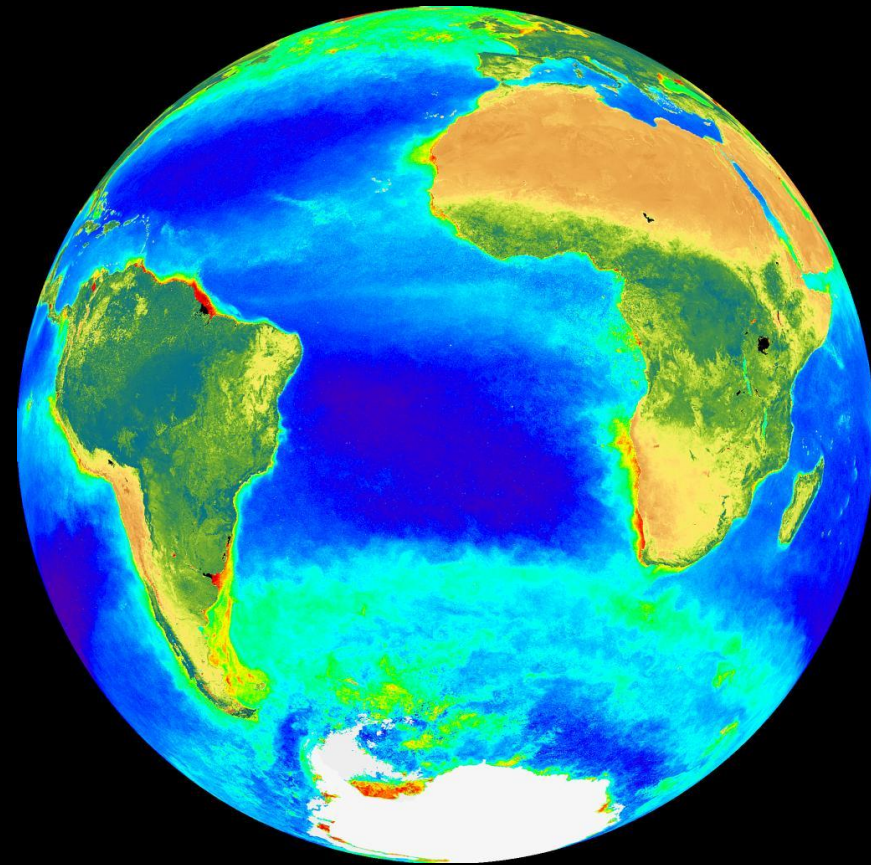
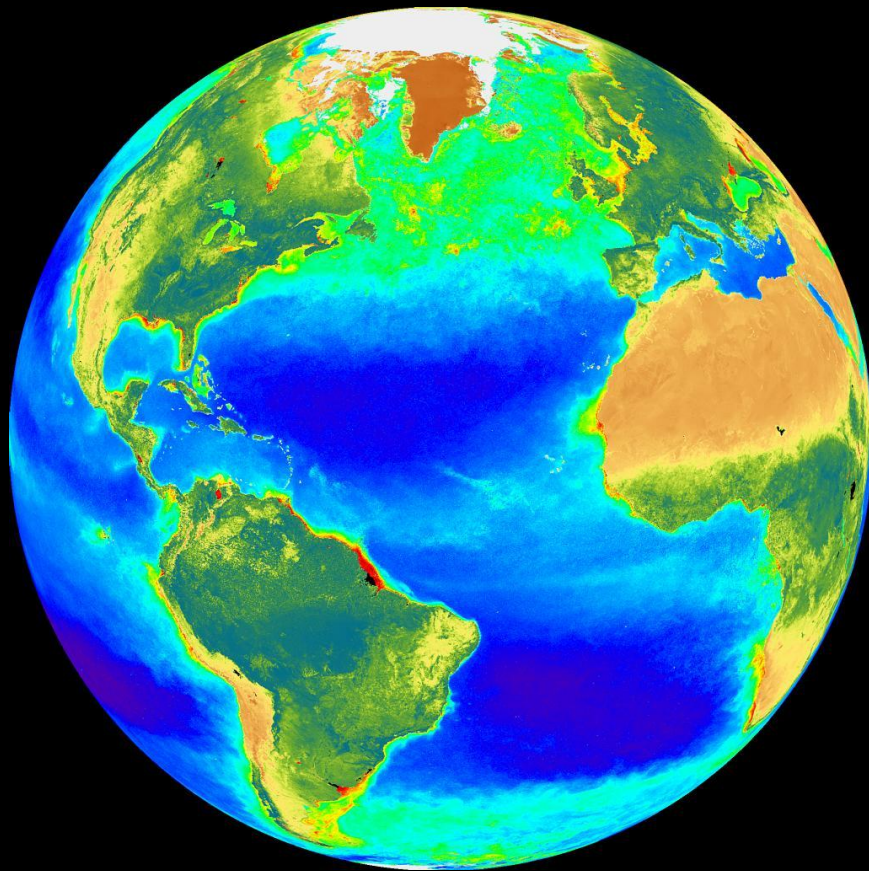


Remote Sensing of Ocean Colour: Visible Spectral Radiometry



The Colour of the Sea.

THE view has been expressed that "the much-admired dark blue of the deep sea has nothing to do with the colour of water, but is simply the blue of the sky seen by reflection" (Rayleigh's Scientific Papers," vol. 5, p. 540, and NATURE, vol. 83, p. 48, 1910). Whether this is really true is shown to be questionable by a simple mode of observation used by the present writer, in which surface-reflection is eliminated, and the other factors remain the same. The

It is useful to remember that the reflecting power of water at normal incidence is quite small (only 2 per cent.), and becomes large only for very oblique reflection. It is when the water is quite smooth and is viewed at an angle nearly parallel to the surface that the sky-light overpowers the light entering from within the water. In other cases the water has a chance of asserting itself.

C. V. RAMAN.

Bombay Harbour,
September 26.

"The view has been expressed that "the much-admired dark blue of the deep sea has nothing to do with the colour of water, but is simply the blue of the sky seen by reflection" (Rayleigh's Scientific Papers, Vol. 5, p. 540, and NATURE, vol. 83, p. 48, 1910)."

It was abundantly clear from the observations that **the blue colour of the deep see is a distinct phenomenon** not merely an effect due to reflected sky light. ... the

hue of the water is of such saturation that the bluest sky in comparison is a dull grey.

What is it that diffracts light and makes its passage visible? The diffraction may, at least in part, be **the molecules of the water themselves**.

As a rough estimate, it was thought that the tracks could be seen to a depth of 100 metres, ..."

The paper also addressed effects of the atmosphere and the viewing angle.

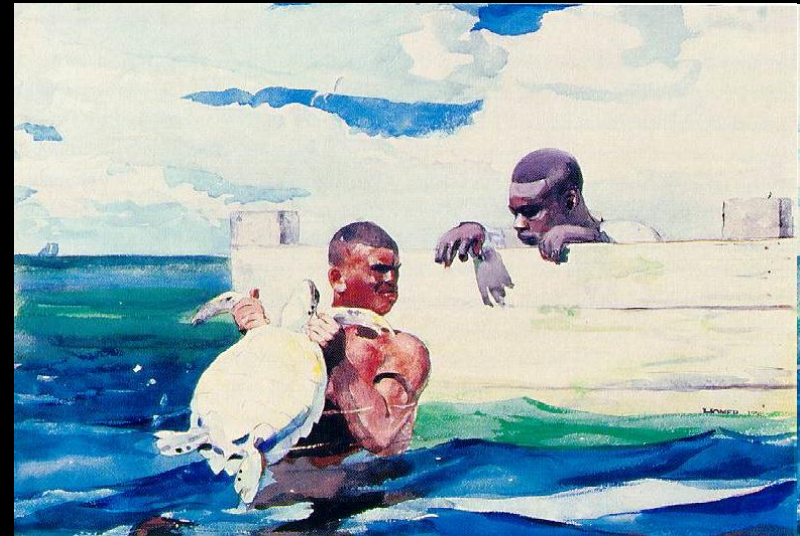
CV Raman, SS Narkunda, Bombay Harbour

Problem Solved?



Colour of water varies depending on what is in it. For scientific applications, we need to quantify the effect of marine constituents on water colour.

Green



Turtle pound, Winslow Homer

Blue



Coral formation, Winslow Homer

Turquoise



Natural Bridge Bermuda, Winslow Homer

Ocean Colour: Spectral Visible Radiometry

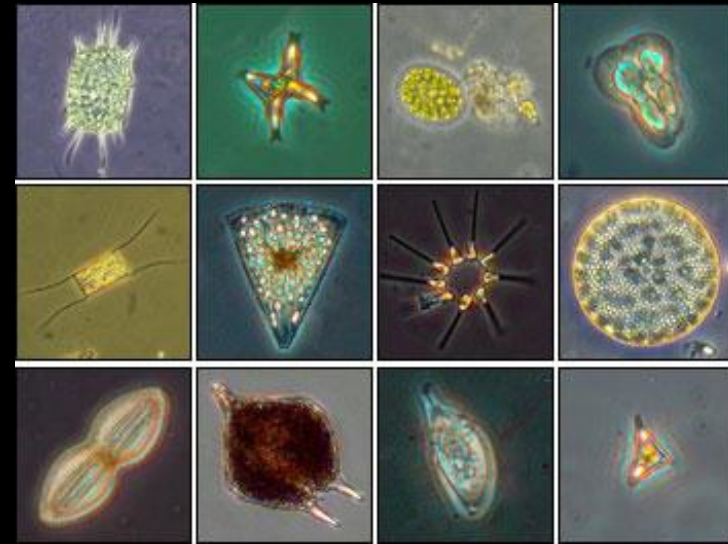
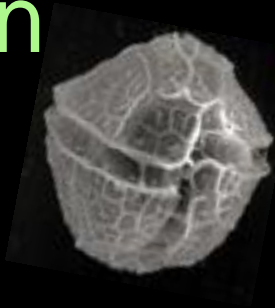
- Colour of the ocean contains latent information on the abundance of the marine microflora (phytoplankton)
- Invisible to the naked eye at close quarters, but huge collective impact visible from space.



Phytoplankton bloom in the North Sea off the coast of Scotland. Image captured by ESA's MERIS sensor on 7 May 2008.

Some properties of phytoplankton

- Predominantly single-celled and microscopic (0.5 to 250 μ m)
- Green plants (chlorophyll pigments, photosynthesis)
- Mostly confined to the surface (illuminated) layer
- Ubiquitous and abundant (up to 10⁵ cells ml⁻¹)
- Control colour of water (detectable from space)
- Absorb light (modulate rate of heating)
- Consume carbon dioxide (climate)
- Collective metabolism enormous (50 x 10⁹ tonnes per annum)
- Slightly negatively buoyant





Ocean-Colour Remote Sensing

Ocean-colour remote sensing was conceived primarily as a method for producing synoptic fields of phytoplankton biomass indexed as chlorophyll



Ocean-Colour Radiometry

Primary Products

Derived directly from the ocean-colour radiometric signal

Secondary Products

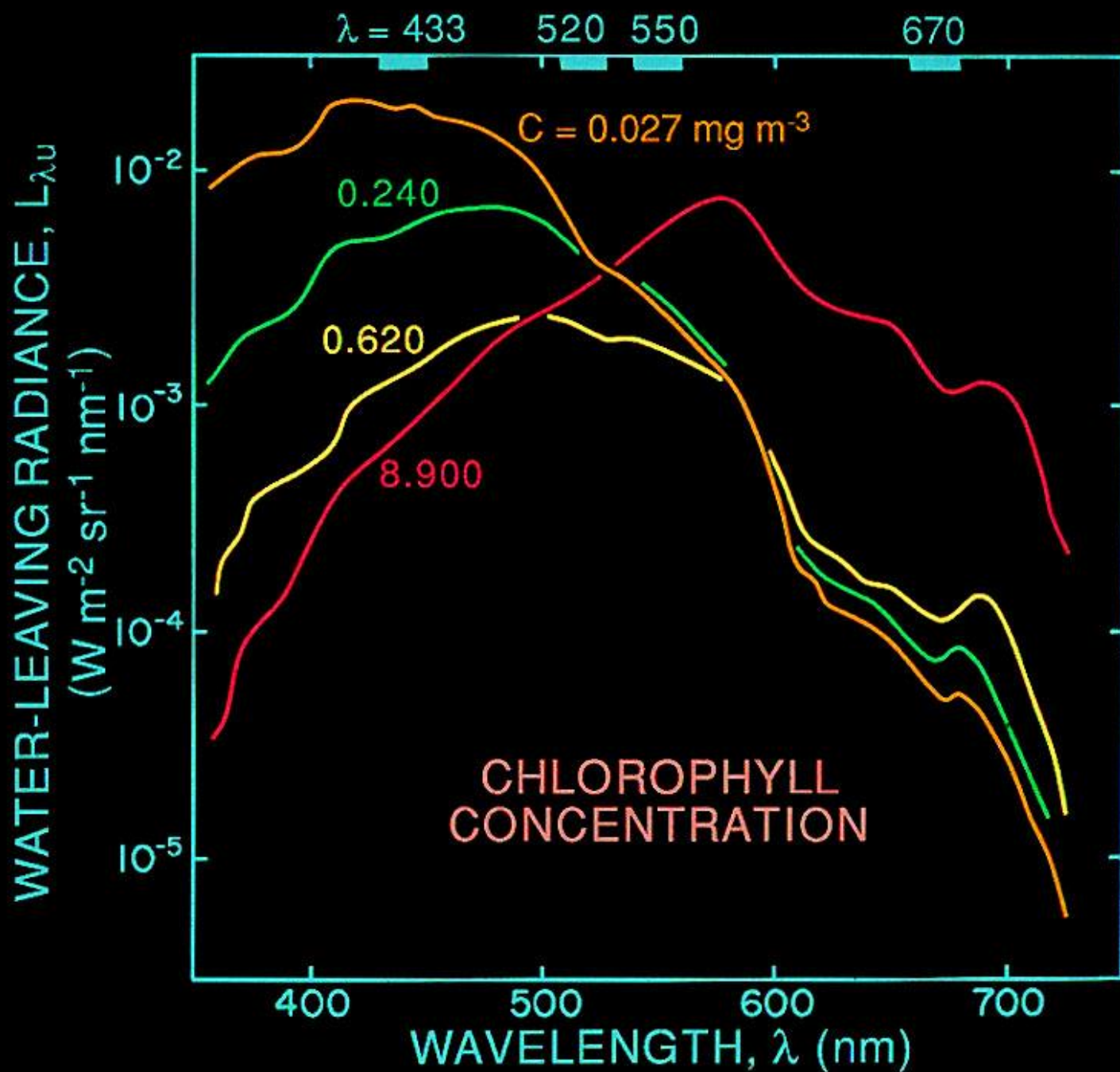
Based on primary products and auxiliary information

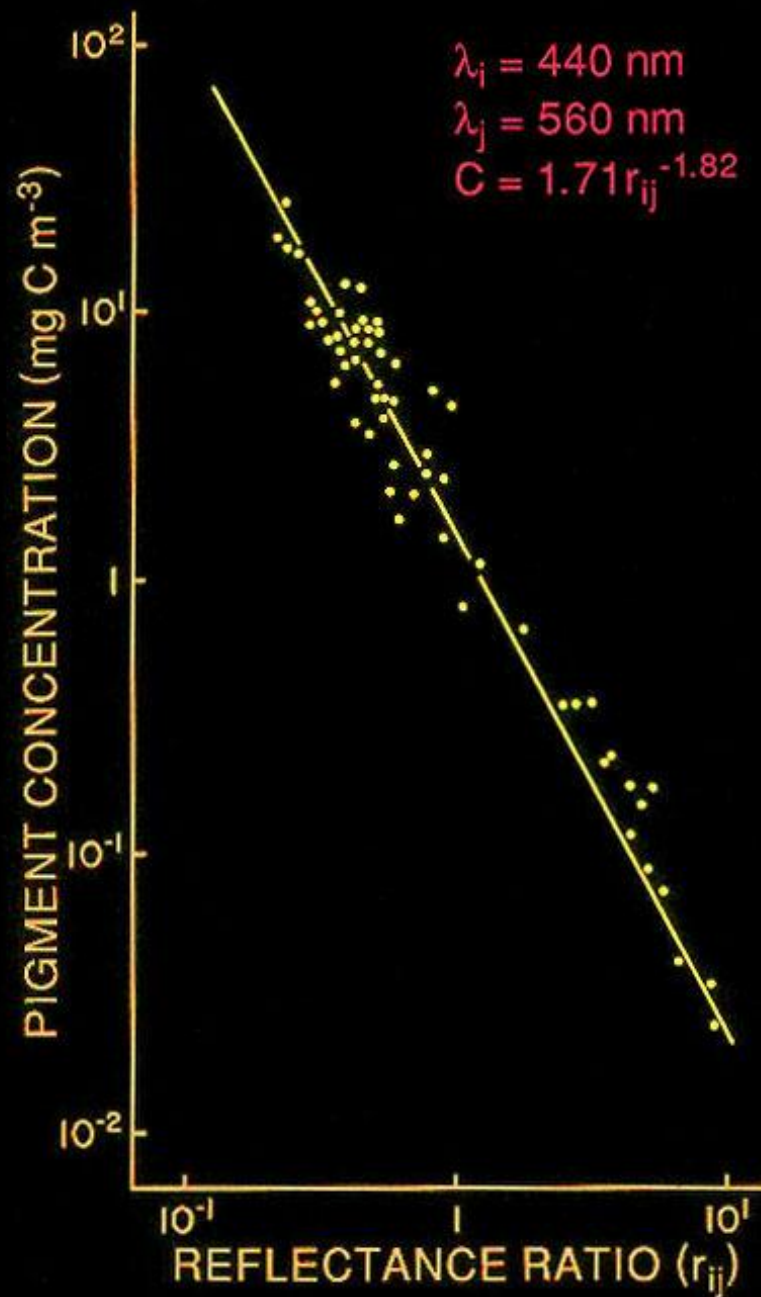
Scientific Applications

Use of primary and secondary products to address scientific issues

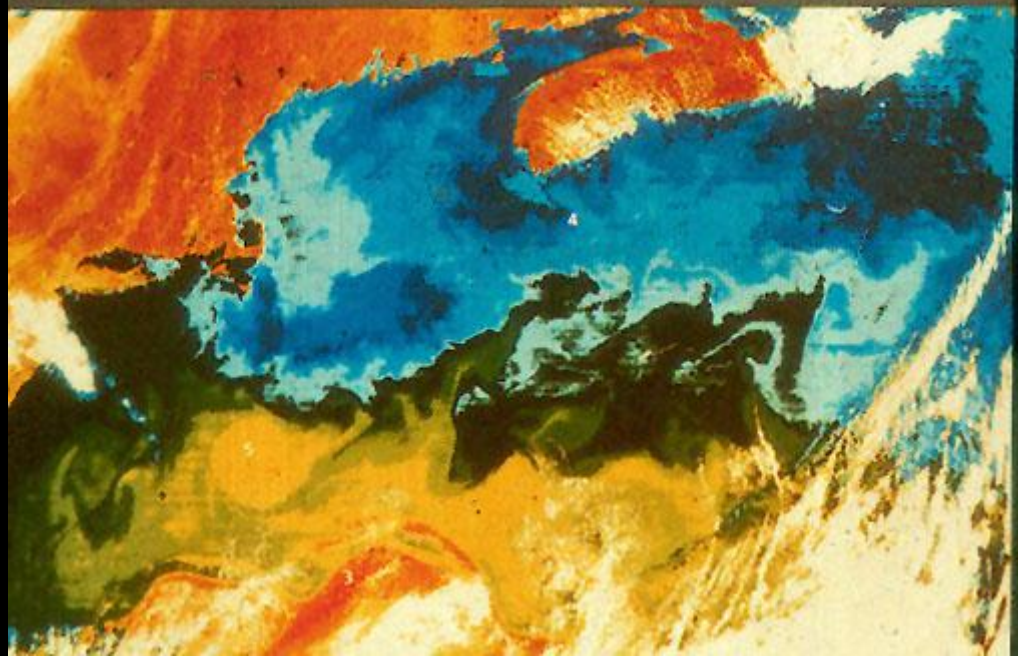
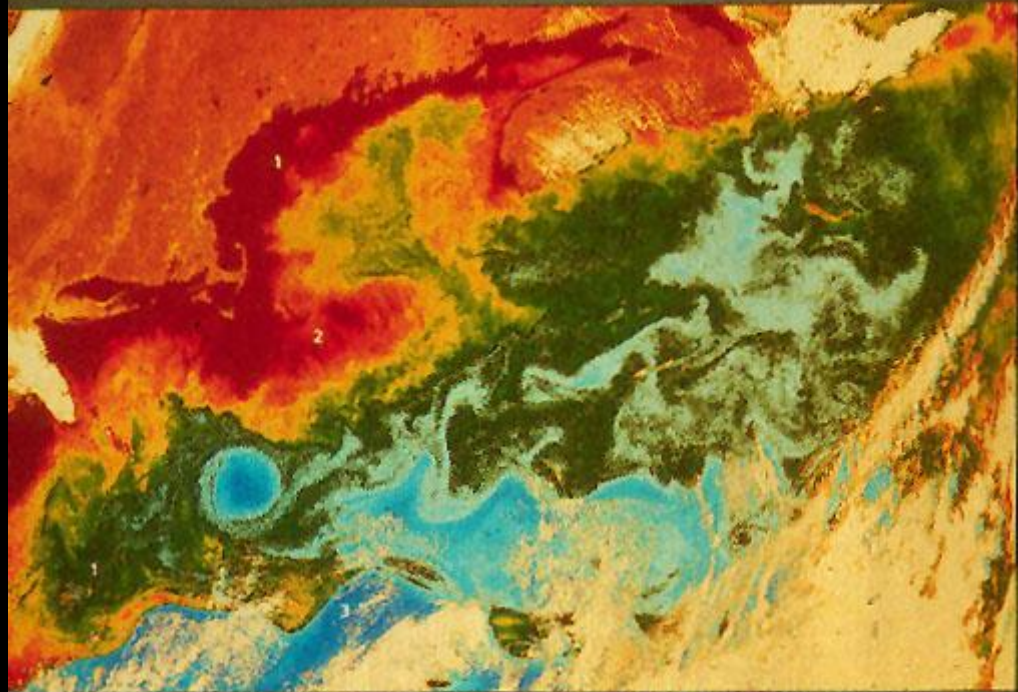
Societal Benefit Areas

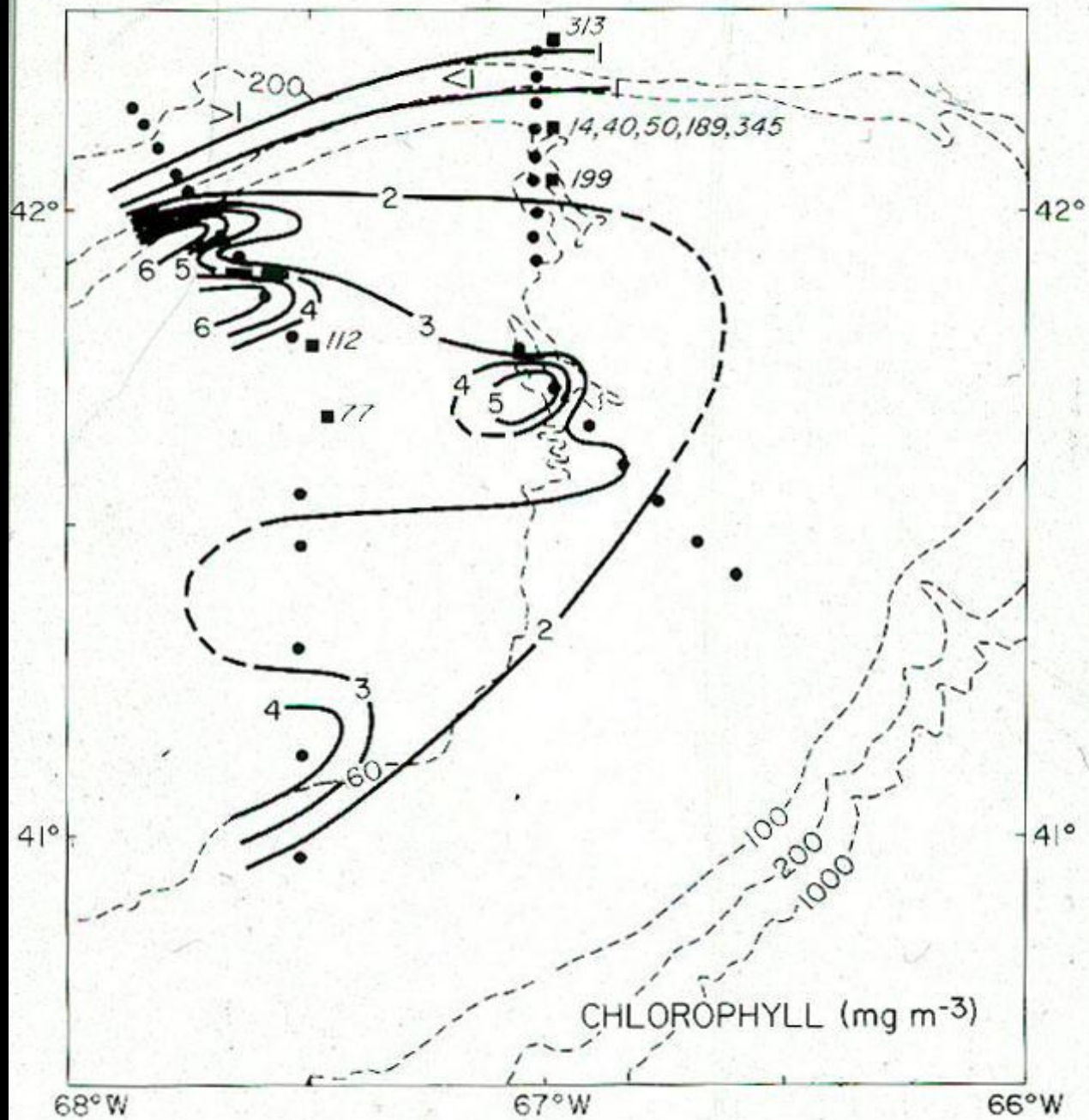
Transition from research & development to operational oceanography

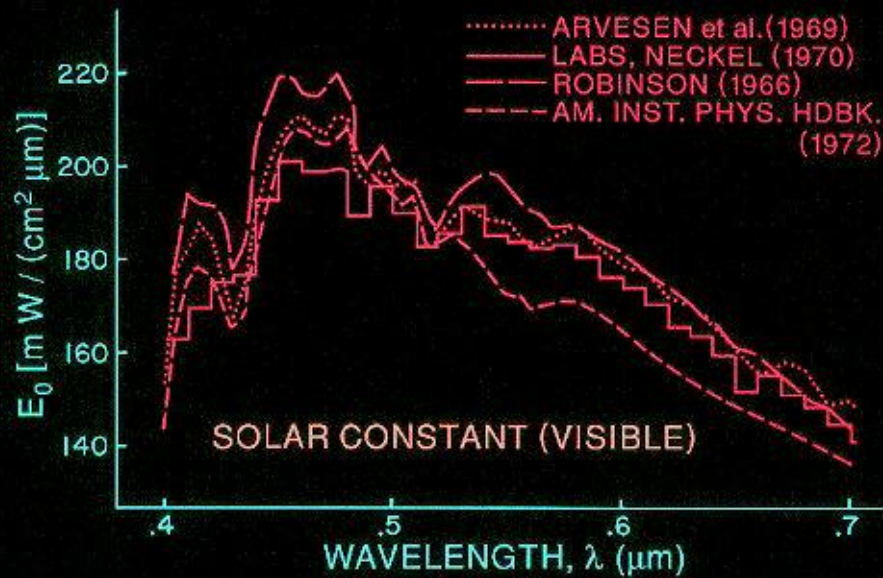
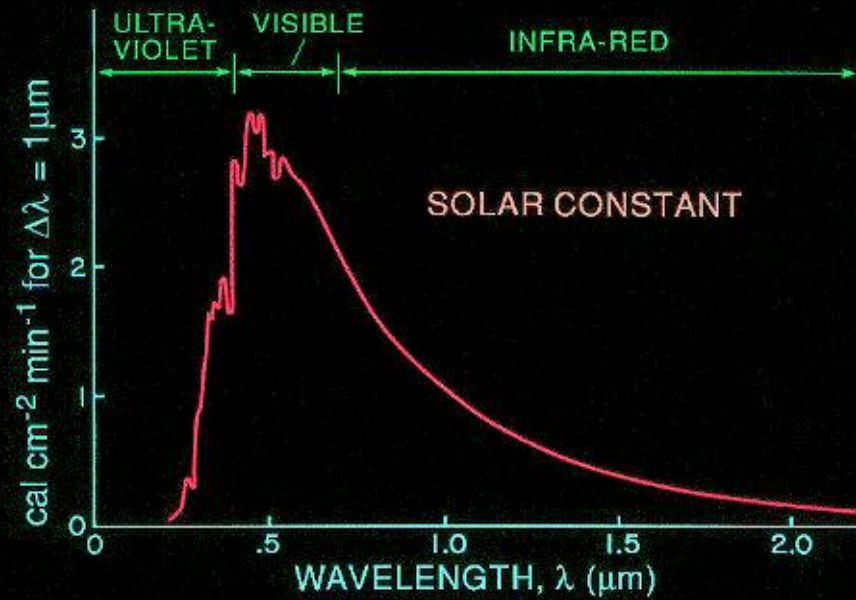


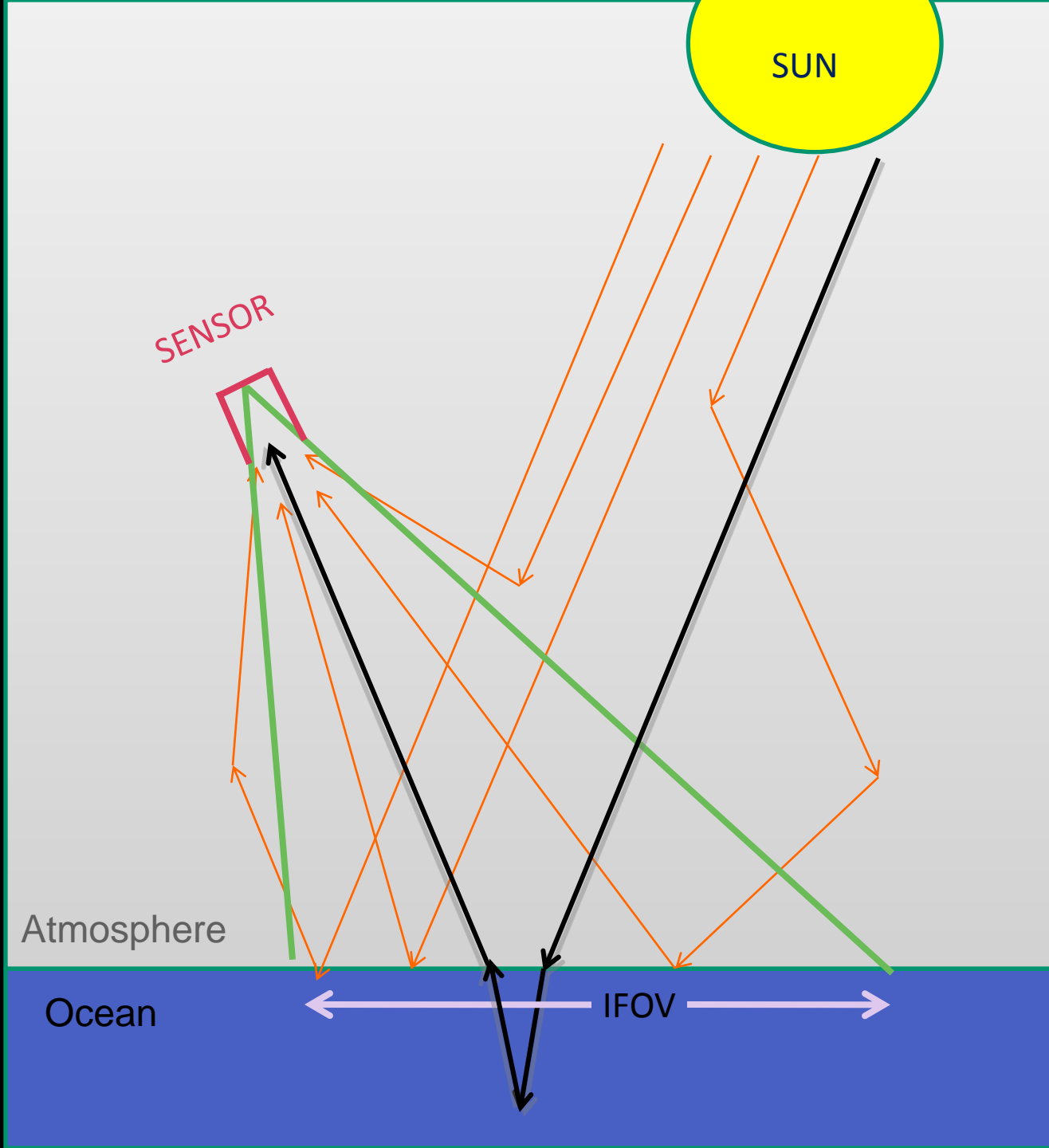


Phytoplankton & Temperature Patts

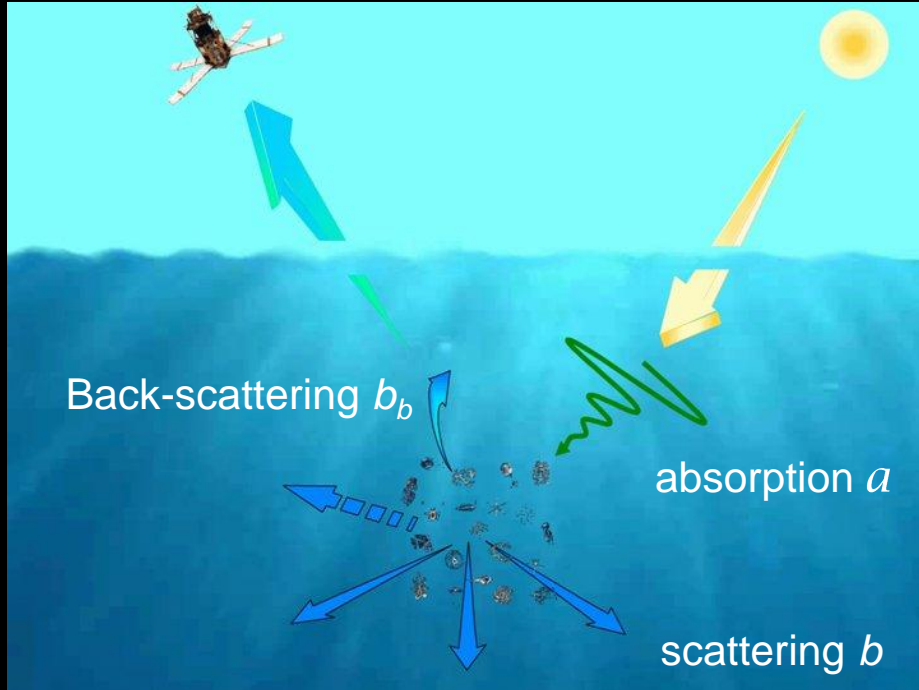




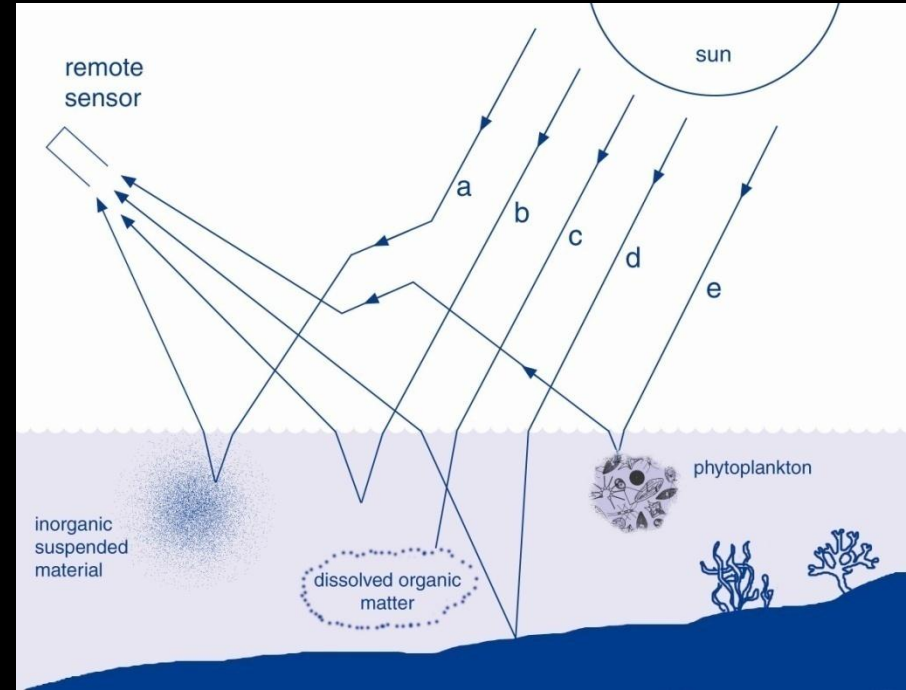




Factors that influence upwelling light leaving the sea surface

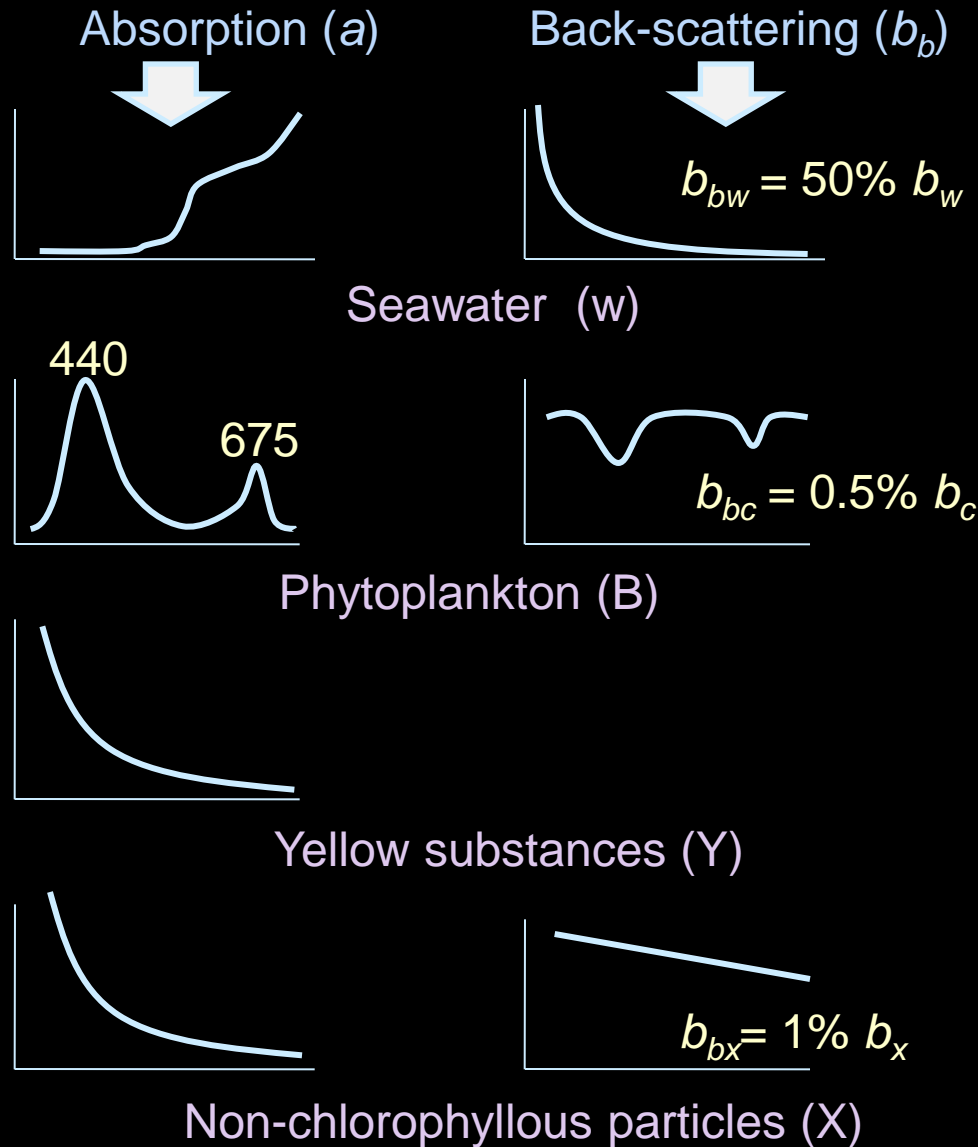


Two optical processes determine the fate of photons that penetrate into the ocean: absorption and scattering



The water-leaving radiance contains information on phytoplankton, suspended sediments, dissolved organic material and bottom type (in shallow waters)

Inherent spectral optical properties of seawater and its contents



Ocean Colour is determined by spectral variations in reflectance R at the sea surface:

$$R = f(a, b_b)$$

Both absorption and back-scattering can be expressed as sum of contributions from individual constituents.

Both absorption and back-scattering of particular components vary spectrally in characteristic manners.

Case 2 Waters

Case 1 Waters

Living algal cells

Variable concentration

Associated detritus

Autochthonous; local source
(grazing, natural decay of
phytoplankton)

Coloured dissolved
organic matter

Autochthonous; originating from
local ecosystem

Resuspended sediments

Along the coastline and in
shallow areas

Terrigenous particles

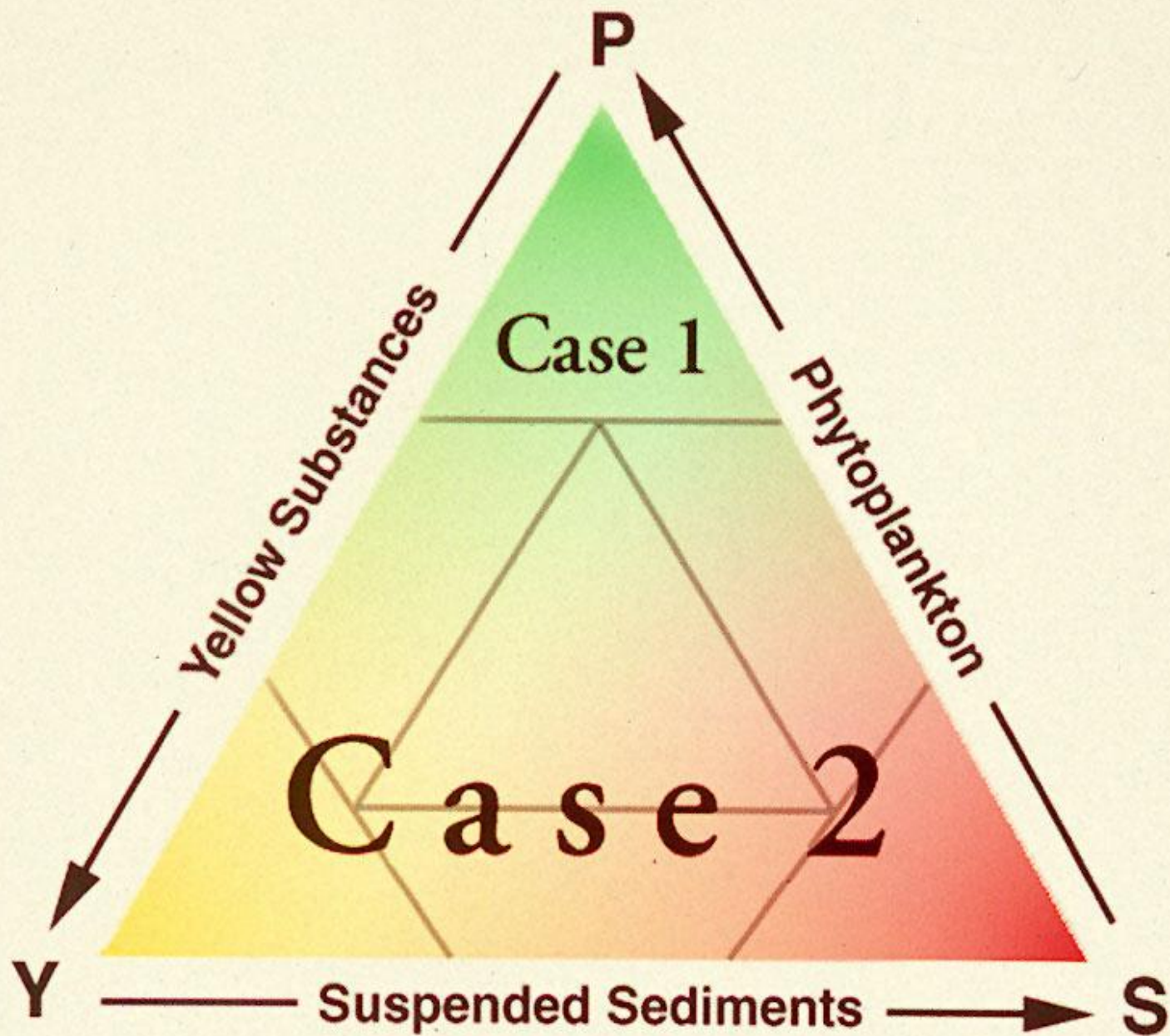
River and glacial runoff

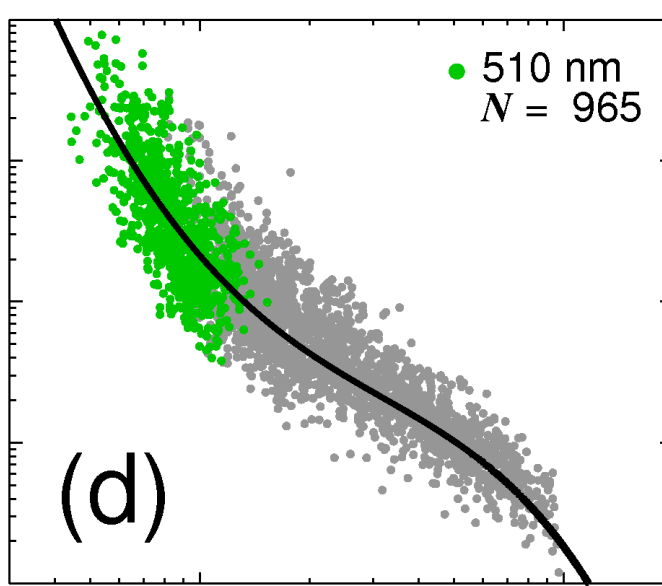
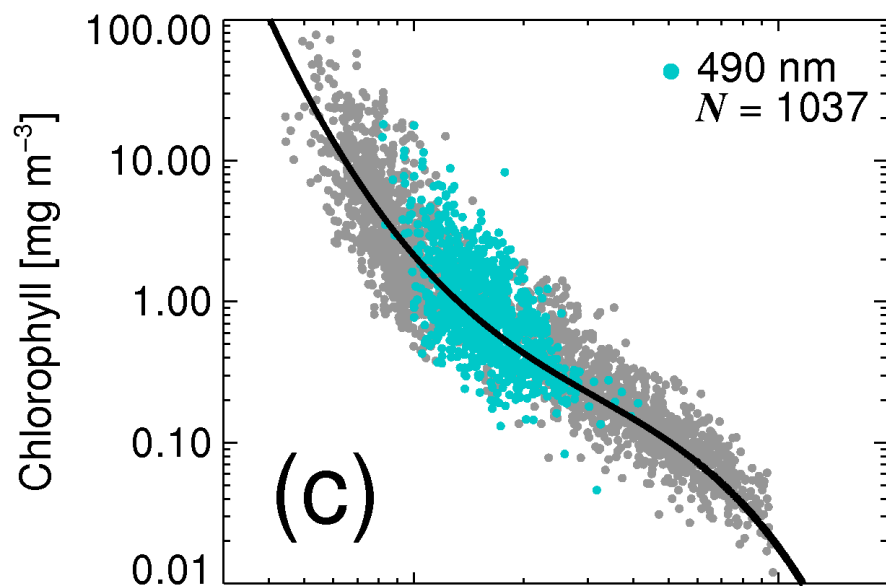
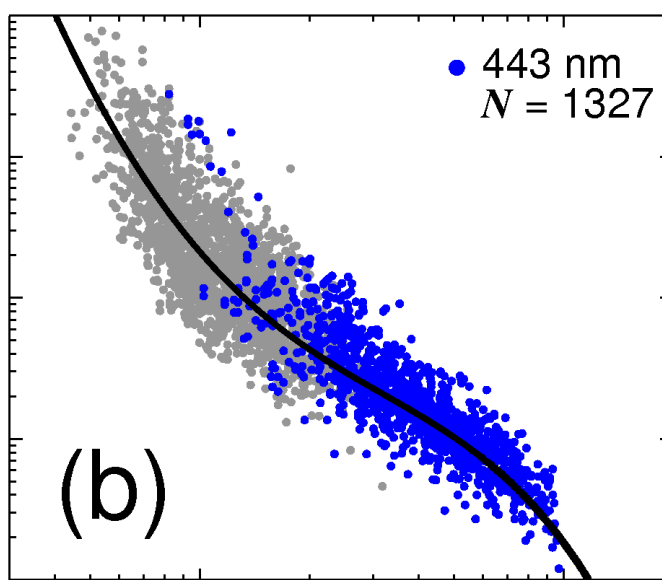
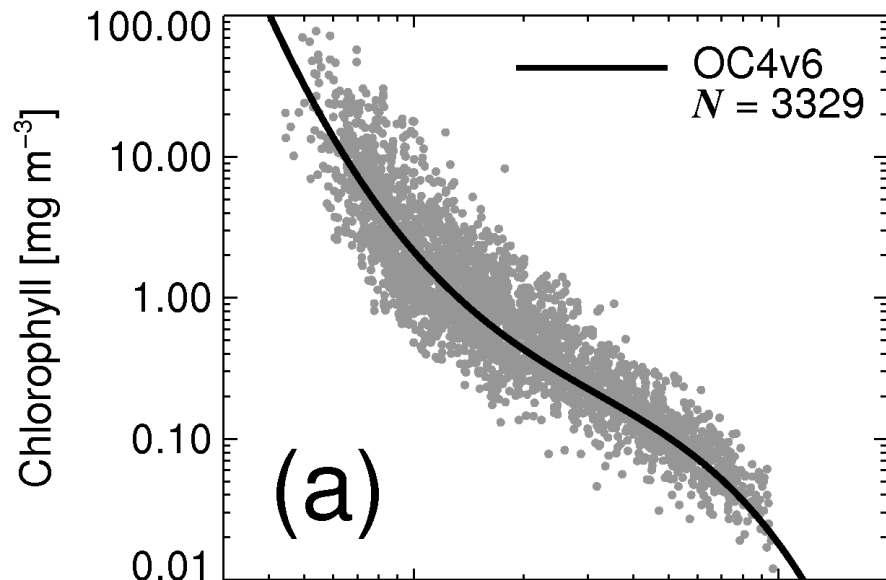
+ Coloured dissolved organic
matter

Allochthonous; external to the
local ecosystem (land drainage,
external to the local ecosystem)

Anthropogenic influx

Particulate and dissolved
materials

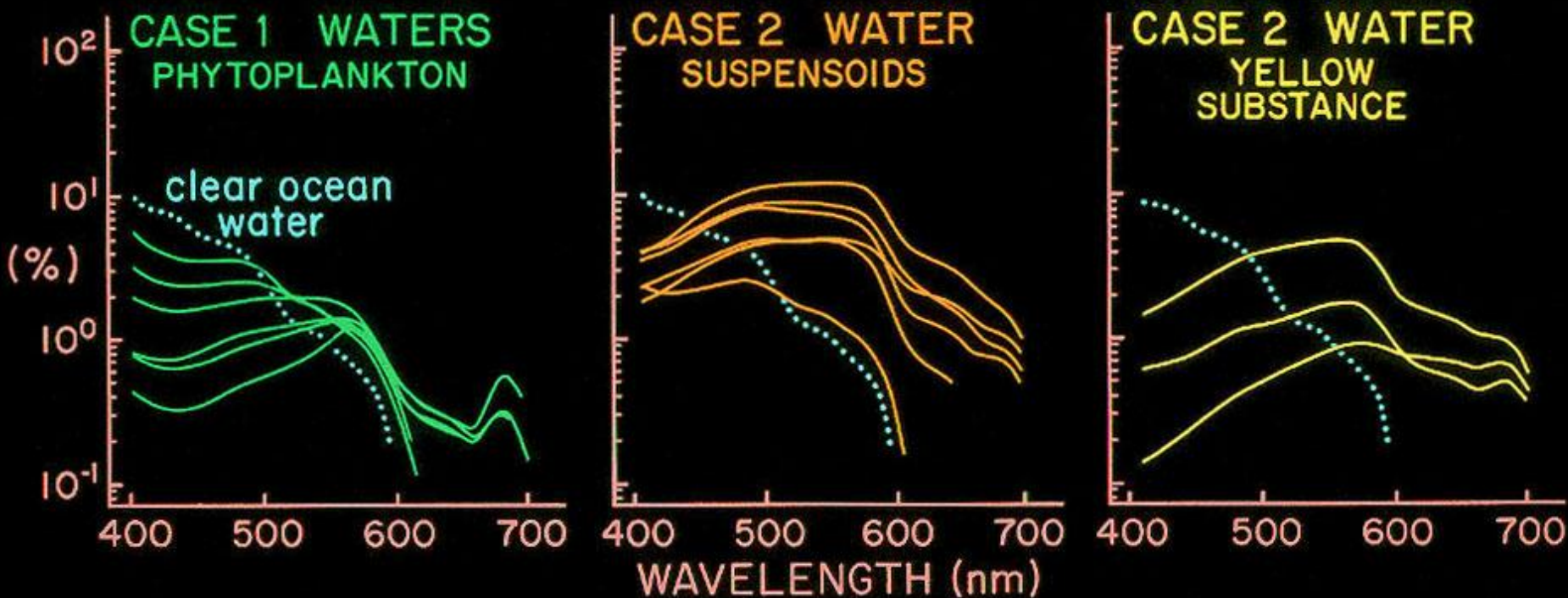


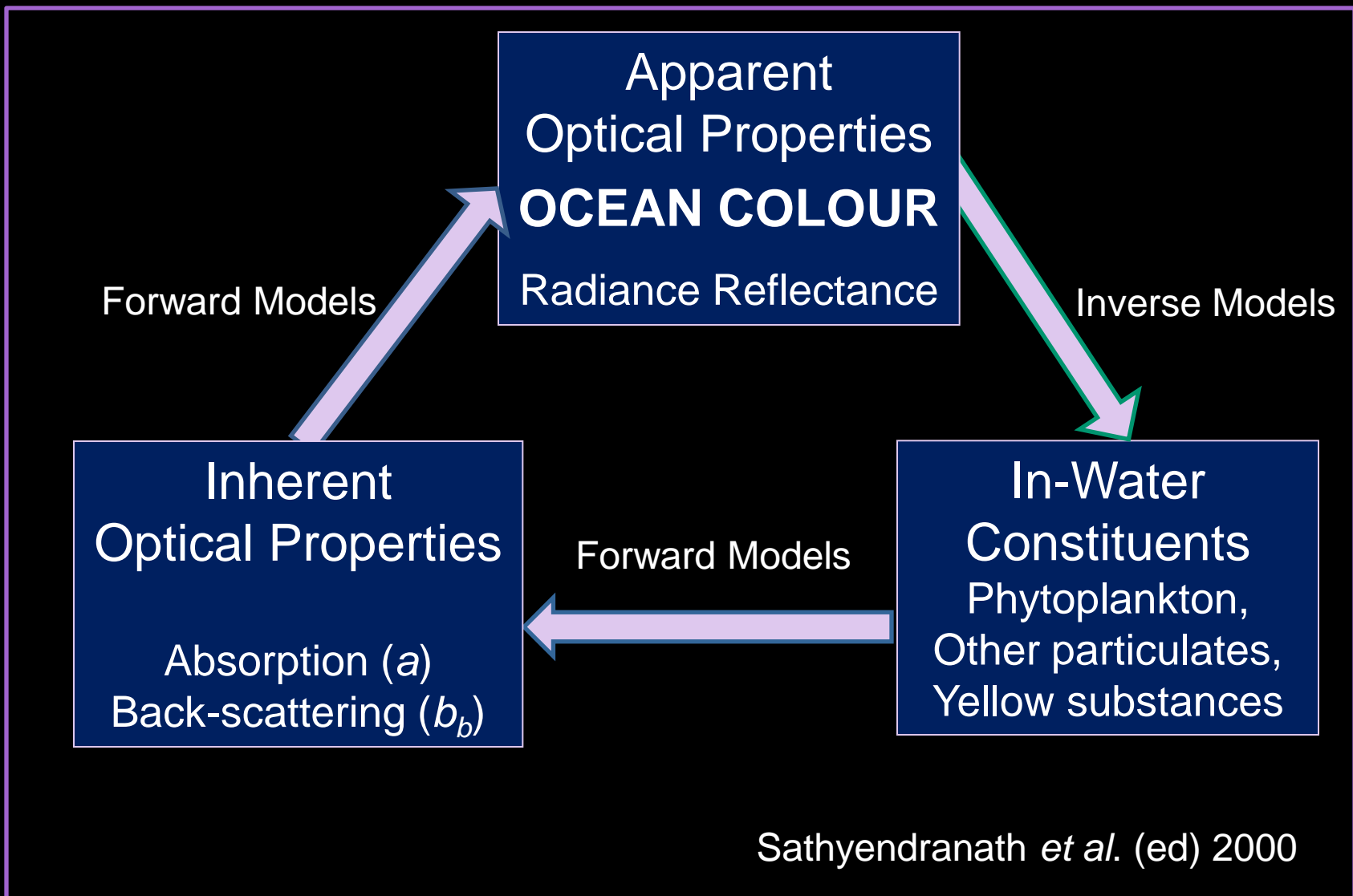


1 10
(Rrs443>Rrs490>Rrs510)/Rrs555

1 10
(Rrs443>Rrs490>Rrs510)/Rrs555

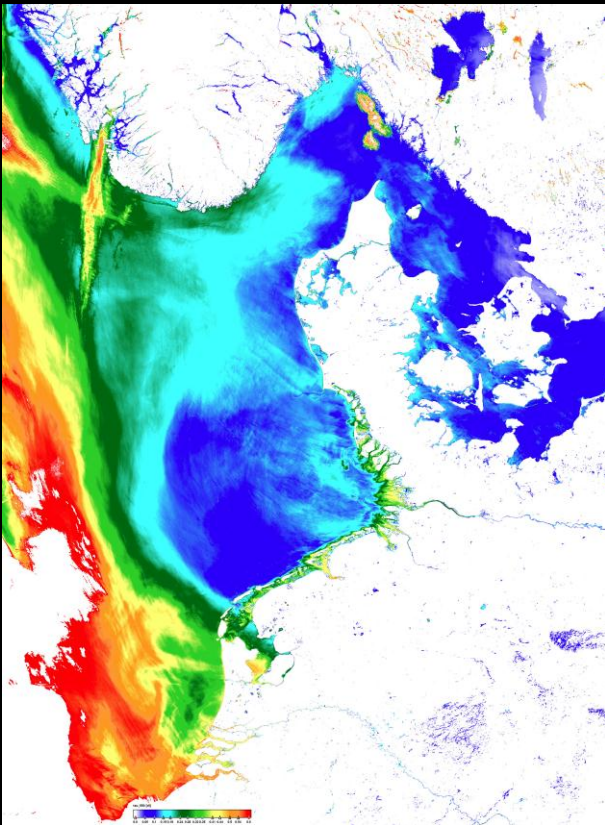
REFLECTANCE SPECTRA



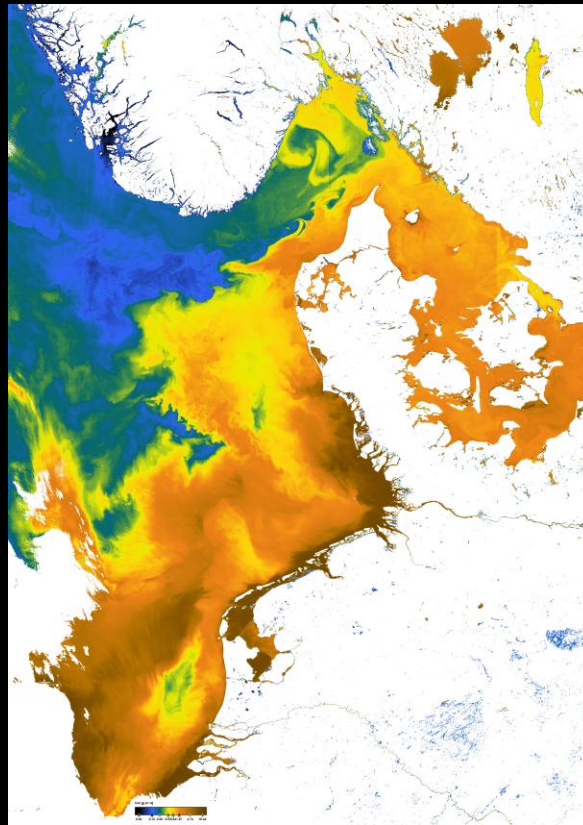


Remote sensing of ocean colour is a rigorous radiometric science, designed to infer the concentrations of the constituents, given spectral reflectance.

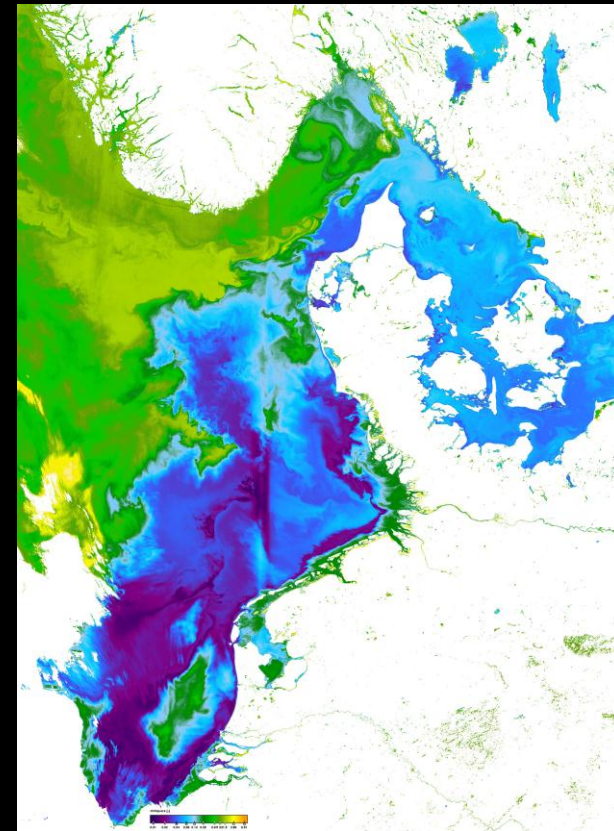
Coastal Products: North Sea



Aerosol Optical
Thickness at 550 nm



Total Suspended Matter



Quality of Retrieval

Samples from ESA's CoastColour Project
www.coastcolour.org

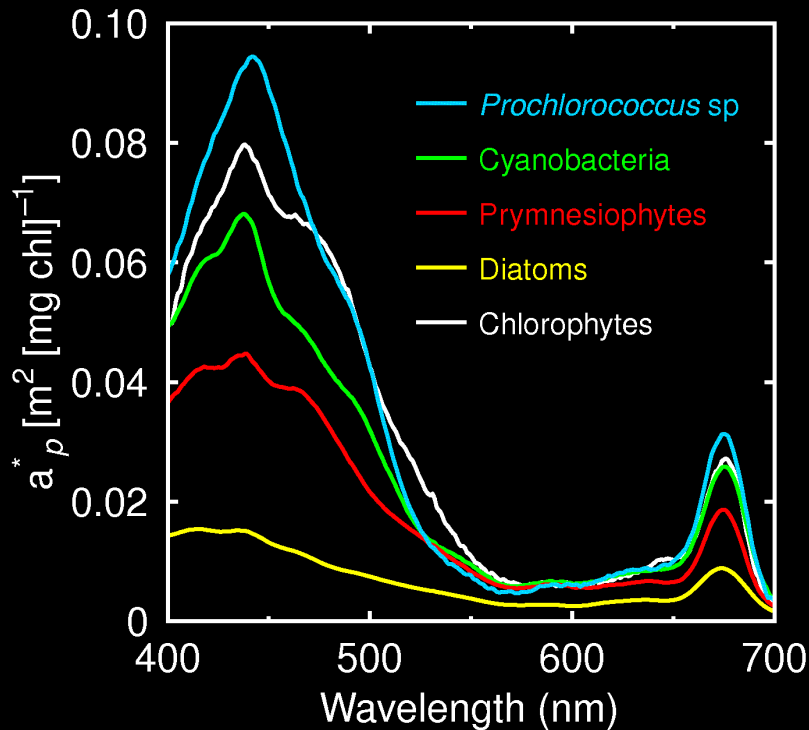
There is more to phytoplankton than just chlorophyll



- Phytoplankton contain a suite of auxiliary pigments whose composition varies with taxa and with growth conditions
- Phytoplankton occupy a broad size range
- Both cell size and pigment composition modify optical characteristics of phytoplankton



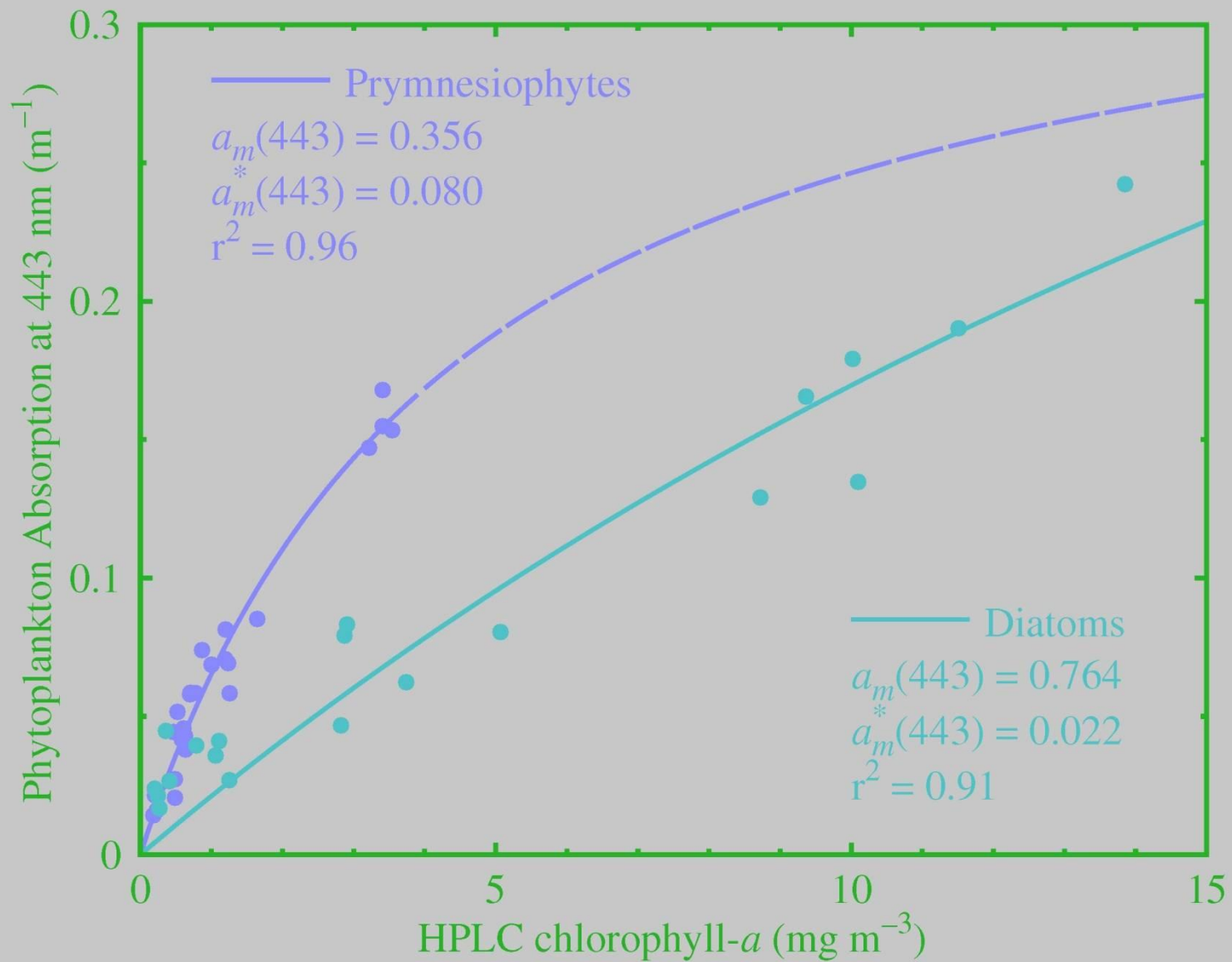
Many phytoplankton types have distinctive optical properties



Field Data

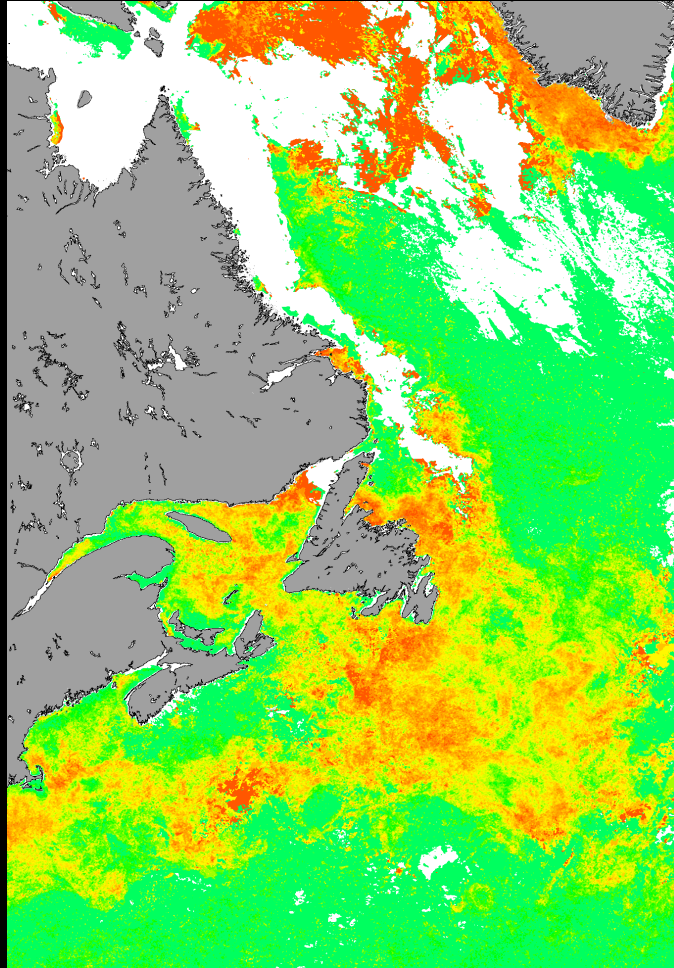


Cultures in the laboratory

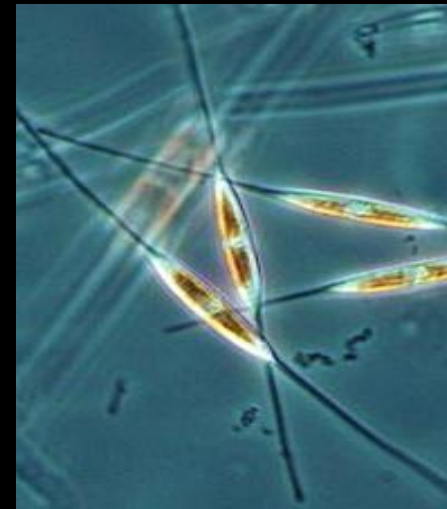
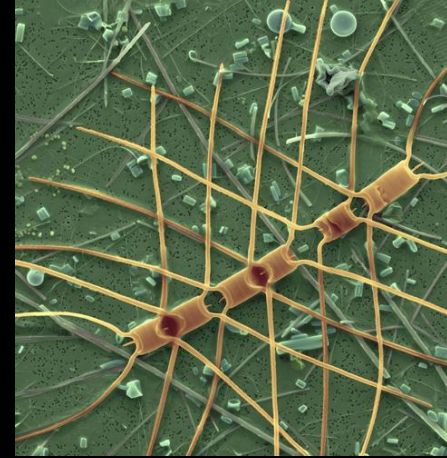
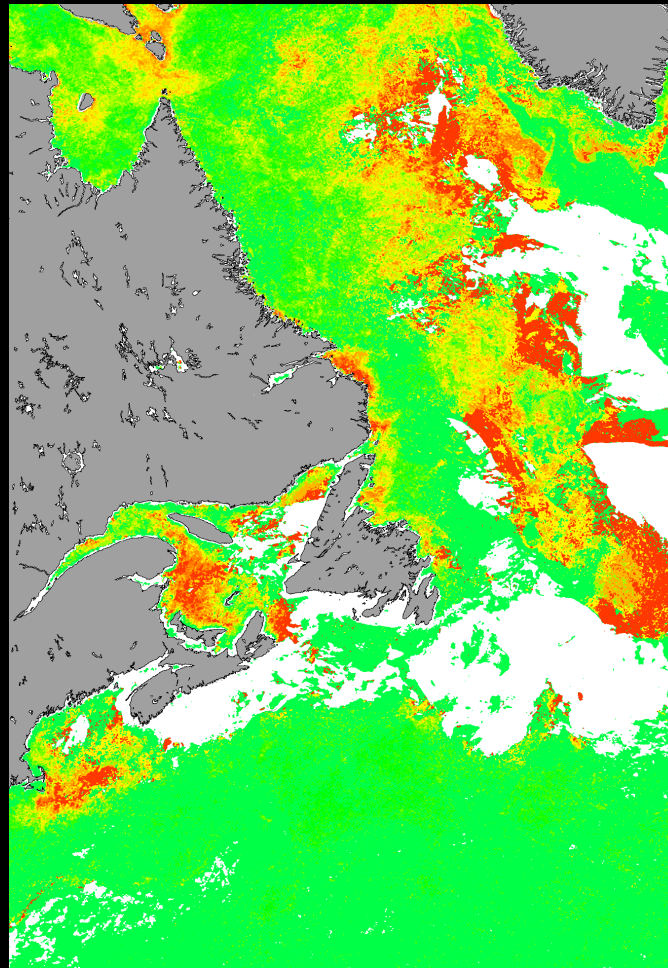


Probability of occurrence of diatoms 2003

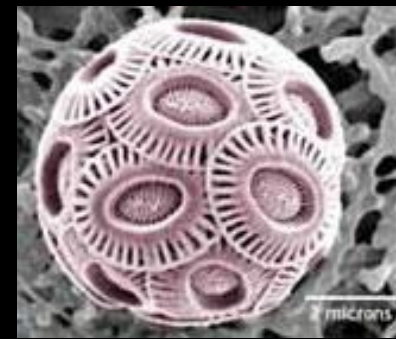
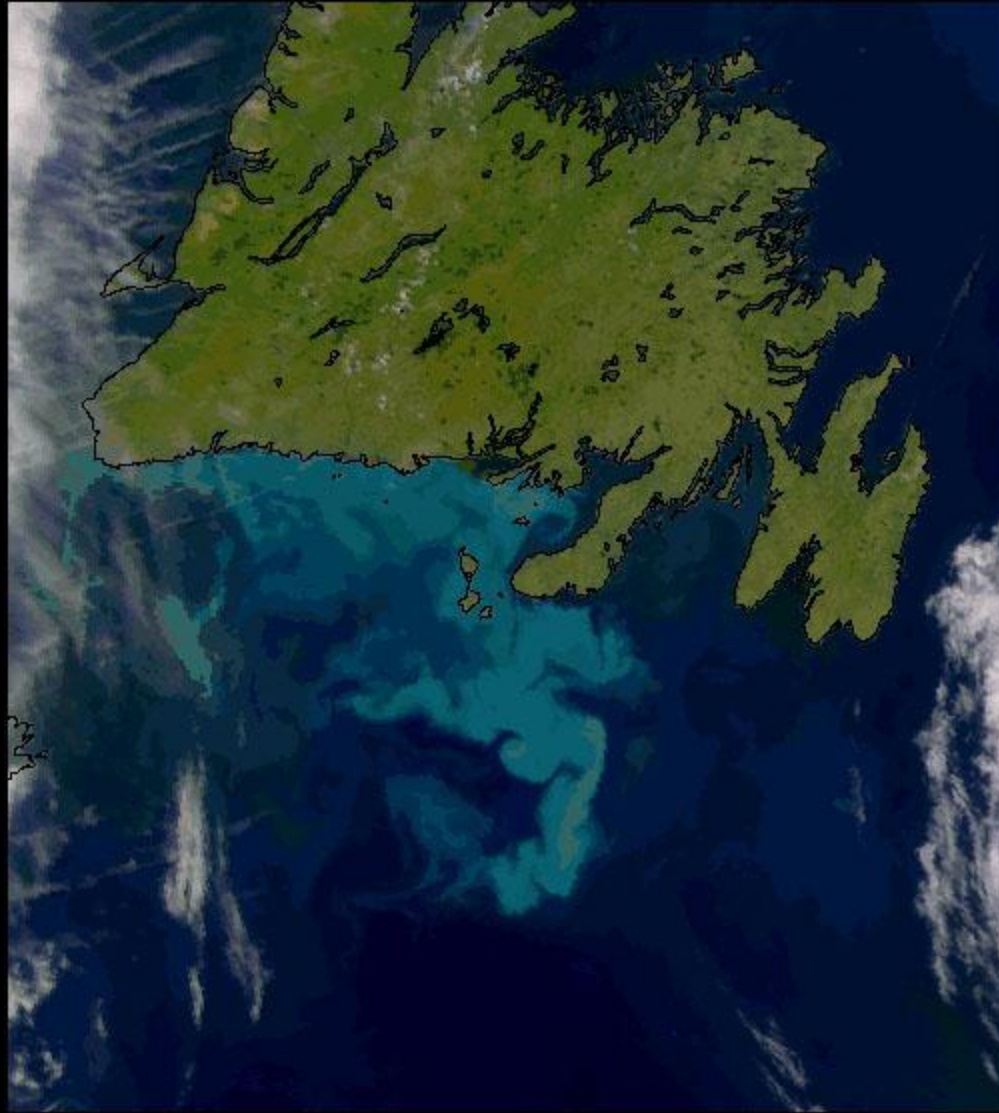
Spring



Summer

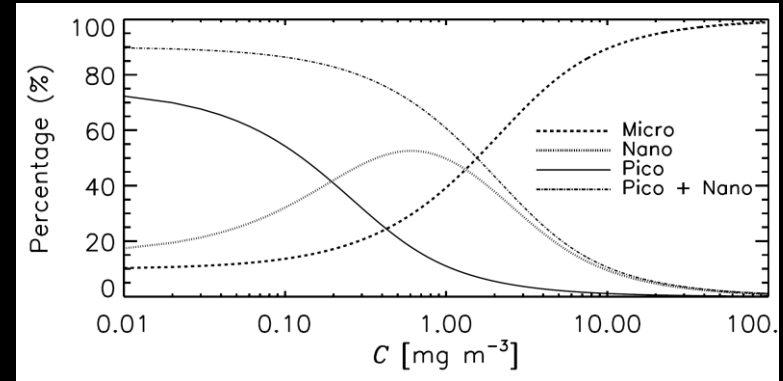
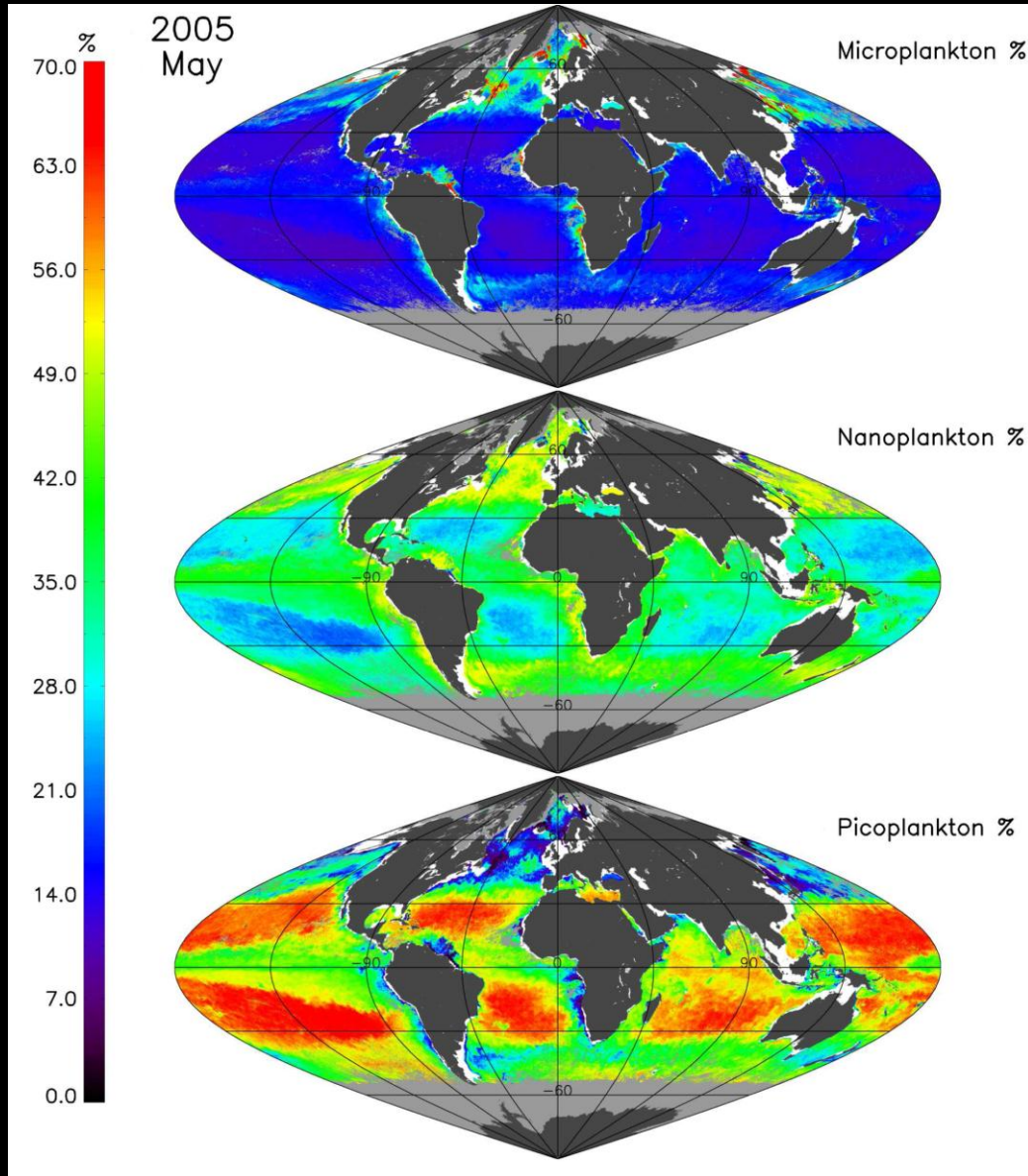


Sathyendranath *et al.* (2004)



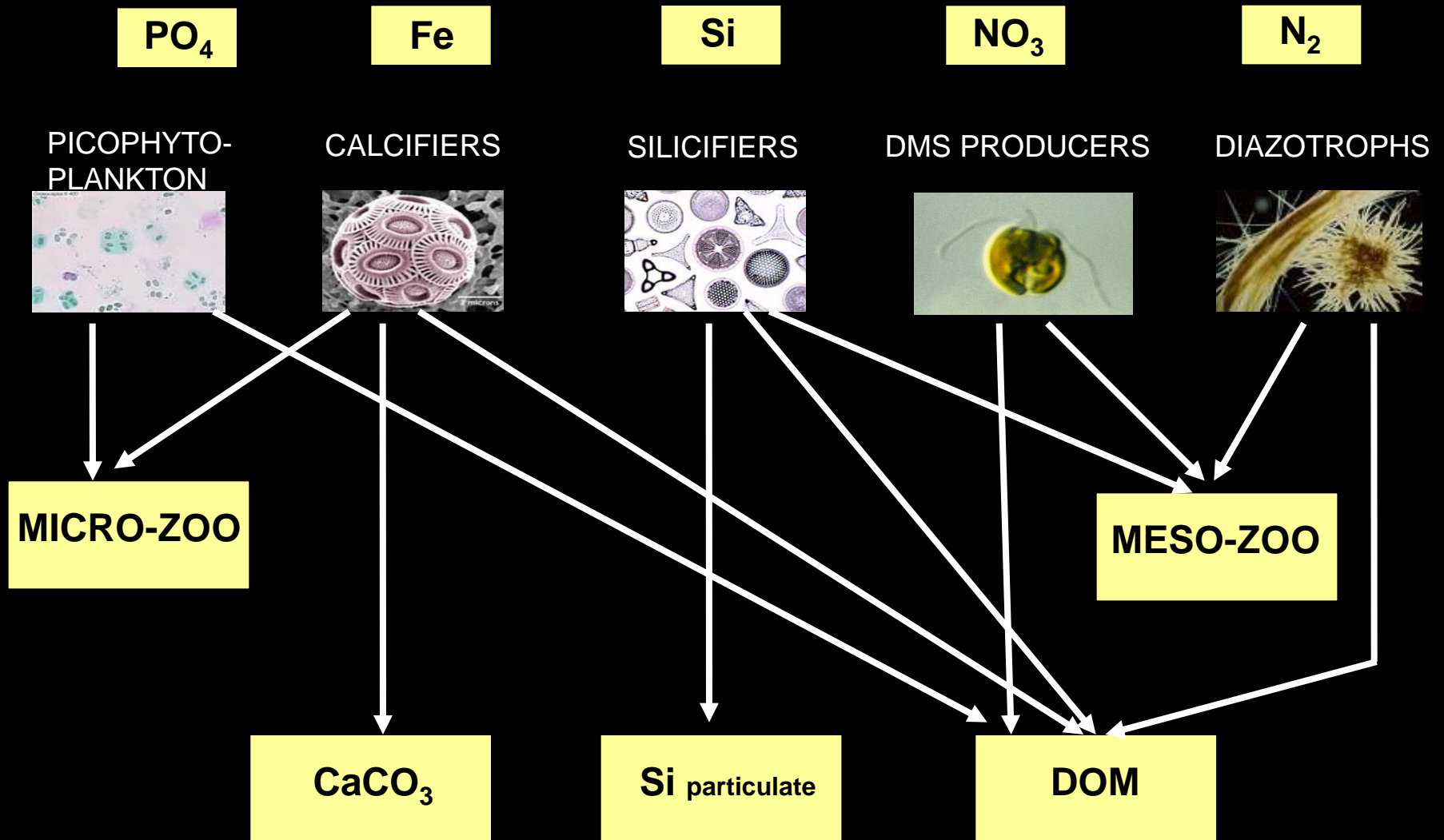
Coccolithophore Bloom - 29 July 2002

Phytoplankton Size Classes from Earth Observation



Derived from chlorophyll, using regressions between chlorophyll concentration and other ecosystem properties such as pigment composition (related to size). Not a direct estimate from ocean colour. Hence a secondary product

DYNAMIC GREEN-OCEAN MODEL



Applications of the Ocean-Colour Archive

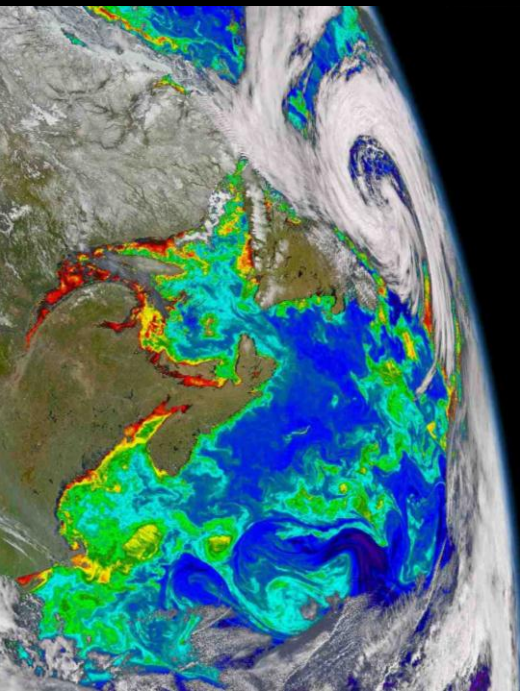
To provide:

1. Synoptic fields of phytoplankton biomass for comparison with results from coupled ocean-ecosystem models;
2. Basis for computation of regional-, and basin-scale estimates of primary production;
3. General tool for extrapolation to large horizontal scale of sparse measurements of ecophysiological rates;
4. Typology of seasonality in the pelagic ecosystem;
5. Basis for study of feedbacks between pelagic microbiota and mixed-layer physics; and
6. Indices of state of the pelagic ecosystem for use in fisheries management and coastal-zone management.

Some Ecological Indicators from Remote Sensing: Compact description of pelagic ecosystem

Initiation of spring bloom
Timing of spring maximum
Total production in spring bloom
Initial slope, light-saturation curve
Particulate organic carbon
Carbon-to-chlorophyll ratio
Phytoplankton loss rate

Amplitude of spring bloom
Duration of spring bloom
Annual phytoplankton production
Assimilation number
Phytoplankton carbon
Phytoplankton growth rate
Integrated phytoplankton loss
Spatial variance in biomass field
Spatial variance in production field
Phytoplankton functional types
Biogeochemical provinces



Pelagic ecosystem can be represented as a time-dependent vector whose elements are chosen from list of ecological indicators. Choice of elements depends on the particular applications envisaged. Gives a concise description of ecosystem.

Platt and Sathyendranath (2008)

Limitations of Ocean-Colour Data

1. Signal-to-noise level is low
2. No data in presence of clouds
3. Retrieved pigment measure only a crude index of biomass
4. Retrieval algorithm may not be universal
5. No information on vertical structure
6. Lack of continuity in data record



Ocean Colour as an Integrating Discipline: Science in the Service of Man

Ocean colour provides our only window into the pelagic ecosystem on synoptic scales.

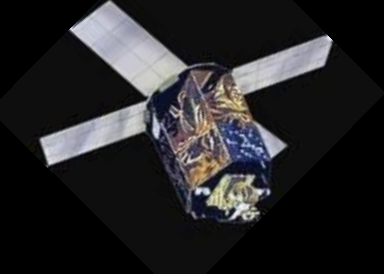
Ocean colour is an integrating discipline because it touches all aspects of marine science, research and operational.

Ocean colour is relevant to important Societal Benefit Areas (GEO/GEOSS) such as climate change (see ESA's Climate Change Initiative; see OCR-Virtual Constellation); fisheries (ecosystem indicators); marine biodiversity.

But users need to understand the limitations as well as the benefits

Ocean colour is not a universal panacea, but it is extremely versatile and cost-effective. Many important and stimulating problems remain to be solved.





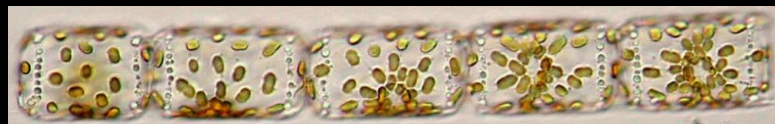
Future Directions

Ocean colour is at its best when combined with other aspects of oceanography (in-water observations, modelling). Much more remains to be done to bring these diverse techniques together, to improve our understanding and predictions of the state of the ocean.

Ocean colour technology is still improving: with corresponding progress in radiative transfer theory, as well as in relevant statistical techniques, we can exploit the full potential of ocean colour.

Ocean colour as a tool in ecosystem-based management deserves further development.

The fascination of ocean colour can draw in new disciples to the field: new recruits are necessary to fill the world-scale shortage of relevant expertise.



Challenges and Opportunities

For existing sensors, a principal challenge is to develop retrieval algorithms for coastal waters, which are optically complex.

Extracting information on phytoplankton community structure is an area of active research

For future sensors, principal challenge is in advanced applications that exploit higher resolution in wavelength.

Geo-stationary satellites (GOCI, Korea and possibly others) are emerging

The Colour of the Ocean

