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2 - 18 February 2009

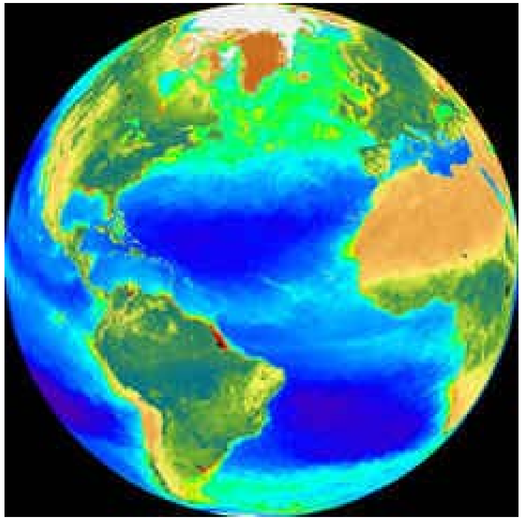
Optical Remote Sensing of the Sea: Radiometry from Space

Zibordi G.

European Commission Joint Research Centre
Italy

Joint Research Centre

Optical Remote Sensing of the Sea: Radiometry from Space



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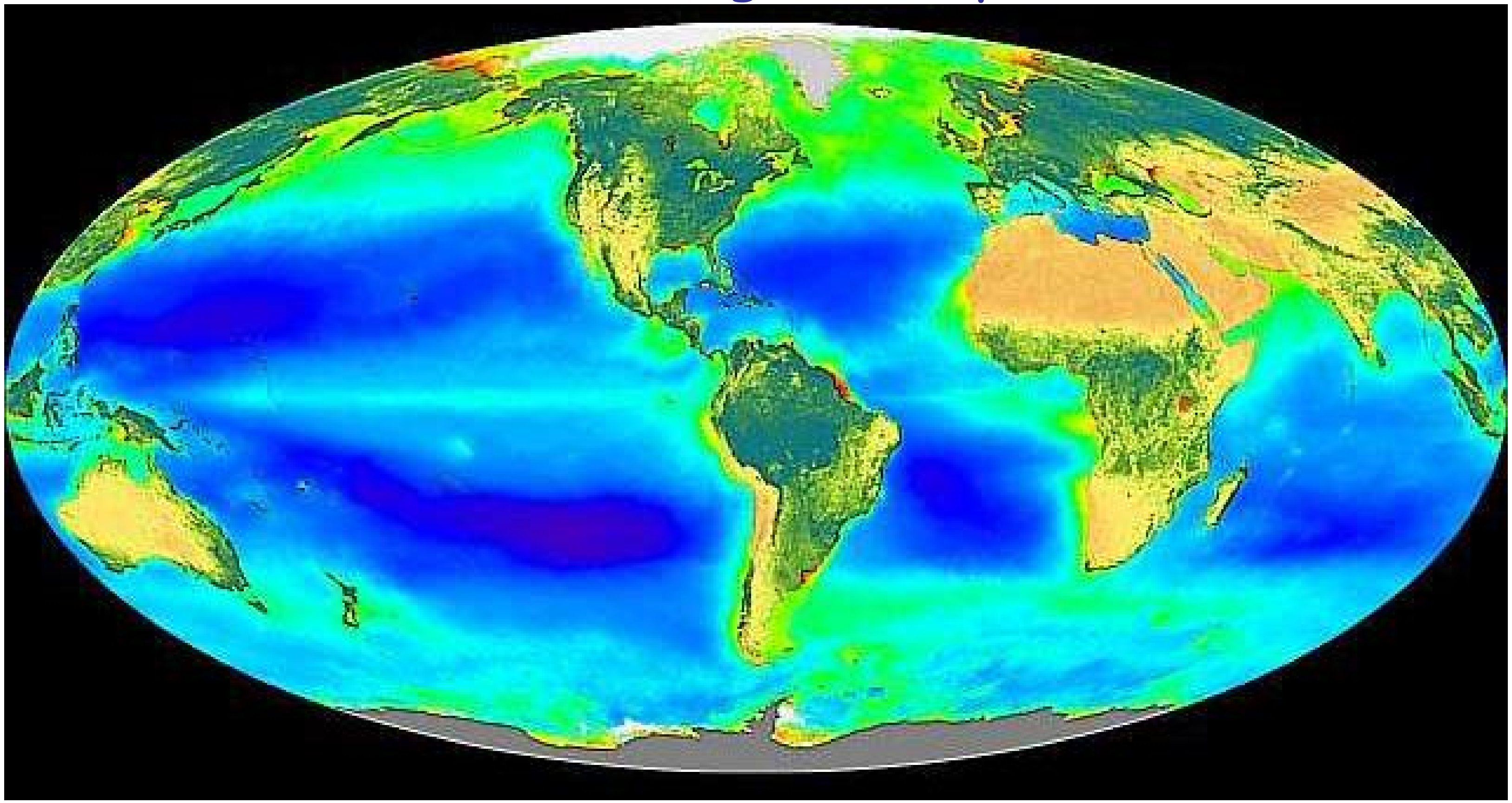
Global Environment Monitoring Unit

Joint Research Centre of EC

Chlorophyll-a (sea) and vegetation index (land) map inferred from remote sensing data (up to 1 km resolution)



This is not a picture taken from space

It results from the physical first and bio-optical later, interpretation of multispectral radiometric measurements of the Earth surface from space

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Optical remote sensing

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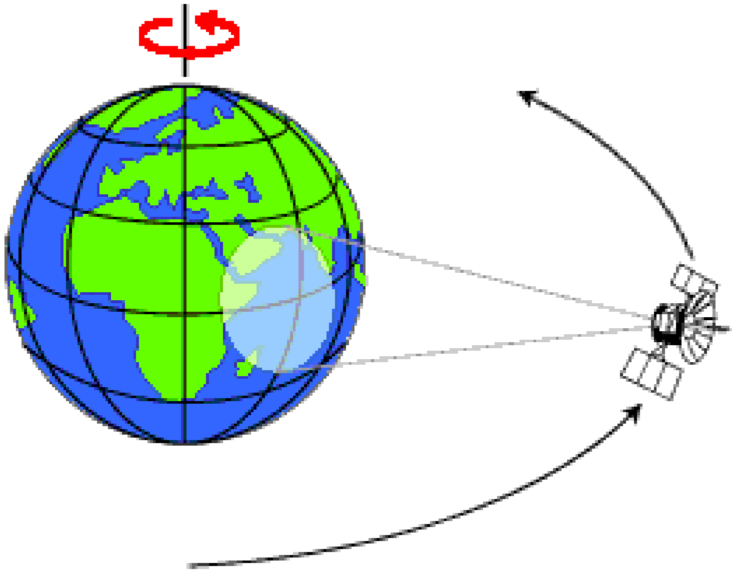
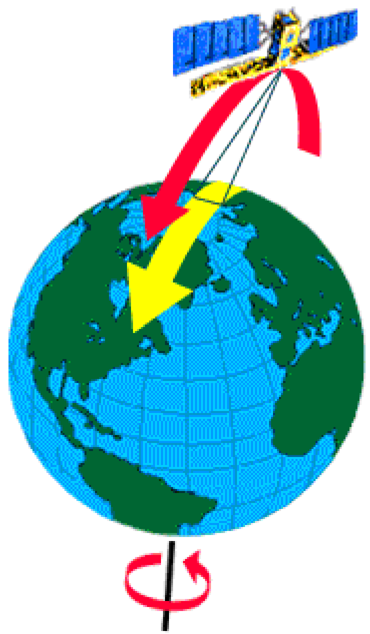
Satellite based observing systems

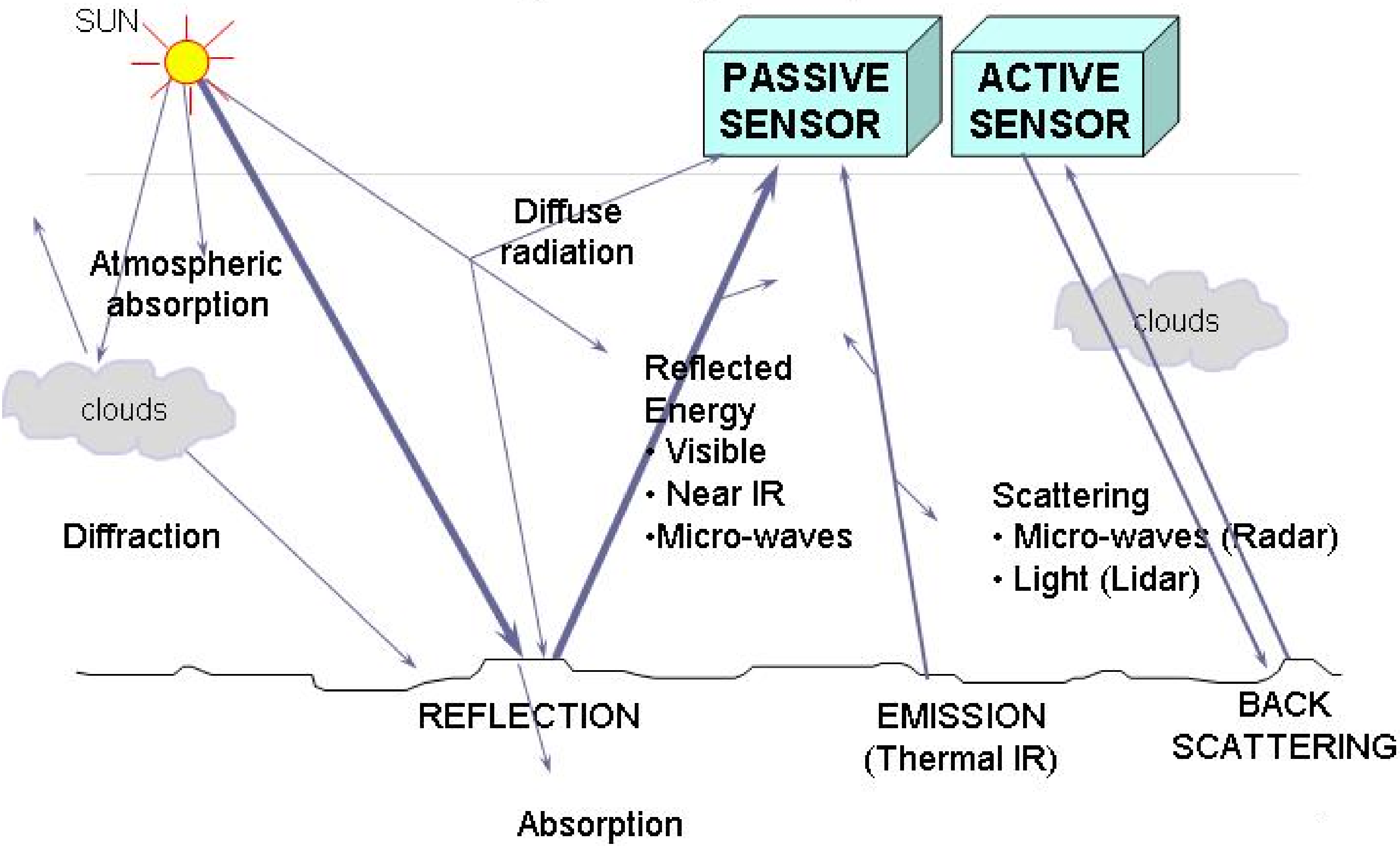


Geostationary

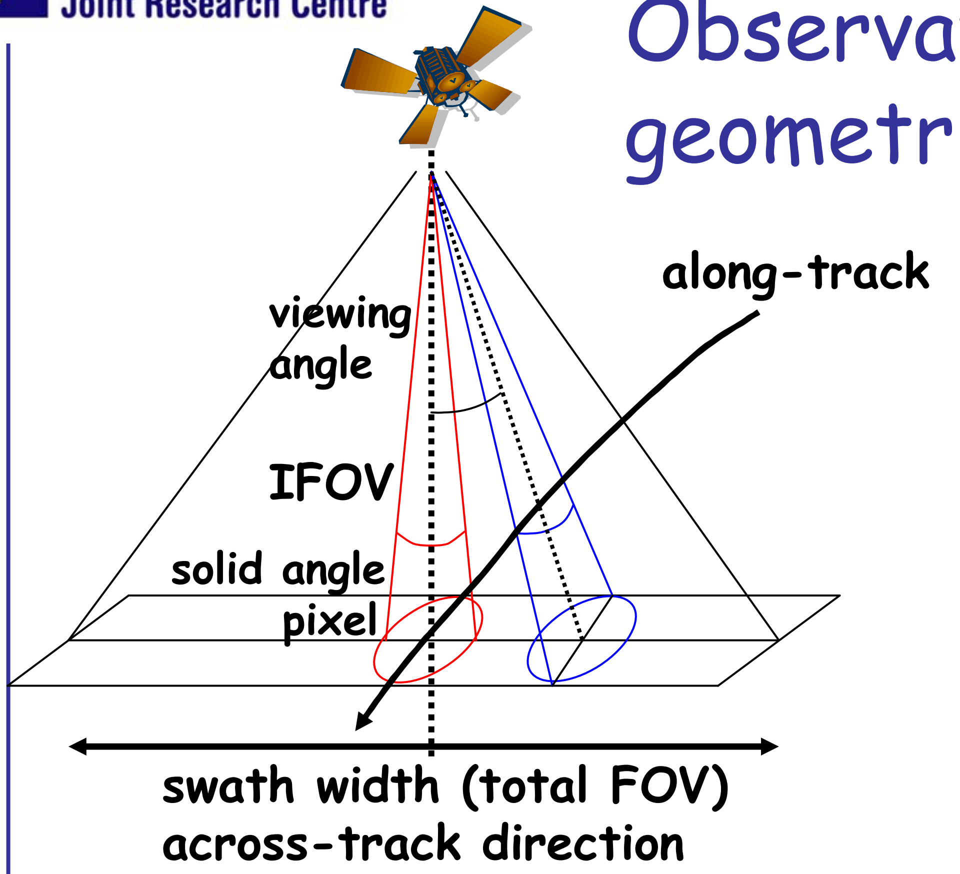


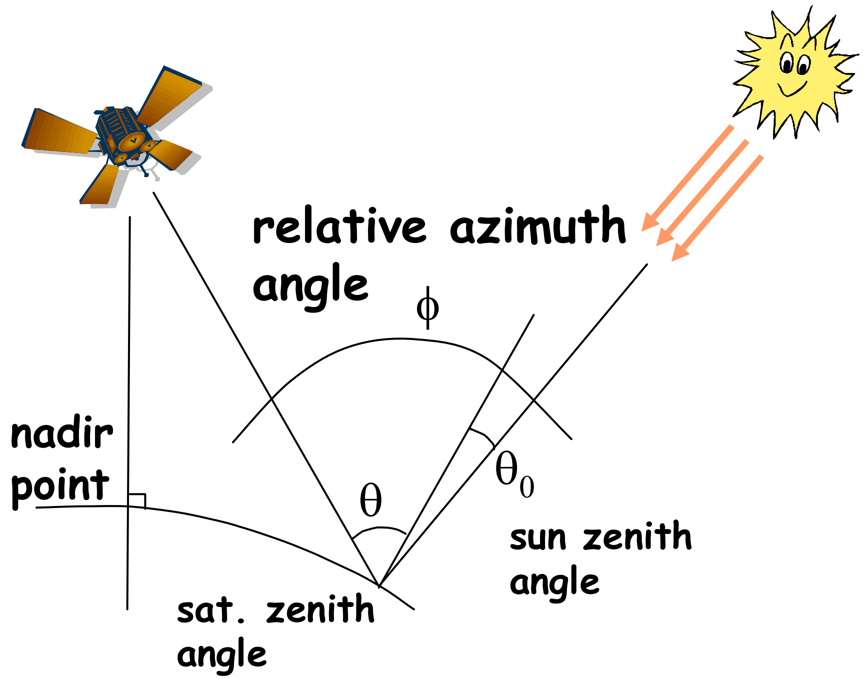
Near-Polar Orbiting

Physical principles of remote sensing



Observation and illumination geometries

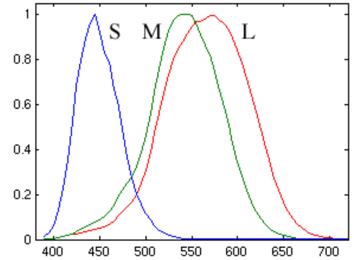




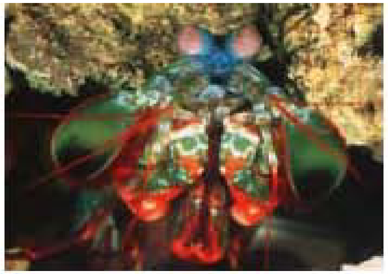
A remote sensing image is generally composed of individual measurements that the satellite acquires as it scans the Earth surface. These individual samples (pixels) have a spatial resolution which depends on the instantaneous field of view (IFOV) of the space sensor, and may vary from a few meters up to several tens kilometers.

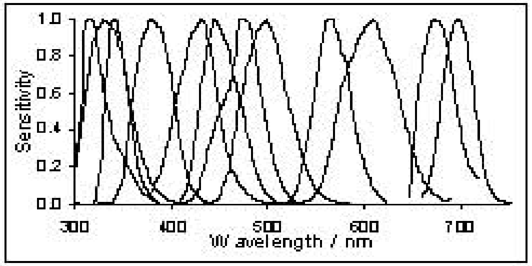
Optical Sensing Systems

Of all the techniques used in remote sensing, the observation of the Earth from optical sensors is perhaps the most easily understood in concept, because it is the most similar to our own personal remote sensing device – the human eye. *Ian Robinson (2004)*

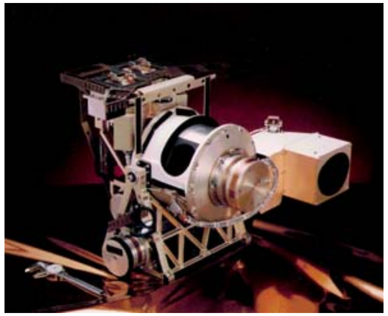


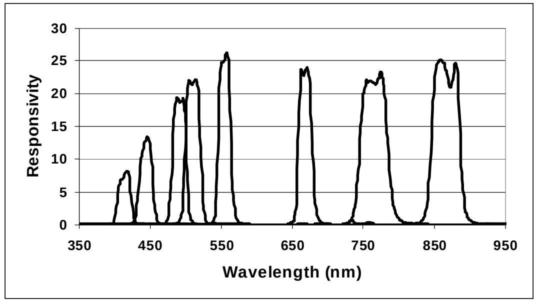
Human eye (tri-chromatic)





Mantis shrimp eye (multi-spectral with UV and polarization sensitivity)





SeaWiFS remote sensor (multi-spectral with NIR sensitivity)

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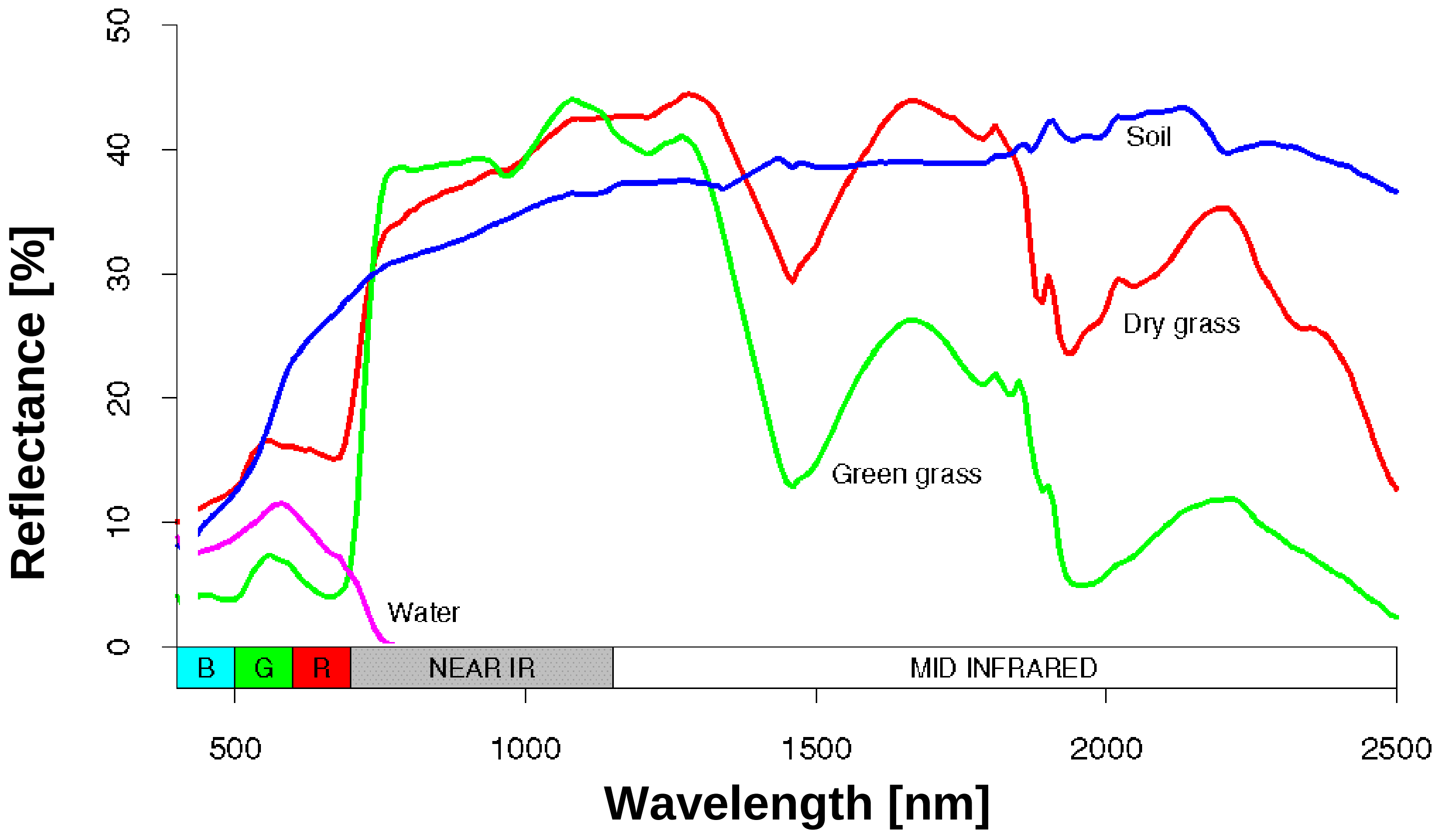
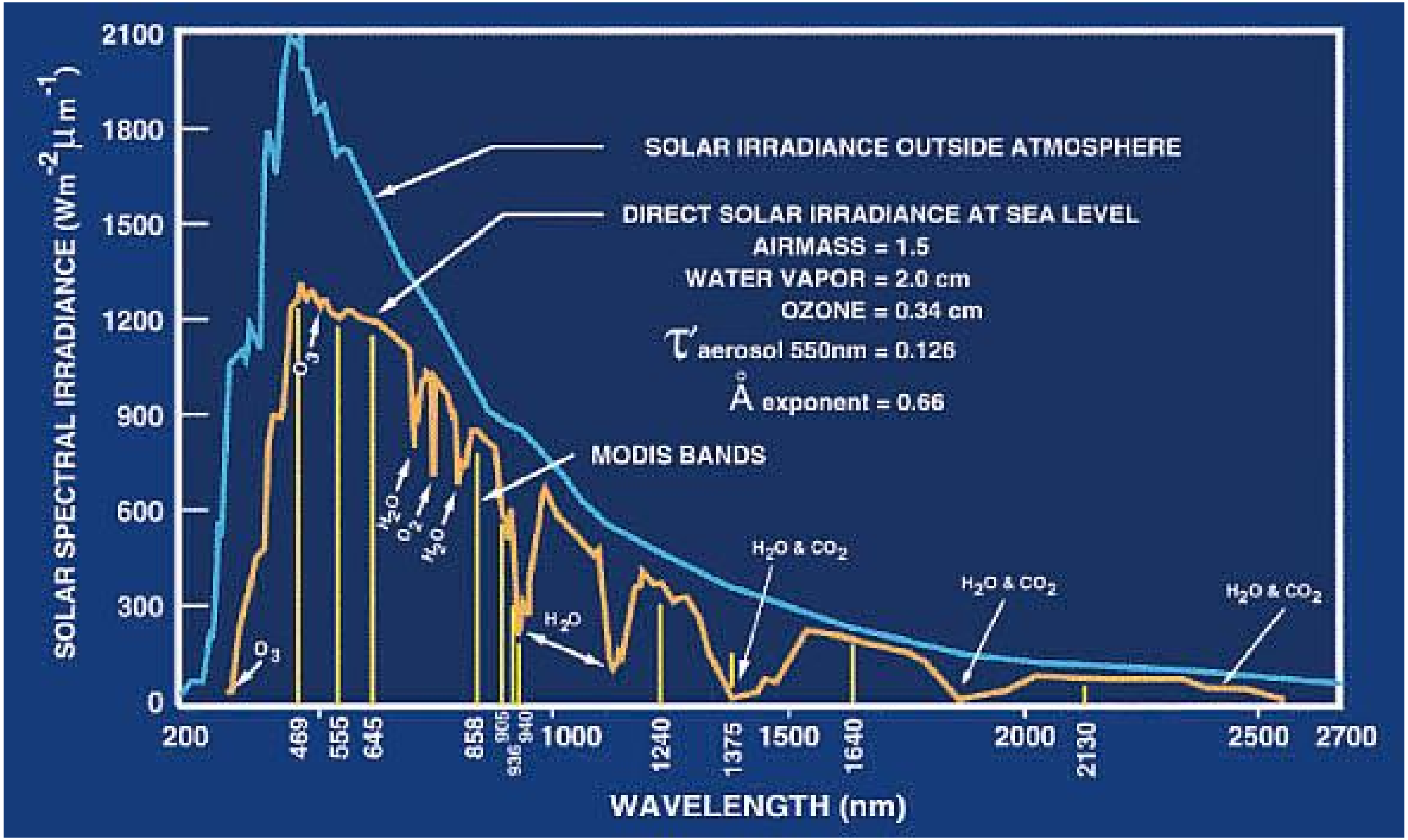
Reflectance spectra of natural surfaces

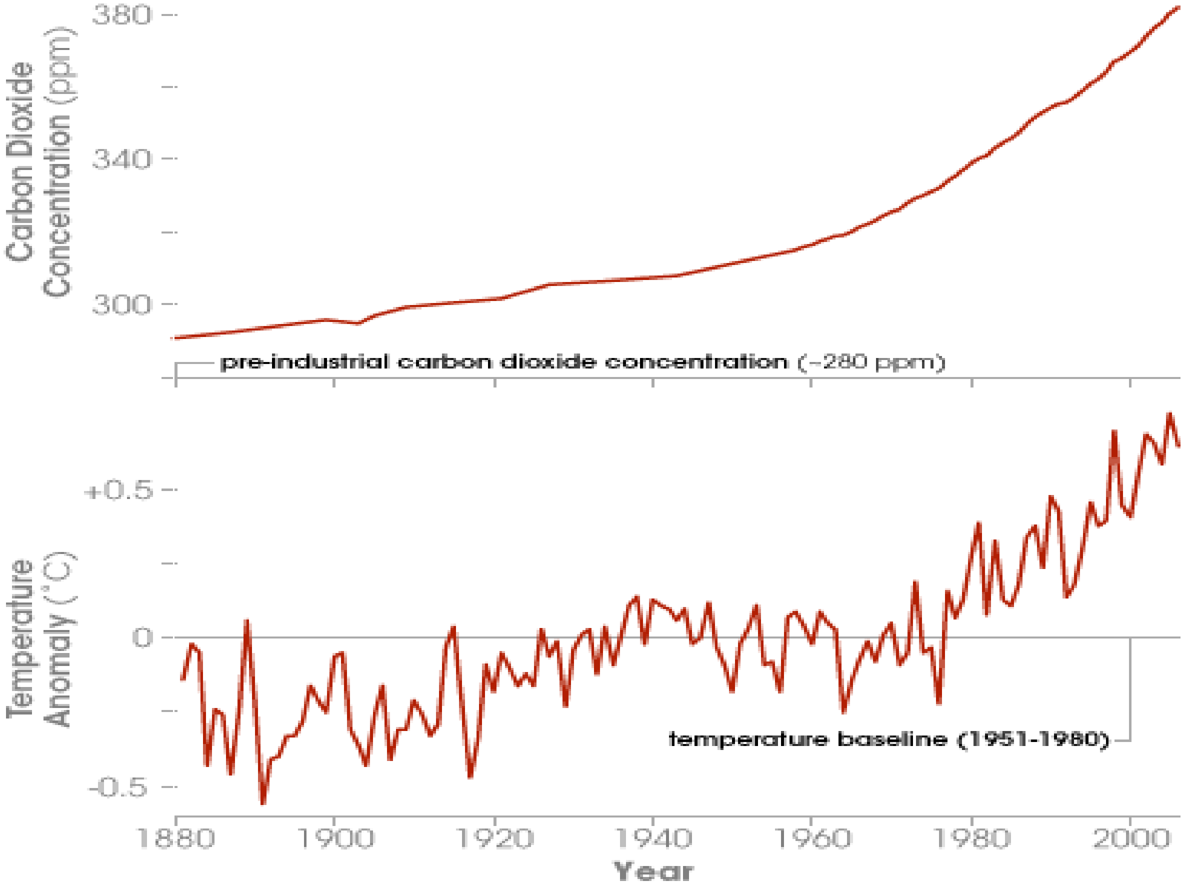


The Visible and Near-Infrared



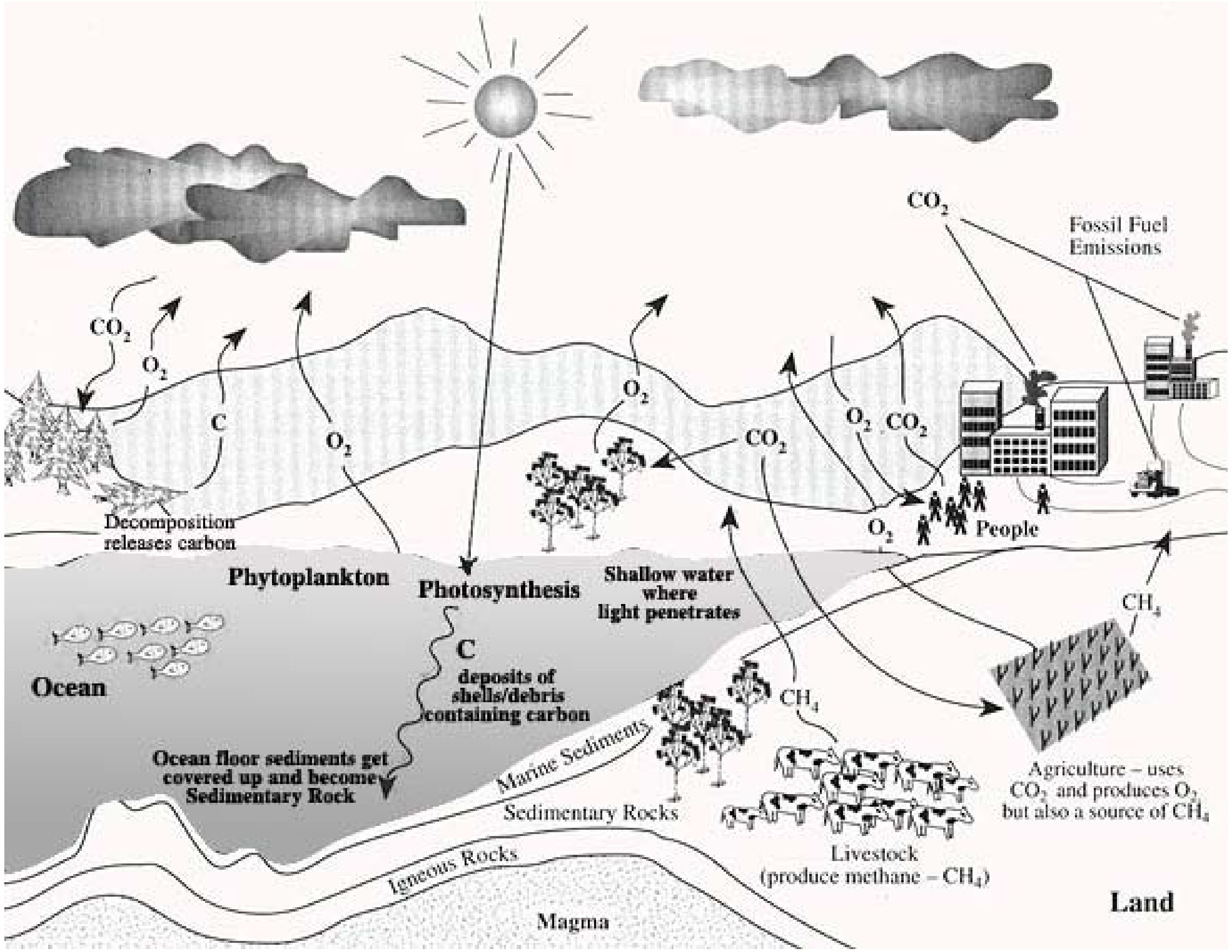
Satellites and climate change

Climate change: a planetary emergency



The Earth's surface temperature has risen by about 0.5°C over the last 100 years. Computer simulations indicate that given a steady rise in levels of greenhouse gases, such as carbon dioxide, there will be a corresponding increase in surface temperatures.

Carbon Budget



Any forecast of climate change requires an accurate understanding and quantification of variables such as clouds, aerosols, and oceans.

Phytoplankton: A Climate Variable

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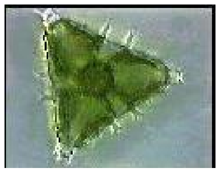
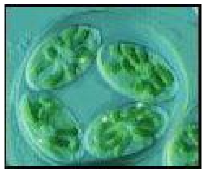
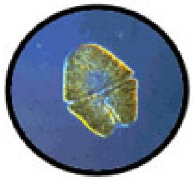
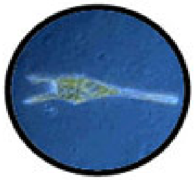
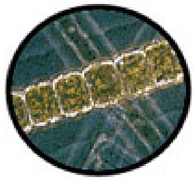
Phytoplankton is composed of microscopic unicellular marine plants which contain chlorophyll. This is vital for photosynthesis: sunlight is absorbed and utilized to fuse water molecules and carbon dioxide into carbohydrates (the plant food). om

When phytoplankton dies, its detritus component sinks to the sea bottom. Although phytoplankton account for approximately 50% of the photosynthesis on the Earth, over 99% of all the carbon dioxide that has been incorporated into living things and permanently pulled from atmosphere over geologic time is buried in marine sediments.

Thus, the larger the world's phytoplankton population, the more carbon dioxide gets pulled from the atmosphere.

Rationale for Ocean Color from Space

Satellite observations ensure global coverage of the Earth surface and a consistent mapping of Essential Climate Variables required by the Global Climate Observing System (GCOS). Ocean Color is listed among the Essential Climate Variable for ocean biology.

GCOS, established in 1992 to ensure that the observations and information needed to tackle climate-related issues are obtained and made available to all potential users, is co-sponsored by the:
World Meteorological Organization (WMO),
Intergovernmental Oceanographic Commission (IOC) of UNESCO,
United Nations Environment Programme (UNEP), and
International Council for Science (ICSU).

Satellite Ocean Color

Basics of Ocean Color

Ocean color observations depend on the electromagnetic energy in the 400-700 nm spectral region. This energy is emitted by the sun, transmitted through the atmosphere and reflected by seawater after being absorbed and scattered by the optically significant seawater components.

The optically significant components responsible of changes in the color of seawater, are:

1. Phytoplankton pigments (chlorophyll-a, carotenoids, …);
2. Colored dissolved organic material (CDOM or yellow substance) from phytoplankton decay or from anthropogenic origin;
3. Suspended particulate matter composed of *i.* organic particulates (detritus) consisting of decomposed phytoplankton and zooplankton cell fragments; and *ii.* inorganic particulates (e.g., sand and dust) from soil erosion, sea bottom re-suspension and rivers transport.

Thus the color of seawater depends on the relative concentrations of optically significant components.

The Color of Seawater

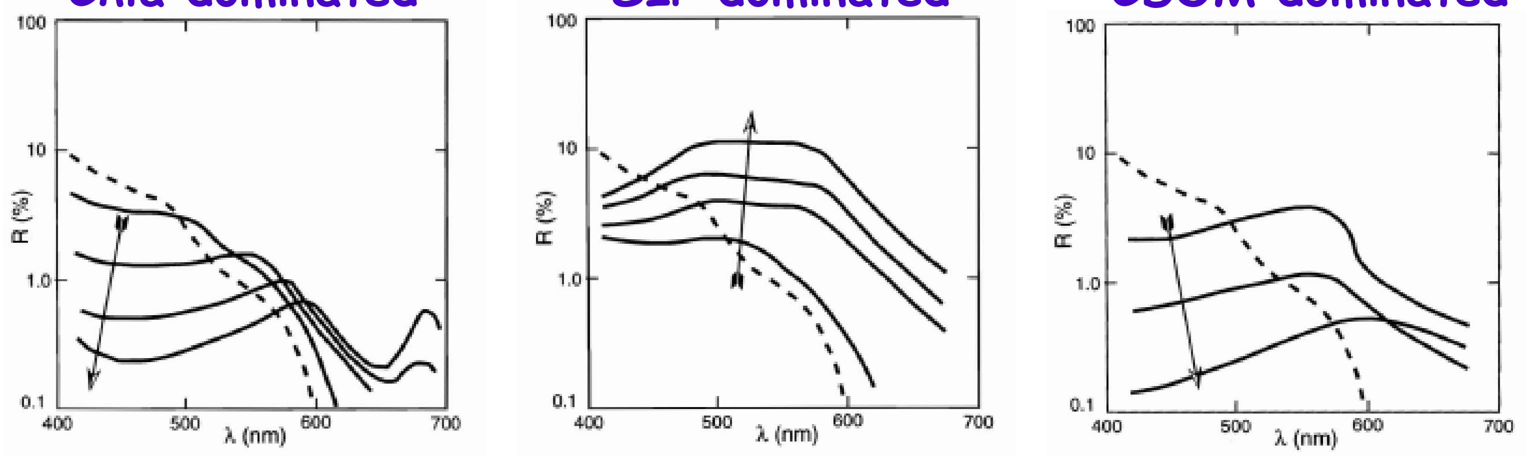
Clear water absorbs in the red spectral region and scatters the light at shorter wavelength: this explains its blue color.

Phytoplankton cells contain chlorophyll-a (**Chla**) that mostly absorbs in the blue spectral region: this explains the green color of phytoplankton dominated seawater.

Suspended inorganic particles (**SIP**) backscatters sunlight at almost all the visible wavelengths: this explains the brightness of sediment dominated seawater.

Colored dissolved organic matter (**CDOM**) highly absorbs in the blue-green spectral region: this explains the brownish color of yellow-substance dominated seawater

Chla dominated **SIP dominated** **CDOM dominated**



Seawater types

The color of seawater is determined from its reflectance spectrum. The concentration of optically significant constituents can be derived the reflectance spectrum.

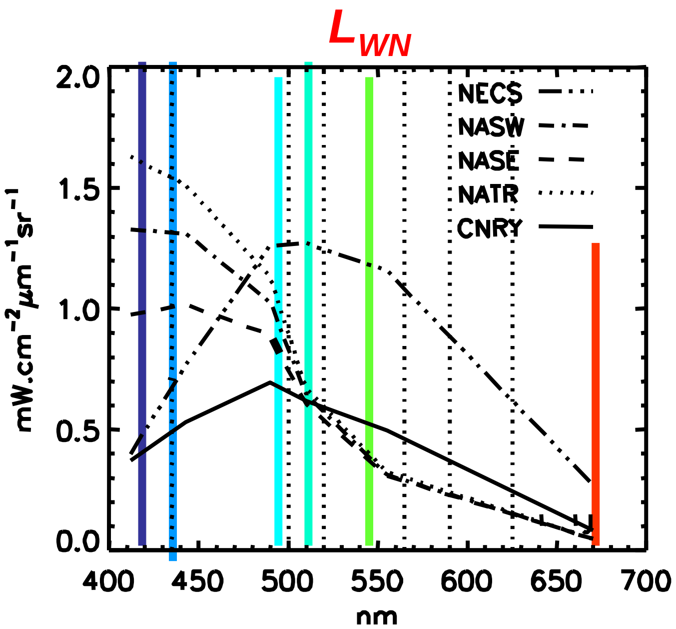
Such a process is straight forward in oceanic waters (classified as **Case-1** waters) which exhibit correlation between phytoplankton and the other optically significant constituents (i.e., particulate and dissolved matter).

The process is much more difficult in optically complex costal waters which exhibit lack of correlation between chlorophyll-a and the other optically significant constituents (these waters are generally classified as **Case-2** and show yellow-brown colors) .

Definition and Principles

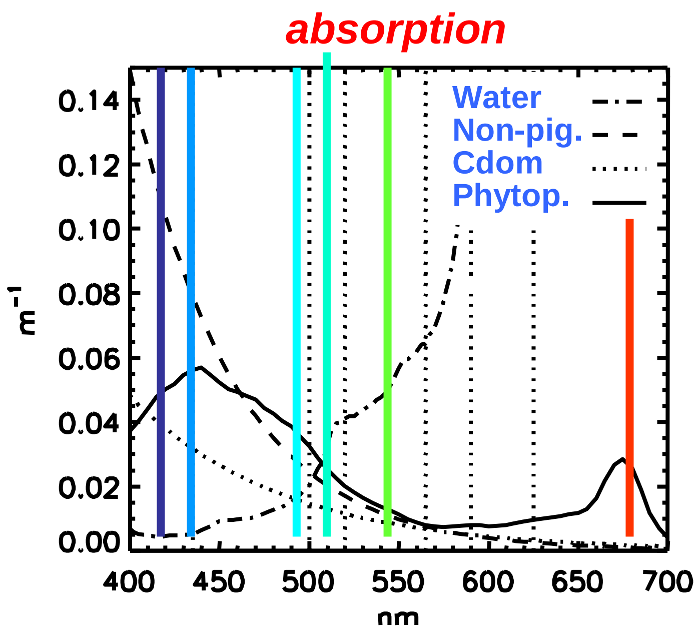
Satellite Ocean Color indicates remote sensing of the sea in the visible and near infrared with the primary objective of determining *the radiance emerging from the sea* from top-of-atmosphere signal.

Apparent optical properties (AOP)



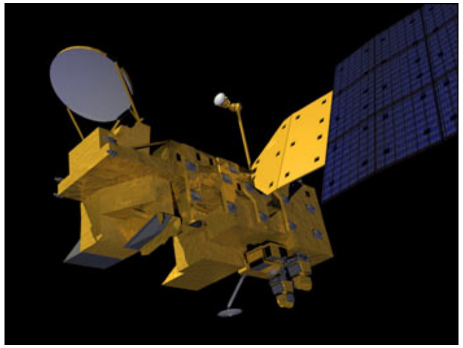
AOPs vary with IOPs

Inherent optical properties (IOP)



Derived Ocean Color products are the concentration of optically significant constituents (e.g., the *chlorophyll a* concentration, used as a proxy for the *marine phytoplankton biomass*).

AQUA and ENVISAT: Two Earth Observing Platforms

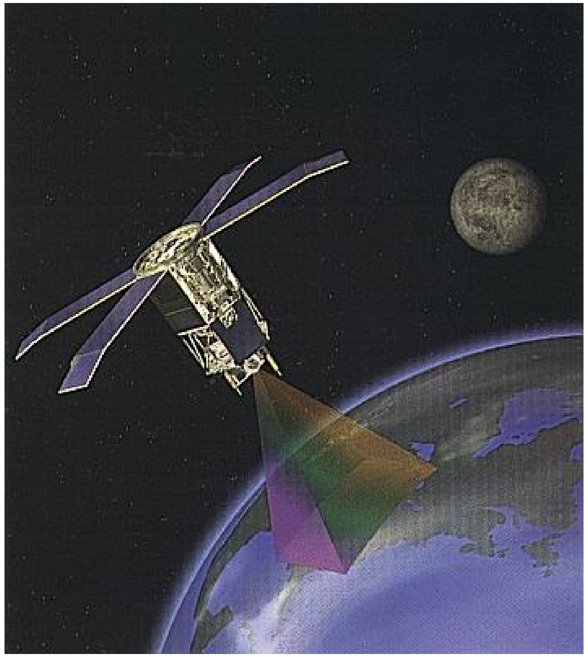


AQUA platform (NASA)

ENVISAT platform (ESA)

AQUA (NASA) and ENVISAT (ESA) are two major Earth Observing Platform to study the complex interactions amongst the land, ocean, air, ice and biological systems.

Sea-viewing Wide Field-of-view Sensor (SeaWiFS)



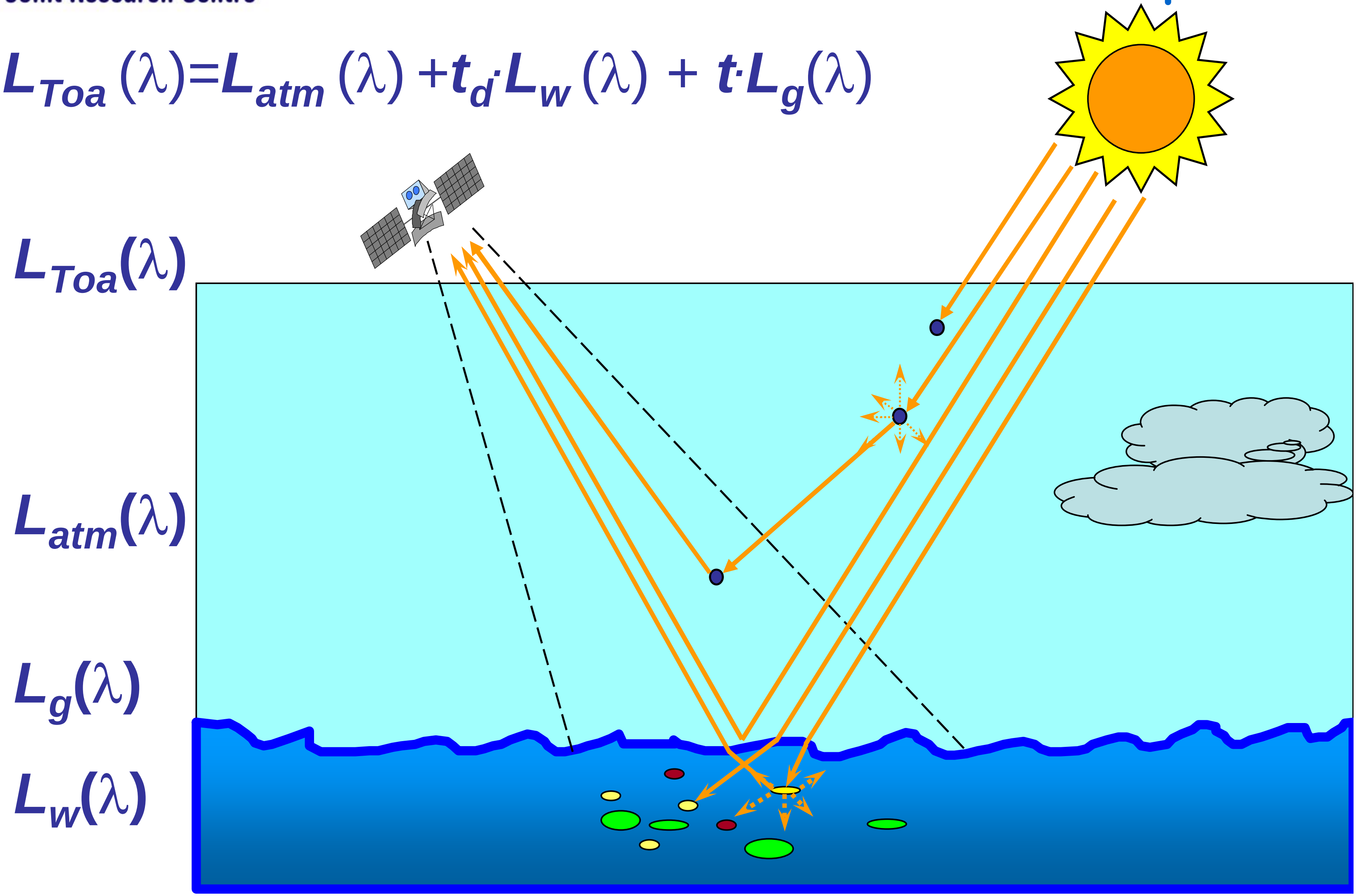
Band	Wavelength
1	402-422 nm
2	433-453 nm
3	480-500 nm
4	500-520 nm
5	545-565 nm
6	660-680 nm
7	745-785 nm
8	845-885 nm

Mission Characteristics

Orbit Type	Sun Synchronous
Altitude	705 km
Equator Crossing	Noon + 20 min
Orbital Period	99 minutes
Swath Width	2,801 km (58.3 deg.)
Spatial Resolution	1.1 km LAC

Ocean Color: the concept

$$L_{Toa}(\lambda) = L_{atm}(\lambda) + t_d \cdot L_w(\lambda) + t \cdot L_g(\lambda)$$



L_W is the desired quantity which carries information on the materials suspended and dissolved in the sea water (L_W is approximately 5-10% of L_{ToA})

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The Water-Leaving Radiance

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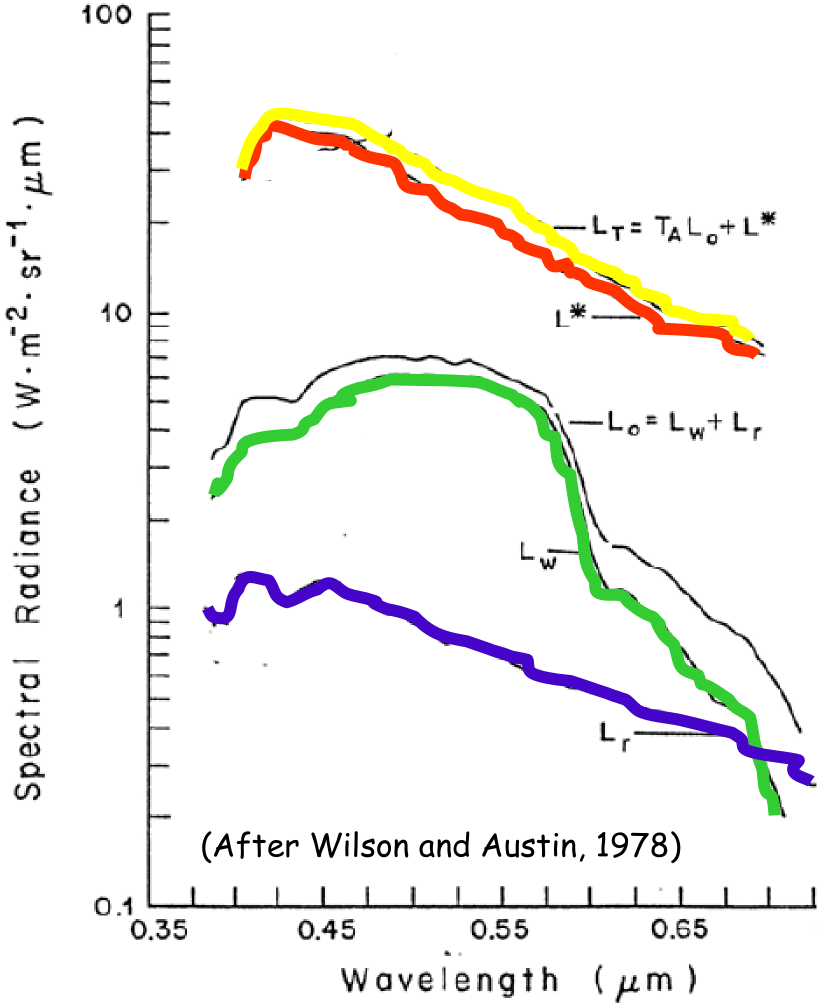
$$L_{ToA}(\lambda) = L_{atm}(\lambda) + t_d \cdot L_W(\lambda) + t \cdot L_g(\lambda)$$



L_{ToA}: Top of Atmosphere Radiance

L_{atm}: Atmospheric Radiance

L_g: Glint Radiance

L_W: Water Leaving Radiance

1% error in atmospheric correction or satellite calibration leads to a 10% error in L_W

→ Thus the need of high quality ocean color radiometric products is supported by a major effort in defining advanced atmospheric correction and calibration methods

Atmospheric correction

Atmospheric correction is the process of quantifying the atmosphere and sea-surface contributions to L_{ToA} aiming at determining the water-leaving radiance L_W.

Total radiance observed by the satellite is composed of 5-10% ocean signal (water-leaving radiance) and 90-95% atmosphere signal (atmospheric and glint radiances) mostly due to scattering by aerosols, and molecules (Rayleigh scattering).

The atmospheric contribution is computed using satellite measurements performed in the near-infrared (e.g., 780 and 870 nm). Since clear water highly absorbs in this spectral region, the radiance measured is almost entirely due to scattering by the atmosphere and surface reflectance. Thus near-infrared satellite measurements, combined with model simulations of atmospheric scattering and absorption processes, are used to remove the contribution due to the atmosphere signal.

Final product is the Normalized Water-Leaving radiance (L_{WN}) determined from L_W in the blue, green and red spectral regions.

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Normalization of L_W

L_W varies with the bidirectional reflectance properties of seawater, which depend on illumination geometry, viewing geometry, seawater content, atmospheric content, sea surface.

The Normalized Water-Leaving radiance L_{WN} is introduced to make ocean color radiometric measurements independent of the measuring conditions: L_{WN} is the ideal radiance that would be measured if the Sun was at the zenith, in the absence of atmosphere, and with the Earth at its mean distance from the Sun.

$$L_{WN}(\lambda) = L_W(\lambda) \left(D^2 t_d(\lambda)\cos\theta_0\right)^{-1} C_{f/Q}(\lambda,\theta_0,\tau_A,Chla)$$

where:

$$\left(D^2 t_d(\lambda)\cos\theta_0\right)^{-1} = \frac{E_0(\lambda)}{E_d(0^+,\lambda)},$$

$$C_{f/Q}(\lambda,\theta_0,\tau_A,Chla) = \frac{f_0(\lambda,\tau_A,Chla)}{Q_0(\lambda,\tau_A,Chla)}\left(\frac{f(\lambda,\theta_0,\tau_A,Chla)}{Q_n(\lambda,\theta_0,\tau_A,Chla)}\right)^{-1}$$

Note: the remote sensing reflectance is given by $R_{rs}(\lambda)=L_{WN}(\lambda)/E_0(\lambda)$

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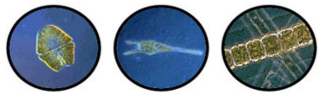
Bio-optical modeling

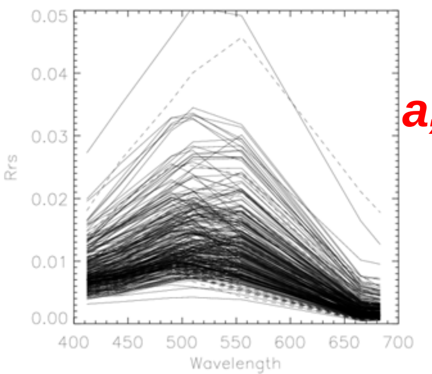
Bio-optical models: the tools to convert satellite atmospherically corrected data into high-level products

empirical

$Chla \sim f(R_{rs}(\lambda_1), R_{rs}(\lambda_2))$

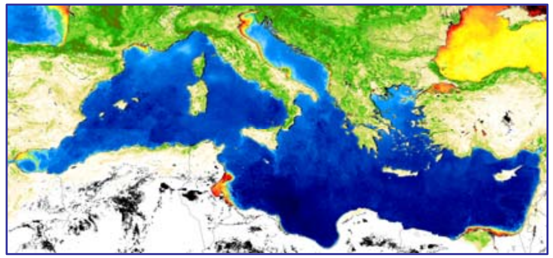
Satellite derived marine signal ("Reflectance" R_{rs}) → Seawater Optically Significant Components (Phytoplankton biomass, Suspended & Dissolved Matter).





$a, b_b \sim \mathfrak{I}(R_{rs}(\lambda))$ → $Chla \sim f(\lambda, a, b_b)$

semi-analytical



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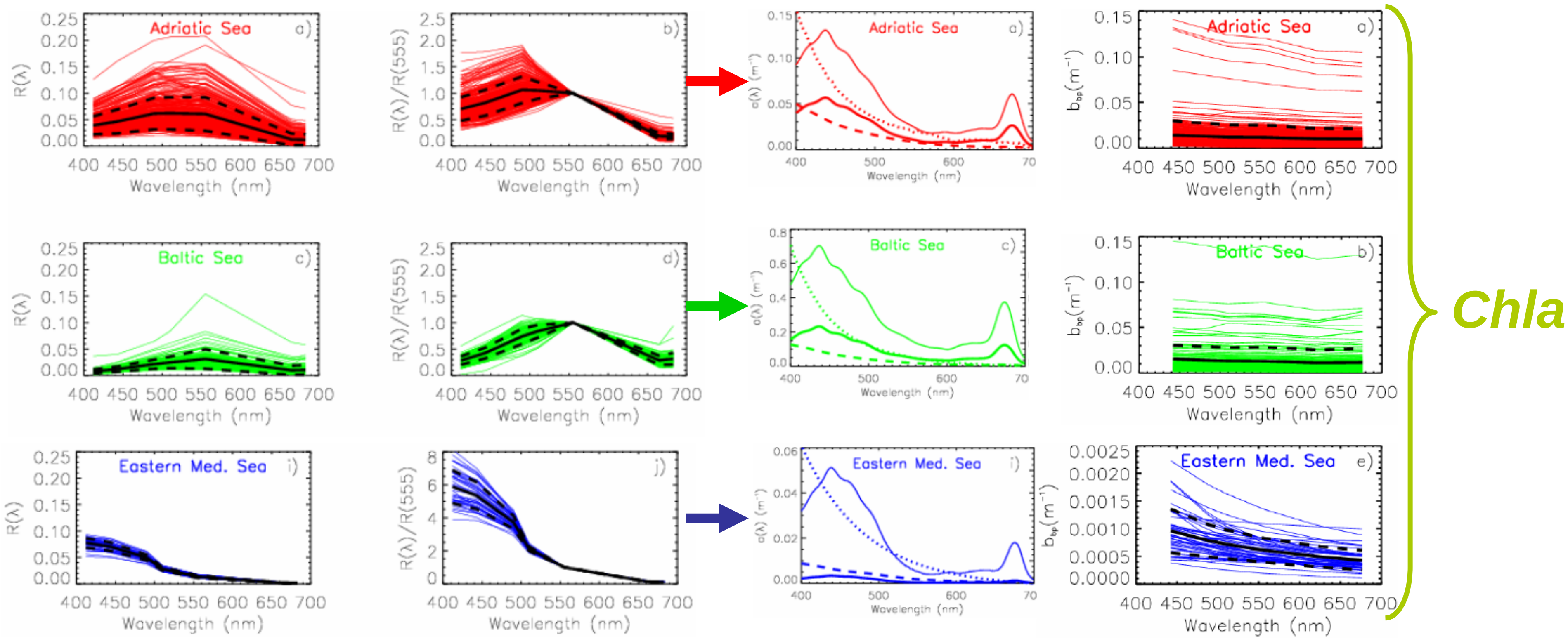
Semi-Analytical Models

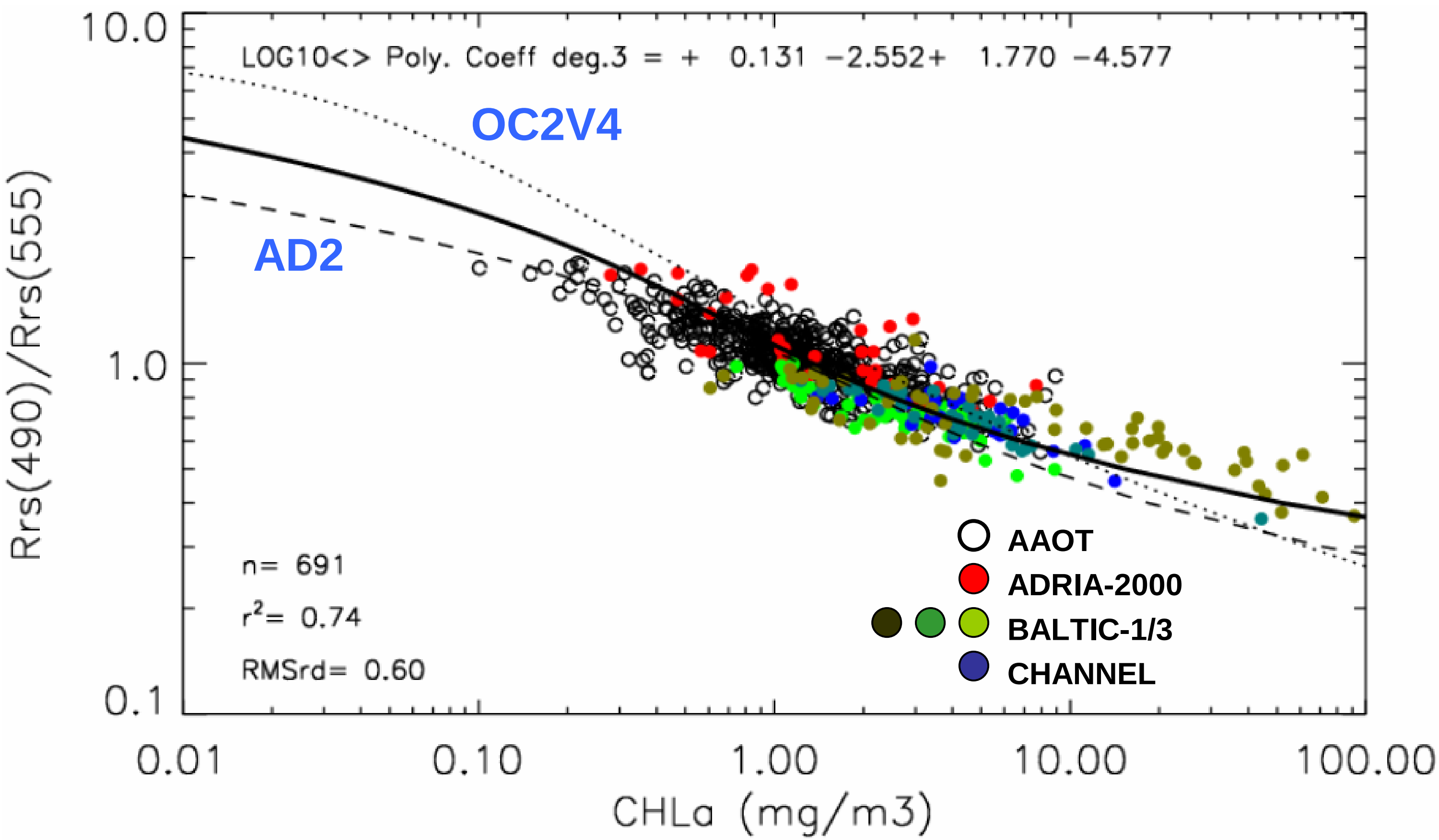
Reflectance (R) **Absorption (a)** **Back-scattering (b_b)**



$a,b_b \sim \Im(R_{rs})$ $Chla \sim f(a,b_b)$

J.F. Berthon, F. Mélin and G. Zibordi (2007), Ocean Colour Remote Sensing of the Optically Complex European Seas, in: V. Barale and M. Gade ed.s, "Remote Sensing of the European Seas", Springer, Dordrecht (NL), pp. 35-52.

Empirical Models (Algorithms)



J.-F., Berthon, G. Zibordi, D. van der Linde, E. Canuti, E. Eker-Develi. Regional bio-optical relationships and algorithms for the Adriatic Sea, the Baltic Sea and the English Channel/North Sea suitable for ocean colour sensors. *EUR 22143EN*, 2006.

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Comparison of Algorithms

AD2 $$Chl\text{-}a = 10.0^{\left(0.091-1.620R_{2S}-1.148R_{2S}^2-4.949R_{2S}^3\right)}$$

OC4v4 $$Chl\text{-}a = 10.0^{\left(0.366-3.067R_{4S}+1.930R_{4S}^2+0.649R_{4S}^3-1.532R_{4S}^4\right)}$$

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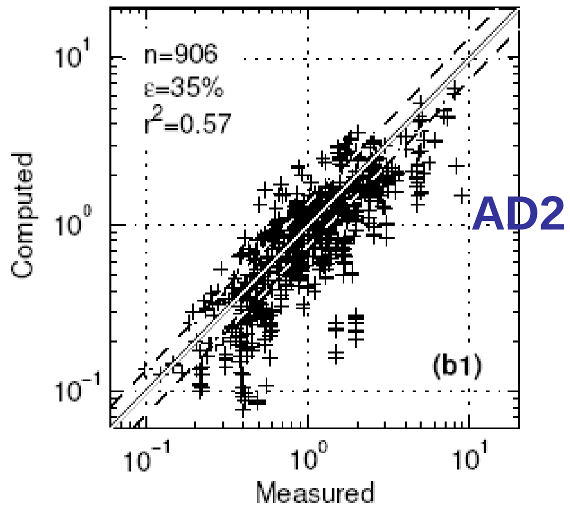

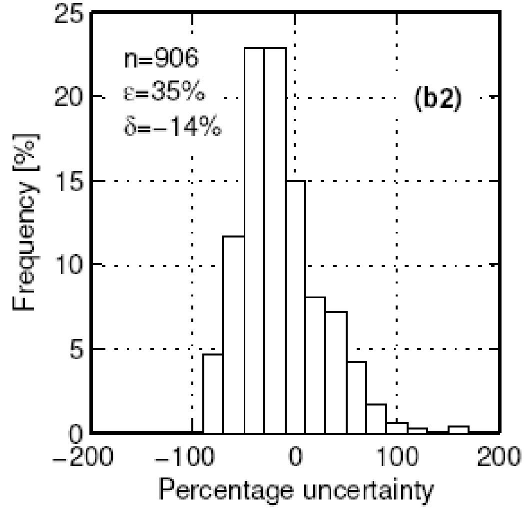

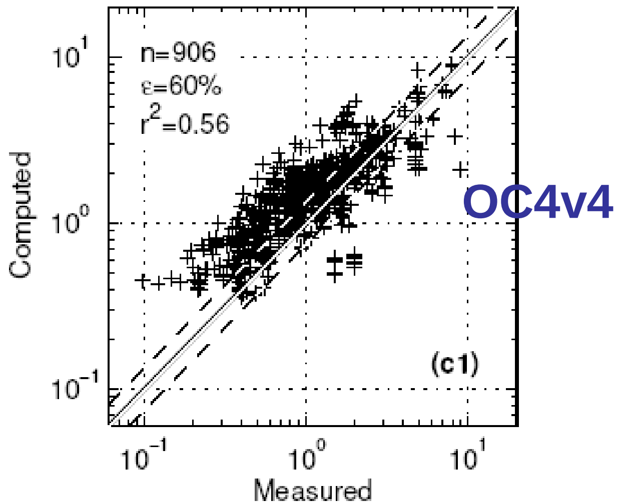

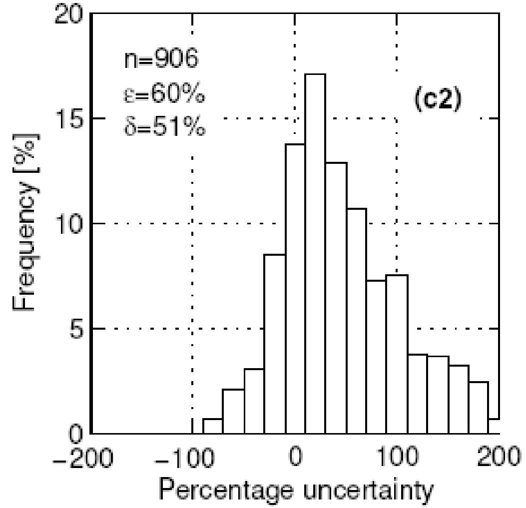

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Algorithms applicability

Novelty Detection provides a mean to identify those inputs (reflectance spectra) for which the performance of an algorithm is likely to be unreliable

The algorithms perform correctly when the satellite data are represented in the training data sets

↓

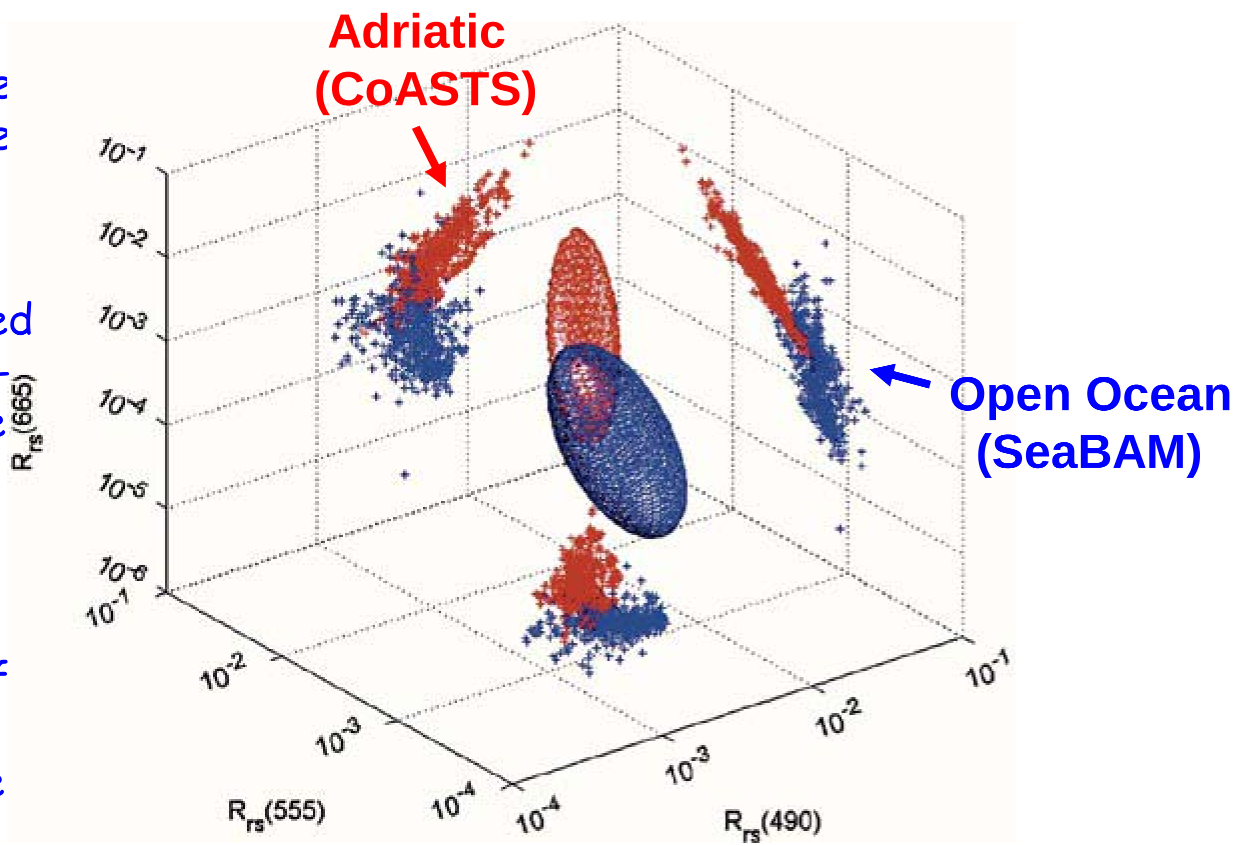
The training data sets applied for developing the bio-optical algorithms, are used to determine

their *probability density function*

which defines the range of applicability of algorithms to satellite data

↓

hyper-ellipsoid (example for a 3D space)



D.D'Alimonte, F.Mélin, G.Zibordi and J.F.Berthon. Use of the novelty detection technique to identify the range of applicability of empirical ocean color algorithms. *IEEE Transactions in Geoscience and Remote Sensing*, 41:2833-2843, 2003.

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Dynamic Algorithms Application

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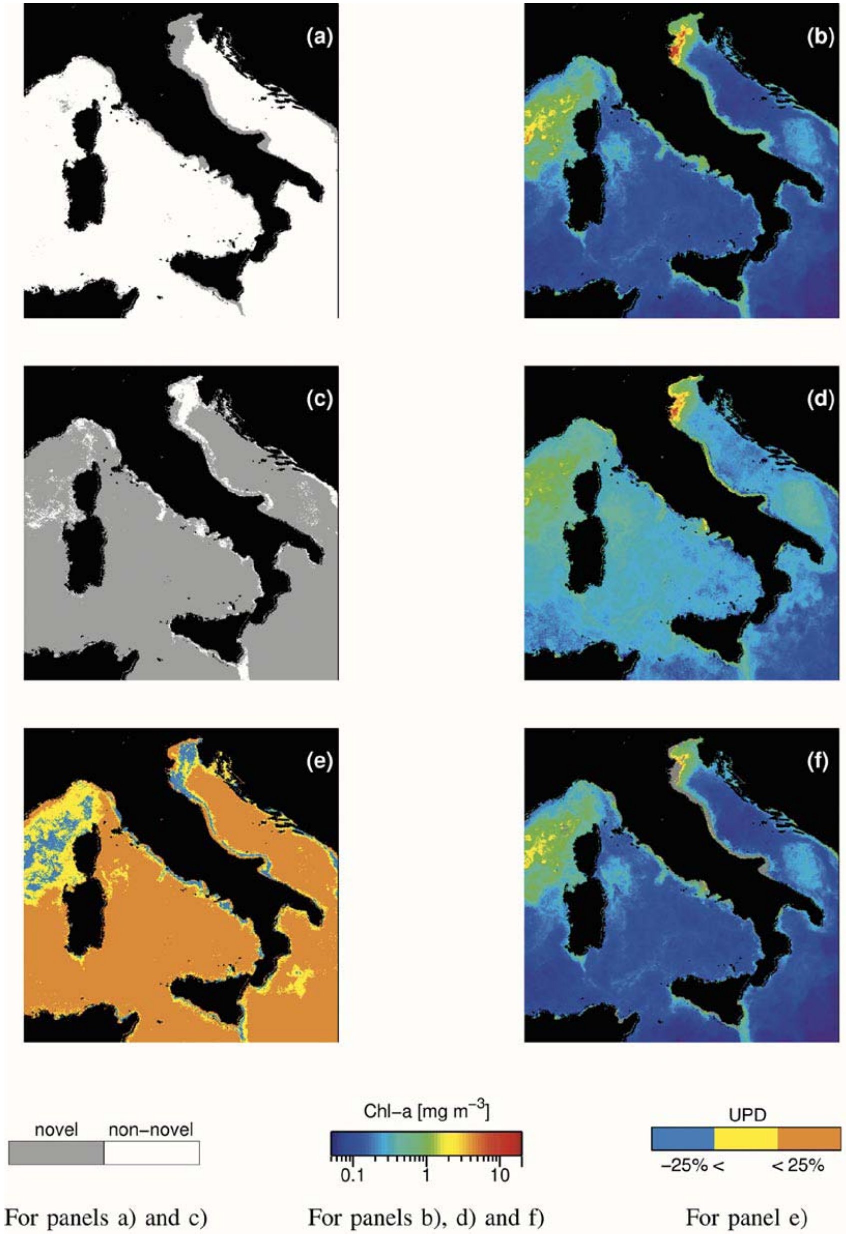
Open Ocean
(SeaBAM)

Adriatic
(CoASTS)

Mix Adriatic /
Open Ocean



Identification of

"novel"

and

"non novel"

data

Mixing
algorithms

Products and Applications

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Mediterranean Sea: Trends

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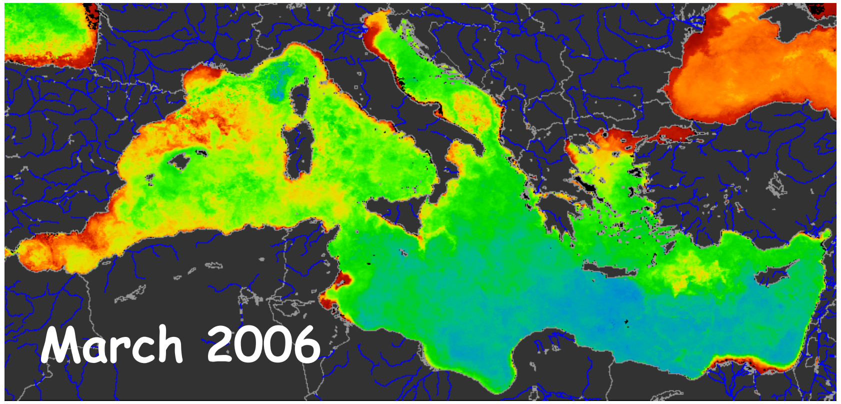
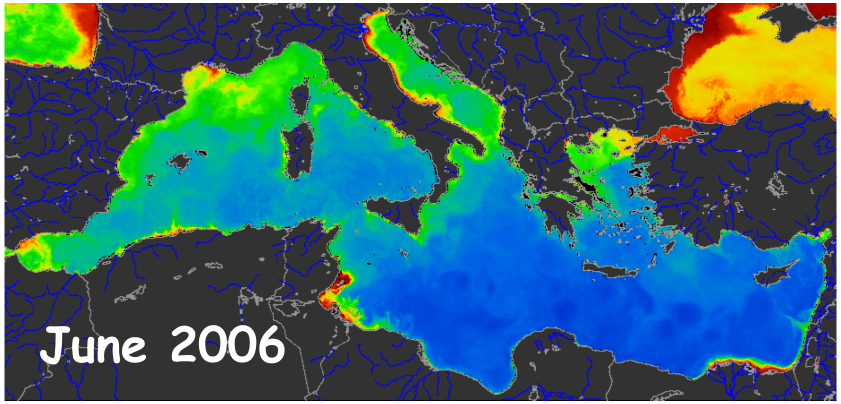
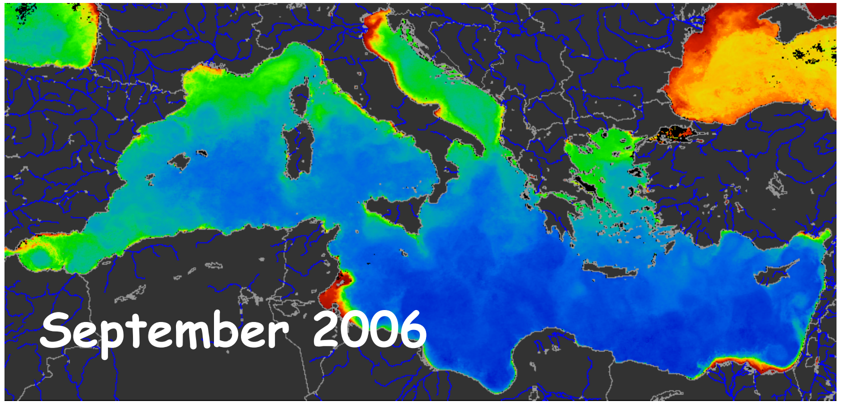
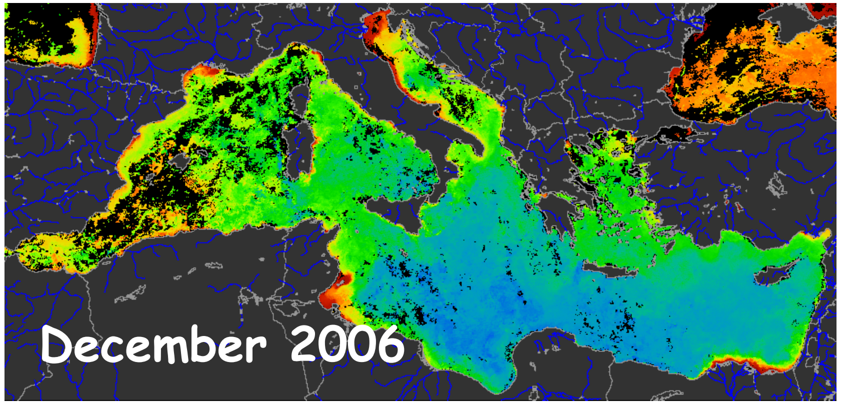
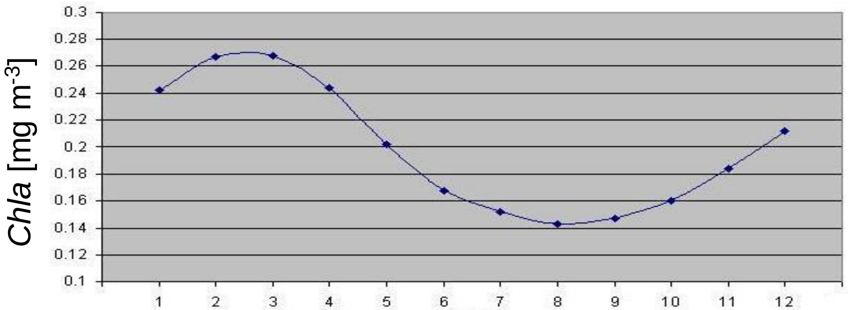


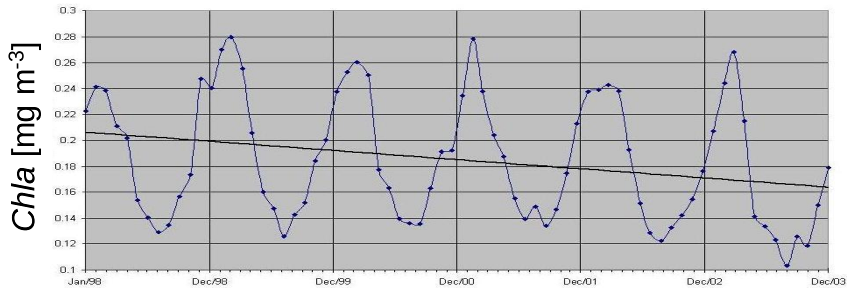








Chla Average Basin Value (98-03)
from 12 Climatological Monthly Means

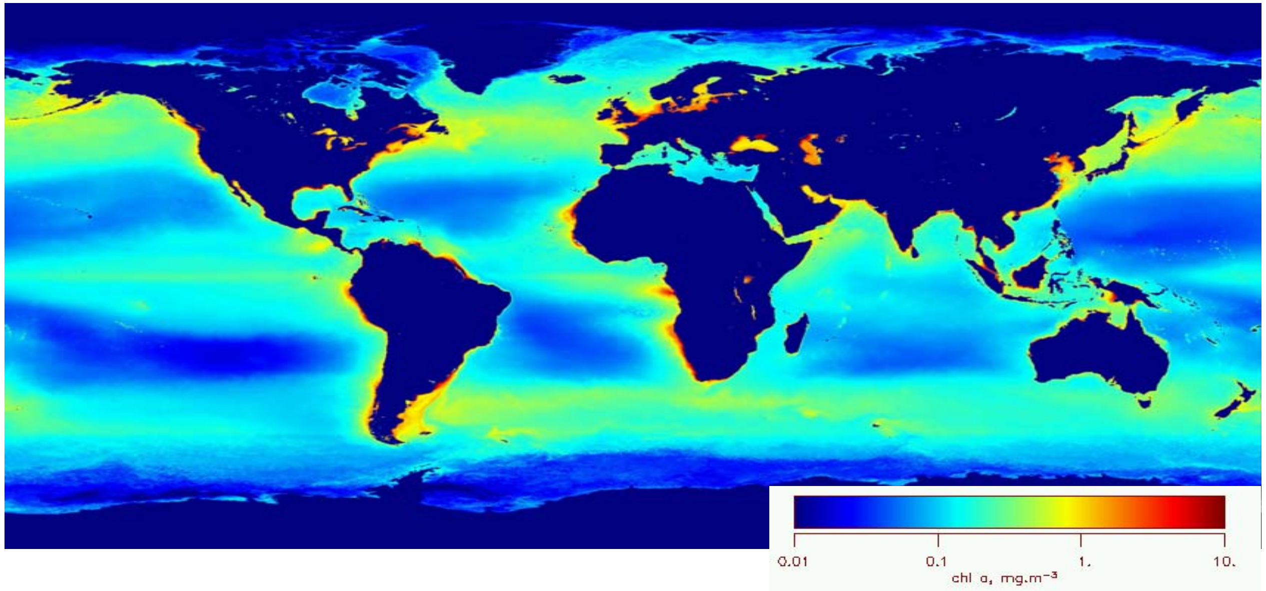


Chla Average Basin Value (98-03)
from 72 Monthly Means

SeaWiFS-derived 5-year average (1998-2002)

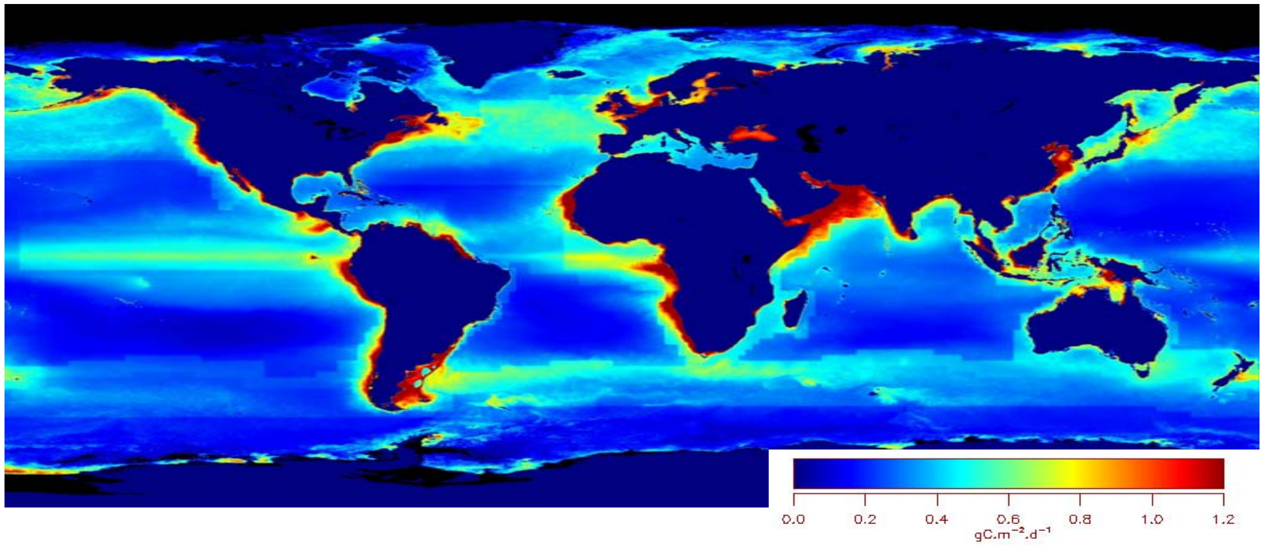
Phytoplankton standing stock

Chl*a*



Primary production (i.e., the production of organic compounds from atmospheric and aquatic carbon dioxide)

48 GtC·yr^{-1}



F.Mélin and N.Hoepffner, Global Marine Primary Production: A Satellite View. *EUR 21084EN*, 2004

Concluding remark

Marine ecosystems are particularly sensitive to climate change.

Future alterations in marine ecosystems will depend as much on global climate change as on our ability to regulate exploitation pressure at sustainable levels. Such a regulation will require high ecological certainty.

Within such a framework ocean color remote sensing is an invaluable technology to support ecosystem studies through synoptic quantification of key environmental parameters.

Any Question ?