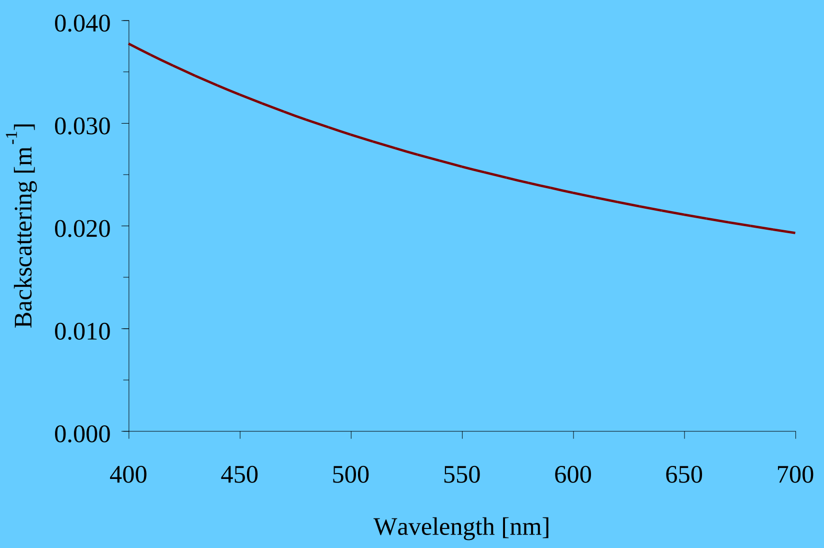
Gelbstoff, Detritus and Suspended Sediment

- 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.

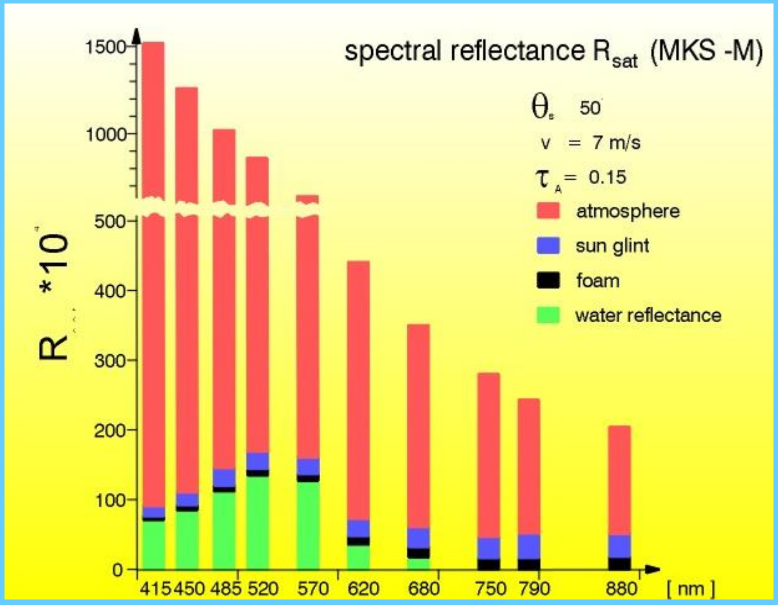
- Inorganic sediments are typically highly scattering with low absorption, and need to be considered on a case specific basis e.g. in areas of high river discharge or resuspension

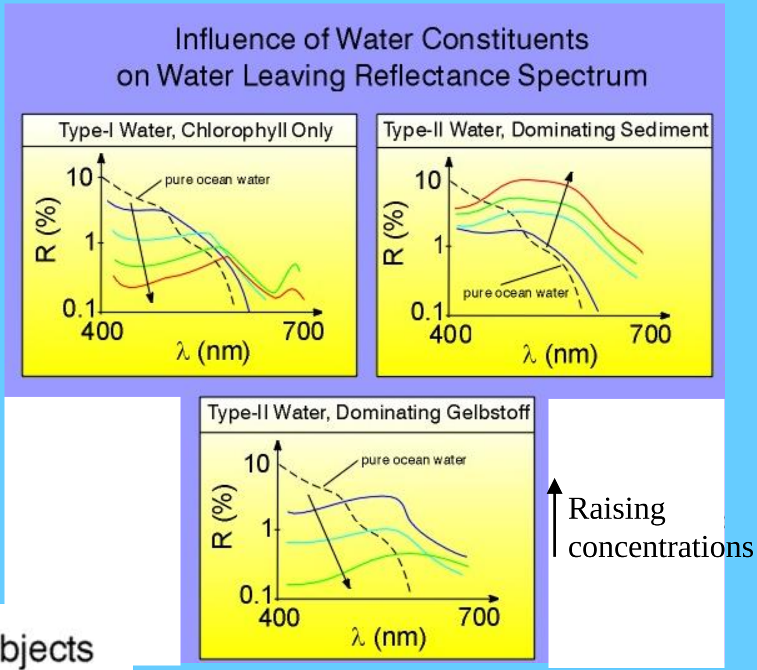


Typical exponential decay with wavelength of gelbstoff and detritus absorption



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





Spectral reflectance of different remote sensing objects

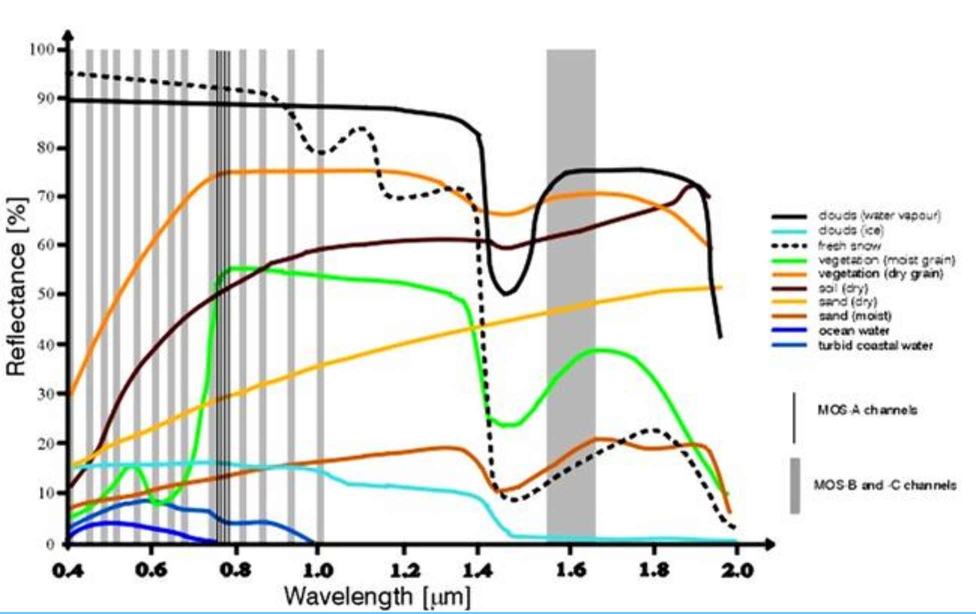
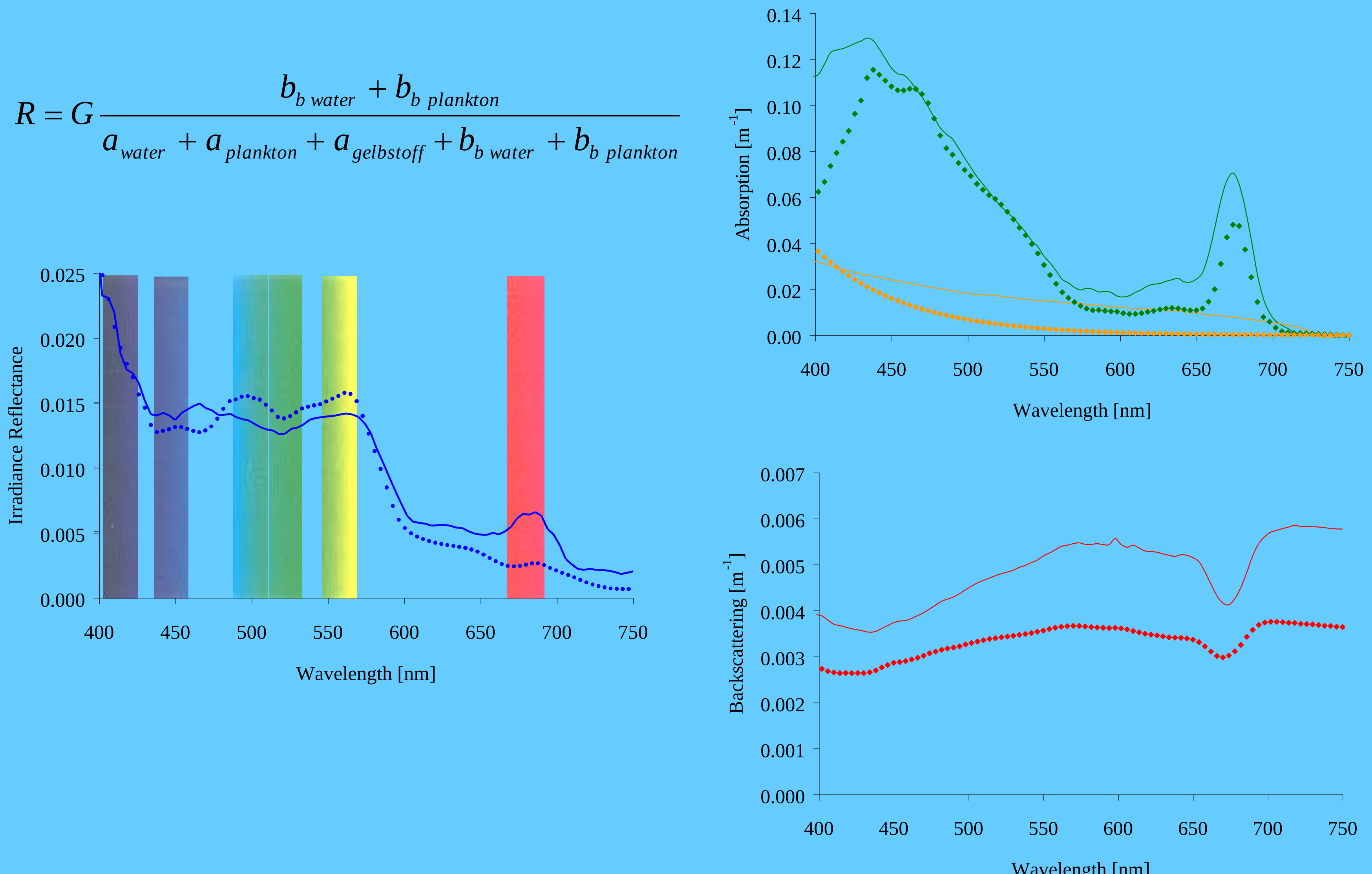


Table 4-2 Chlorophyll algorithms used in this study

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	$C = 10^\wedge((a_0 + a_1 R + a_2 \times R^2 + a_3 \times R^3 + a_4)/e)$	$\log(L_W[N]443/L_W[N]551)$	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

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



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

THE REFLECTANCE FROM WATER

- DEPTH
- SUSPENDED PARTICLES IN WATER
- FLOATING VEGETATION, IF ANY
- SUN ANGLE

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

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

THANK YOU