→ EARTH OBSERVATION SUMMER SCHOOL

Earth System Monitoring & Modelling

30 July–10 August 2018 | ESA–ESRIN | Frascati (Rome) Italy

Ocean Colour theory

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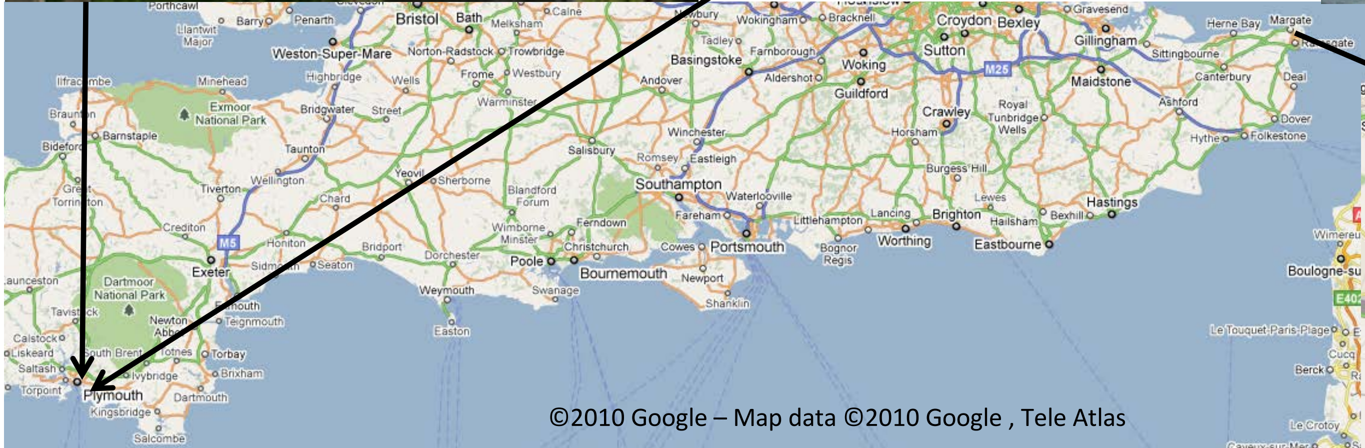
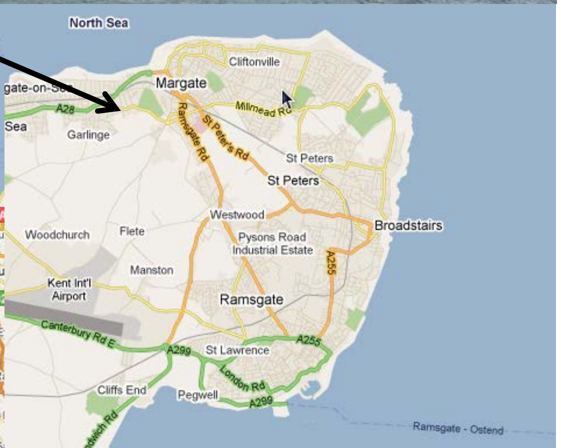
National Centre for Earth Observation
NATURAL ENVIRONMENT RESEARCH COUNCIL

PML Plymouth Marine Laboratory

A bit about myself

University of Plymouth
BSc Surf Science and Technology
MSc Applied Marine Science
PhD Marine Remote Sensing

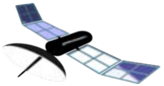


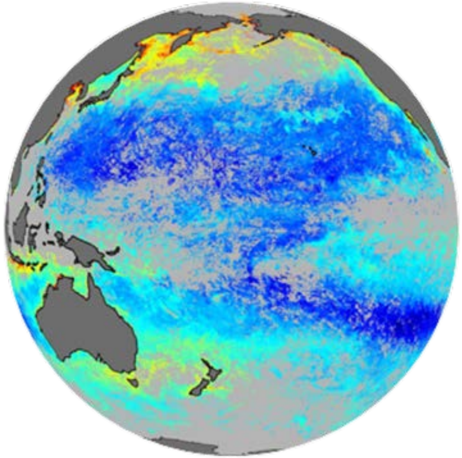


A bit about myself

esa

Remote sensing





esa

NERC
SCIENCE OF THE ENVIRONMENT

National Centre for Earth Observation
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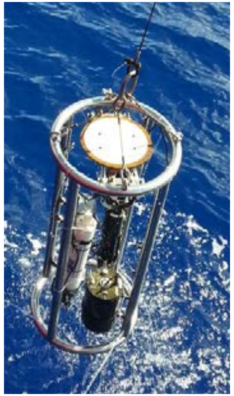
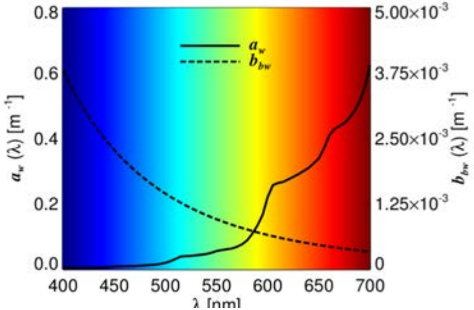
Field work

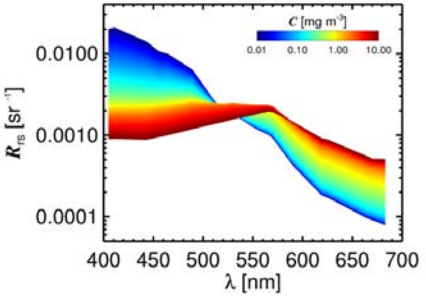


Citizen Science

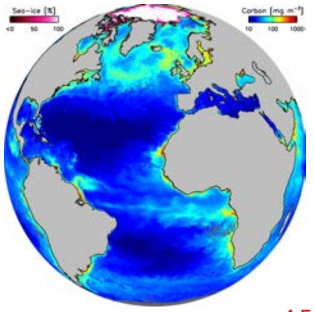
Overview of ocean colour lectures

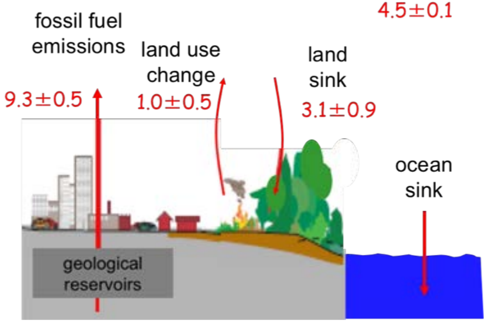
Ocean Colour theory
11:30 -12:30 1st August



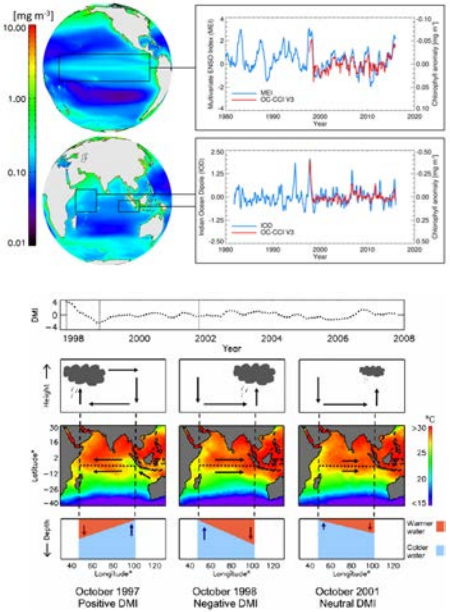


Ocean Colour and the marine carbon cycle
12:30 -13:30 2nd August





Ocean Colour and climate
11:30 -12:30 3rd August



Outline Ocean Colour Theory

1) What is ocean colour

2) History of ocean colour

3) Optical properties of water and its constituents

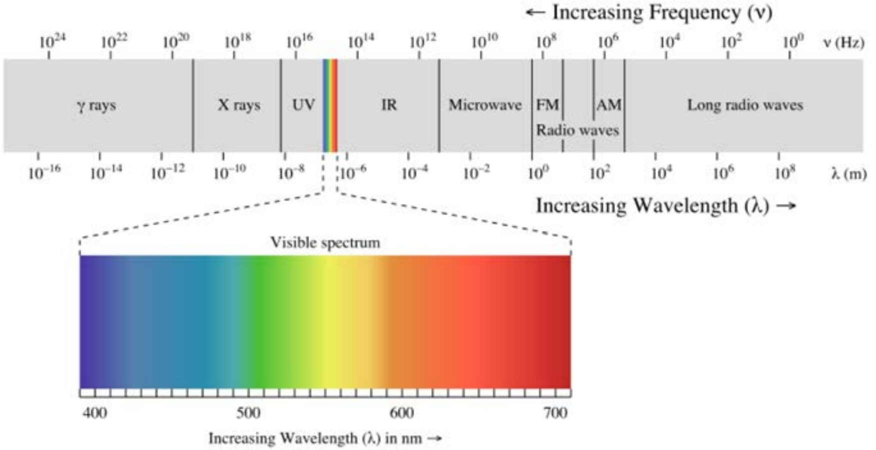
4) In situ measurements of ocean colour

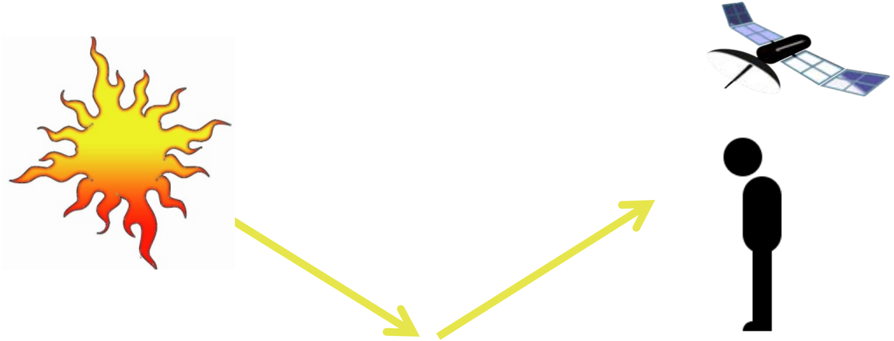
5) Satellite remote-sensing of ocean colour

What is ocean colour

The interaction of incident visible light with sea water.

Sunlight that enters the ocean is absorbed, scattered and reflected by seawater and the constituents that make up the seawater. These processes vary with wavelength of light. Spectral variations in the reflected light determine the colour of the ocean.





History of ocean colour

Albert Bierstadt

Farrallon Island

1887

Emil Nolde

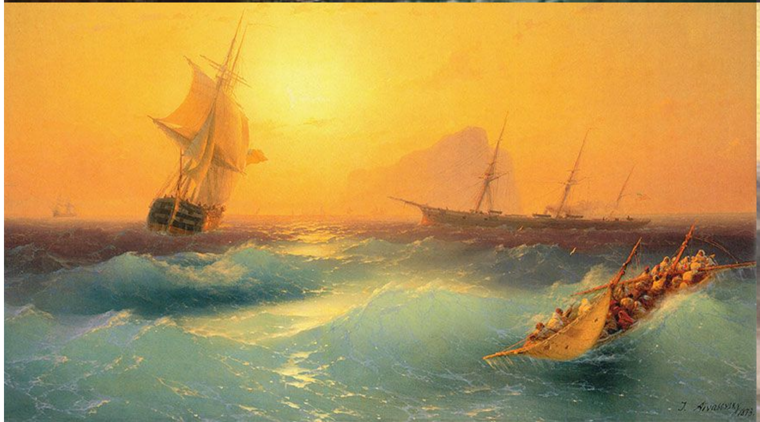
Sea with Red Sun

Undated (1867-1956)

Ivan Aivazovsky

American Shipping off the Rock of Gibraltar

1873



Ivan Aivazovsky

Bracing the Waves

1890

History of ocean colour

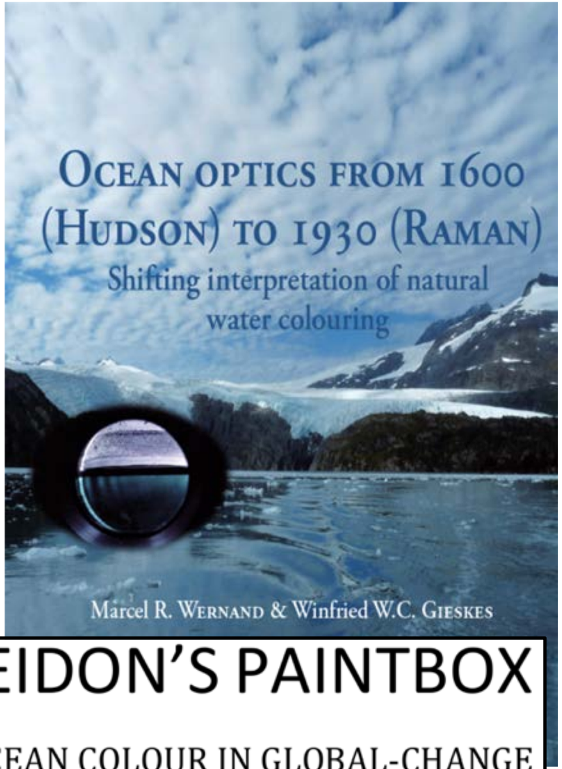
The foureteenth, in the morning, was calme with fogge. At nine, the wind at east, a small gale with thicke fogge; wee steered south-east and by east, and running this course we found our greene sea againe, which by proofe we found to be freest from ice, and our azure blue sea to be our ice sea. At this time we had more birds then we usually found.

H. Hudson, First voyage, 1607

The colour of the Greenland Sea varies from ultramarine blue to olive green, and from the most pure transparency to striking opacity. These appearances are not transitory, but permanent; not depending on the state of the weather, but on the quality of the water.

W. Scoresby, 1820

Change in sea colour used in early navigation
- change in bottom topography
- presence of ice bergs
- river discharge
- occurrence of fish



POSEIDON'S PAINTBOX

HISTORICAL ARCHIVES OF OCEAN COLOUR IN GLOBAL-CHANGE PERSPECTIVE

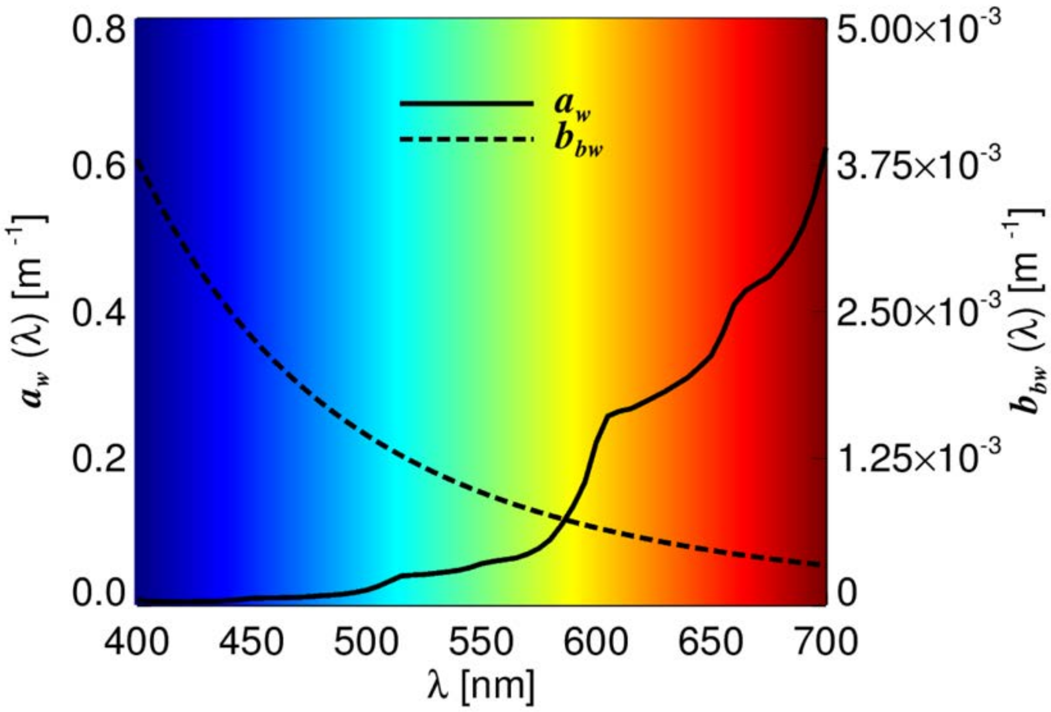
Marcel Robert Wernand

Optical properties of water and its constituents

A sufficient deep layer of pure water exhibits by molecular scattering a deep blue colour more saturated than sky-light and of comparable intensity. The colour is primarily due to diffraction, the absorption only making it of a fuller hue. The theories hitherto advanced that the dark blue of the deep sea is reflected sky-light or that it is due to suspended matter are discussed and shown to be erroneous

C. Raman, 1922

$$R(\lambda) \approx r\frac{b_b(\lambda)}{a(\lambda)}$$



Evolution from human fascination to experimentation to rigorous science

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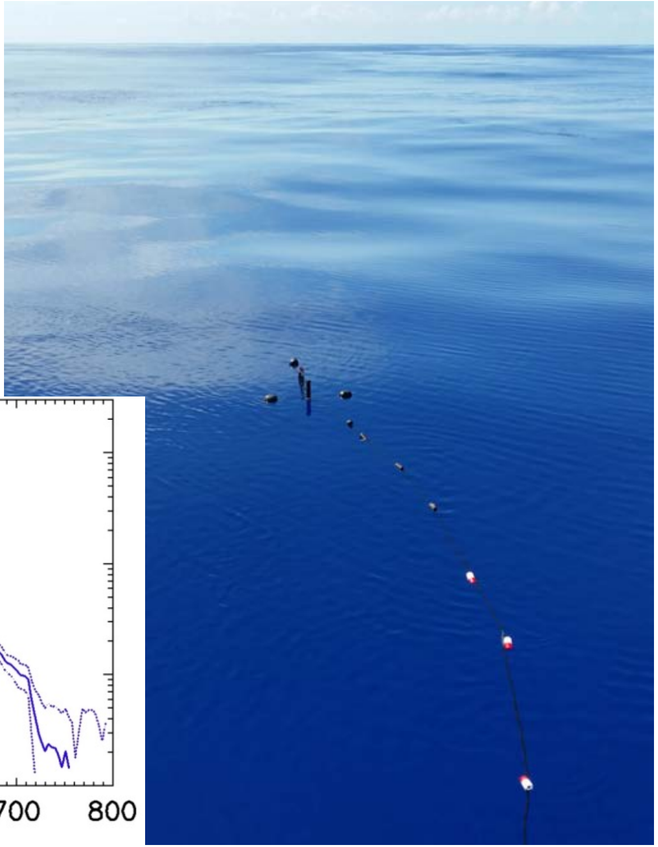

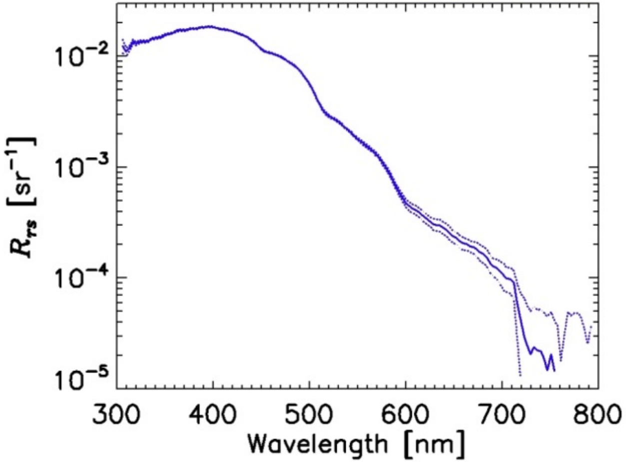

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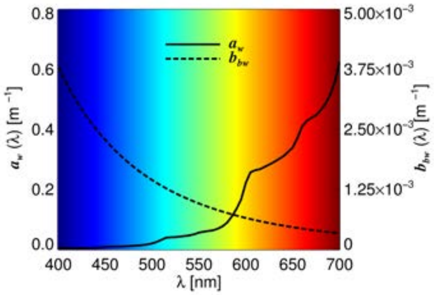
C. Raman, 1922

Taken from Wernand (2011)

Optical properties of water and its constituents

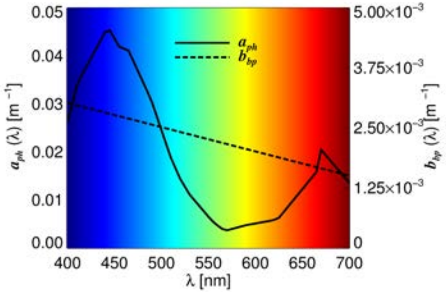
Sea water and its principle constituents

Pure seawater

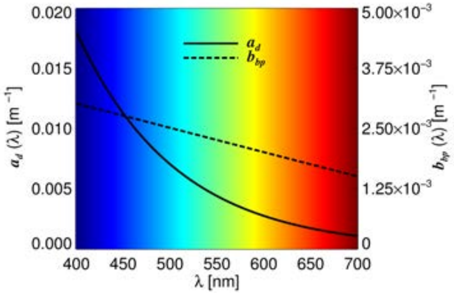


Particles

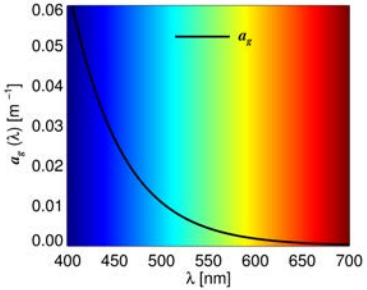
Phytoplankton



Non-algal



Dissolved matter



Optical properties of water and its constituents

Apparent optical properties (AOPs)

While these vary depending on the inherent optical properties of the water, and the directional distribution of the light field in the sea (e.g. water leaving radiance, reflectance and diffuse attenuation coefficient of seawater)

Inherent optical properties (IOPs)

The optical properties of the water and its constituents independent of the directional distribution of the light field in the sea (e.g. absorption, backscattering, beam attenuation).

Inherent Optical Properties

Specific inherent optical properties: the individual scattering and absorption components per unit concentration ($a^*_p(\lambda) = a_p(\lambda)/P$)

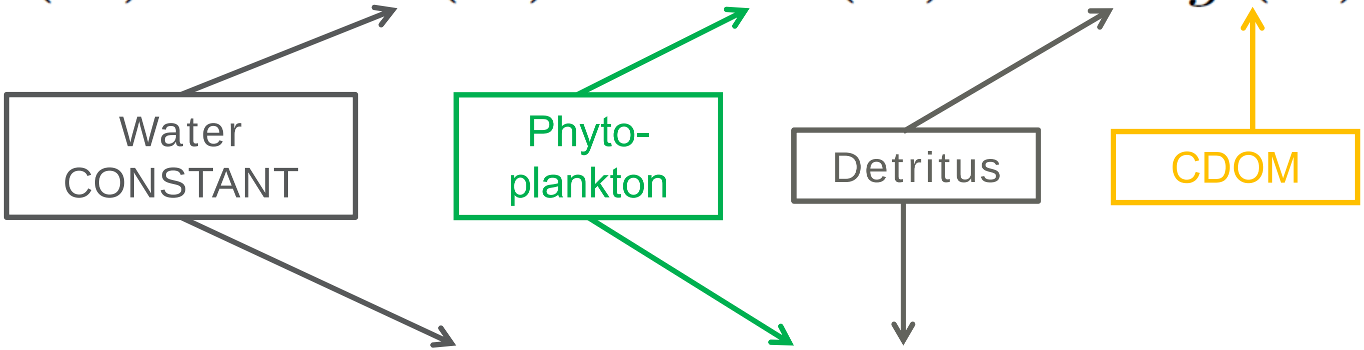
Bulk inherent optical properties: the individual scattering and absorption components per unit concentration multiplied by concentration ($a_p(\lambda) = a^*_p(\lambda)P$). Will vary with variations in specific IOPs and concentration.

$$a = a_w + P \cdot a^*{}_p + CDOM \cdot a^*{}_{CDOM}$$

$$b = b_w + P \cdot b^*{}_p$$

Optical properties of water and its constituents

$$a(\lambda) = a_w(\lambda) + a_B(\lambda) + a_{dg}(\lambda)$$



$$b_b(\lambda) = b_{bw}(\lambda) + b_{bp}(\lambda)$$

$$R(\lambda) \approx r \frac{b_b(\lambda)}{a(\lambda)}$$

Case-2: Phytoplankton biomass does not covary with detritus and CDOM
Case-1: Phytoplankton biomass covaries with detritus and CDOM IOPs can be tied to the chlorophyll concentration (*C*)

Morel and Prieur (1977) Limnol. Oceanogr.

Optical properties of water and its constituents

$$a(\lambda) = a_w(\lambda) + a_B(\lambda) + a_{dg}(\lambda)$$

Water CONSTANT

∝ Chlorophyll (C)

$$b_b(\lambda) = b_{bw}(\lambda) + b_{bp}(\lambda)$$

$$R(\lambda) \approx r\frac{b_b(\lambda)}{a(\lambda)}$$

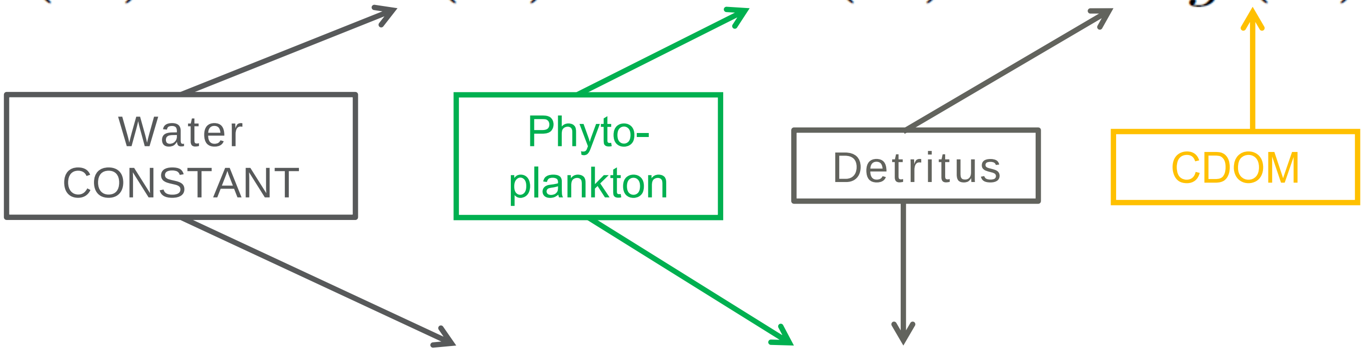
Case-2: Phytoplankton biomass does not covary with detritus and CDOM

Case-1: Phytoplankton biomass covaries with detritus and CDOM. IOPs can be tied with reasonable confidence to the chlorophyll concentration (C)

Morel and Prieur (1977) Limnol. Oceanogr.

Optical properties of water and its constituents

$$a(\lambda) = a_w(\lambda) + a_B(\lambda) + a_{dg}(\lambda)$$



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Morel and Prieur (1977) Limnol. Oceanogr.

Optical properties of water and its constituents

$$a(\lambda) = a_w(\lambda) + a_B(\lambda) + a_{dg}(\lambda)$$

Phytoplankton

- Total Chlorophyll-a
- Phytoplankton pigment composition
- Phytoplankton size structure
- Phytoplankton Chl for different groups
- Phytoplankton Carbon for different groups
- Light attenuation (heating of ocean and primary production)

Detritus

- Sinking of material
- Coastal erosion of terrigenous sediments
- River deposition
- Dust / Volcanic / Cosmogenic deposition
- Recycling
- Light attenuation

CDOM

- Dissolved organic carbon cycle
- Proportions of humic and fulvic acids
- Semi-labile and refractory fractions
- Photodegradation status
- Water mass change
- Light attenuation

Optical properties of water and its constituents

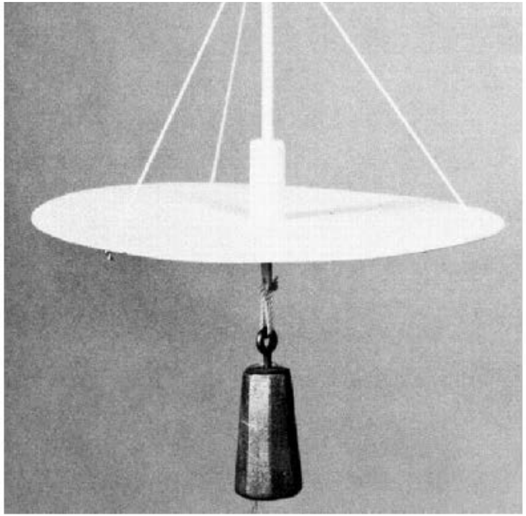
$$b_b(\lambda) = b_{bw}(\lambda) + b_{bp}(\lambda)$$

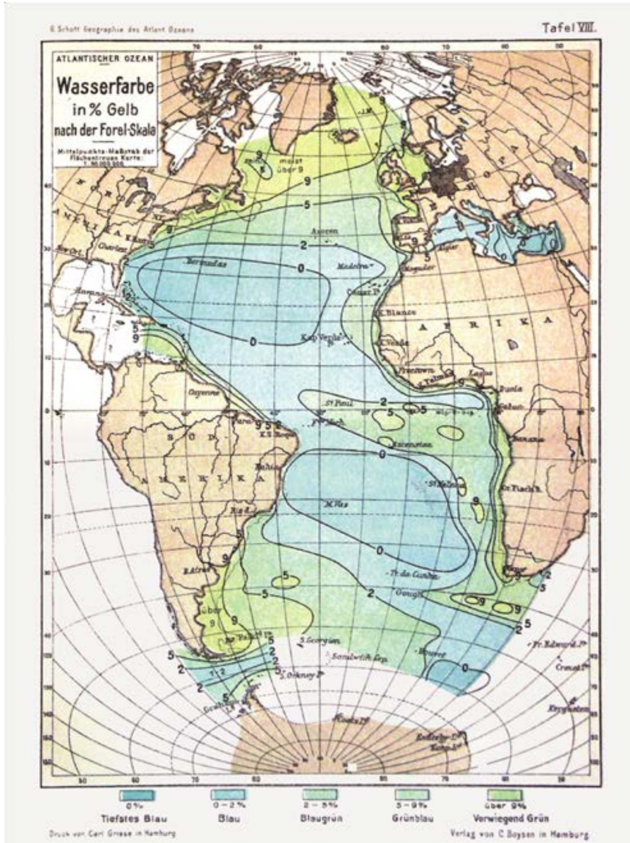
Particles

- Suspended particulate material
- Light attenuation
- Particle size structure
- Phytoplankton Carbon
- Phytoplankton Carbon for different groups
- Particulate Organic Carbon
- Particulate Inorganic Carbon

Traditional measurements of ocean colour

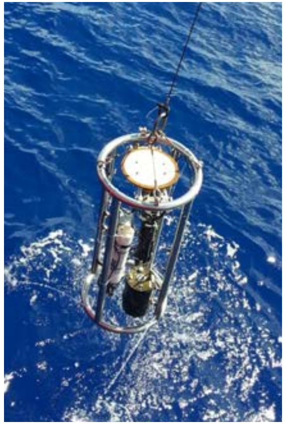
Siegel & Franz (2010) Nature

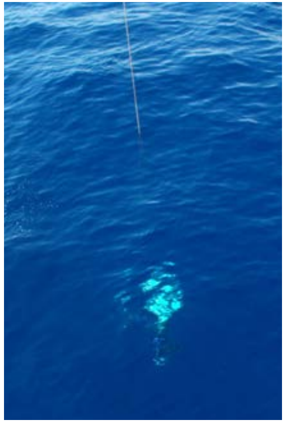




Wernand et al. (2011) PhD Thesis

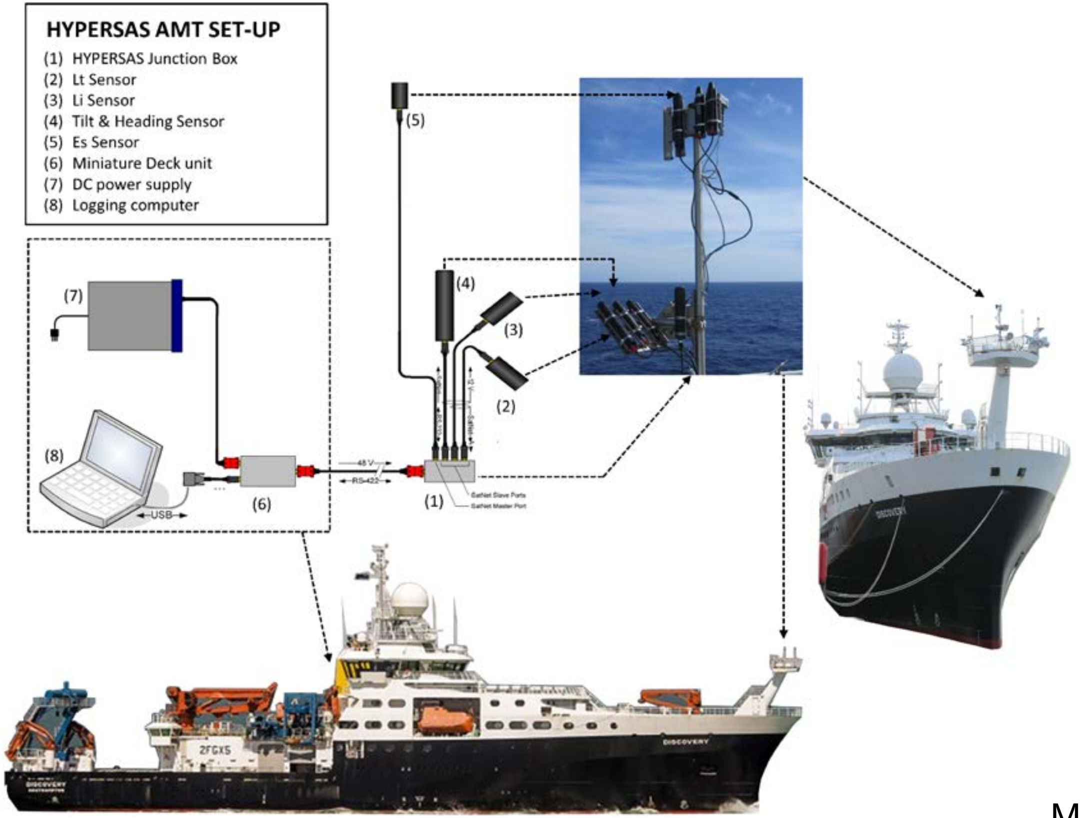
Traditional measurements of ocean colour

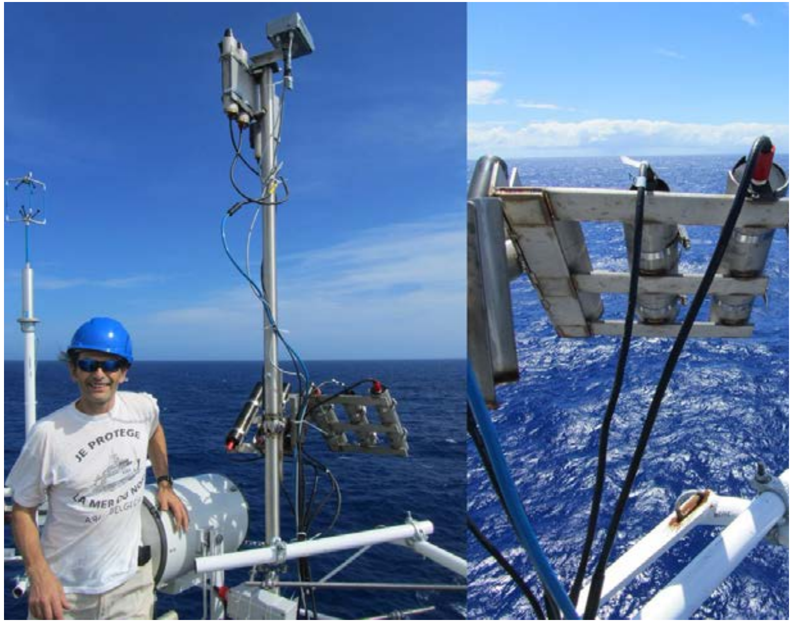




Courtesy of
Marcel Wernand

Modern measurements of ocean colour

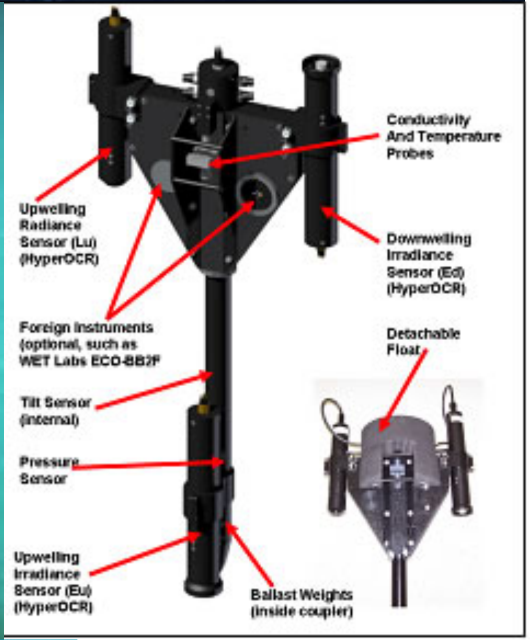


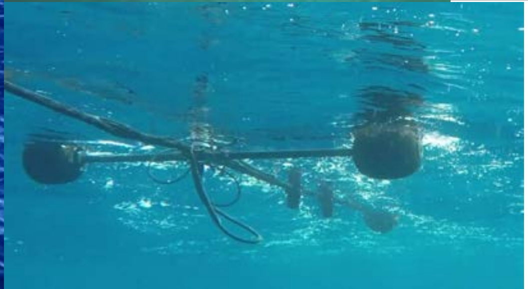


Above-water radiometry

Measurements of apparent optical properties

Modern measurements of ocean colour

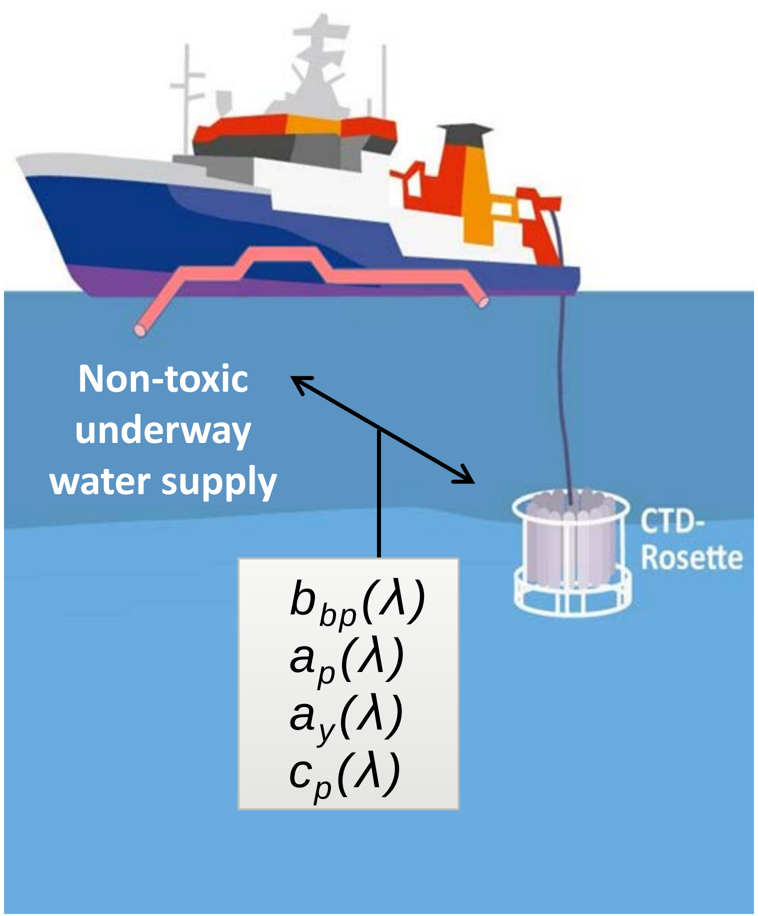


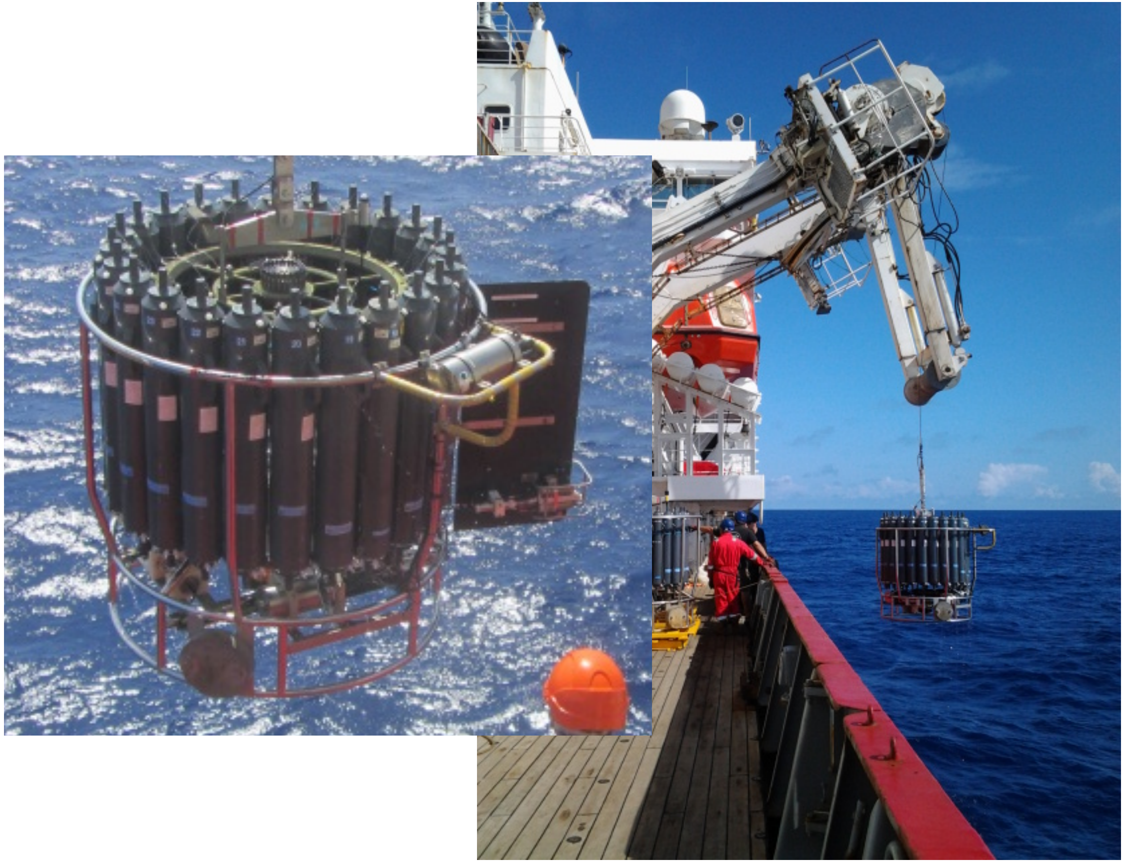


In water radiometry

Measurements of apparent optical properties

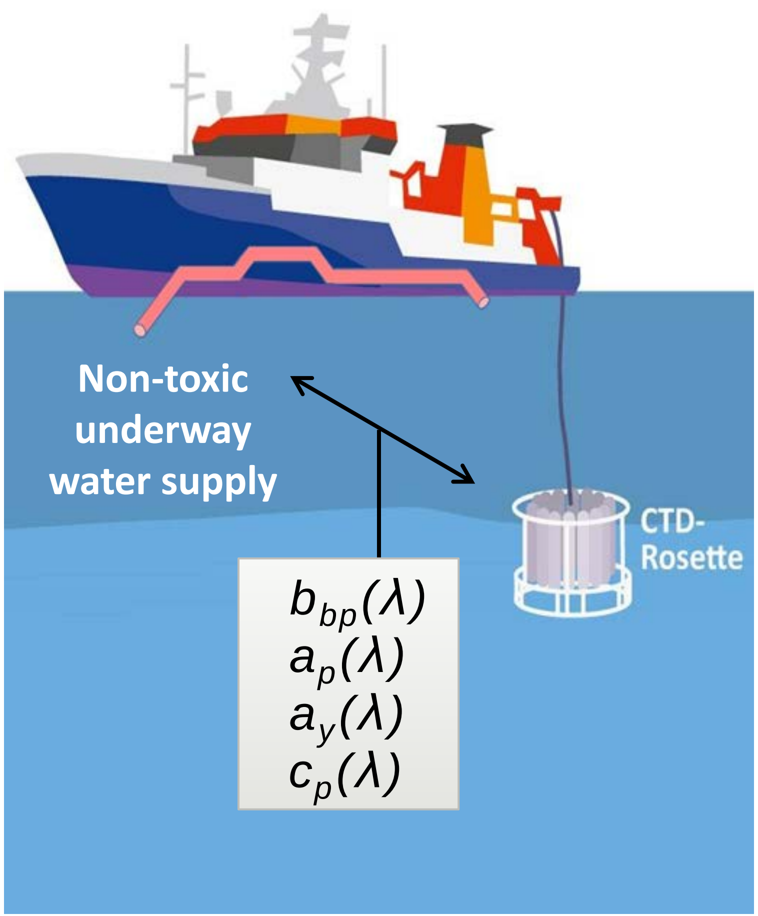
Modern measurements of ocean colour

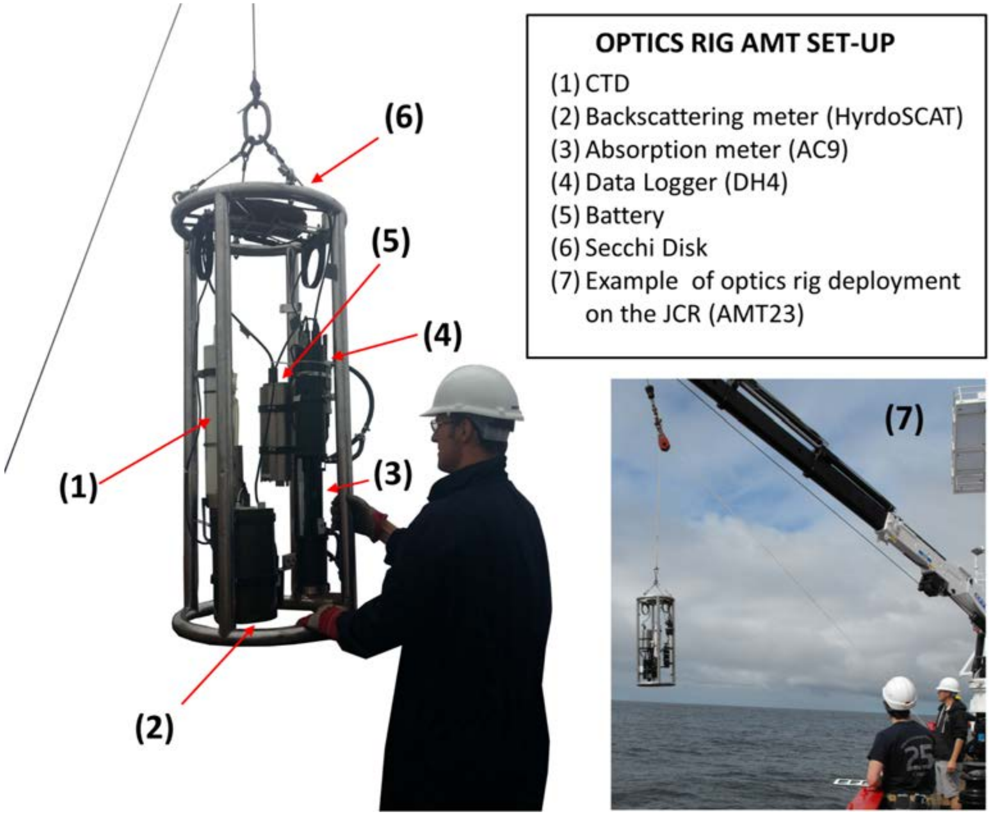




In water measurements of inherent optical properties

Modern measurements of ocean colour





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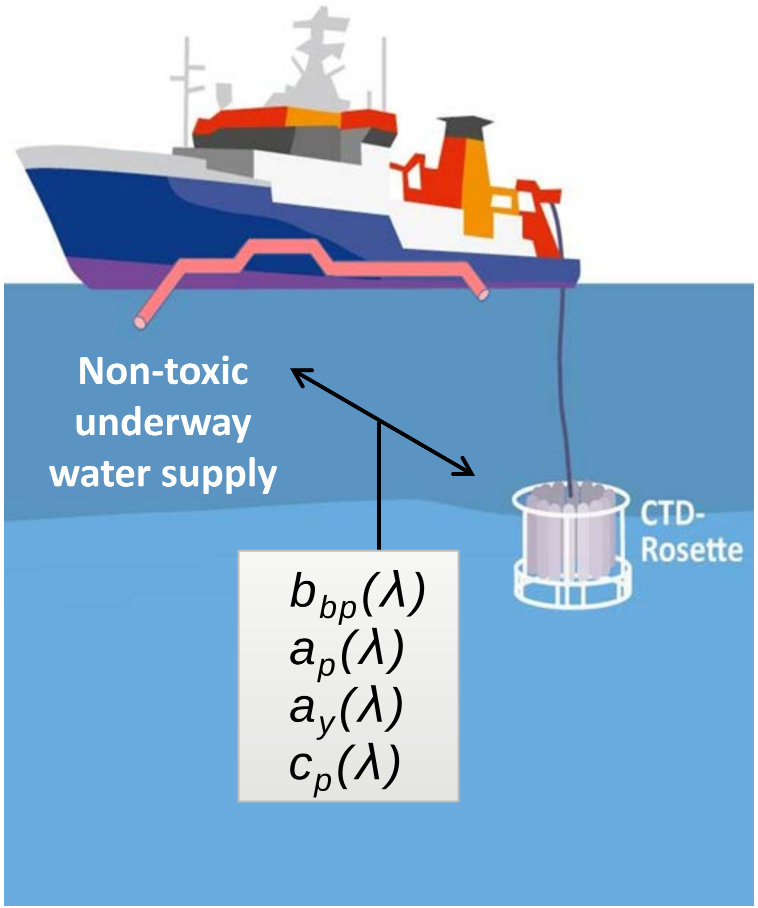
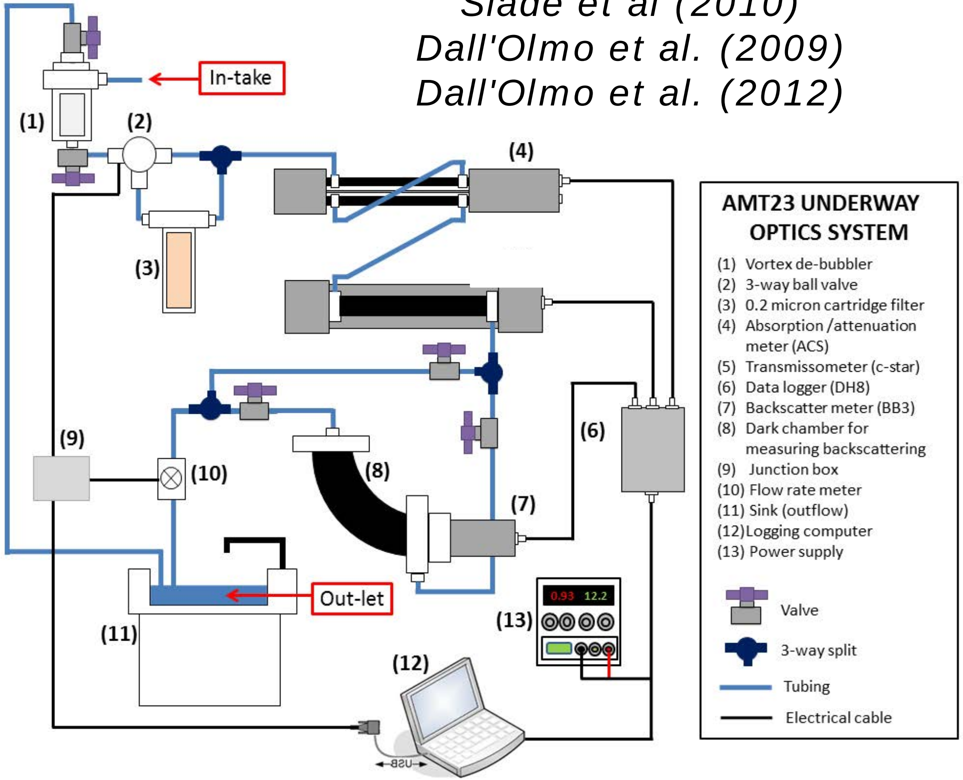
Modern measurements of ocean colour

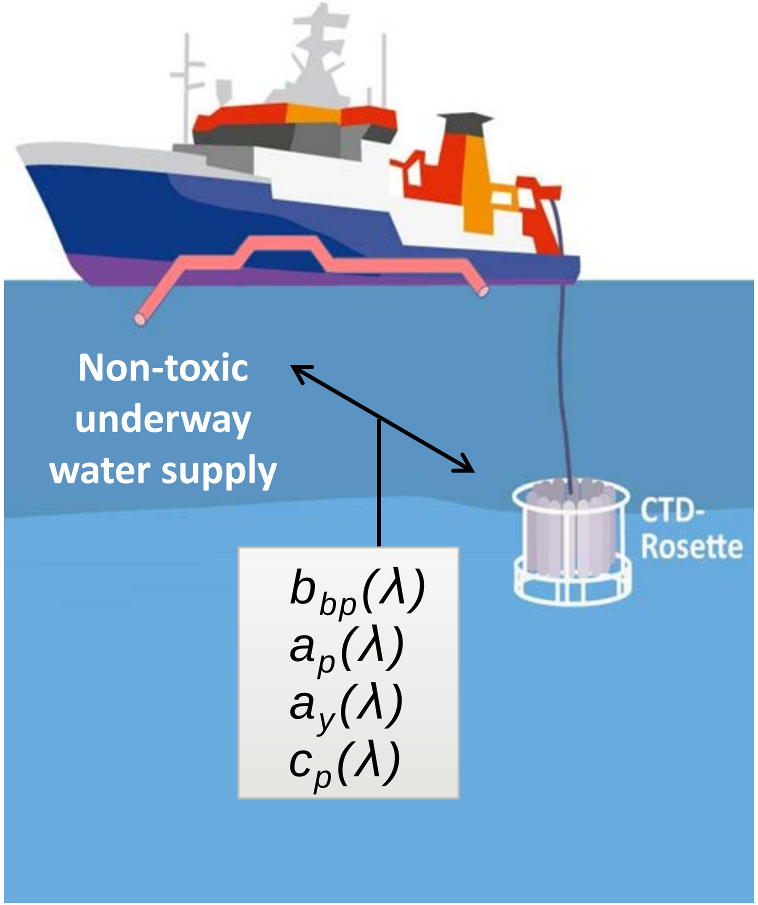


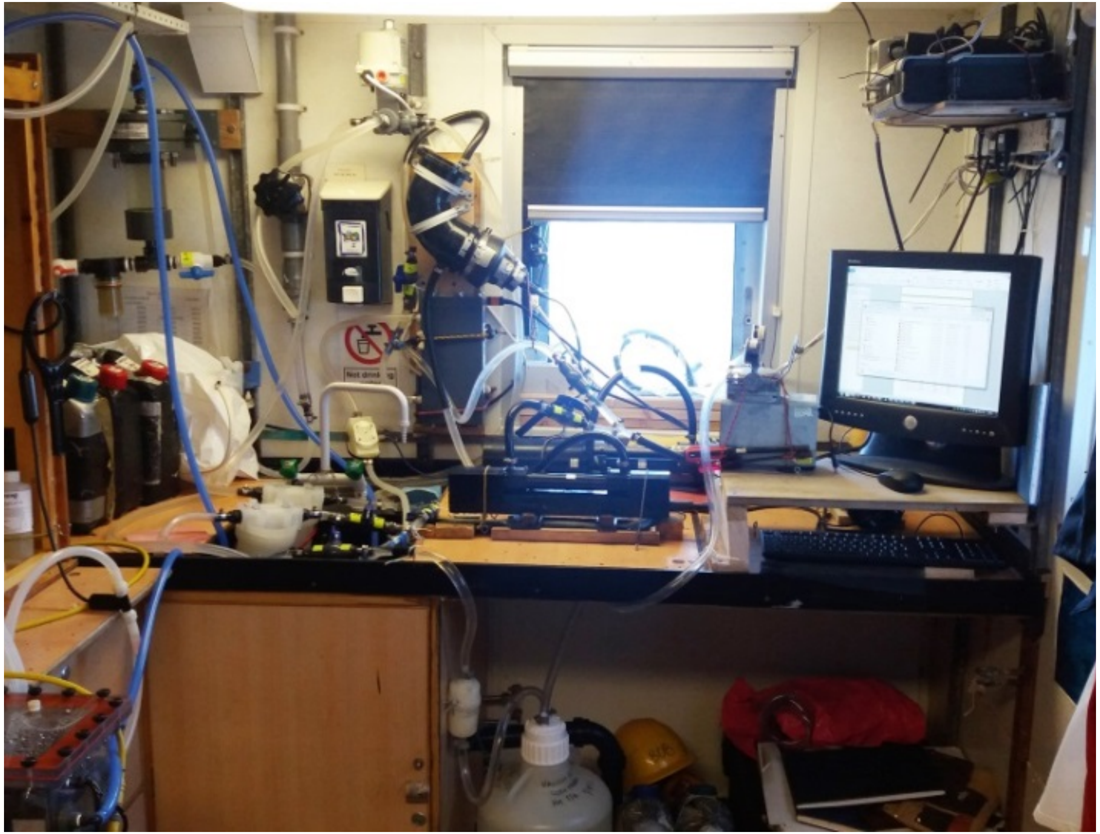
Slade et al (2010)
Dall'Olmo et al. (2009)
Dall'Olmo et al. (2012)



In water measurements of inherent optical properties

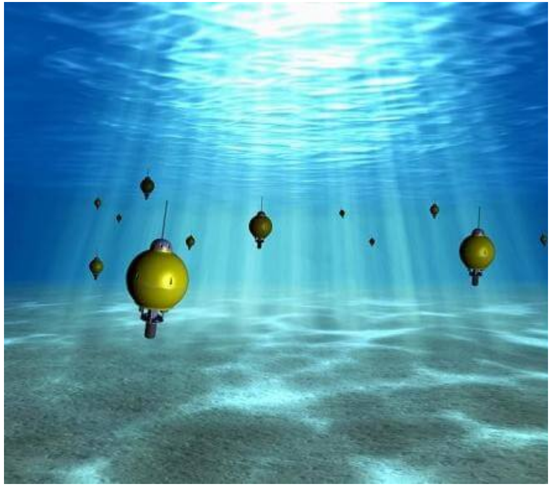
Modern measurements of ocean colour

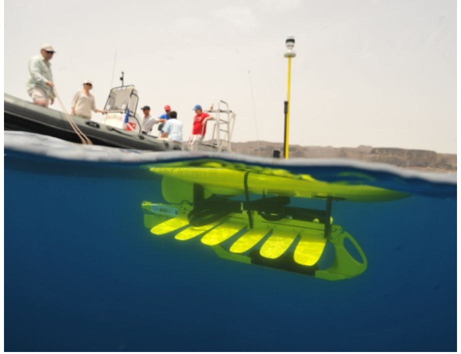




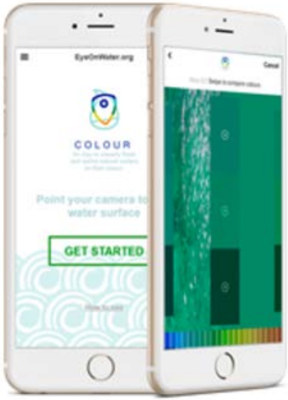
In water measurements of inherent optical properties

The future of ocean colour measurements





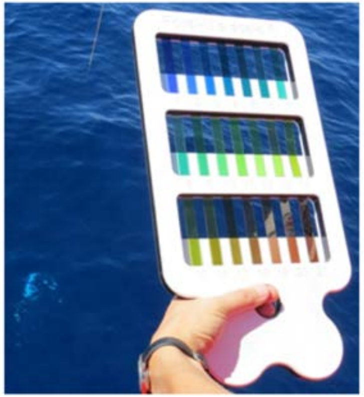
The future of ocean colour measurements



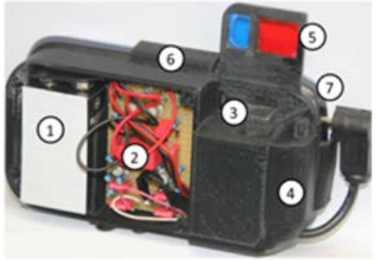
www.eyeonwater.org
Busch et al. (2016a,b)

HydroColor app
Leeuw & Boss (2018)

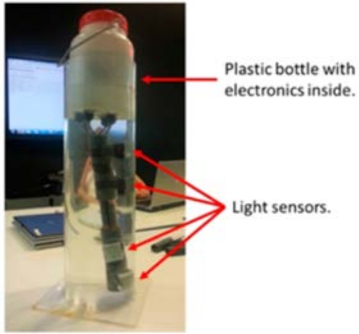
www.secchidisk.org
Seafarers et al. (2017)



Courtesy of Marcel Wernand



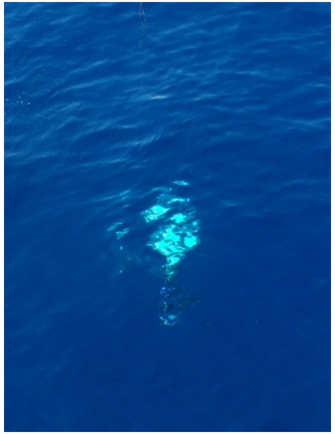
SmartFluo
Friedrichs et al. (2017)

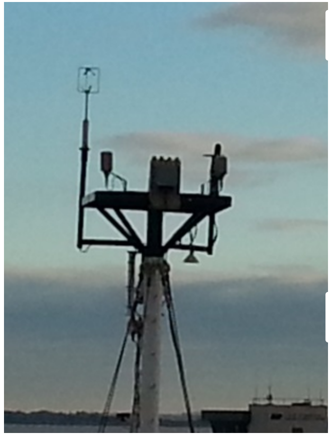


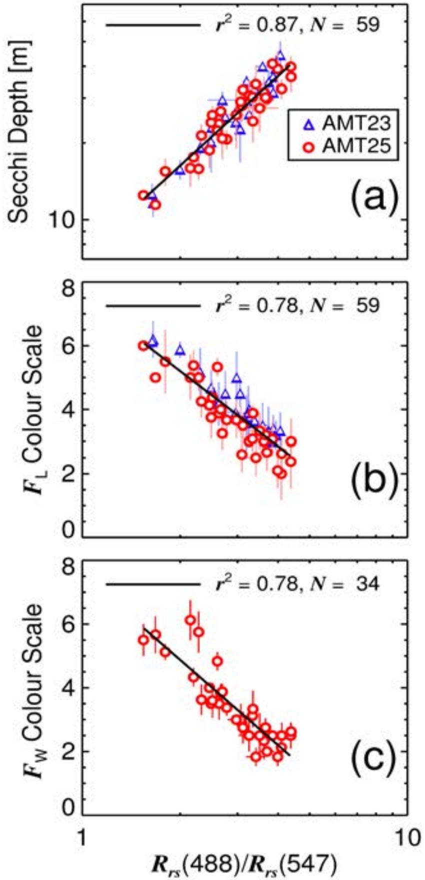
KdUINO DIY Buoy
Bardaji et al. (2016)

Brewin & Brewin (In prep)
NERC REVIVAL

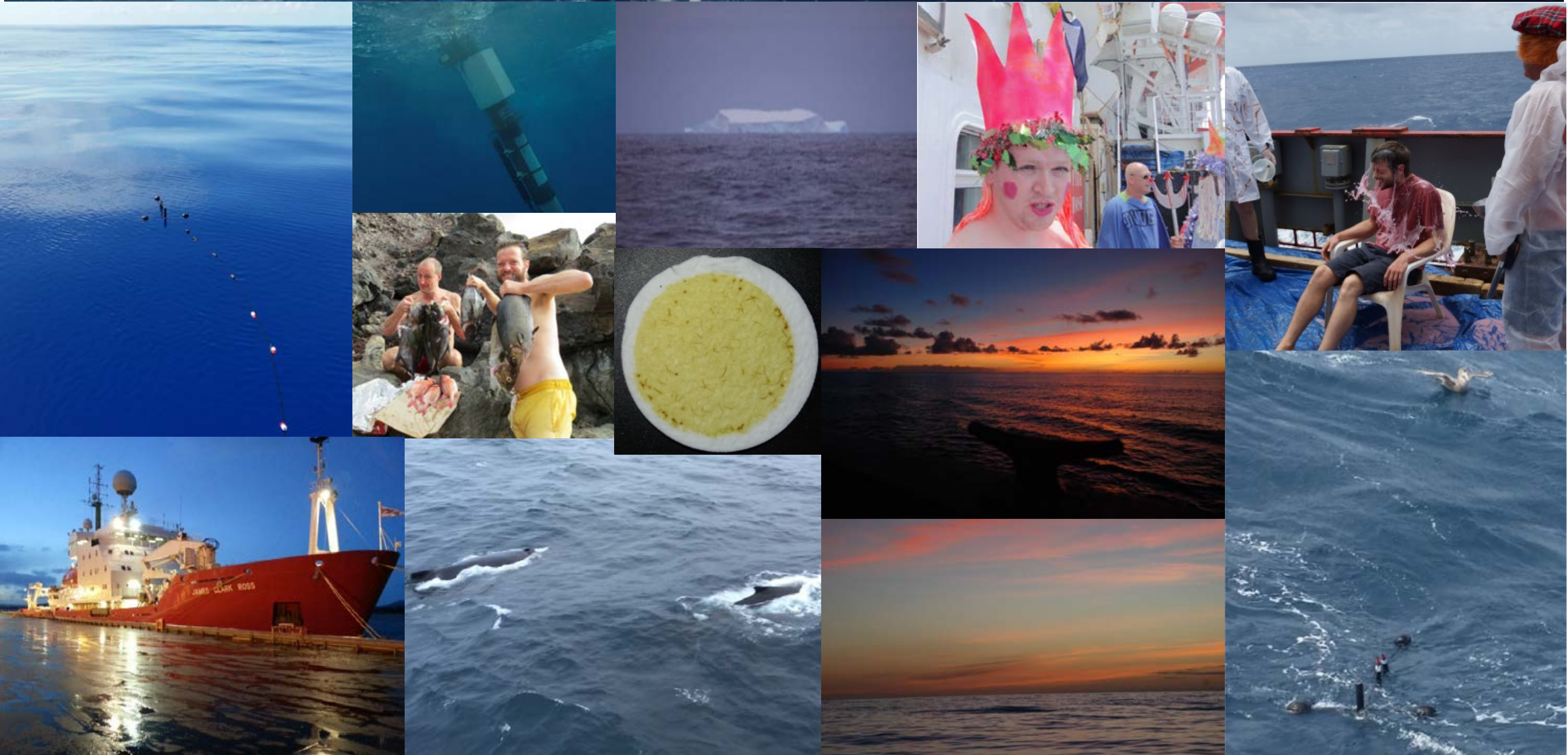
Traditional and modern measurements of ocean colour





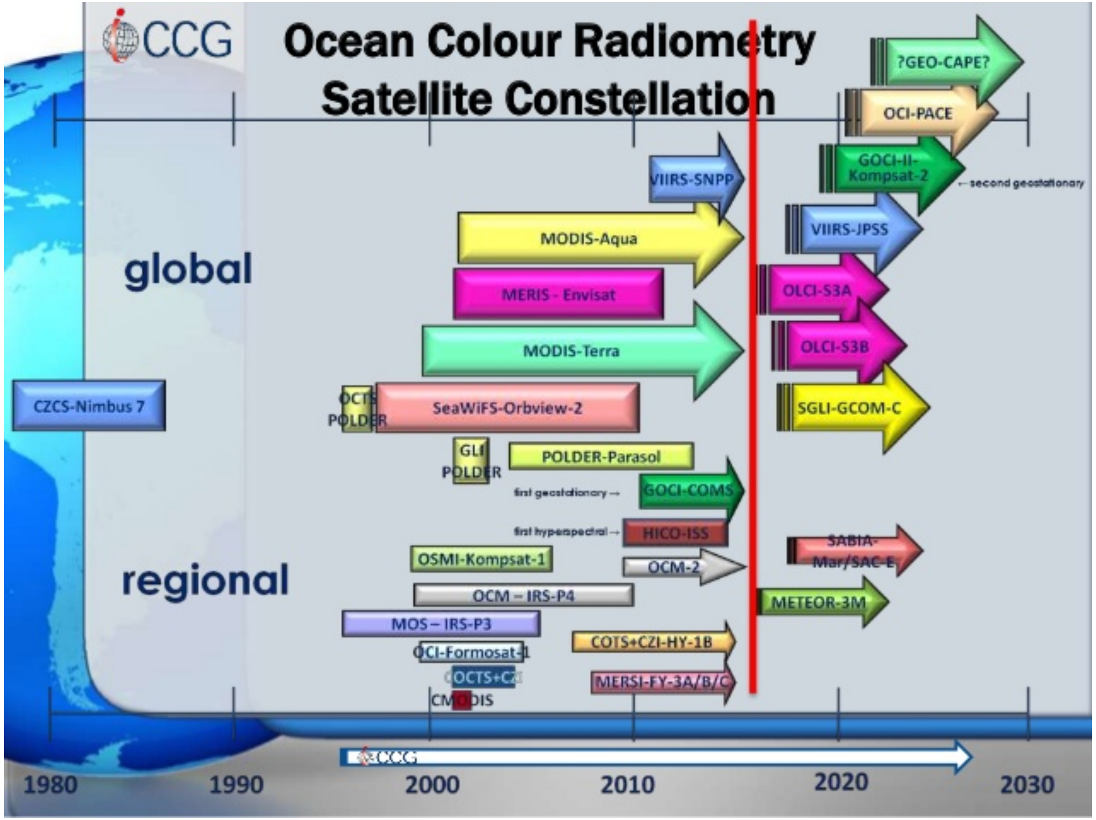


If you get the chance go to sea ☺



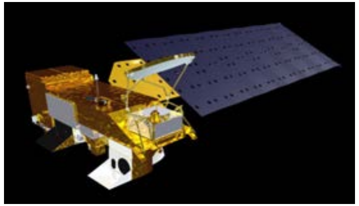
Satellite measurements of ocean colour

Satellite measurements of ocean colour

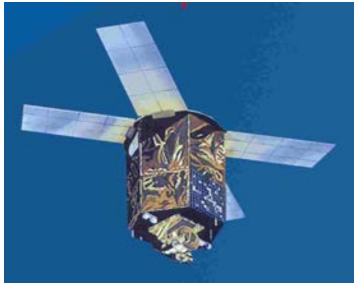


http://chlo4msfd.azti.es/products-and-services-for-satellite-chlorophyll-a-data/

MERIS
2002-
2012

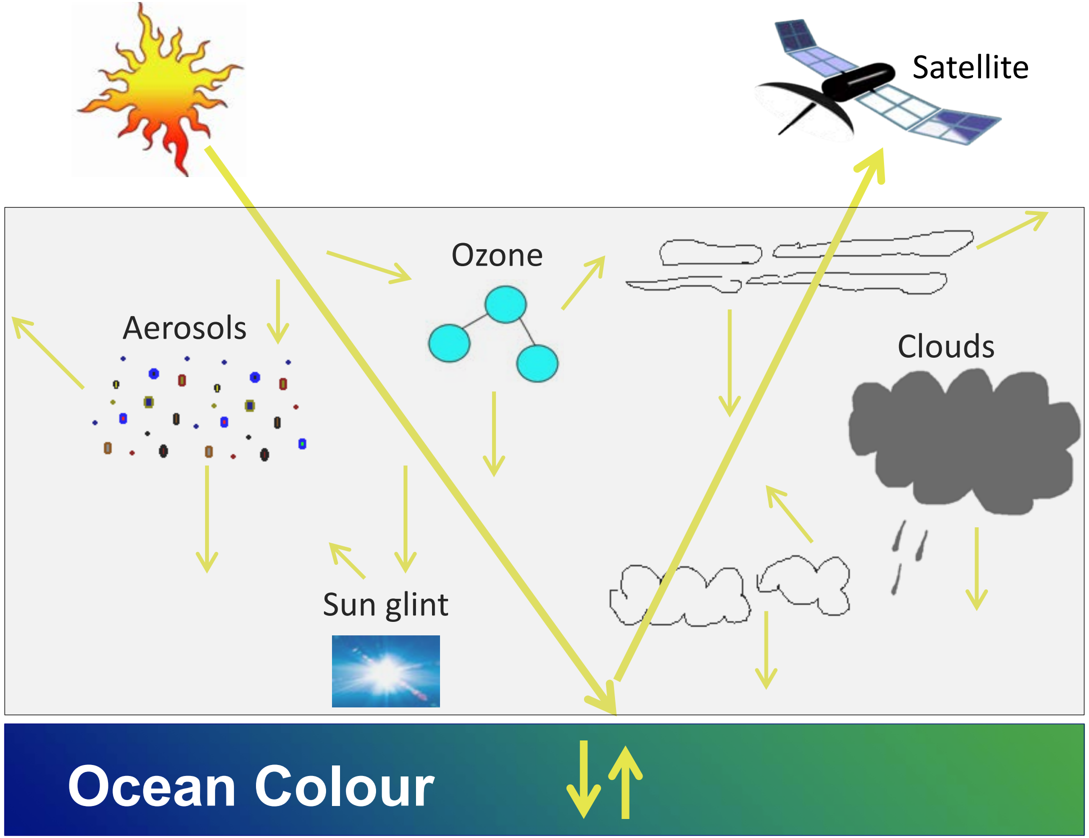


MODIS
2002-
present



SeaWiFS
1997-
2010

Satellite measurements of ocean colour

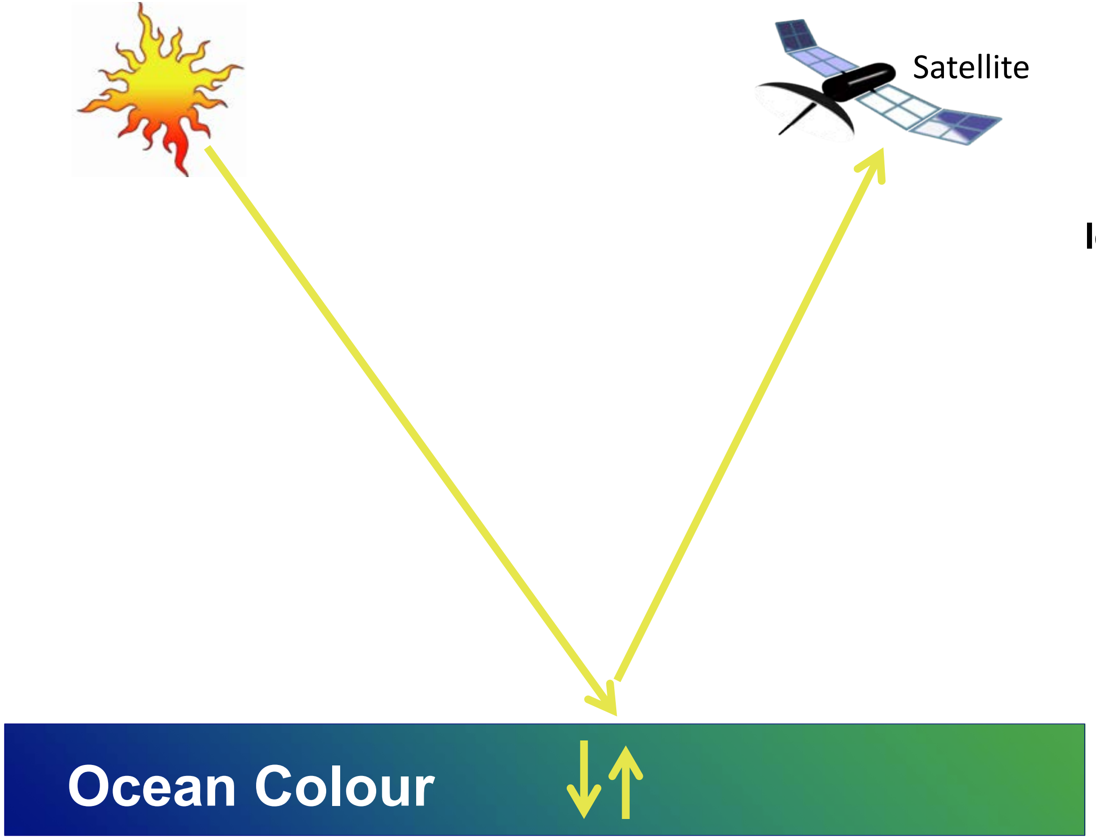


Atmosphere responsible for >80% of the satellite signal, the ocean only <20%

Atmosphere

Ocean

Satellite measurements of ocean colour



Remove atmosphere to capture the <20% ocean signal (water leaving radiance)

Ocean

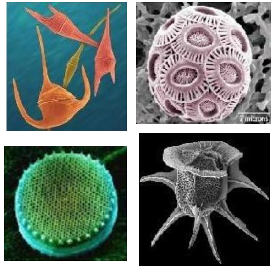
Satellite measurements of ocean colour

Satellite

Convert ocean colour to derive bio-optical variables (e.g. biomass of phytoplankton)

$$R_{rs}(\lambda) \propto \frac{b_b(\lambda)}{a(\lambda)}$$

$a(\lambda)$ = Absorption coefficient
$b_b(\lambda)$ = Backscattering coefficient

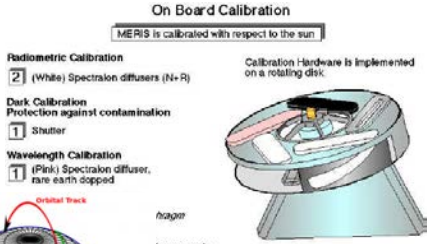


Ocean Colour

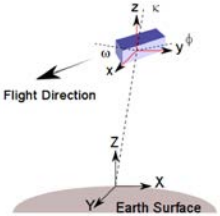
Ocean

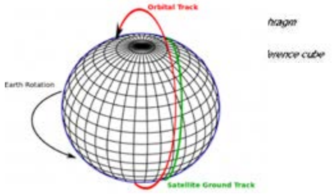
Basic steps in satellite ocean colour data processing

1) Radiometric and spectral calibration

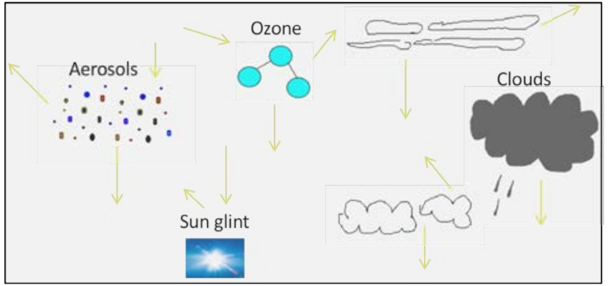


2) Geometric correction

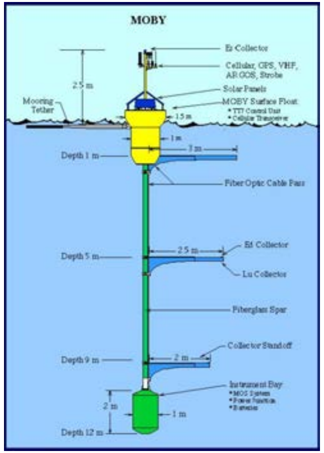




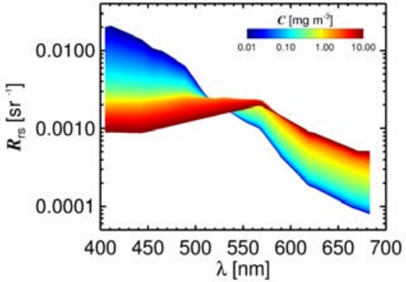
3) Atmospheric Correction



4) Vicarious calibration

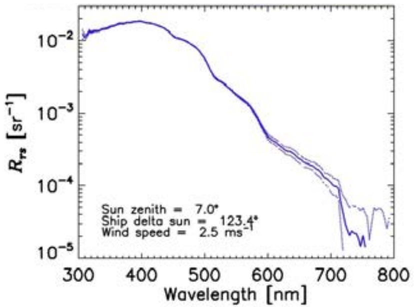


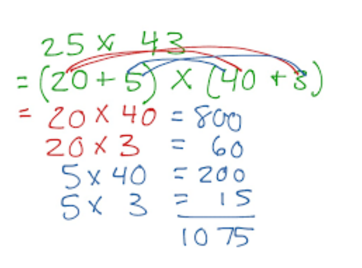
5) In-water algorithm application



In-water ocean-colour algorithms

Algebraic

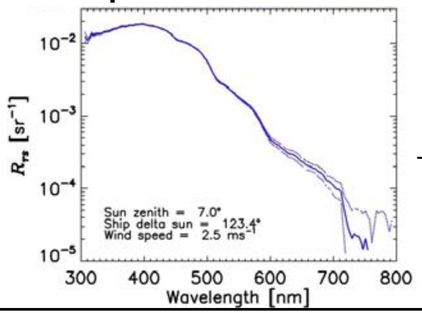




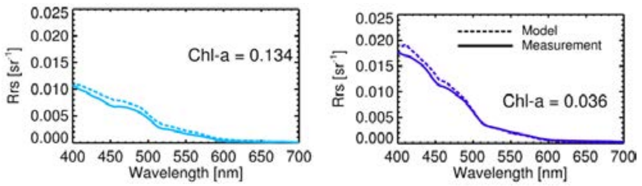
$$b_{bp}(\lambda)\ \ a_B(\lambda)\, a_{dg}(\lambda)$$

Lee et al. (2002) Applied optics
Smyth et al. (2006) Applied optics

Optimization



$$R_{rs}(\lambda) = \left\{ \sum_{i=1}^{2} g_i \left[\frac{b_{bw} + b_{bp}(\lambda_0)\left(\frac{\lambda}{\lambda_0}\right)^{-\gamma}}{b_{bw} + b_{bp}(\lambda_0)\left(\frac{\lambda}{\lambda_0}\right)^{-\gamma} + a_w(\lambda) + C a^*_{ph}(\lambda) + a_{dg}(\lambda_0)\exp\left[-S_{dg}(\lambda - \lambda_0)\right]} \right]^i \right\} 0.5238,$$



$$b_{bp}(\lambda)\ \ a_B(\lambda)\, a_{dg}(\lambda)$$

Lee et al. (1998,1999) Applied optics
Maritorena et al. (2002) Applied optics
Werdell et al. (2011) Applied Optics

In-water ocean-colour algorithms

IOCCG Report Number 3, 2000

Remote Sensing of Ocean Colour in Coastal, and Other Optically-Complex, Waters

Edited by:
Shubha Sathyendranath (Bedford Institute of Oceanography, Canada)

Generalized ocean color inversion model for retrieving marine inherent optical properties

P. Jeremy Werdell,[1,2,*] Bryan A. Franz,[1] Sean W. Bailey,[1,3] Gene C. Feldman,[1]
Emmanuel Boss,[2] Vittorio E. Brando,[4] Mark Dowell,[5] Takafumi Hirata,[6]
Samantha J. Lavender,[7] ZhongPing Lee,[8] Hubert Loisel,[9]
Stéphane Maritorena,[10] Fréderic Mélin,[5] Timothy S. Moore,[11]
Timothy J. Smyth,[12] David Antoine,[13] Emmanuel Devred,[14]
Odile Hembise Fanton d'Andon,[15] and Antoine Mangin[15]

1559-128X/13/102019-19$15.00/0

1 April 2013 / Vol. 52, No. 10 / APPLIED OPTICS 2019

IOCCG Report Number 5, 2006

Remote Sensing of Inherent Optical Properties: Fundamentals, Tests of Algorithms, and Applications

Editor:
ZhongPing Lee (Naval Research Laboratory, Stennis Space Center, USA)

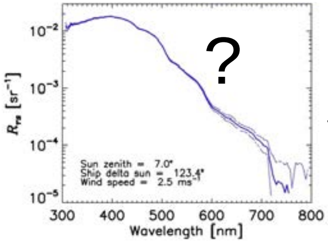
Contents lists available at ScienceDirect
Remote Sensing of Environment
journal homepage: www.elsevier.com/locate/rse

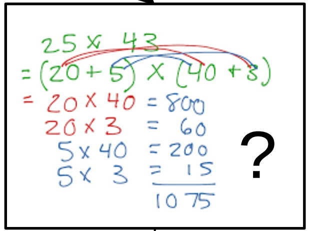
The Ocean Colour Climate Change Initiative: III. A round-robin comparison on in-water bio-optical algorithms

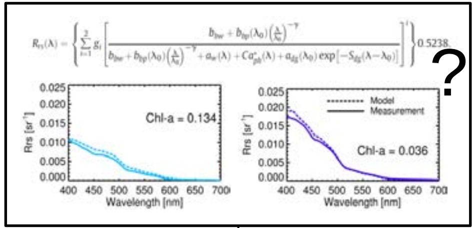
Robert J.W. Brewin [a,b,*], Shubha Sathyendranath [a,b], Dagmar Müller [c], Carsten Brockmann [d], Pierre-Yves Deschamps [e], Emmanuel Devred [f], Roland Doerffer [c], Norman Fomferra [d], Bryan Franz [g], Mike Grant [a], Steve Groom [a], Andrew Horseman [a], Chuanmin Hu [h], Hajo Krasemann [c], ZhongPing Lee [i], Stéphane Maritorena [j], Frédéric Mélin [k], Marco Peters [d], Trevor Platt [a], Peter Regner [l], Tim Smyth [a], Francois Steinmetz [e], John Swinton [m], Jeremy Werdell [g], George N. White III [n]

Uncertainties in satellite ocean colour products

Model-based error (error propagation)





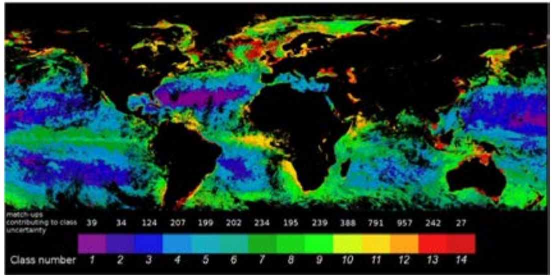


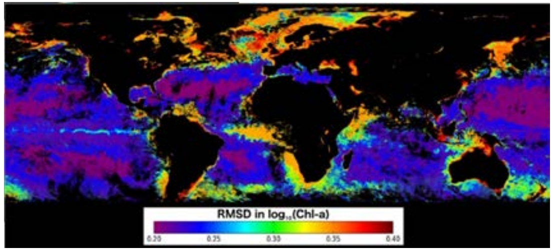
?

$$b_{bp}(\lambda)\ a_B(\lambda)\ a_{dg}(\lambda)$$

GlobColour

Errors based on validation





?

$$b_{bp}(\lambda)\ a_B(\lambda)\ a_{dg}(\lambda)$$

Ocean-Colour Climate Change Initiative

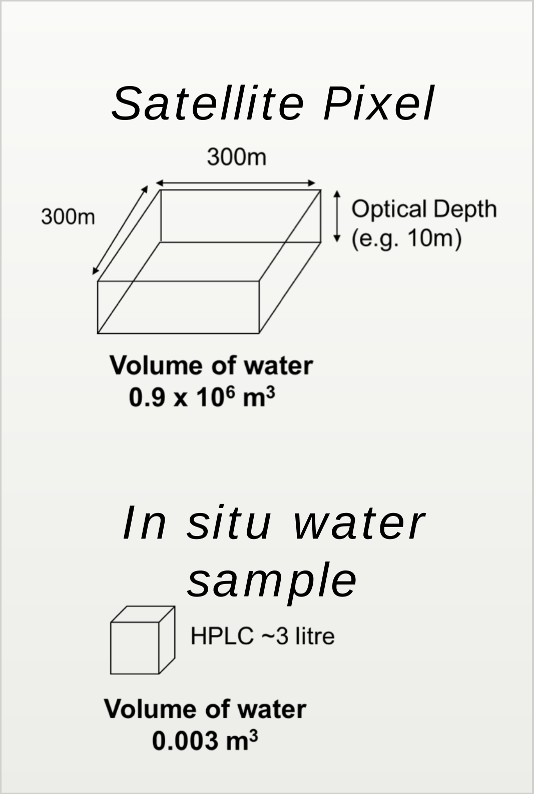
Satellite validation

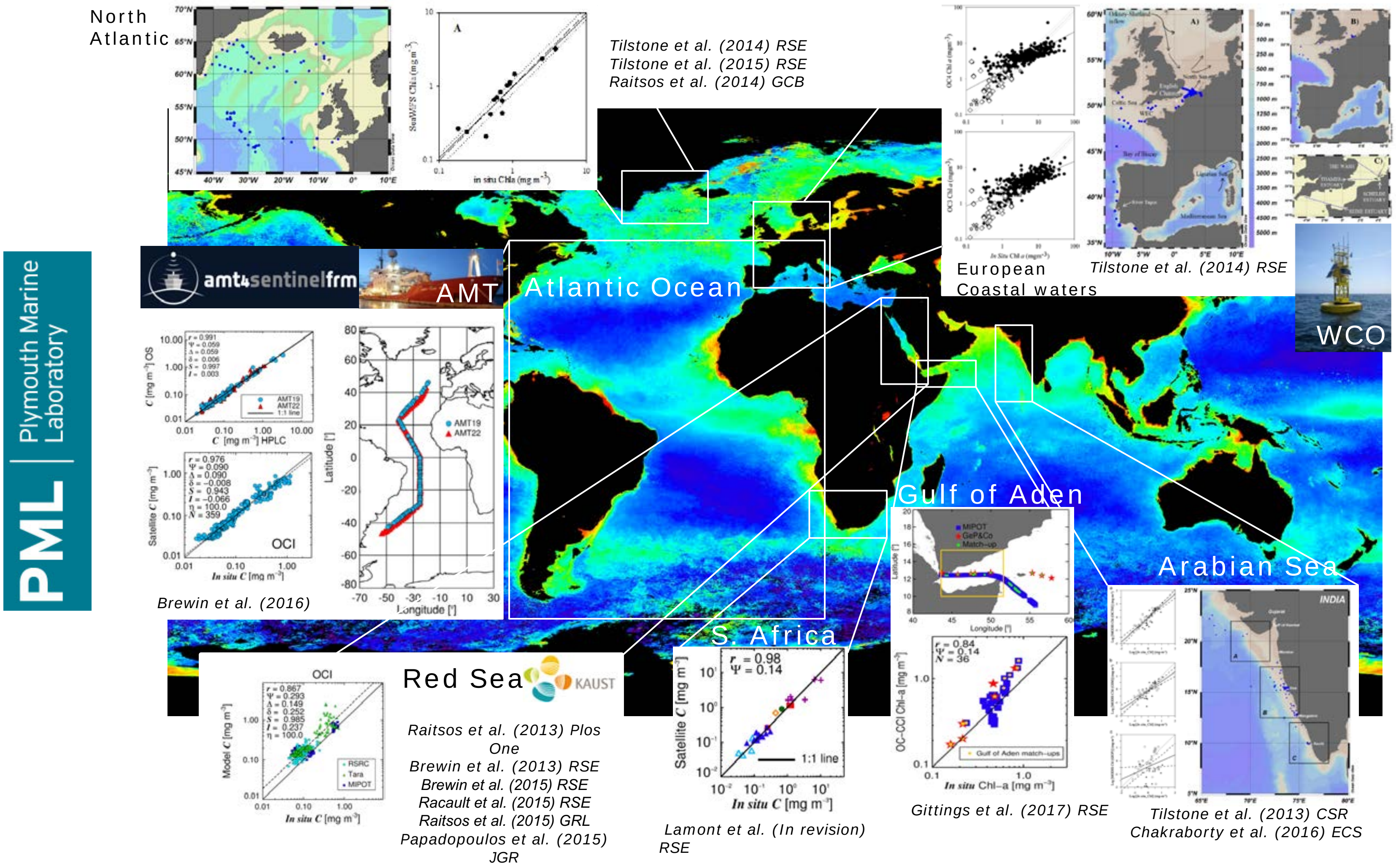
Oceanographic samples are typically poorly matched in scale compared with satellite-derived measurements.

Nominal resolution for Sentinel-3a is 300 m. Suppose penetration depth is 10 m. One pixel represents 0.9×10^6 m^3

Suppose a three litre sample is taken for pigment analysis. This equates to a volume of 0.003 m^3

Pigment sample volume is only 3×10^{-9} of volume represented by pixel.





North Atlantic
Tilstone et al. (2014) RSE
Tilstone et al. (2015) RSE
Raitsos et al. (2014) GCB
European Coastal waters
Tilstone et al. (2014) RSE
WCO
PML | Plymouth Marine Laboratory
amt4sentinelfrm
AMT
Atlantic Ocean
Brewin et al. (2016)
AMT19
AMT22
OCI
Gulf of Aden
MIPOT
GeP&Co
Match-up
Gittings et al. (2017) RSE
Arabian Sea
INDIA
Tilstone et al. (2013) CSR
Chakraborty et al. (2016) ECS
Red Sea
KAUST
Raitsos et al. (2013) Plos One
Brewin et al. (2013) RSE
Brewin et al. (2015) RSE
Racault et al. (2015) RSE
Raitsos et al. (2015) GRL
Papadopoulos et al. (2015) JGR
S. Africa
1:1 line
Lamont et al. (In revision) RSE

Summary

1) What is ocean colour

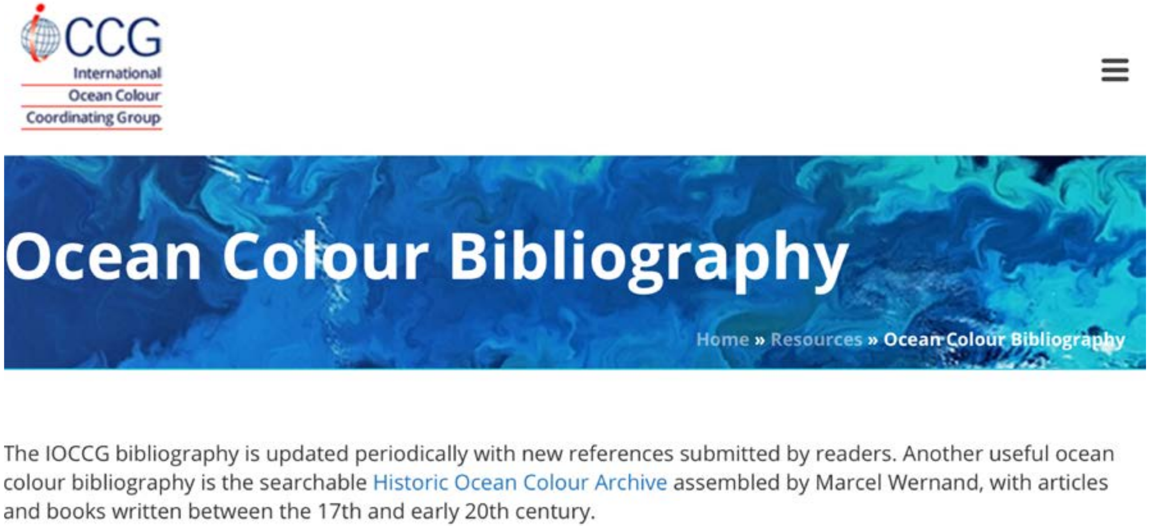
2) History of ocean colour

3) Optical properties of water and its constituents

4) In situ measurements of ocean colour

5) Satellite remote-sensing of ocean colour

Further reading



http://ioccg.org/what-we-do/ioccg-publications/

http://ioccg.org/resources/ocean-colour-bibliography/

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