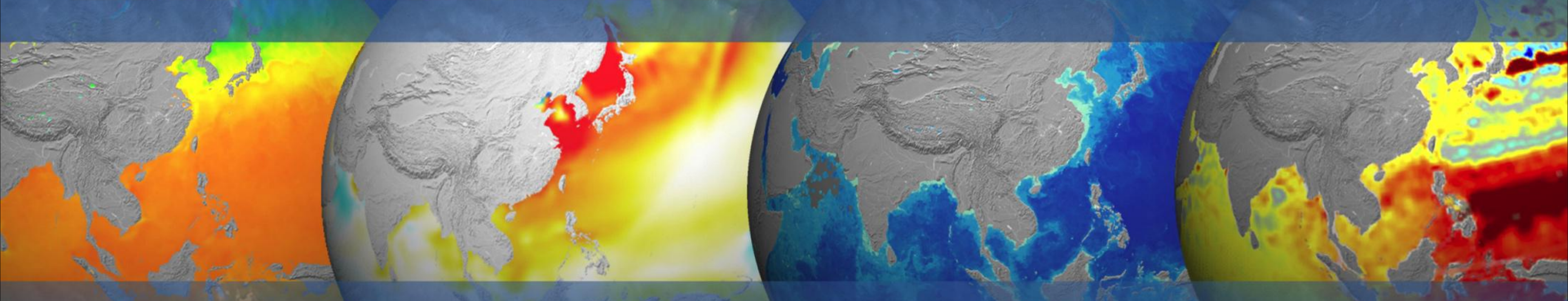
ESA–MOST China Dragon 4 Cooperation

→ ADVANCED TRAINING COURSE IN OCEAN AND COASTAL REMOTE SENSING



12 to 17 November 2018 | Shenzhen University | P.R. China

Ocean-Colour and Intro to S3 OLCI

Thomas Jackson (Plymouth Marine Laboratory)

Hosted by

Lecture Outline and Info

What we will cover:

- What can we learn from Ocean-Colour?
- Why is remote sensing important for this field?
- How do we measure Ocean-Colour from space?
- Ocean-Colour Algorithms.
- Evolution of Ocean-Colour Satellites.
- Sentinel 3 and OLCI.
- Data Access and Processing Chains
- Introduction to SNAP (this will be covered more in the practical session).

Side note… Who am I?

Dr Thomas Jackson

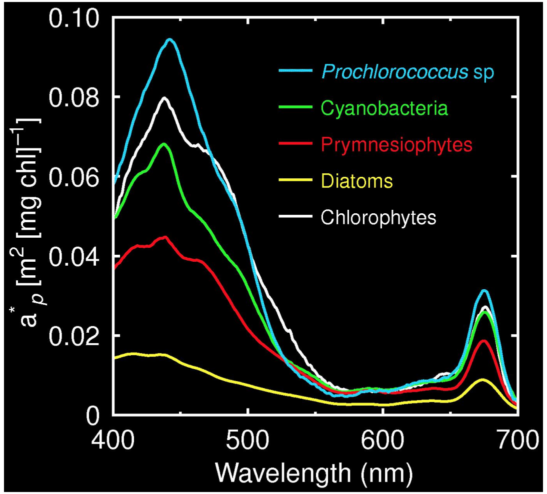
Senior Scientist (Remote Sensing and Ocean Optics)

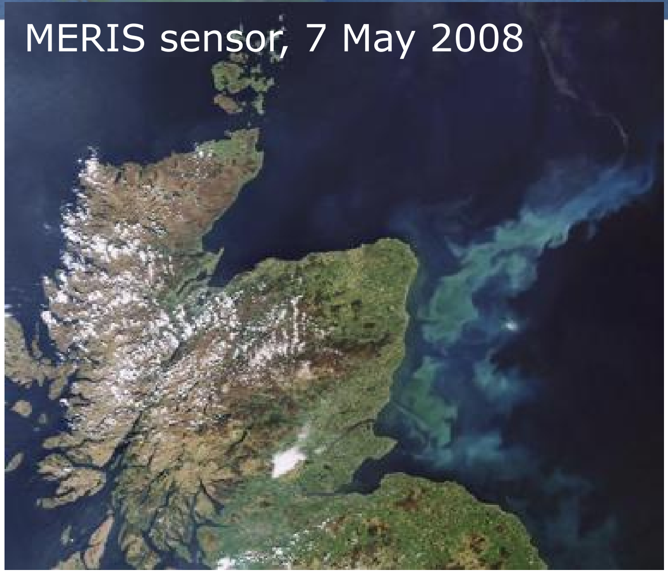
Plymouth Marine Laboratory, UK.

Also thanks to contributions from colleagues at PML, such as Trevor Platt, Shubha Sathyendranath, Bob Brewin and Hayley Evers-King.

What can we learn from Ocean-Colour?

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





Light escaping from the ocean (basis of the ocean-colour signal), carries coded information on ocean biology & biogeochemistry.

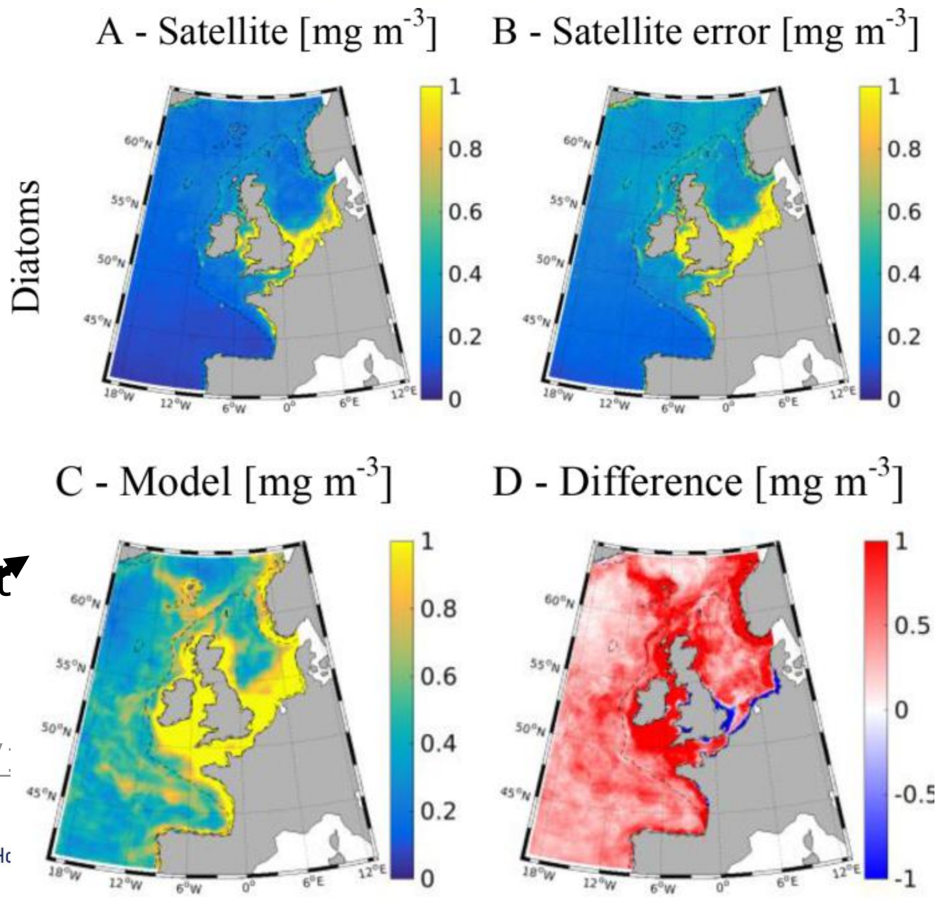
Indicator	Label
Initiation of spring bloom	b_i
Amplitude of spring bloom	b_a
Timing of spring maximum	b_t
Duration of spring bloom	b_d
Total production in spring bloom	b_p
Annual phytoplankton production	P_Y
Initial slope of light-saturation curve	α^B
Assimilation number	P^B_m
Particulate organic carbon	C_T
Phytoplankton carbon	C_p
Carbon-to-chlorophyll ratio	χ
Phytoplankton growth rate	μ
Generalised phytoplankton loss rate	L
Integrated phytoplankton loss	L_T
Spatial variance in biomass field	σ_B^2
Spatial variance in production field	σ_P^2
Phytoplankton functional types	NA
Delineation of biogeochemical provinces	NA

Platt & Sathyendranath (2008)

What can we learn from Ocean-Colour?

The light that escapes from the ocean carries coded information on ocean biology and biogeochemistry. Examples of derived products:
-Phenology of phytoplankton blooms
-Phytoplankton biomass
-Primary production
-Biogeochemical province mapping
-Phytoplankton Functional Types

Remote-sensing data can also be assimilat into earth system models.



https://agupubs.onlinelibrary.wiley.com/doi/full/1 002/2017JC013490 (Ciavatta et al 2017)

What can we learn from Ocean-Colour?

Phytoplankton undertake roughly half of the photosynthesis on the planet, meaning that they produce as much oxygen as the terrestrial biosphere.

Due to the importance of phytoplankton in the Global Carbon Cycle and their fundamental role in the marine food web, the Global Climate Observing System (GCOS) designated Ocean Colour as one of the 50 Essential Climate Variables (ECVs) that should be monitored in order to support the work of the IPCC and UNFCCC.

Phytoplankton can bloom rapidly if conditions are favourable, form blooms covering thousands of km^2, and can be moved by ocean currents and tides.

This means that we have to monitor enormous areas at relatively short time scales.

Why is remote sensing key for this field?

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 or OCR-Virtual Constellation); fisheries (ecosystem indicators); marine biodiversity.

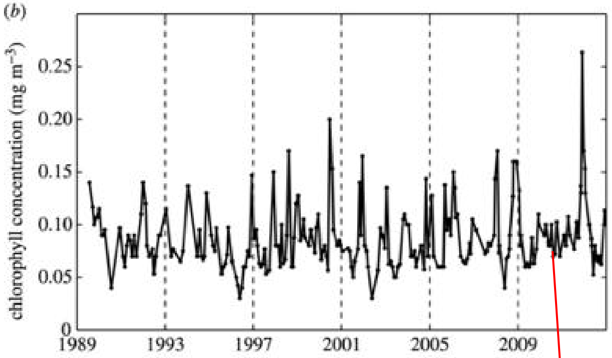
See IOGGC report http://www.ioccg.org/reports/report7.pdf Platt et al (2008) 'Why Ocean Colour? The Societal Benefits of Ocean- Colour Technology'

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

Ocean colour is not a universal panacea, but it is extremely versatile & cost-effective.

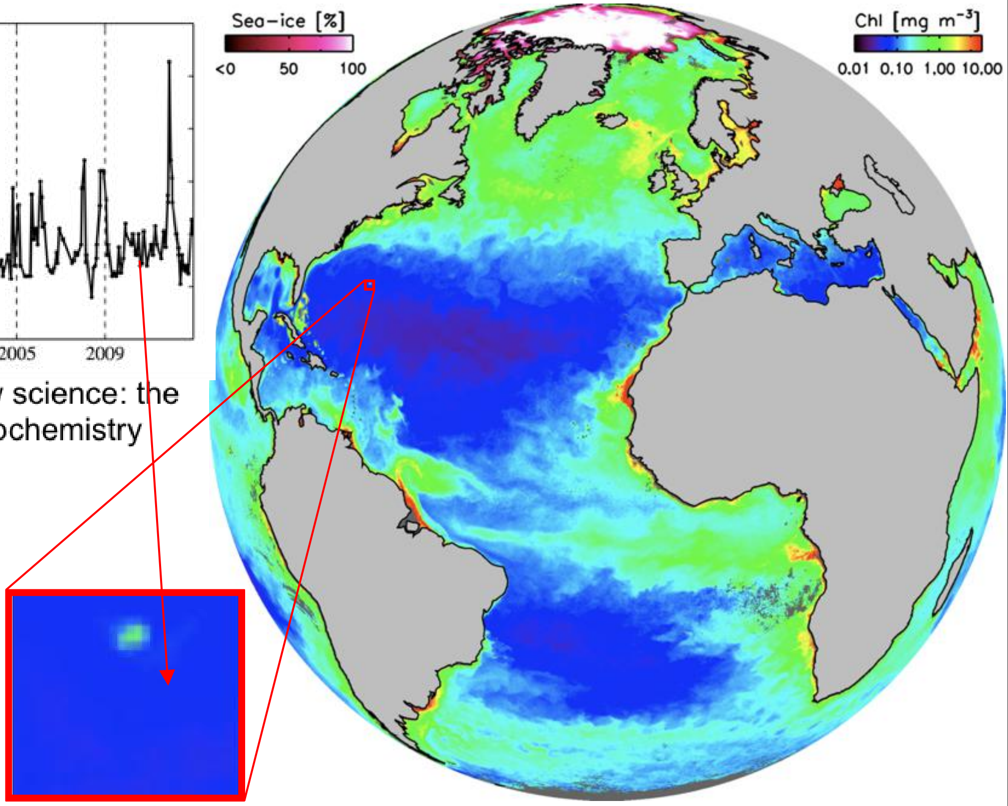
Why is remote sensing key for this field?

In-situ data from long observation stations such as the Hawaii Ocean Time-series (HOT) and Bermuda Atlantic Time-series Study (BATS) have elucidated the annual cycle and inter-annual variability of phytoplankton chlorophyll in remote ocean-gyre regions (Henson *et al*. 2014).



Henson SA. *et al*. 2014 Slow science: the value of long ocean biogeochemistry records.

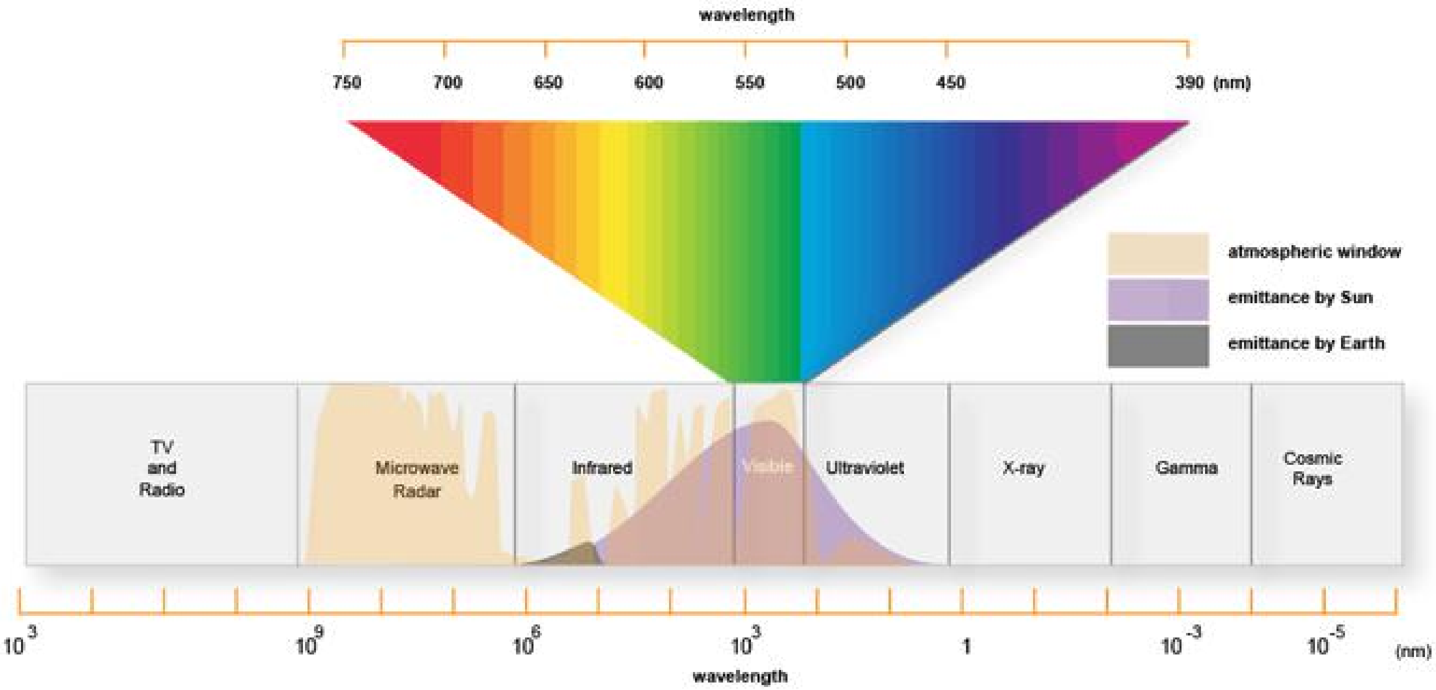
But we cannot continuously take in-situ measurements for the entire ocean…



How to measure Ocean Colour from space?

Ocean Colour remote sensing is Passive, meaning that the sensor detect light from the natural environment.

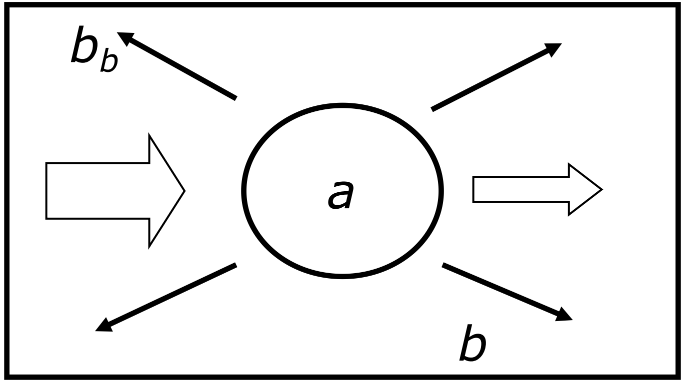
Data coverage depends on environmental conditions (e.g high-latitude winter or clouds excludes data).

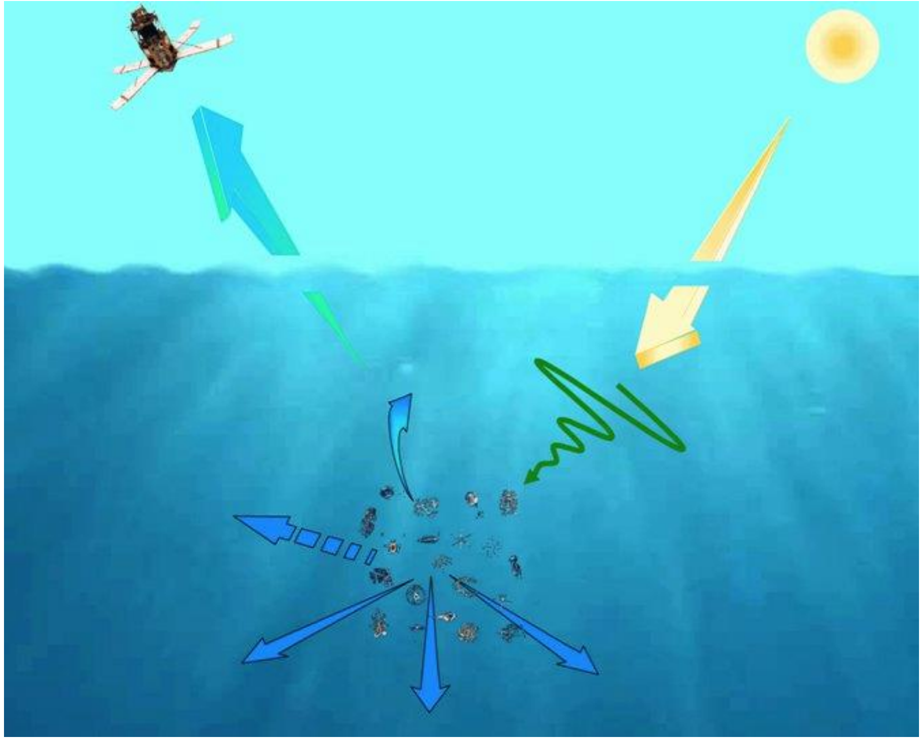


How to measure Ocean Colour from space?

When photons interact with the ocean their fate is dictated by 2 optical processes: scattering (*b*) and absorption (*a*).

Scattering can also occur in forward or backward directions. Backscattering is referred to as b_b.



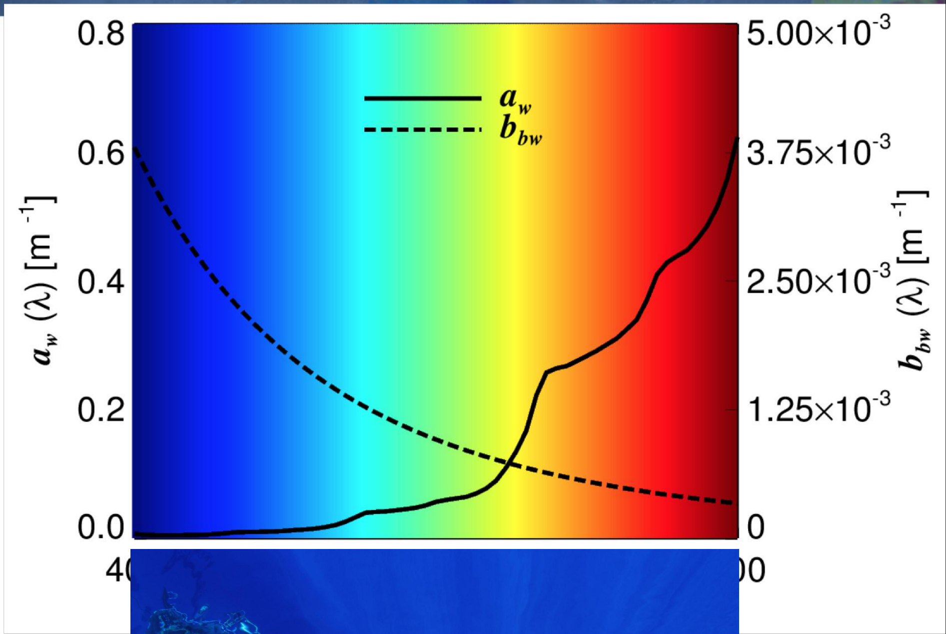


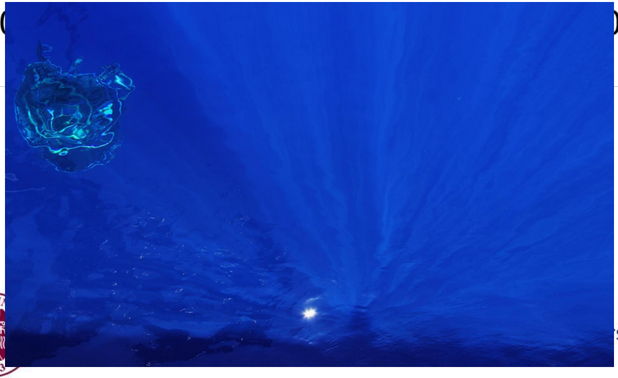
How to measure Ocean Colour from space?

Scattering (*b*) and absorption (*a*) are both spectrally varying properties.

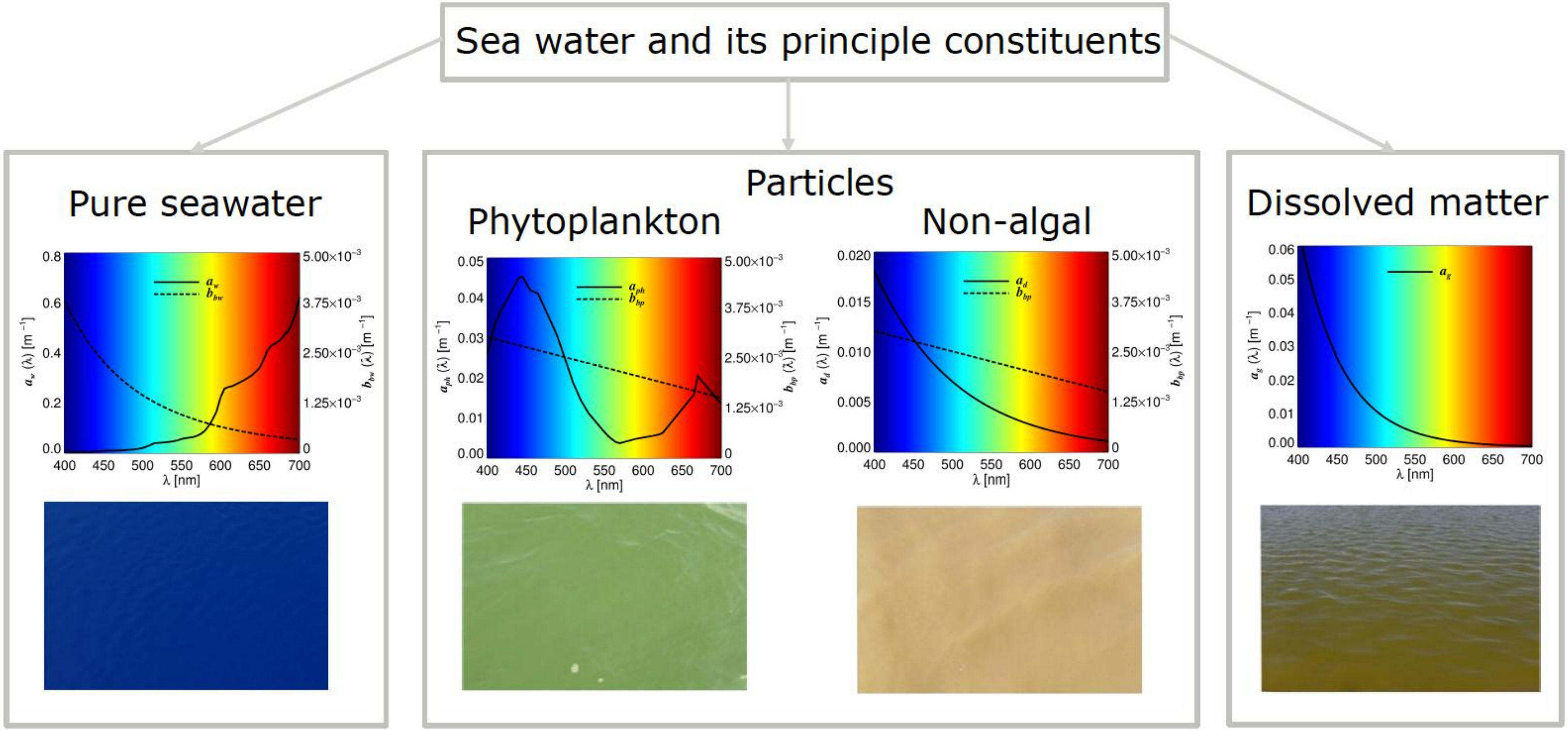
Different substances scatter or absorb light differently, this is also usually noted in the subscript.

For example, a_w and b_{bw} are absorption by water and backscattering by water.





How to measure Ocean Colour from space?



(Brewin 2018)

How to measure Ocean Colour from space?

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

The processes of scattering and absorption can also happen in the atmosphere, both before and after the light has interacted with the surface ocean.

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

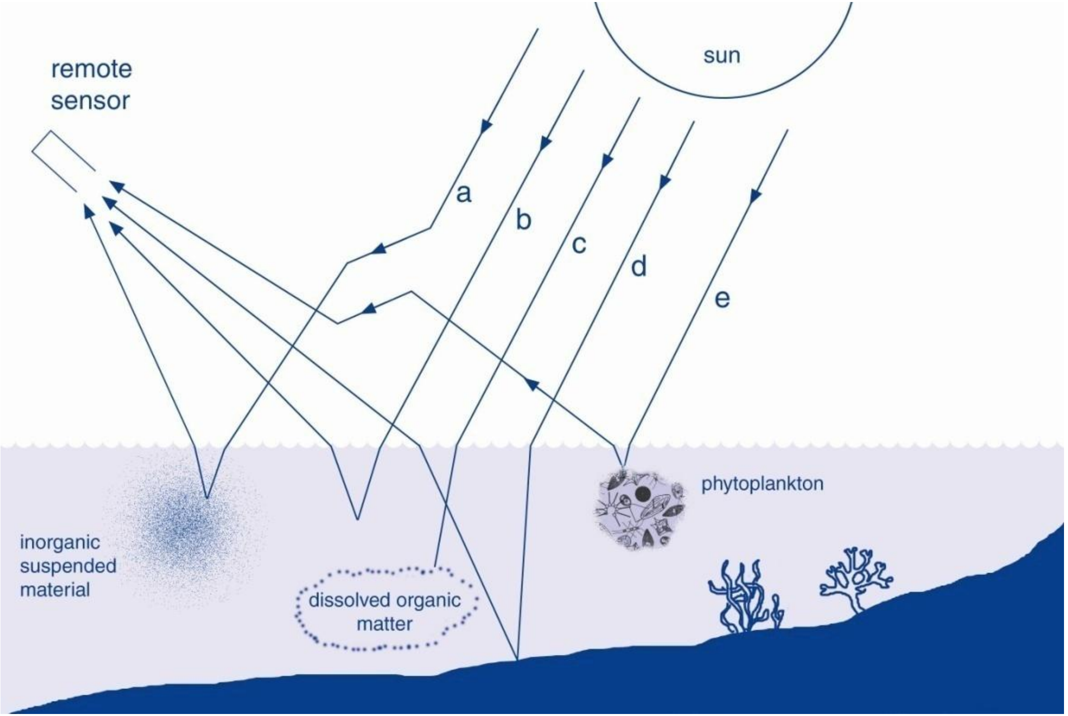


Figure from IOCCG report 3

How to measure Ocean Colour from space?

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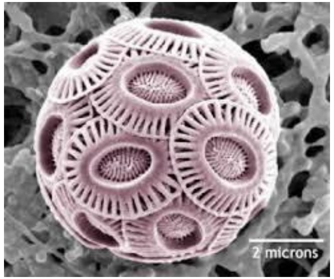


How to measure Ocean Colour from space?

Prior to in-water product generation, satellite remote sensing data must pass through a number of important processing stages.

1) Radiometric and spectral calibration: The sensor must be pre-calibrated so that the Digital Numbers (DN) can be converted to radiometric units (μW nm-1 sr-1 cm-2) and the wavebands determined.

2) Geometric correction: Conversion of the pixel to map co-ordinates, so that the image can be 'placed' on the earth and compared with other data sets.

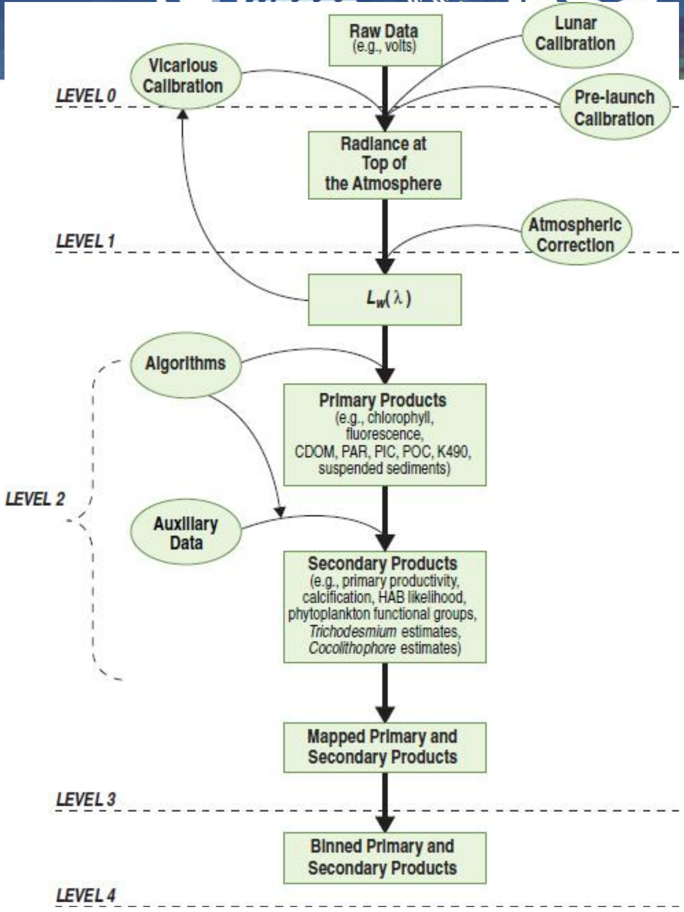
3) Atmospheric Correction: Removal of the atmospheric signal, so that we have a measure of the water-leaving radiance.

A note on Data processing levels

Within remote sensing and ocean colour applications datasets are often described in terms of levels. The level is representative of the amount of processing that has been performed:

Level 0

This is the most raw data format available. Full resolution data, as it comes from the instrument, with some processing applied to remove artefacts from data communication between the satellite and the ground stations. It is unlikely you will work with this level of data, as this data lack information such as geo-referencing and time-referencing ancillary information.



Flow diagram of data processing levels. National Research Council, 2011 https://doi.org/10.17226/13127

Data processing levels

Level 1 (L1A and L1B)

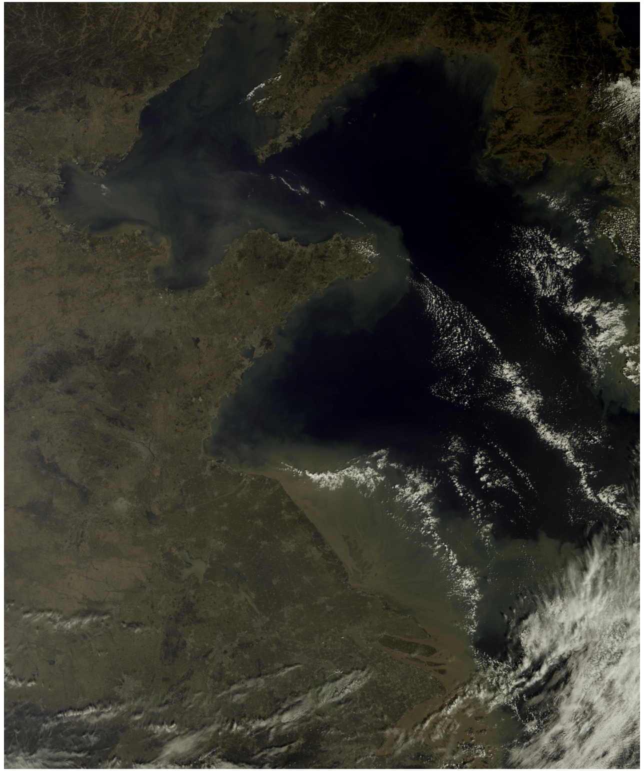
Level 1A is full resolution sensor data with time-referencing, ancillary information including radiometric and geometric calibration coefficients and georeferencing parameters computed and added to the file.

Level 1B has had the parameters applied to the data. For ocean colour this is often referred to as the "top of atmosphere" radiance [mW m^{-2} sr^{-1} nm^{-1}]. This level also includes quality and classification flags.

Level 2

This refers to derived geophysical variables (such as water-leaving reflectance or ocean colour products) at full resolution. This will have required processing to remove the atmospheric component of the signal.

Pixels will also be masked by use of data quality flags.

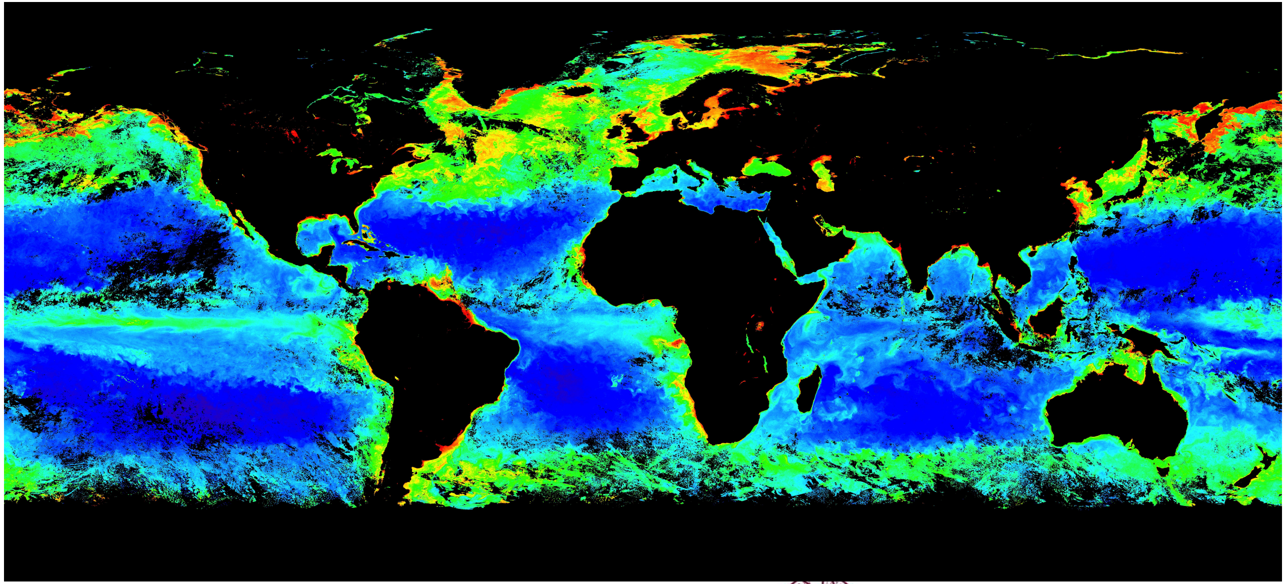


Tri-stimulus from OLCI level 1 Full resolution data (2018-10-02)

Data processing levels

Level 3
A binned version of the level 2 data for a given spatial or temporal resolution.

For example:
4km Ocean Colour Climate Change Initiative Chl-a, 8-day composite (2010/05/09)

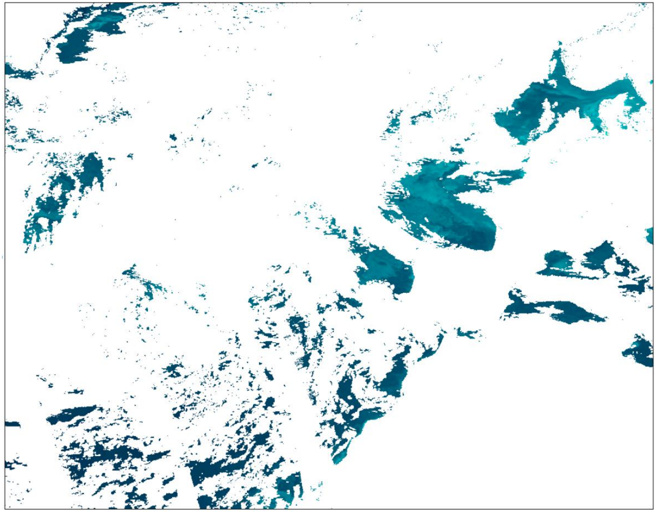


Data processing levels

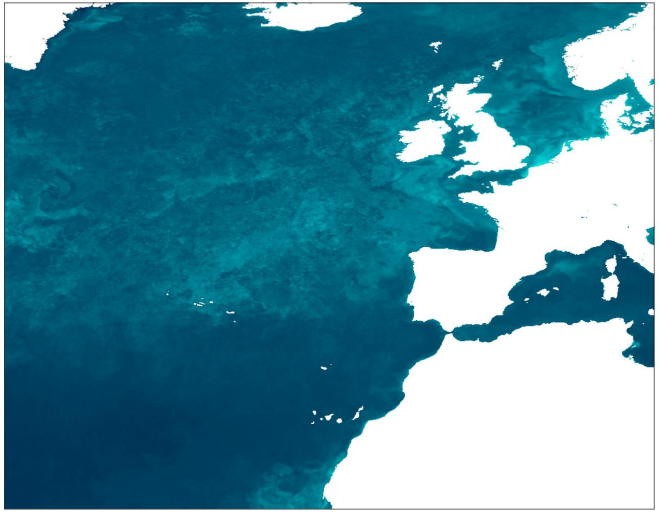
Level 4

Derived from a combination of satellite data and ancillary information, such as ecosystem model output. Usually created for instances in which users require a gap-less data field.

Satellite Derived Chlorophyll-a OC5CI



DINEOF gap filled Chlorophyll-a OC5CI



Radiometric and spectral calibration

Before the launch of the satellite, scientists can run very precise tests in order to calibrate the sensor and produce look-up tables describing the relationship between digital counts and the radiances at each spectral channel.

Sentinel 2B

Sentinel 3A

How to measure Ocean Colour from space?

Ideally sensor function would not change during the life of the sensor. However, this is not the case in reality. Optical surfaces and detectors may degrade slightly, therefore, it is essential to continue calibration throughout the mission.

Scientists must monitor changes to the calibration function throughout the life of the mission in order so they can be applied to the processing.

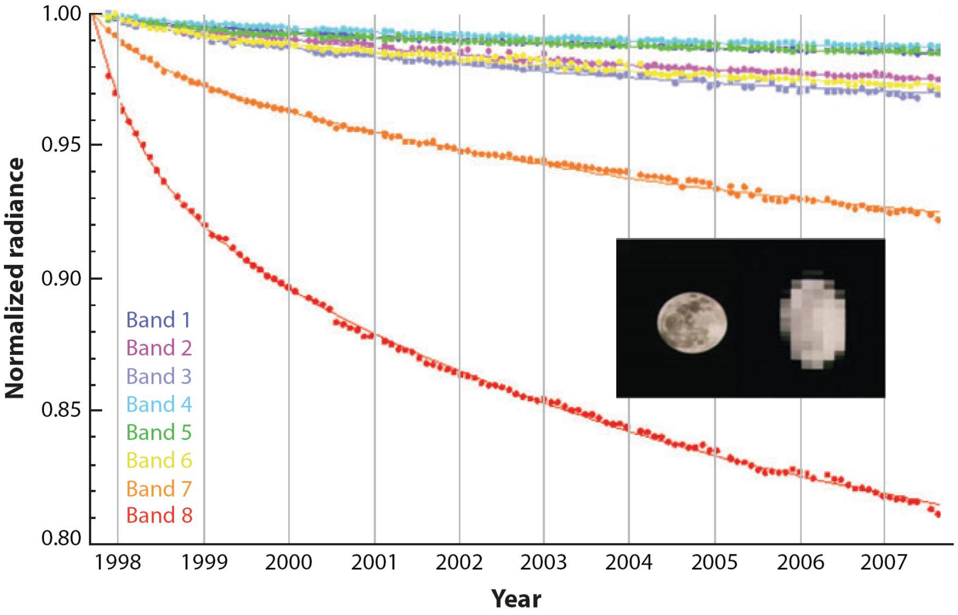


Figure 1

The temporal loss in Sea-viewing Wide Field-of-view Sensor (SeaWiFS) spectral radiometric sensitivity relative to the first lunar calibration. Vertical gray lines denote January 1st of each year. The insert depicts a SeaWiFS image of the moon.

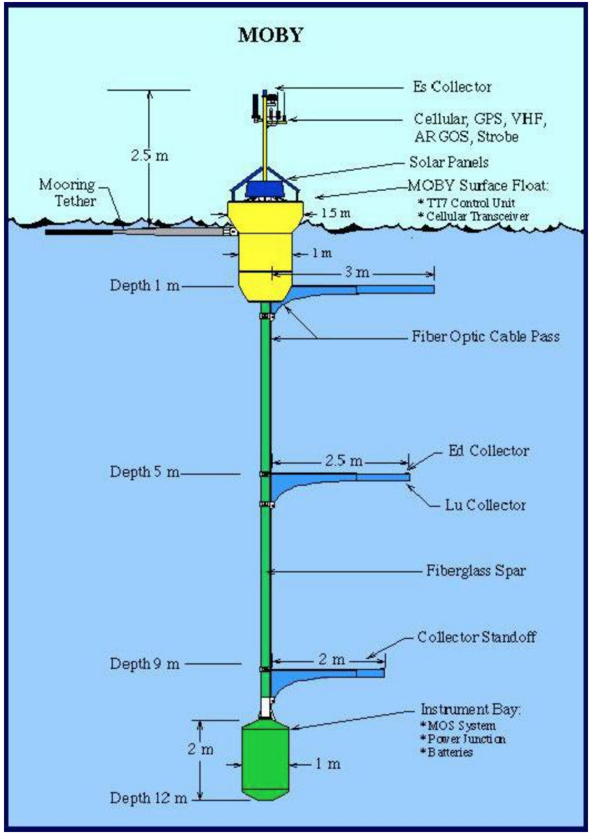
McClain, C. R. (2009) A Decade of Satellite Ocean Color Observations. Annual Review of Marine Science. Vol. 1: 19-42

How to measure Ocean Colour from space?

Vicarious calibration refers to "calibration through the eyes of another". In ocean colour sensors it is derived from comparison between in situ measurements and the satellite measurements.

Atmospheric correction is applied to the satellite measurements before being compared to the in situ measurement, so it is essentially a comparison of instrument calibration and atmospheric correction.

MOBY (Moored Optical BouY) located in Hawaii.

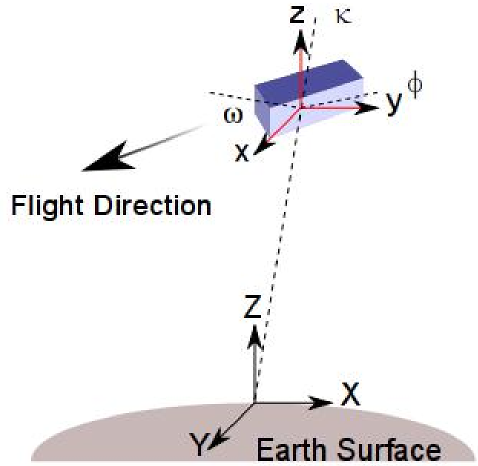


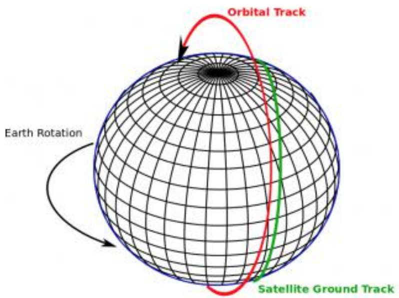
How to measure Ocean Colour from space?

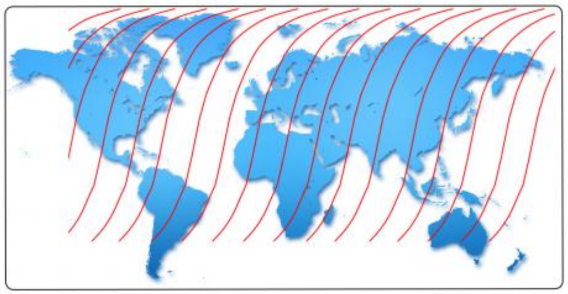
Geometric correction is where we geographically reference the pixel

For this we need either the positional data from the satellite flight path (e.g. GPS) and/or Ground Control Points (GCPs).

For land applications a further stage is orthorectification, where the imagery is corrected for horizontal and vertical distortions using a digital terrain model (DTM).







How to measure Ocean Colour from space?

Earth Rotation: a problem for satellite pushbroom scanners due to time required to acquire frame of data. Earth rotation during acquisition skews the image.

Earth Curvature: large swath width satellites (e.g VIIRS swath width=3040 km), can have distortion at edges.

Aspect Ratio Distortion: the along track scale compared to the across scan i.e. the pixels are not square.

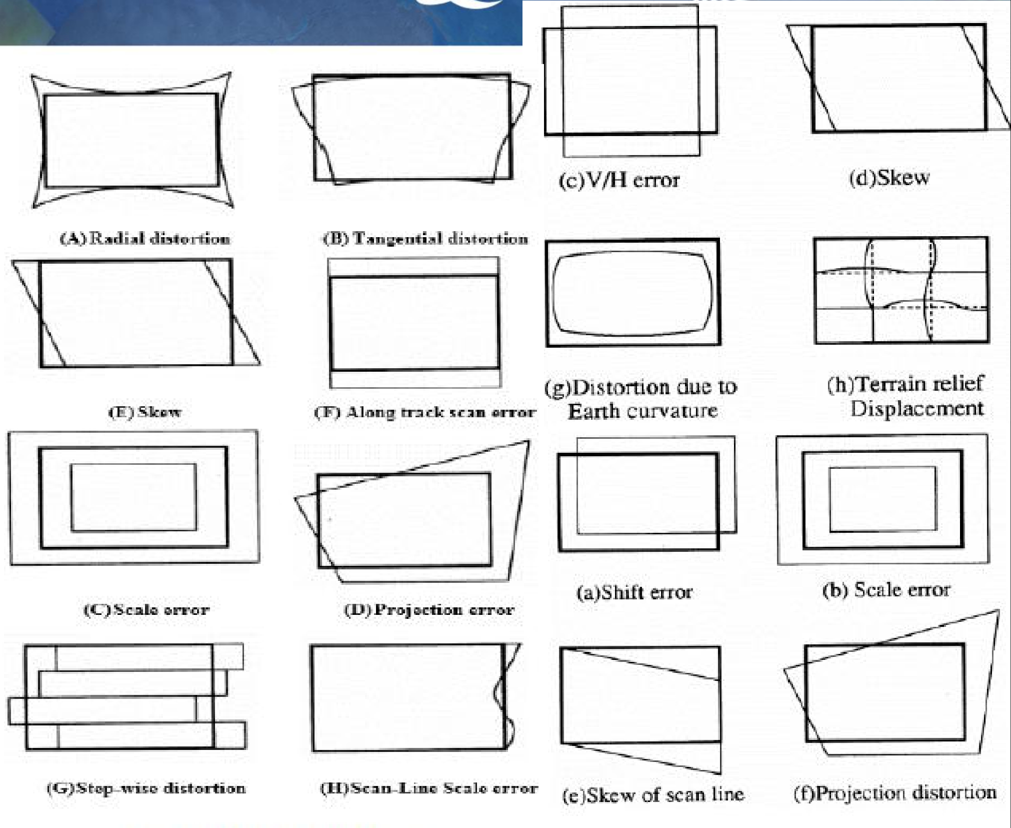
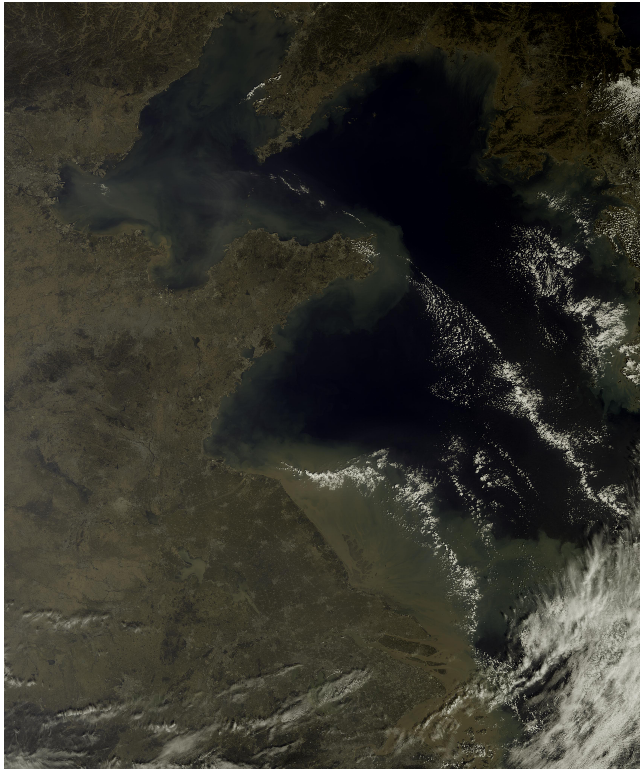
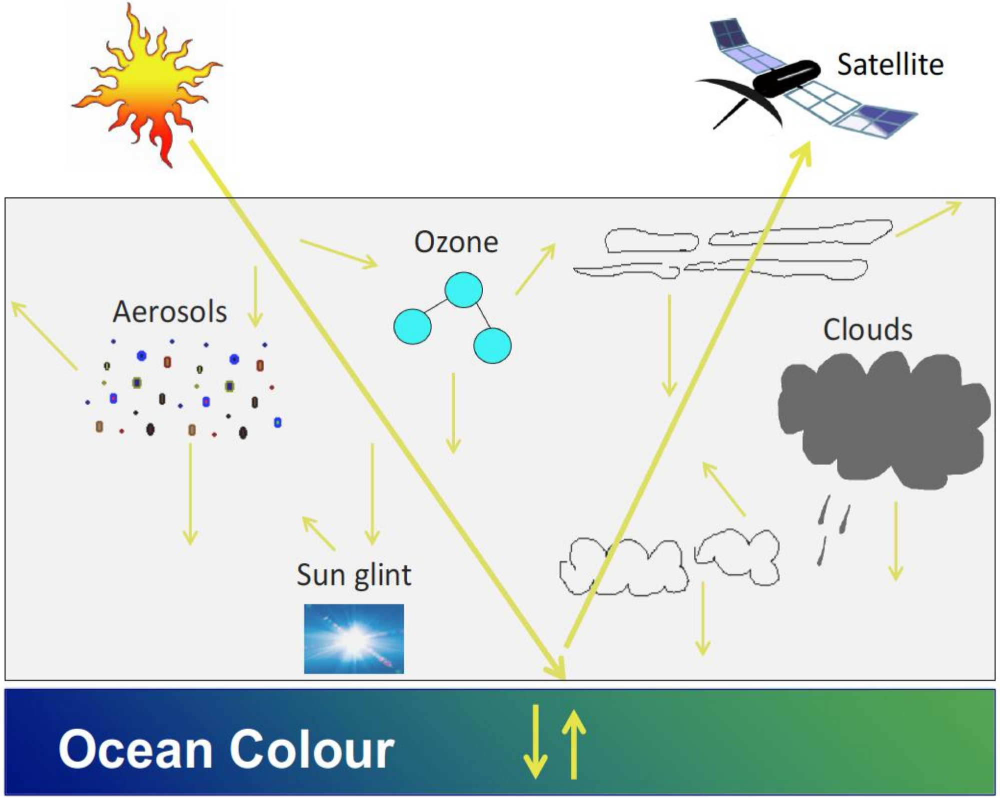


Fig 1: Internal Distortions **Fig 2: External Distortions**

Dave et al. (2015) *International Journal of Computer Applications (0975 – 8887) Volume 116 – No. 12, April 2015*

How to measure Ocean Colour from space?



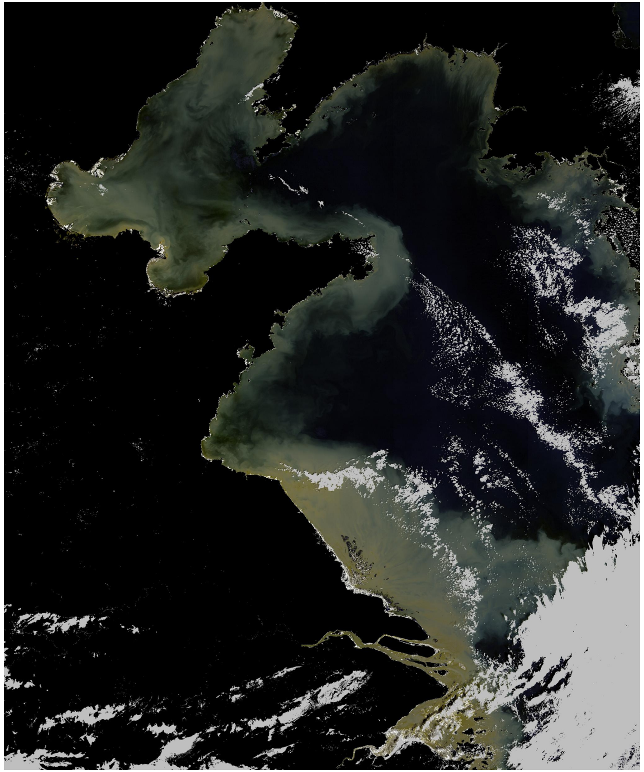


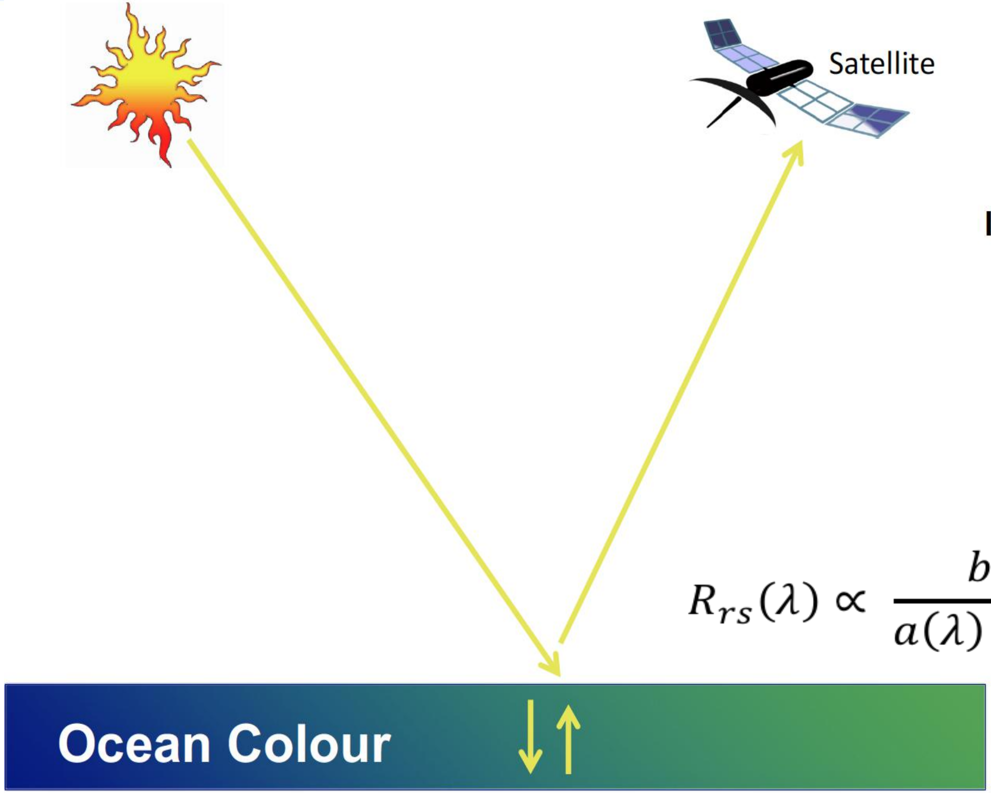
Atmosphere responsible for >90% of the satellite signal, the ocean only <10%

Atmosphere

Ocean

How to measure Ocean Colour from space?

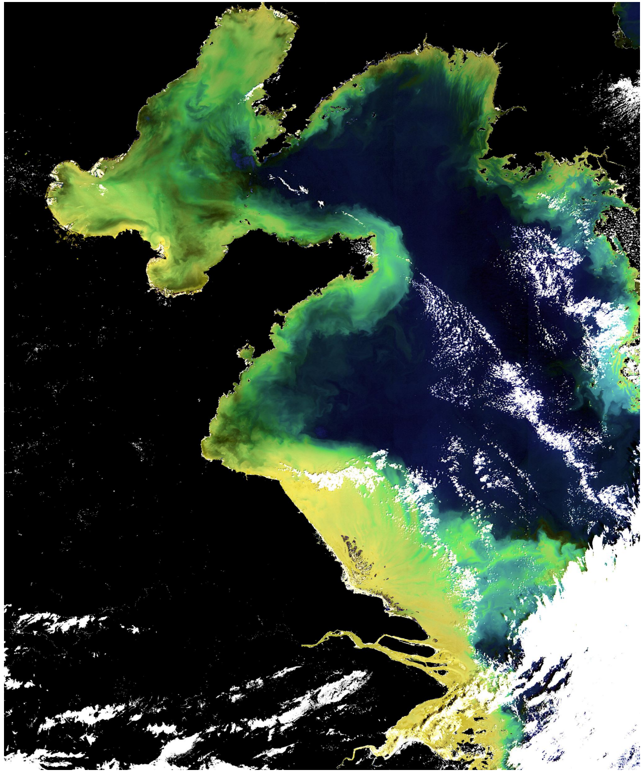


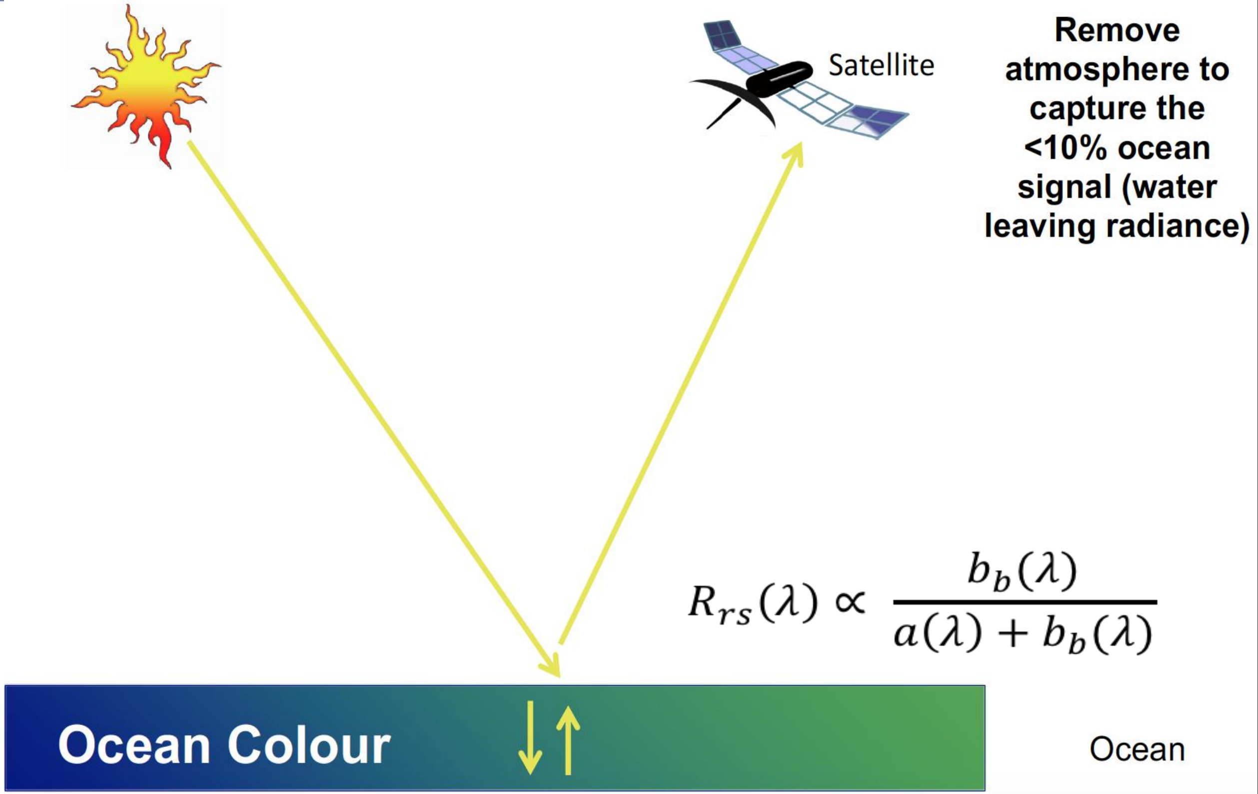


Remove atmosphere to capture the <10% ocean signal (water leaving radiance)

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

How to measure Ocean Colour from space?





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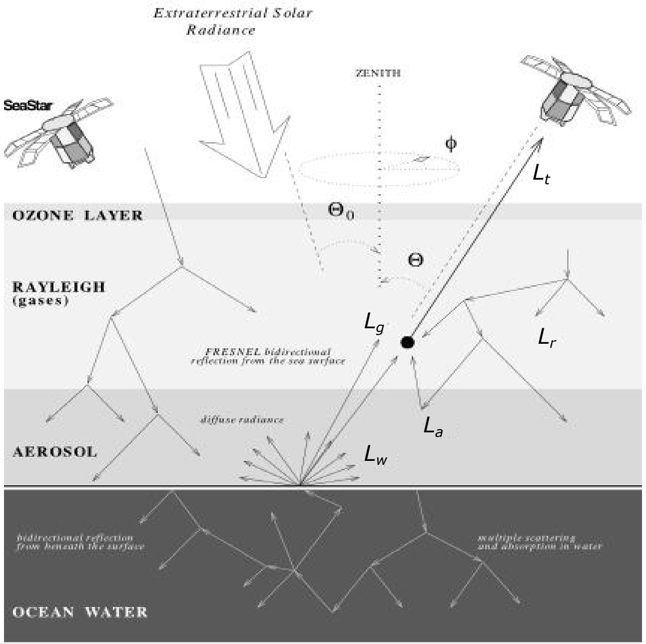


Reflectance *ρ(λ)*, is defined at a given wavelength *λ*, to be related to the radiance through:

$\rho(\lambda) = \pi L(\lambda)/\{F_0(\lambda)\cos\theta_0\}$,

where:

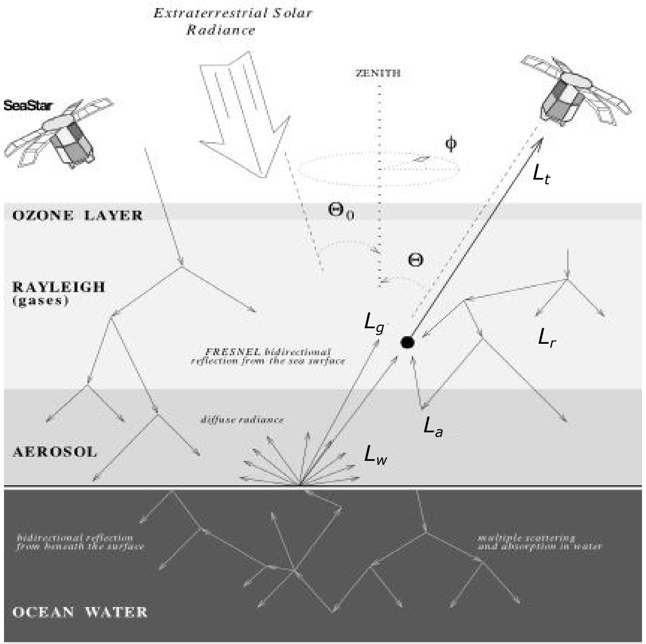
L is radiance

$F_0(\lambda)$ is the extraterrestrial solar irradiance

θ_0 is the solar-zenith angle

Atmospheric correction aims to remove atmospheric and surface effects from the signal measured by the satellite-sensor, thereby deriving the radiances coming from the ocean waters.

How to measure Ocean Colour from space?

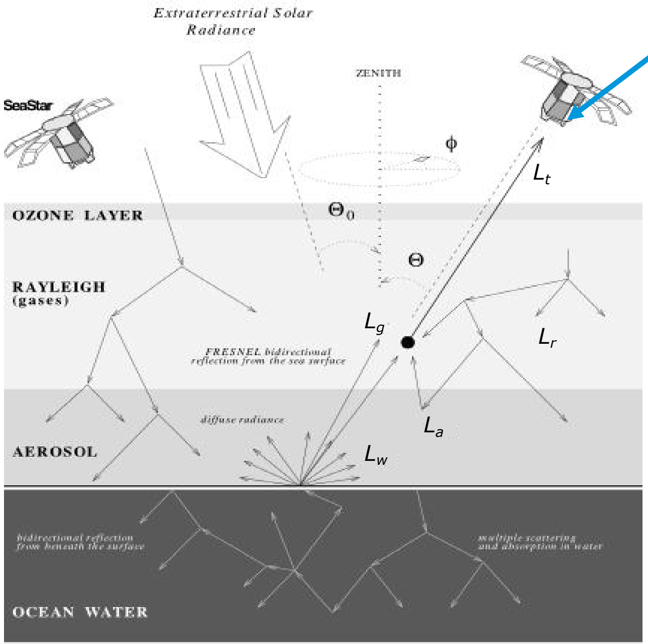


For the ocean-atmosphere system, the top-of-atmosphere (TOA) radiance $L_t\ (\lambda)$ can be partitioned linearly into various distinct physical contributions:

$$L_t(\lambda)=L_r(\lambda)+L_a(\lambda)+L_{ra}(\lambda)+t(\lambda)L_{wc}(\lambda)+T(\lambda)L_g(\lambda)+t(\lambda)t_0(\lambda)\cos\theta_0[nL_w(\lambda)]$$

$L_r(\lambda)$ is Rayleigh scattering (air molecules)
$L_a(\lambda)$ is the scattering by aerosols
$L_{ra}(\lambda)$ is the multiple interaction term for molecules and aerosols
$L_{wc}(\lambda)$ is radiance from whitecaps
$L_g(\lambda)$ is radiance due to the specular reflection of sunlight off the sea surface (sun glitter)
$Lw\ (\lambda)$ *is* actual water-leaving radiance
$[nL_w(\lambda)]$ is the normalized water-leaving radiance
$t_0(\lambda)$ and $t(\lambda)$ are the diffuse transmittances of the atmosphere (sun to surface and surface to sensor)
$T\ (\lambda)$ is the direct transmittance from the surface to the sensor.

How to measure Ocean Colour from space?



Detected

Diffuse transmittances
- Second most important calculation
- Depends on angular distribution of radiance

$$L_t(\lambda)=L_r(\lambda)+L_a(\lambda)+L_{ra}(\lambda)+t(\lambda)L_{wc}(\lambda)+T(\lambda)L_g(\lambda)+t(\lambda)t_0(\lambda)\cos\theta_0[nL_w(\lambda)]$$

Path radiance
- Most significant challenge in atmospheric correction
- 90% of blue and green signal in clear ocean waters (Case 1)

White caps estimated from wind speed

What we want to know

Can be removed by calculating region affected by specular image of the sun

How to measure Ocean Colour from space?

Some atmospheric correction algorithms now provide retrievals further into glint contaminated regions (such as the POLYMER algorithm). These then have to explicitly calculate the $L_g(\lambda)$ component rather than simply masking areas that might be contaminated.

Also, $L_g(\lambda)$ can be considered as having 2 components:

Sun-glitter radiance originating from specular reflection of direct sunlight

sky-glitter radiance originating from specular reflection of skylight.

So coming back to the equation given earlier and assuming we can correct for the path radiances, glitter radiance, whitecaps and have good estimates of atmospheric transmissivity.

$$L_t(\lambda)=L_r(\lambda)+L_a(\lambda)+L_{ra}(\lambda)+t(\lambda)L_{wc}(\lambda)+T(\lambda)L_g(\lambda)+t(\lambda)t_0(\lambda)\cos\theta_0[nL_w(\lambda)]$$

Then we can calculate the water leaving radiance from the TOA radiance.

The concept of spectral "normalized water-leaving radiance", nLw (Gordon and Clark 1981) or L_{wn}, was introduced to try and account for differing viewing angles across track, between sensors, etc.

How to measure Ocean Colour from space?

Normalised Remote-sensing reflectance

Once corrected, the water-leaving radiance is normalized, L_{wn}, to approximate the Sun at zenith, absence of the atmosphere, and a mean Sun-Earth distance (Morel and Gentili, 1996):

$$L_{wn}(\lambda) = L_w(\lambda)/t_{down}(\lambda)\mu_s C_s$$

where t_{down} is the total (i.e. direct plus diffuse, Rayleigh plus aerosol) downward transmittance of the atmosphere, μ_s - the cosine of the solar zenith angle, and C_s - a coefficient accounting for the variation in the Sun-Earth distance.

Conversion to remote-sensing reflectance (R_{rs}) is given by:

$$R_{rs}(\lambda) = L_{wn}(\lambda)/F_0(\lambda),$$

and to water-leaving reflectance is expressed:

$$\rho_w(\lambda) = \pi L_w(\lambda)/t_{down}(\lambda)F_0(\lambda)\mu_s C_s$$

Normalised Remote-sensing reflectance

Important Note!

The reflectance equations given above are not corrected for the Bidirectional Reflectance Distribution Function (BRDF) (Morel et al., 2002).

These are directional reflectances and are still dependent on their viewing direction, i.e. on the angular distribution of the upwelling underwater radiance and on the transmittance through the sea surface from water to air.

Radiance or reflectance products from various missions are often corrected for the BRDF.

OLCI standard product is the directional water-leaving reflectance ($\rho_w(\lambda) = \pi L_w(\lambda)/t_{down}(\lambda)F_0(\lambda)\mu_s C_s$), meaning the reflectance is not corrected for the BRDF effect.

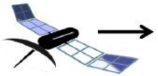
How to measure Ocean Colour from space?

PRODUCT NAME	Normalised Water-Leaving Reflectance
PARAMETER ID	Rxxx, where *xxx* represents the band wavelength in nm
PRODUCT LEVEL	2
DESCRIPTION	Surface directional reflectance, corrected for atmosphere and sun specular reflection, at all OLCI channels except those dedicated to atmosphere absorption measurements, and associated error estimates.
Product Parameters	
COVERAGE	global
PACKAGING	half-orbit
LATENCY	NRT, NTC
UNITS	*Dimensionless*
RANGE	0-0.2, exceptionally higher
SAMPLING	Spatial: approximately 300 m x 300 m (FR) and 1.2 km x 1.2 km (RR); spectral: variable with 16 channels.
FORMAT	2-bytes integer
APPENDED DATA	Error estimate (2-byte integer)
FREQUENCY	1 product per orbit
SIZE OF PRODUCT	Approx. 17.4 GB (FR), 1.1 GB (RR)
Additional Information	
INPUT BANDS	All OLCI bands except Oa13, Oa14, Oa15, Oa19, and Oa20
ANCILLARY AND AUXILIARY DATA	Aerosol models, aerosol LUT, atmospheric diffuse transmittances LUT, RT LUT (solar zenith angle, viewing zenith angle, wavelength, aerosol optical thickness, gaseous absorption, chlorophyll concentration).

Here we can see details on one of the OLCI L2 products.
Note:
Normalised Reflectance
Have been corrected for atmospheric effects to give **surface** values.
Have been corrected for **specular** reflection.

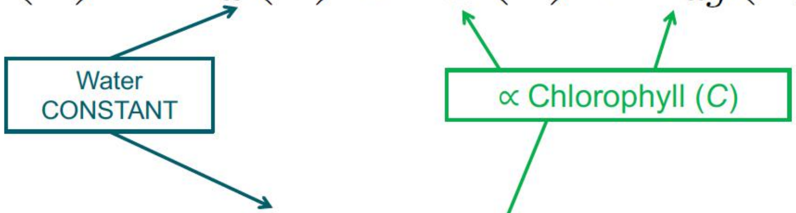
This has involved much ancillary/ auxiliary data.

Ocean Colour Algorithms



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

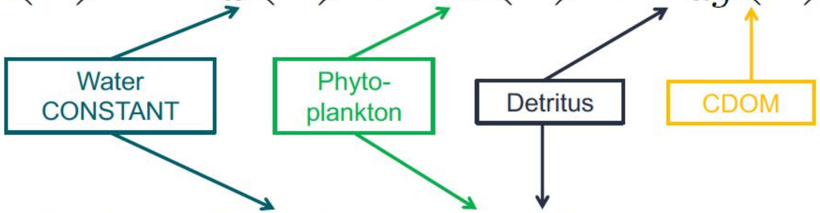
$$a(\lambda) = a_w(\lambda) + a_B(\lambda) + a_{dg}(\lambda)$$



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

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*)

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



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

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*)

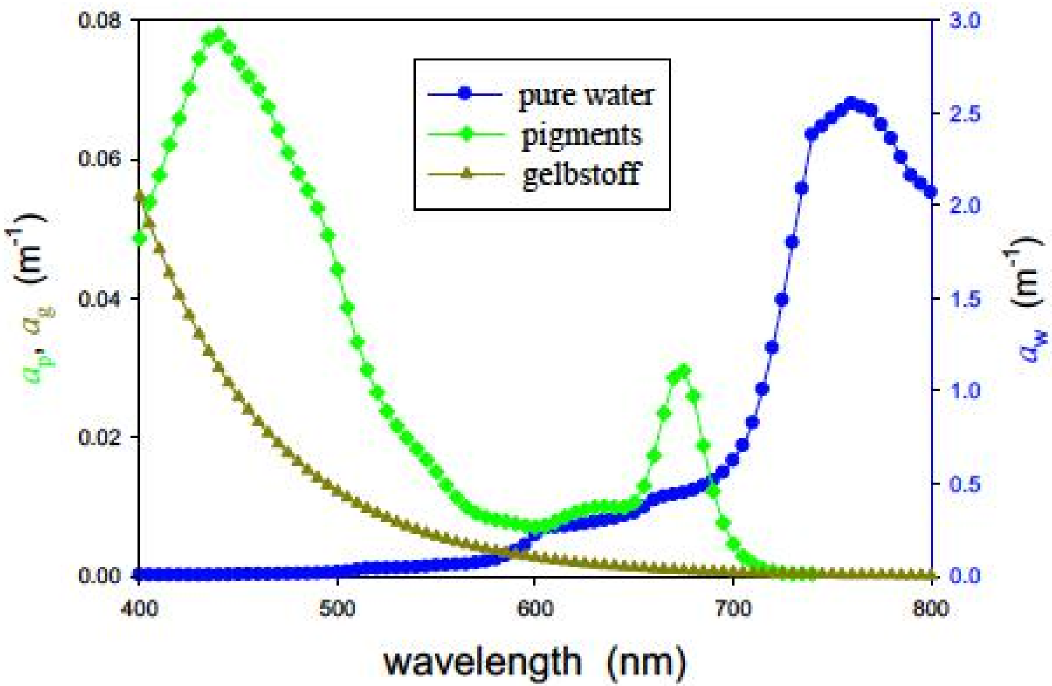
Morel and Prieur (1977) Limnol. Oceanogr.

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).

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)

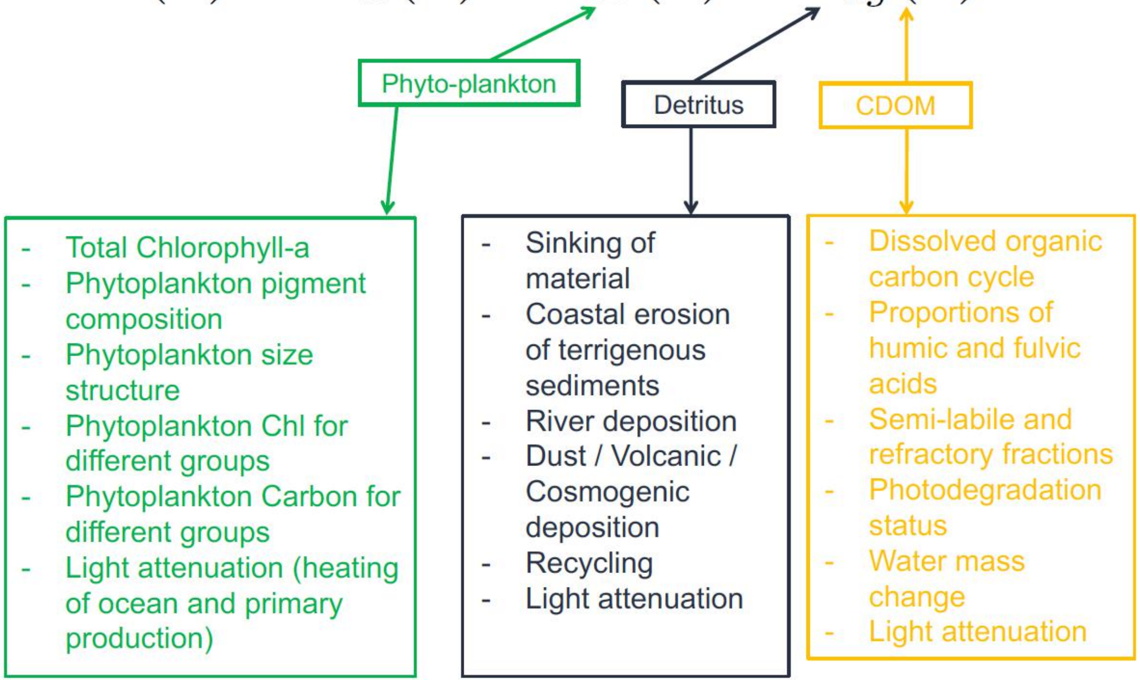


Ocean Colour Algorithms

So in summary:

1. Sensors measure TOA radiance.
2. We correct for other sources of radiance and estimate reflectance of surface ocean waters.
3. We use algorithms to convert R_{rs} into IOPs and constituents of surface waters eg. Chl, sediments, etc.

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



Ocean Colour Algorithms

Empirical algorithms

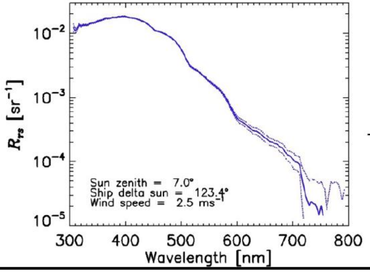
For example the OC4 algorithm from (O'Reilly et al., 2000)

$$Chl_a = 10^{(a+bx+cx^2+dx^3+ex^4)}$$

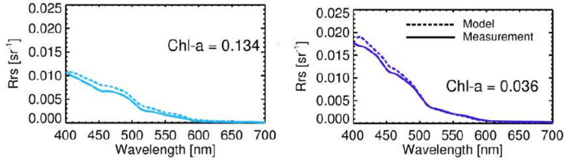
Where *x* is a maximum reflectance band ratio from 4 R_{rs} bands and *a*, *b*, *c*, *d* and *e* are empirically derived using in-situ data.

A good recent review of IOP approaches in Werdell et al (2018) *`An overview of approaches and challenges for retrieving marine inherent optical properties from ocean color remote sensing'*

Semi-analytical algorithms



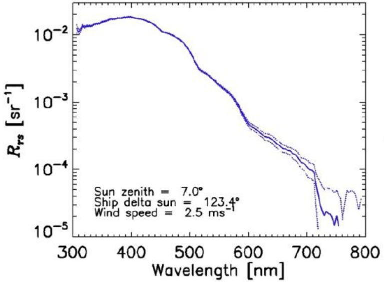
$$R_{rs}(\lambda) = \left\{\sum_{i=1}^{2} g_i \left[\frac{b_{bw}+b_{bp}(\lambda_0)\left(\frac{\lambda}{\lambda_0}\right)^{-\gamma}}{b_{bw}+b_{bp}(\lambda_0)\left(\frac{\lambda}{\lambda_0}\right)^{-\gamma}+a_w(\lambda)+Ca^*_{ph}(\lambda)+a_{dg}(\lambda_0)\exp[-S_{dg}(\lambda-\lambda_0)]}\right]^i\right\}0.5238,$$

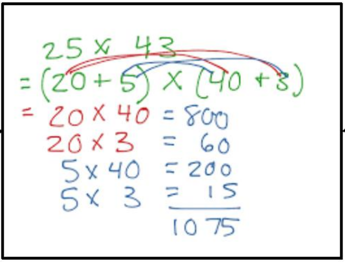


$$b_{bp}(\lambda)\ a_B(\lambda)\, a_{dg}(\lambda)$$

Lee et al. (1998,1999)
Maritorena et al. (2002)
Smyth et al. (2006)
Werdell et al. (2011)

Algebraic approaches





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

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

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)

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]

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]

IOCCG Report Number 5, 2006

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

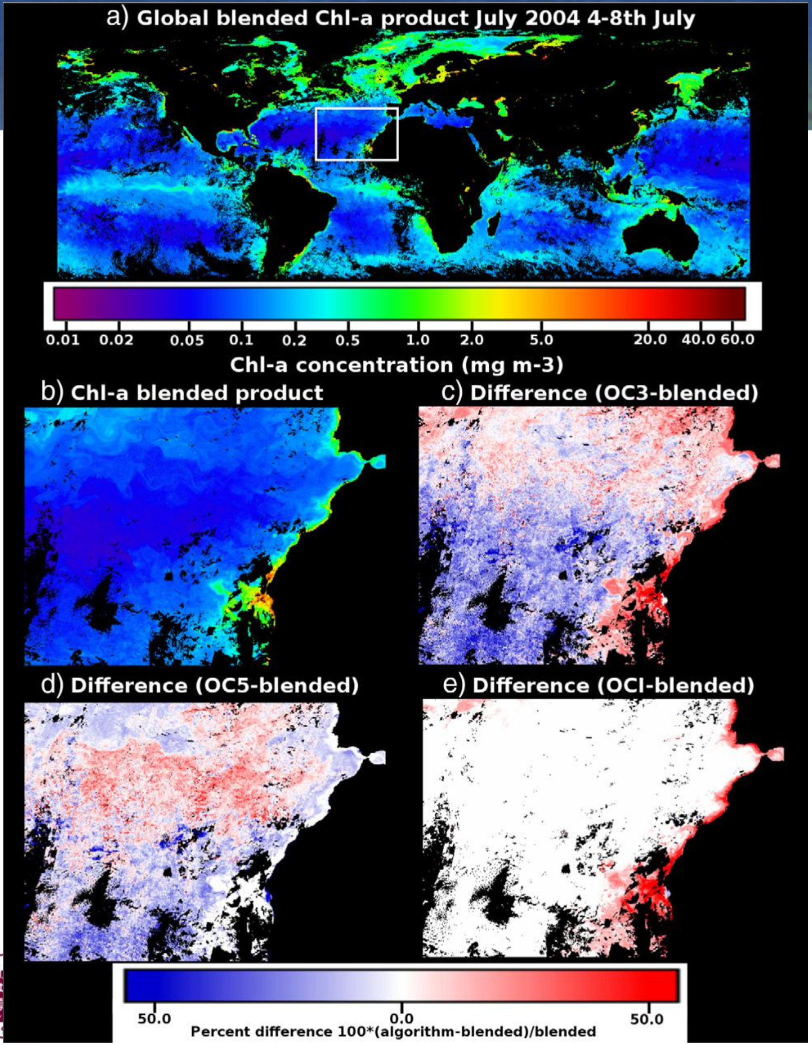
Editor:
ZhongPing Lee (Naval Research Laboratory, Stennis Space Center, USA)

Ocean Colour Algorithms

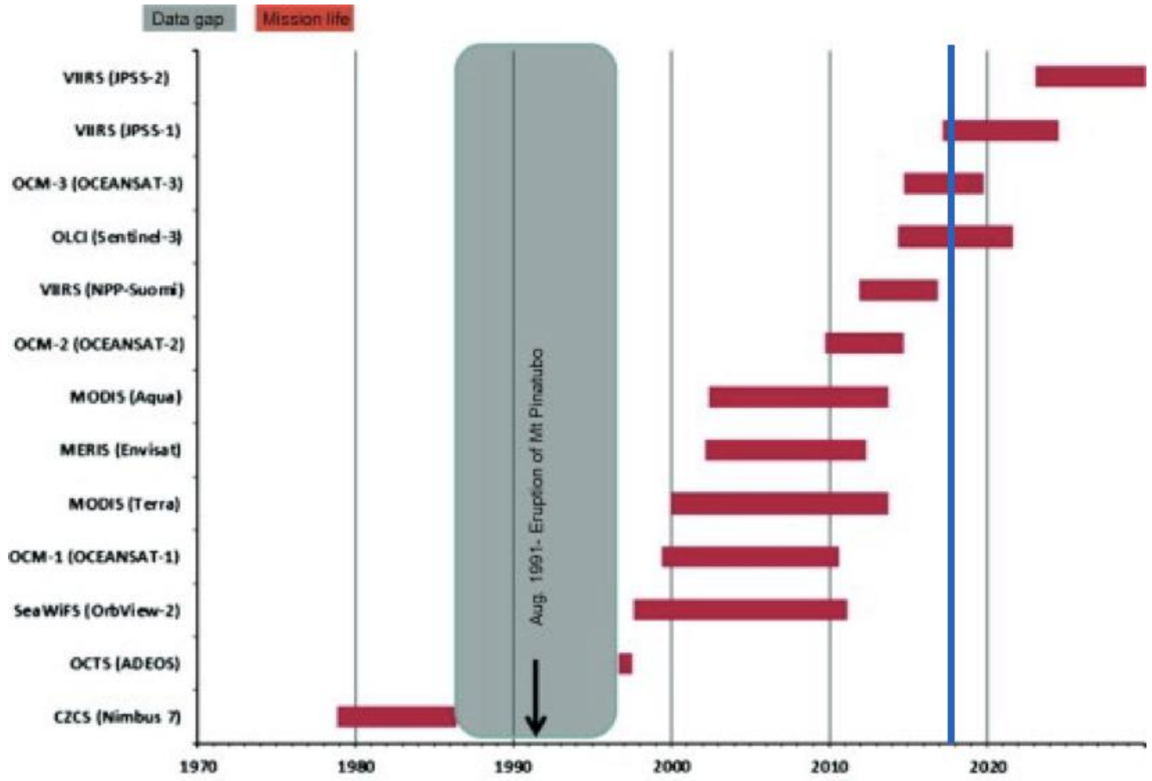
Thus far it has not been possible to create a single algorithm that performs optimally in all oceanographic conditions.

Recently developments have included the blending of algorithms such that the algorithms are used for waters in which they are known to perform best.

For example this is currently done within the OC-CCI products following optical classification of waters (Jackson et al 2017 http://dx.doi.org/10.1016/j.rse.2017.03.036)



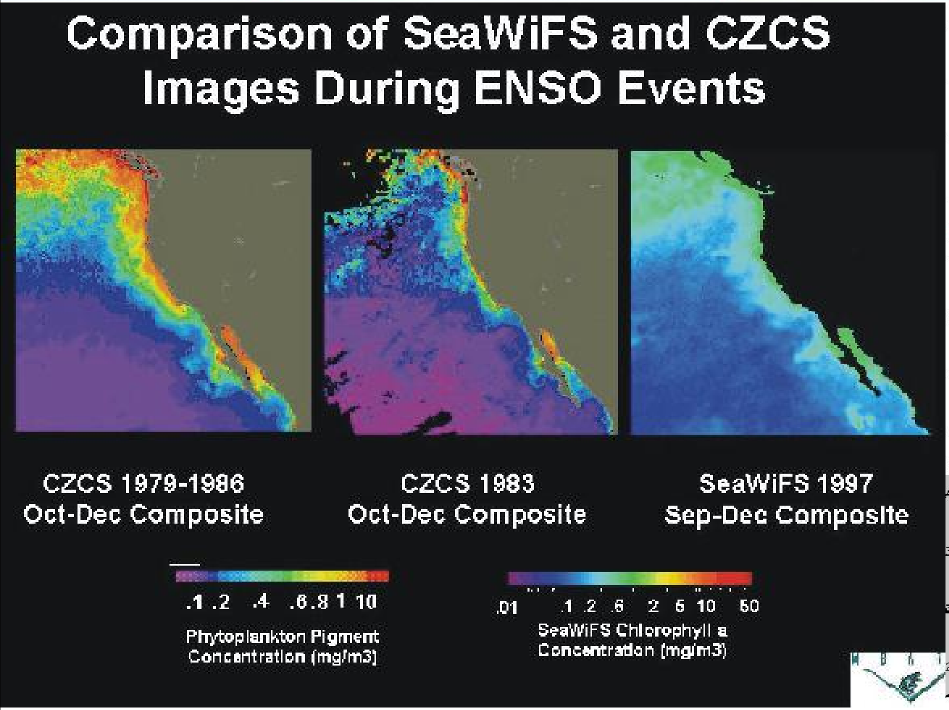
Evolution of Ocean Colour Satellites

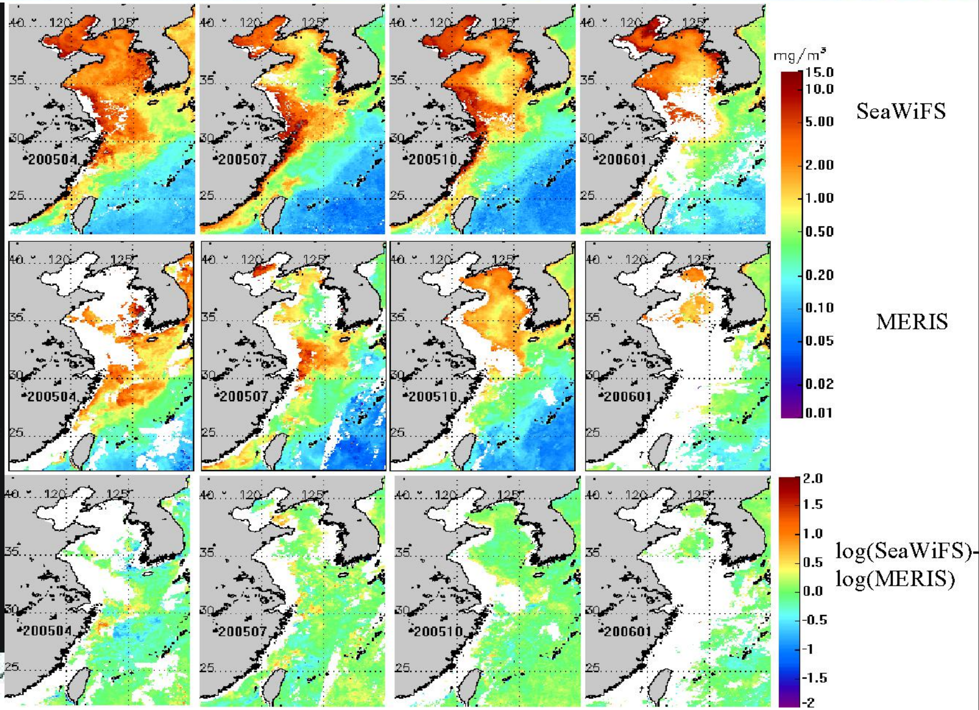


Timeline 1970–2030 illustrating past, current, and future global ocean-color satellite missions. Missions after 1999 were extracted from the online CEOS Earth Observation Handbook.

David Blondeau-Patissier , et al (2014) Progress in Oceanography, Volume 123, 123 - 144

Evolution of Ocean Colour Satellites





Kudela and Francisco P. Chavez (SPIE Ocean Optics OOXIV, Kailua-Kona, Hawaii Nov. 1998)

Hu et al. (2007). Comparison of Ocean Color Data Products from Meris , Modis , and Seawifs : Preliminary Results for the East China Seas.

Evolution of Ocean Colour Satellites

Scientific development has fuelled progress in remote sensing of ocean colour, but with progress comes change in factors such as:

- Resolution
- Swaths
- Orbits
- Measured wavelengths

http://ioccg.org/resources/missions-instruments/current-ocean-colour-sensors/

SENSOR / DATA LINK	AGENCY	SATELLITE	LAUNCH DATE	SWATH (KM)	SPATIAL RESOLUTION (M)	BANDS	SPECTRAL COVERAGE (NM)	SPECTRAL RESPONSE FUNCTION	EQUATORIAL CROSSING TIME
COCTS UI CZI	CNSA/NSOAS (China)	HY-1C	7 September 2018	3000 3000 950	1100 550 50	10 2 4	402 - 12,500 345 - 395 433 - 885		10:30
GOCI Geostationary	KARI/KIOST (South Korea)	COMS	26 June 2010	2500	500	8	400 - 865		8 times/day
MODIS-Aqua	NASA (USA)	Aqua (EOS-PM1)	4 May 2002	2330	250/500/1000	36	405-14,385	SRF-link	13:30
MODIS-Terra	NASA (USA)	Terra (EOS-AM1)	18 Dec 1999	2330	250/500/1000	36	405-14,385	SRF-link	10:30
OCM-2	ISRO (India)	Oceansat-2 (India)	23 Sept 2009	1420	360/4000	8	400 - 900		12:00
OLCI	ESA/ EUMETSAT	Sentinel 3A	16 Feb 2016	1270	300/1200	21	400 - 1020	SRF-link	10:00
OLCI	ESA/ EUMETSAT	Sentinel 3B	25 April 2018	1270	300/1200	21	400 - 1020		10:00
SGLI	JAXA (Japan)	GCOM-C	23 Dec 2017	1150 - 1400	250/1000	19	375 - 12,500		10:30
SGLI	JAXA (Japan)	GCOM-C	23 Dec 2017	1150 - 1400	250/1000	19	375 - 12,500		10:30
VIIRS	NOAA (USA)	Suomi NPP	28 Oct 2011	3000	375 / 750	22	402 - 11,800	SRF-link	13:30
VIIRS	NOAA/NASA (USA)	JPSS-1/NOAA-20	18 Nov 2017	3000	370 / 740	22	402 - 11,800	SRF-link	13:30

Evolution of Ocean Colour Satellites

It is important to note that in order to characterise biogeochemical cycles and identify trends, time-series duration > natural period of system variability.

The number of years required to detect a trend primarily depends on:

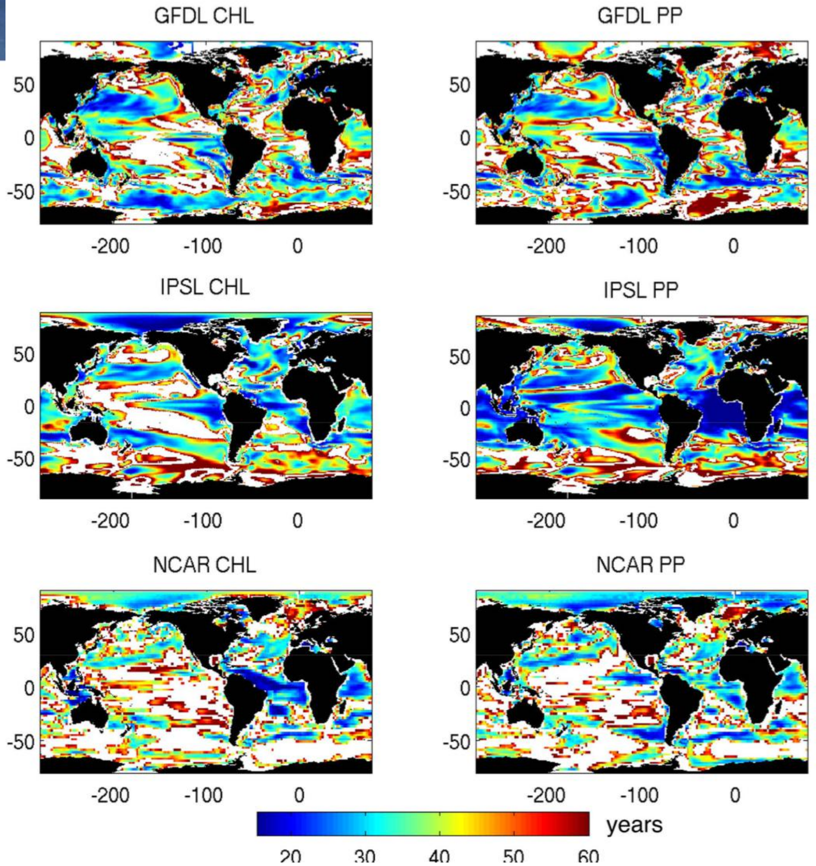
-The standard dev of the noise

-The magnitude of the trend

-autocorrelation of autoregressive noise

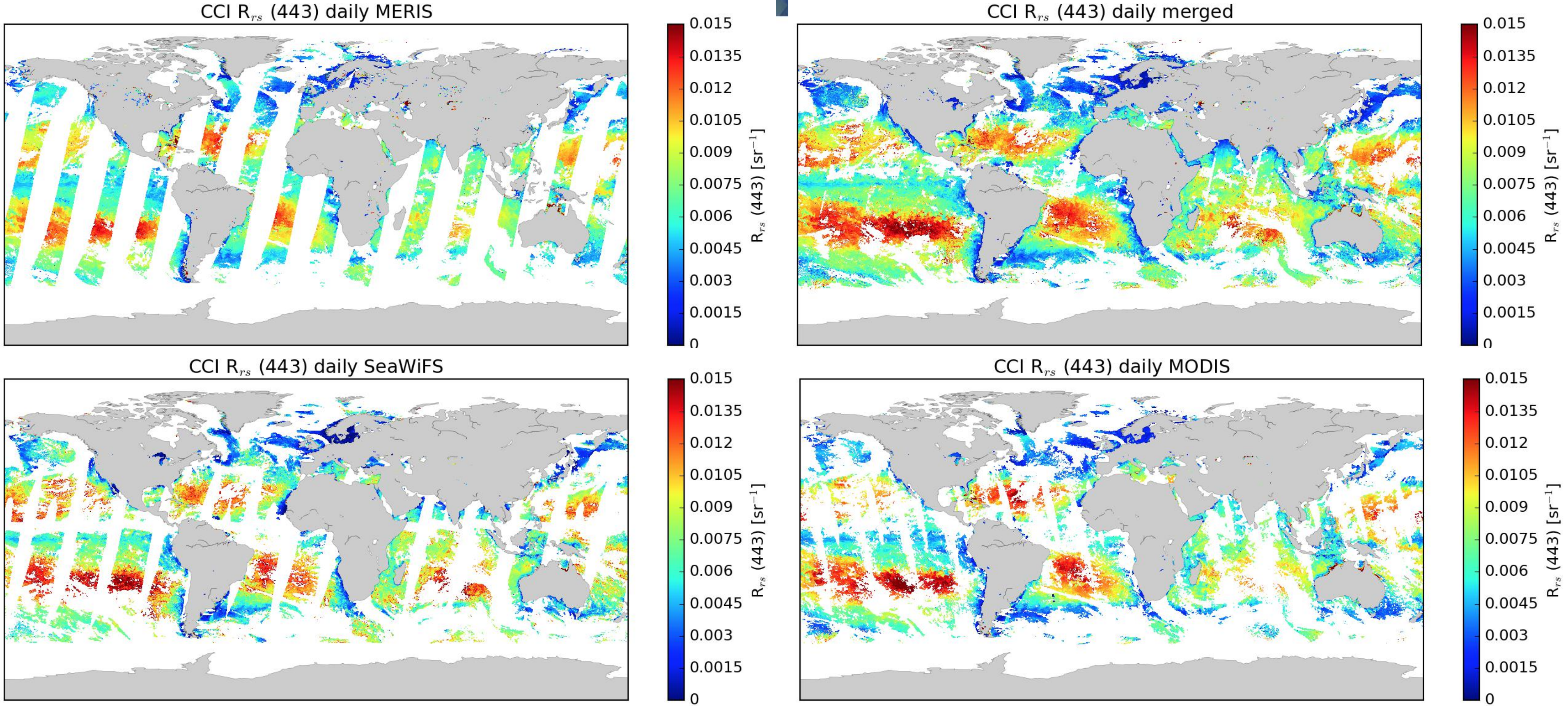
The length of the time series required is extended if there are gaps in the record.

No single ocean colour sensor has provided a data record of 20 years but we are getting to the point where the total record is sufficient.



Henson et al. (2010) *Detection of anthropogenic climate change in satellite records of ocean chlorophyll and productivity.*

Merged data records

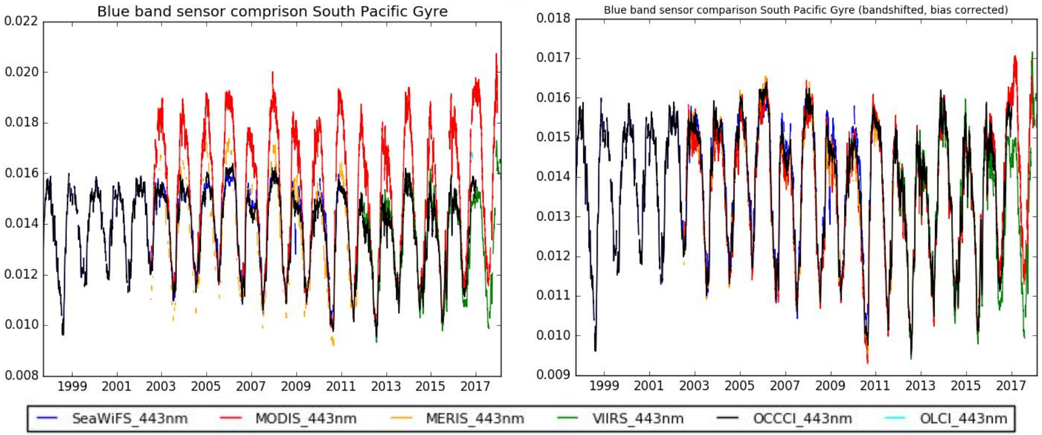


ESA Ocean Colour CCI

Merged data records

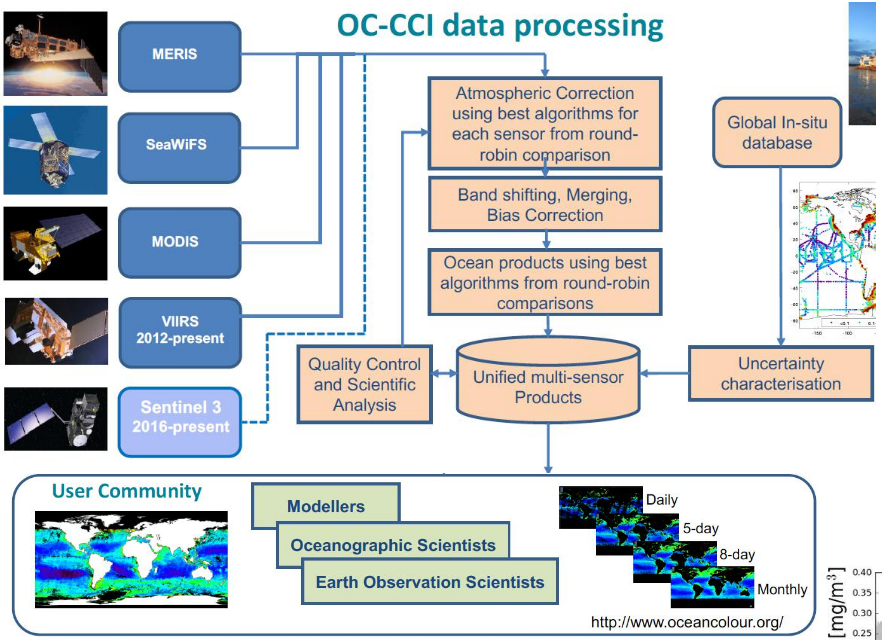
Merged records can give enhanced spatial and temporal coverage but inter-sensor differences must be accounted/corrected before any form of meaningful analysis can be performed.

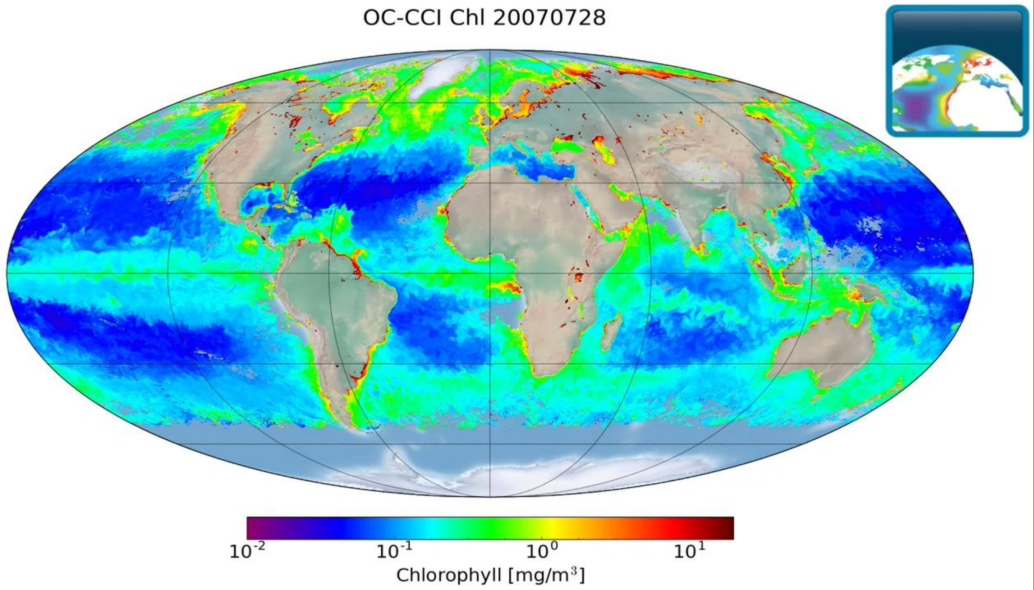
ESA's OC-CCI project has put a great deal of effort into this task to produce a climate quality Ocean Colour record.

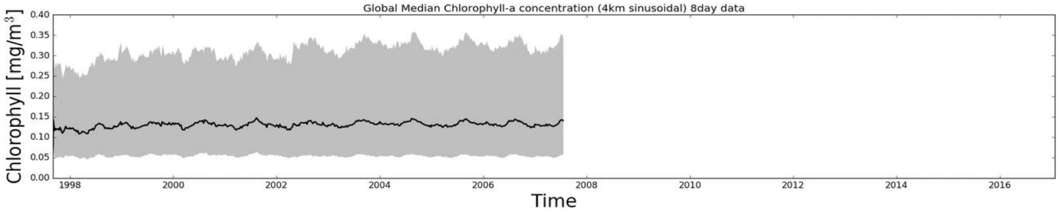


SeaWiFS		412			443		490	510			555					670											765
MERIS			412.5	442.5			490	510				560	620	665						681.25	705					753.75	
MODIS-A			412.5		443	488			531	547					667				678						748		
VIIRS		412			443	486					555						672							745			
Sentinel-3	400		412.5	442.5			490	510				560	620	665				673.75		681.25		708.75				753.75	
OCM-2		412			443		490	510			555		620										740				

Merged data records





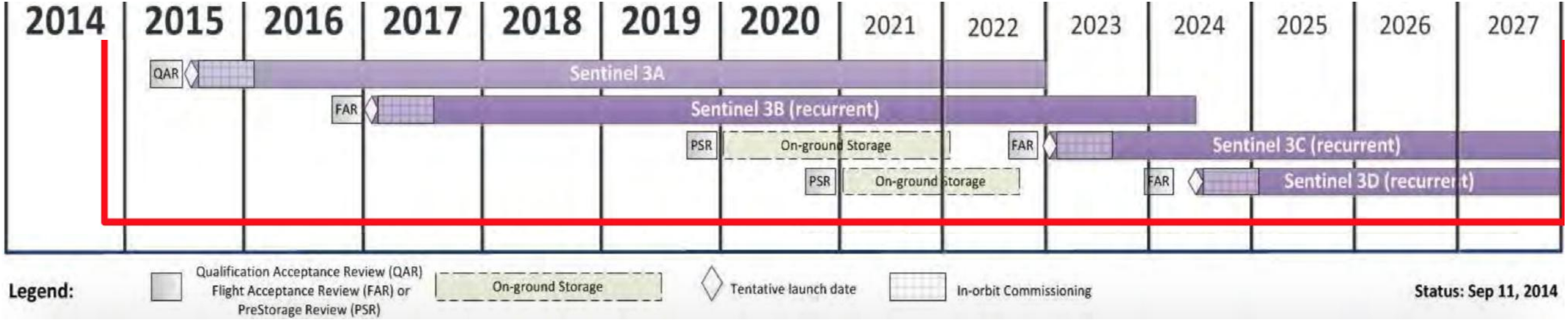


ESA Ocean Colour CCI

Sentinel 3 and OLCI

OLCI instruments are now in operation aboard Sentinel 3A and 3B which were successfully launched into orbit and provide data from 2016-present.

With the addition of Sentinels 3C and 3D in the future we will have a consistent and continuous ocean colour dataset over a long period.



Sentinels 3A and 3B have been initially flown in a 'tandem' phase to allow inter-comparison of sensors **in orbit** with near simultaneous measurements.

Sentinel 3 and OLCI

With S3 A & B OLCI operating 180 degrees apart, global coverage **every 2 days**, swath 1270km of the nadir instrument (300m data)

Sentinel 3 and OLCI

The SENTINEL-3 OLCI instrument is based on the design of ENVISAT MERIS.

The instrument is a visible push-broom imaging spectrometer and incorporates the following significant improvements compared to MERIS:

- an increase in the number of spectral bands (from 15 to 21)
- improved SNR and a 14-bit analogue to digital converter
- improved long-term radiometric stability
- mitigation of sun-glint contamination by tilting cameras in a westerly direction
- improved instrument characterisation including stray light, camera overlap and calibration diffusers
- improved coverage of the global ocean (<4 days), land (<3 days with one satellite, ignoring the effect of clouds), where MERIS is approximately 15 days
- 100% overlap with SLSTR instrument swath and simultaneous acquisitions facilitating the use of OLCI and SLSTR in synergy.

Sentinel 3 and OLCI

Mitigation of sun-glint contamination by tilting has reduced glint compared to MERIS but it still exists on right side of some images.

Sometime glint regions can be of particular interest for spotting features such as oil slicks (Hu et al 2009).

Sentinel 3 and OLCI

The SENTINEL-3 OLCI User Guide provides a high level description of the available instrument modes and products. It also provides an introduction to relevant application areas, information on data distribution, product formatting and software tools available from ESA.

The categories are:

- **Overview**
  Gives a brief overview of the OLCI heritage and new instrument features. This also describes the main characteristics in terms of geophysical measurements.
- **Applications**
  Describes the support of the SENTINEL-3 OLCI mission to maritime monitoring, land mapping and monitoring, atmospheric monitoring and climate change monitoring.
- **Product Types**
  Describes the granularity of SENTINEL-3 OLCI products distributed to the users: Level-1B, Level-2 land and Level-2 water.
- **Processing Levels**
  Illustrates the processing steps from Level-0, Level-1 to Level-2.
- **Resolutions** and **Coverage**
  Defines the spatial full or reduced resolutions, the radiometric resolutions and describes the revisit frequency and coverage.
- **Naming Convention** and **Data Formats**
  Describes the data naming conventions used and introduces the formatting used for Level-0, Level-1 and Level-2 products.
- **Definitions**
  Provides information on the units, notations and product grids used in the acquisition and processing of OLCI products.

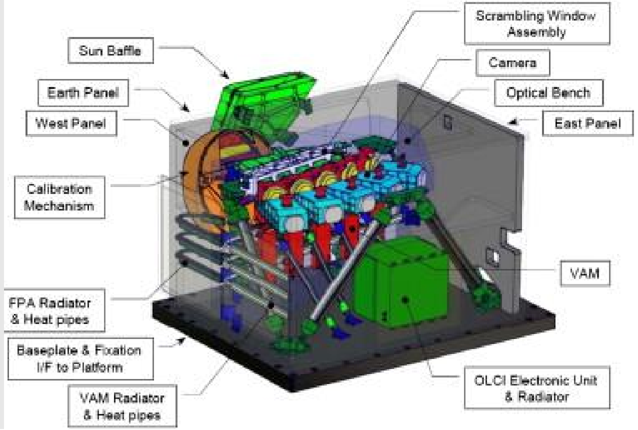
For an in-depth description of the mission's products and algorithms, as well as details on the SAR instrument and its performance, please refer to the SENTINEL-3 OLCI Technical Guide. The detailed information available in the Technical Guide is focused upon users such as academics and industrial software engineers who have previous experience of similar EO missions, and in-depth experience of data manipulation and management.

Key Resources

- S3 Handbook
- Sentinel-3 OLCI Data Product Quality Reports
- Sentinel-3 Optical Annual Performance Report - Year 1
- Tools
- Acronyms and Abbreviations
- Copernicus Services

Not enough time to cover all information so for further details on OLCI see:

https://sentinel.esa.int/web/sentinel/user-guides/sentinel-3-olci



Sentinel 3 and OLCI

Band #	λ center nm	Width nm	Lmin W/(m².sr.µm)	Lref W/(m².sr.µm)	Lsat W/(m².sr.µm)	SNR@Lref
Oa1	400	15	21.60	62.95	413.5	2188
Oa2	412.5	10	25.93	74.14	501.3	2061
Oa3	442.5	10	23.96	65.61	466.1	1811
Oa4	490	10	19.78	51.21	483.3	1541
Oa5	510	10	17.45	44.39	449.6	1488
Oa6	560	10	12.73	31.49	524.5	1280
Oa7	620	10	8.86	21.14	397.9	997
Oa8	665	10	7.12	16.38	364.9	883
Oa9	673.75	7.5	6.87	15.70	443.1	707
Oa10	681.25	7.5	6.65	15.11	350.3	745
Oa11	708.75	10	5.66	12.73	332.4	785
Oa12	753.75	7.5	4.70	10.33	377.7	605
Oa13	761.25	2.5	2.53	6.09	369.5	232
Oa14	764.375	3.75	3.00	7.13	373.4	305
Oa15	767.5	2.5	3.27	7.58	250.0	330
Oa16	778.75	15	4.22	9.18	277.5	812
Oa17	865	20	2.88	6.17	229.5	666
Oa18	885	10	2.80	6.00	281.0	395
Oa19	900	10	2.05	4.73	237.6	308
Oa20	940	20	0.94	2.39	171.7	203
Oa21	1020	40	1.81	3.86	163.7	152

The Global Monitoring for Environment and Security SENTINEL-3 mission, C.Donlon et al

Visible

Aerosol, CDOM properties
Yellow substances & detritus
Chl-a peak
Pigment absorption
Suspended sediment & red tide
Chl-a absorption minimum
Suspended sediment
Chl-a absorption
Fluorescence retrieval
Chl-a fluorescence peak
Chl-a fluorescence ref, Atmo

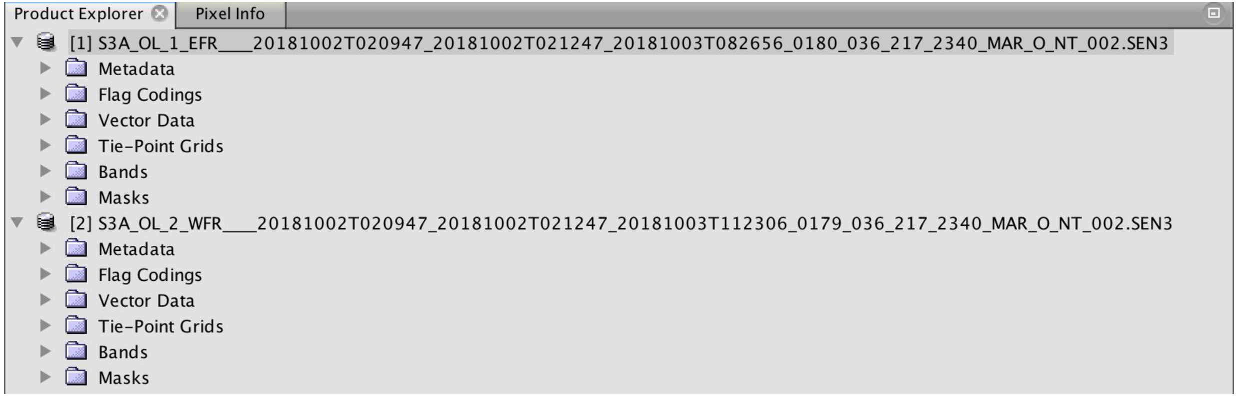
Infra-red

Sentinel 3 and OLCI product formats

```
MacBook-Pro-5:Data thja$ ls S3A_OL_1_EFR____20181002T020947_20181002T021247_20181003T082656_0180_036_217_2340_MAR_O_NT_002.SEN3/
Oa01_radiance.nc       Oa06_radiance.nc       Oa11_radiance.nc       Oa16_radiance.nc       Oa21_radiance.nc       tie_geo_coordinates.nc
Oa02_radiance.nc       Oa07_radiance.nc       Oa12_radiance.nc       Oa17_radiance.nc       geo_coordinates.nc     tie_geometries.nc
Oa03_radiance.nc       Oa08_radiance.nc       Oa13_radiance.nc       Oa18_radiance.nc       instrument_data.nc     tie_meteo.nc
Oa04_radiance.nc       Oa09_radiance.nc       Oa14_radiance.nc       Oa19_radiance.nc       qualityFlags.nc        time_coordinates.nc
Oa05_radiance.nc       Oa10_radiance.nc       Oa15_radiance.nc       Oa20_radiance.nc       removed_pixels.nc      xfdumanifest.xml
MacBook-Pro-5:Data thja$ ls S3A_OL_2_WFR____20181002T020947_20181002T021247_20181003T112306_0179_036_217_2340_MAR_O_NT_002.SEN3/
Oa01_reflectance.nc    Oa07_reflectance.nc    Oa16_reflectance.nc    geo_coordinates.nc     tie_geometries.nc      wqsf.nc
Oa02_reflectance.nc    Oa08_reflectance.nc    Oa17_reflectance.nc    instrument_data.nc     tie_meteo.nc           xfdumanifest.xml
Oa03_reflectance.nc    Oa09_reflectance.nc    Oa18_reflectance.nc    iop_nn.nc              time_coordinates.nc
Oa04_reflectance.nc    Oa10_reflectance.nc    Oa21_reflectance.nc    iwv.nc                 trsp.nc
Oa05_reflectance.nc    Oa11_reflectance.nc    chl_nn.nc              par.nc                 tsm_nn.nc
Oa06_reflectance.nc    Oa12_reflectance.nc    chl_oc4me.nc           tie_geo_coordinates.nc w_aer.nc
```

Folders contain NetCDF and XML files which when loaded provide information on:

Metadata, Flags, Bands, Tie-points, etc



Sentinel 3 and OLCI

OLCI data flags

Allow rapid filtering of data for analysis.

This could be filtering in order to leave only high quality data or you could be looking in particular at pixels in particular conditions (eg glint region)

Flag	Description
BPAC_ON	Bright Pixel Correction converged and a NIR signal was determined
WHITE_SCATT	"White" scatterer within the water e.g. coccoliths
LOWRW	Water-leaving reflectance at 560 nm is less than a defined threshold or HIINLD_F raised (flag for low pressure water i.e., high altitude inland waters)
HIGHRW	High water-leaving reflectance at 560 nm or the TSM retrieved as part of the BPAC is above a threshold
ANNOT	Annotation flags for the quality of the atmospheric correction, including: • ANGSTROM (Ångström exponent cannot be computed); • AERO_B (blue aerosols); • ABSO_D (desert dust absorbing aerosols); • ACLIM (aerosol model does not match aerosol climatology); • ABSOA (absorbing aerosols); • MIXR1 (aerosol mixing ratio is equal to 0 or 1); • DROUT (minimum absolute value of the reflectance error at 510 nm is greater than a defined threshold); • TAU06 (aerosol optical thickness is greater than a defined threshold)
RWNEG_O01 to RWNEG_O21	Provides a "negative water-leaving reflectance" flag for each band's water-leaving reflectance: the value below which pixels are flagged varies according to the band, with the threshold stored within a Look-Up Table

Flag	Description
INVALID	Invalid flag: instrument data missing or invalid
WATER	Water (marine) with clear sky conditions, i.e. no clouds
CLOUD	Cloudy pixel
CLOUD_AMIBUOUS	Possibly a cloudy pixel, the flag removes semi-transparent clouds and other ambiguous cloud signatures
CLOUD_MARGIN	Cloud edge pixel, the flag provides an a-priori margin on the 'CLOUD or CLOUD_AMBIGUOUS' flag of 2 pixels at RR and 4 pixels at FR
SNOW_ICE	Possible sea-ice or snow contamination
INLAND_WATER	Fresh inland waters flag (from L1B); these pixels will also be flagged as LAND rather than WATER.
TIDAL	Pixel is in a tidal zone (from L1B)
COSMETIC	Cosmetic flag (from L1B)
SUSPECT	Suspect flag (from L1B)
HISOLZEN	High solar zenith: SZA > 70°
SATURATED	Saturation flag: saturated within any band from 400 to 754 nm or in bands 779, 865, 885 and 1020 nm
MEGLINT	Flag for pixels corrected for sun glint
HIGHGLINT	Flag for when the sun glint correction is not reliable
WHITECAPS	Flag for when the sea surface is rough enough for there to be whitecaps, which cause a brightening of the water-leaving reflectance
ADJAC	reserved for future use for an adjacency correction, so always set to false
WV_FAIL	IWV retrieval algorithm failed
AC_FAIL	BAC atmospheric correction is suspect
OC4ME_FAIL	OC4Me algorithm failed
OCNN_FAIL	NN algorithm failed
KDM_ FAIL	KD490 algorithm failed

Data access

There are 3 main methods for accessing and processing ocean colour (and associated) data. The best method depends on the users data requirement in terms of complexity and volume of data.

Portals

Often the easiest way to rapidly view and analyse part of a dataset.

GUIs

Purpose built interfaces that allow the viewing and analysis of data on a local machine. Allows experimentation with, investigation and analysis of data.

FTP, OPENDAP, THREDDS

Allow batch data downloads to a local machine with variable and regional subsetting.

Data access

CODA is an online rolling archive with https access to Sentinel-3 Level 1 and Level 2 (Marine) global data in different latency modes, as shown in the following table:

LATENCY MODES	DESCRIPTION	TIME ARCHIVE
Near Real-Time (NRT)	Products available to users within three hours after sensing	1 month
Short time critical (STC)	Products available to users within within 48 hours after sensing. (Only for SRAL products)	
Non time critical (NTC)	Products available to users within one month after sensing	1 year

If you already have an Earth Observation Portal (EO Portal) account, you can use your account credentials to log into CODA. Go to **https://coda.eumetsat.int** (please use Chrome or Firefox). Click 'OK' to be redirected to the EO Portal login screen. Alternatively go to https://eoportal.eumetsat.int/userMgmt/login.faces, log in and follow the link 'Access CODA'.

Data access

Data availability from OLCI.

For more detail on file naming see https://sentinel.esa.int/web/sentinel/user-guides/sentinel-3-olci/naming-convention

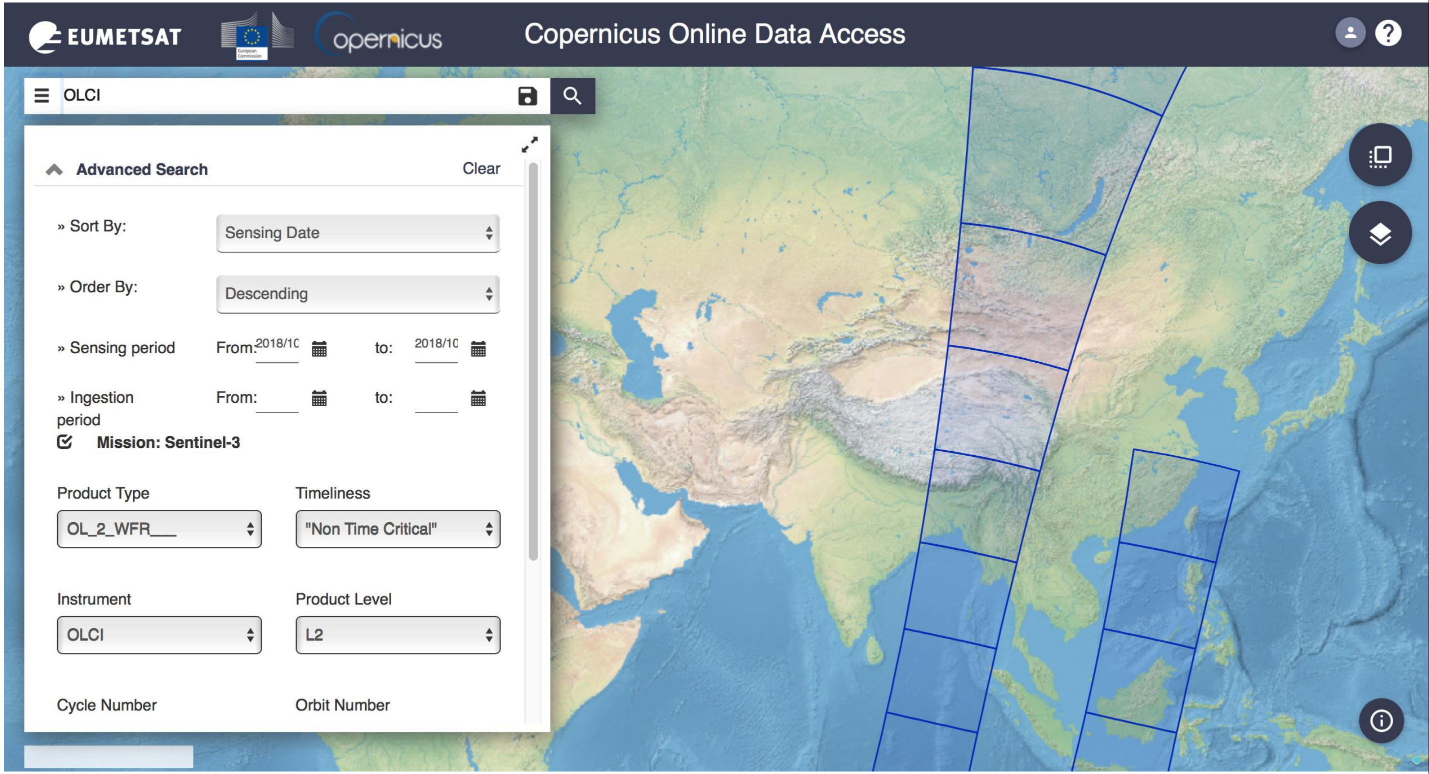
Product type	Available to the User?	Description	Level
OL_1_EFR___	Yes	Full Resolution Top Of Atmosphere radiance	Level 1
OL_1_ERR___	Yes	Reduced Resolution Top Of Atmosphere radiance	
OL_1_RAC___	No	Dark offset and gain coefficients from radiometric calibration	
OL_1_SPC___	No	Wavelength characterization from spectral calibration	
OL_2_WFR___	Yes	Full Resolution Water & Atmosphere geophysical products	Level 2
OL_2_LFR___	Yes	Full Resolution Land & Atmosphere geophysical products	
OL_2_WRR___	Yes	Reduced Resolution Water & Atmosphere geophysical products	
OL_2_LRR___	Yes	Reduced Resolution Land & Atmosphere geophysical products	

Data access

Granule browsing and searching available at https://coda.eumetsat.int/#/home

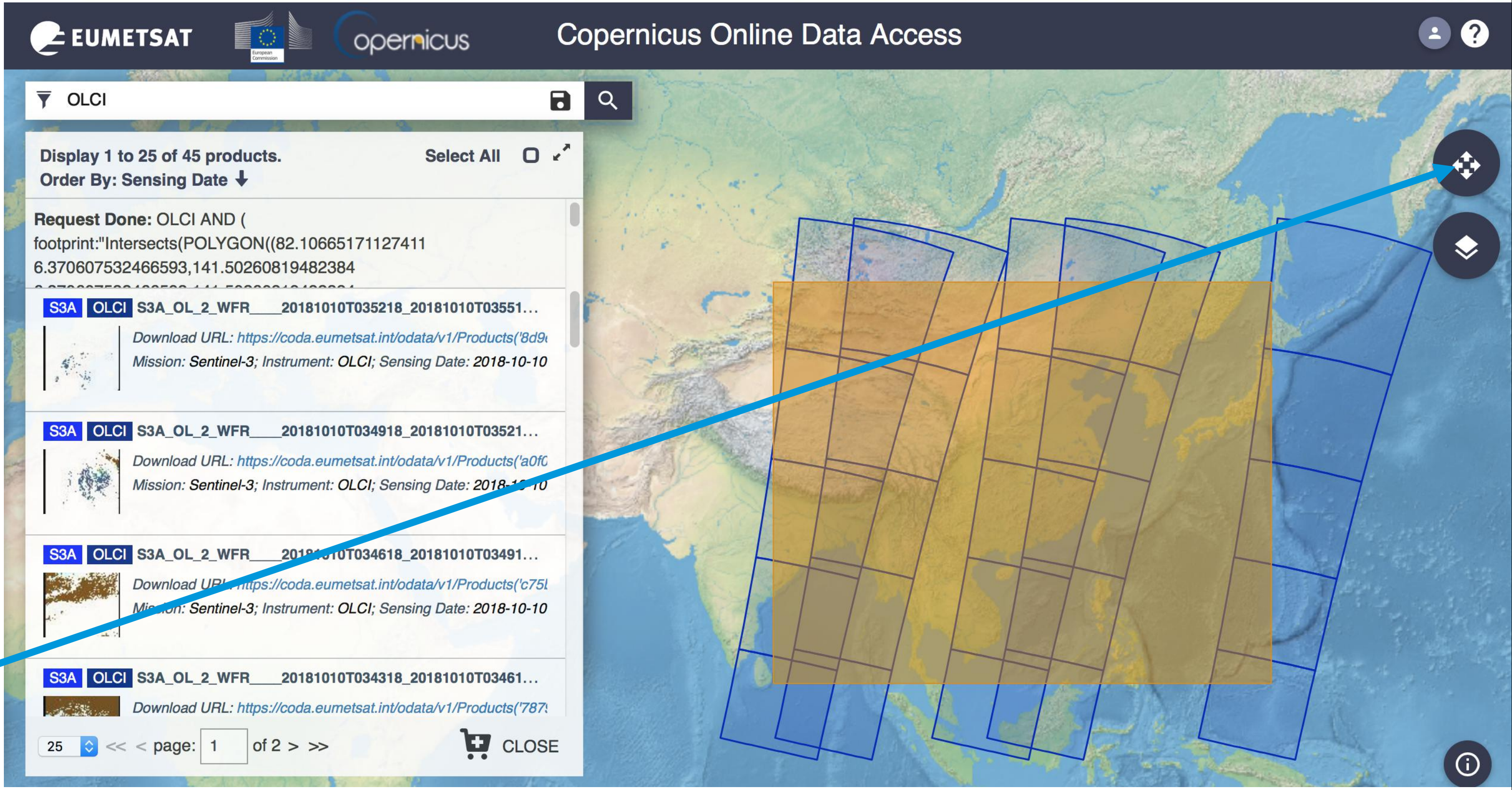
- Download single granules or full orbits
- Mass download via ftp

Guide at https://coda.eumetsat.int/manual/CODA-user-manual.pdf



Data access

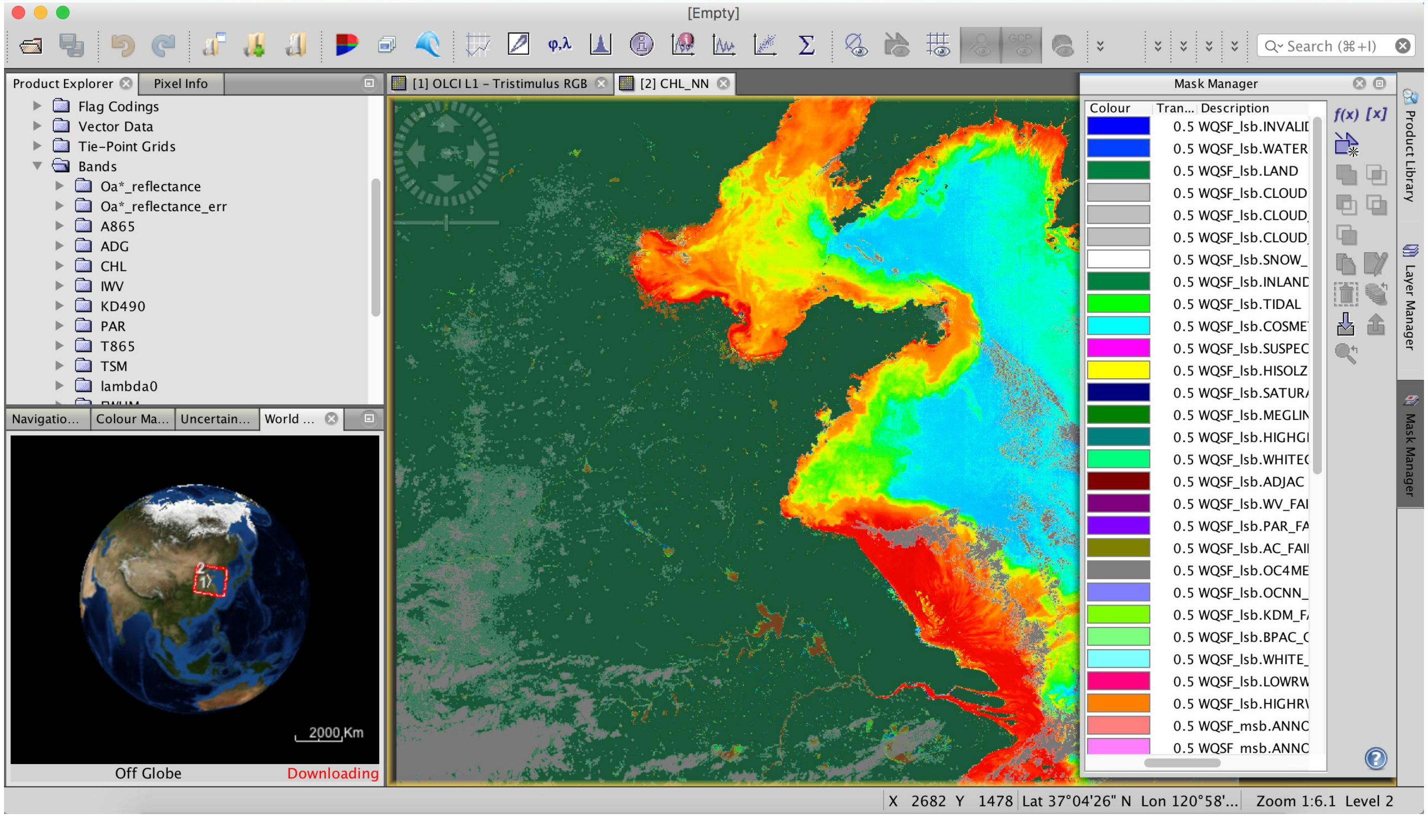
Region filtering is also possible through the CODA data browser using the 'Draw region of interest' toggle rather than the 'Navigate on map' mode.



SNAP as a data viewing & processing tool

SNAP allows visualisation of bands, flags, etc. It also has data processing and analysis tools.

http://step.esa.int/main/toolboxes/snap/



SNAP as a data viewing & processing tool

SNAP allows visualisation of bands, flags, etc. It also has data processing and analysis tools.

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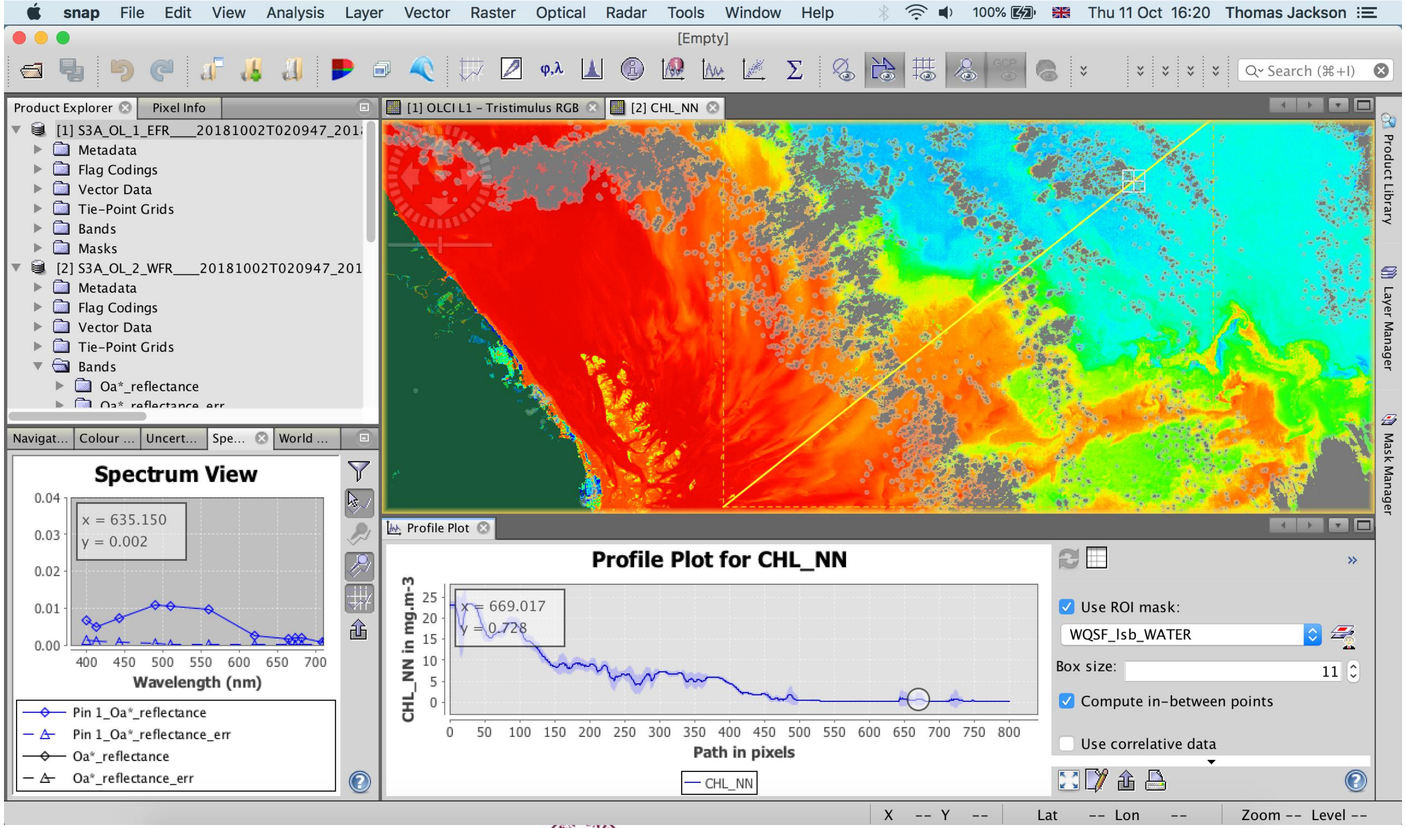

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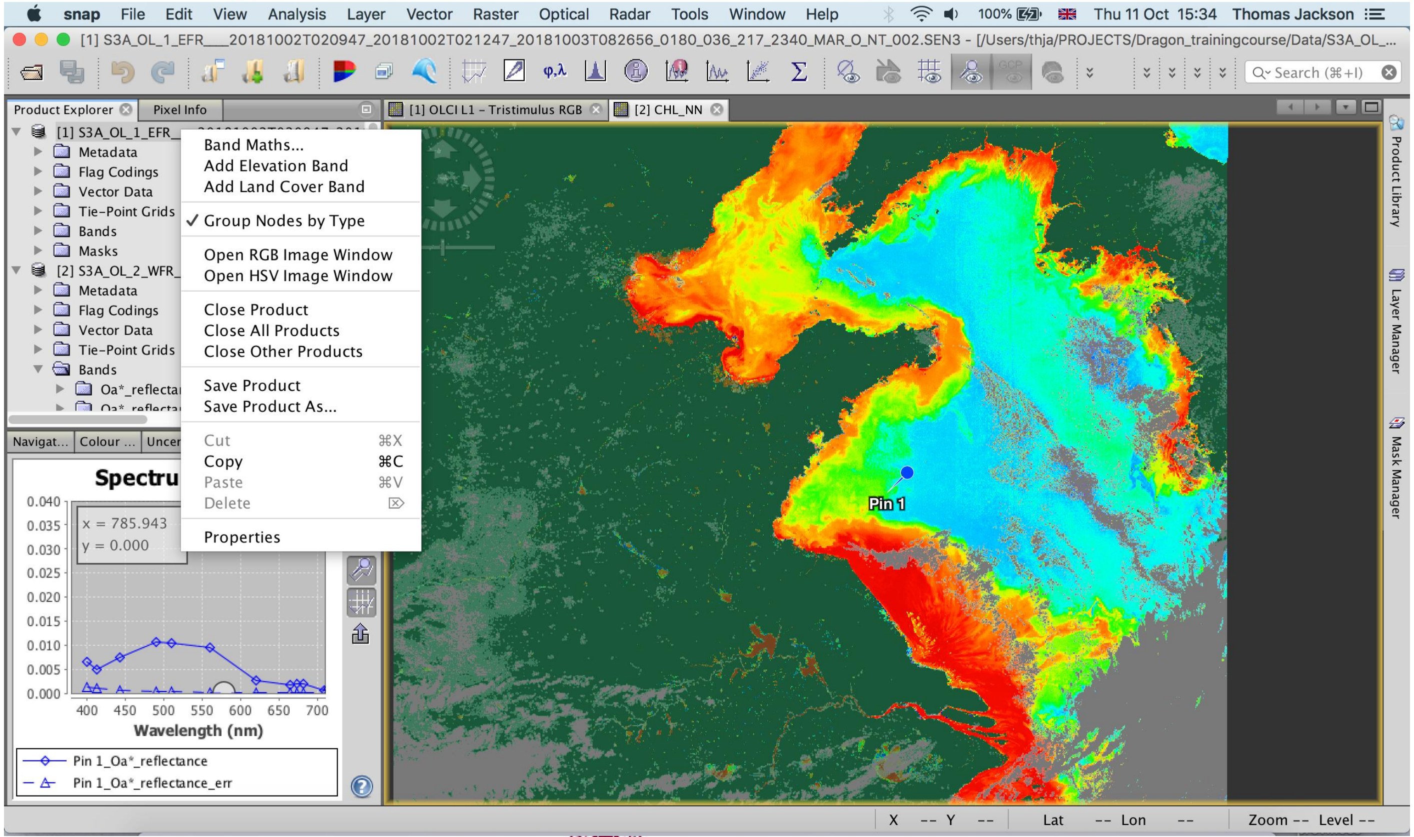
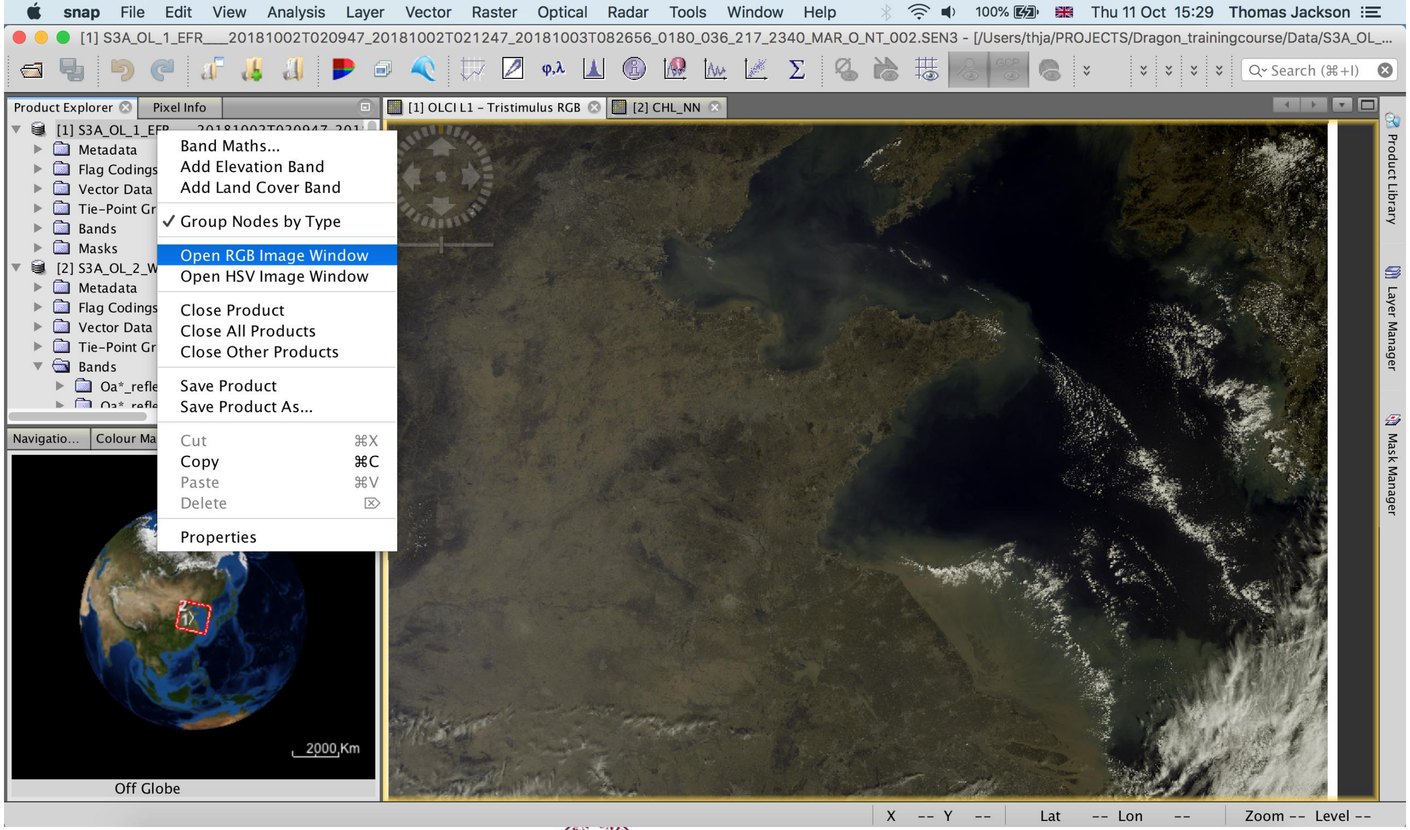


SNAP as a data viewing & processing tool

SNAP allows visualisation of bands, flags, etc. It also has data processing and analysis tools.

http://step.esa.int/main/toolboxes/snap/



Coding and batch processing

GUIs and portals give a great way to quickly view and interrogate data but if you want to do any significant bulk processing of data you will probably end up resorting to using some sort of dedicated coding. A number of languages can be used for processing of remote sensing data including:

- C (and its derivatives)
- python
- IDL
- R
- Java

Each language has its own benefits and drawbacks such as memory usage, ease of use, speed of processing, compilation requirements etc, etc.

In order to choose the best language for the task it is worth framing and understanding your process before you begin coding.

Coding and batch processing

Here is an example of some python code that is designed to read in data from a netcdf file and plot an image.

```
#!/usr/bin/env python
# global map of chlorophyll
import netCDF4
import numpy as np
import matplotlib.pyplot as plt
import matplotlib as mpl
from mpl_toolkits.basemap import Basemap
#from mpl_toolkits.axes_grid1 import ImageGrid

file = ".//Example_Ocean_colour_file.nc"
ds = netCDF4.Dataset(file)

def plot_var(ds, var):
    m = Basemap(projection='cyl', resolution='c', llcrnrlat=-90, urcrnrlat=90, llcrnrlon
        =-175, urcrnrlon=175)
    # find x,y of map projection grid.
    lon, lat = ds.variables['lon'][:], ds.variables['lat'][:]
    lons, lats = np.meshgrid(lon, lat)
    x, y = m(lons, lats)
    array = ds.variables[var][:]
    if var == "esa_oc4":
        masked = np.ma.masked_where(array == 0, array)
    else:
        masked = array
    norm = mpl.colors.LogNorm()
    im = m.pcolormesh(x, y, masked, vmin=0.01, vmax=30, norm=norm)
    m.drawcoastlines(linewidth=0.1)
    m.fillcontinents(color='0.8', lake_color='white', zorder=0)
    return im


fig = plt.figure(figsize=(9, 4))
plt.title("Chlorophyll-a from remote sensing")
im = plot_var(ds,"chlor_a")
cbar = plt.colorbar(im, format="%g")
cbar.set_label("Chl a mg/m$^3$")
plt.tight_layout()
plt.savefig('example_out_chlorophyll.png', bbox_inches='tight', dpi=150)
plt.close("all")
```

Coding and batch processing

Here you can see modules that provide useful functions for data processing are being made available.

```python
#!/usr/bin/env python
# global map of chlorophyll
import netCDF4
import numpy as np
import matplotlib.pyplot as plt
import matplotlib as mpl
from mpl_toolkits.basemap import Basemap
#from mpl_toolkits.axes_grid1 import ImageGrid

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   m = Basemap(projection='cyl', resolution='c', llcrnrlat=-90, urcrnrlat=90, llcrnrlon=-175, urcrnrlon=175)
   # find x,y of map projection grid.
   lon, lat = ds.variables['lon'][:], ds.variables['lat'][:]
   lons, lats = np.meshgrid(lon, lat)
   x, y = m(lons, lats)
   array = ds.variables[var][:]
   if var == "esa_oc4":
      masked = np.ma.masked_where(array == 0, array)
   else:
      masked = array
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   im = m.pcolormesh(x, y, masked, vmin=0.01, vmax=30, norm=norm)
   m.drawcoastlines(linewidth=0.1)
   m.fillcontinents(color='0.8', lake_color='white', zorder=0)
   return im


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plt.savefig('example_out_chlorophyll.png', bbox_inches='tight', dpi=150)
plt.close("all")
```

Coding and batch processing

Here the netcdf4 file is identified.

```python
#!/usr/bin/env python
# global map of chlorophyll
import netCDF4
import numpy as np
import matplotlib.pyplot as plt
import matplotlib as mpl
from mpl_toolkits.basemap import Basemap
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    m = Basemap(projection='cyl', resolution='c', llcrnrlat=-90, urcrnrlat=90, llcrnrlon=-175, urcrnrlon=175)
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    lon, lat = ds.variables['lon'][:], ds.variables['lat'][:]
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        masked = np.ma.masked_where(array == 0, array)
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        masked = array
    norm = mpl.colors.LogNorm()
    im = m.pcolormesh(x, y, masked, vmin=0.01, vmax=30, norm=norm)
    m.drawcoastlines(linewidth=0.1)
    m.fillcontinents(color='0.8', lake_color='white', zorder=0)
    return im


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plt.savefig('example_out_chlorophyll.png', bbox_inches='tight', dpi=150)
plt.close("all")
```

Coding and batch processing

This is a definition of a plotting function which should be handed a dataset and a variable name.

```python
#!/usr/bin/env python
# global map of chlorophyll
import netCDF4
import numpy as np
import matplotlib.pyplot as plt
import matplotlib as mpl
from mpl_toolkits.basemap import Basemap
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   lon, lat = ds.variables['lon'][:], ds.variables['lat'][:]
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   x, y = m(lons, lats)
   array = ds.variables[var][:]
   if var == "esa_oc4":
      masked = np.ma.masked_where(array == 0, array)
   else:
      masked = array
   norm = mpl.colors.LogNorm()
   im = m.pcolormesh(x, y, masked, vmin=0.01, vmax=30, norm=norm)
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   return im


fig = plt.figure(figsize=(9, 4))
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cbar = plt.colorbar(im, format="%g")
cbar.set_label("Chl a mg/m$^3$")
plt.tight_layout()
plt.savefig('example_out_chlorophyll.png', bbox_inches='tight', dpi=150)
plt.close("all")
```
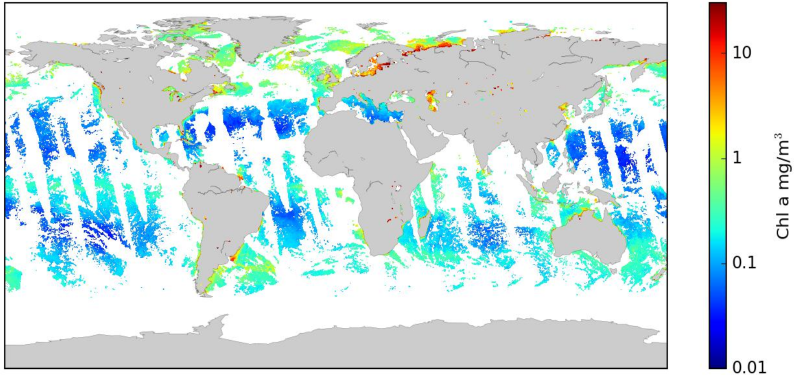

Coding and batch processing

Chlorophyll-a from remote sensing



A figure is created with the plotting function described above. A title is set and the plot saved to a .png file.

```python
#!/usr/bin/env python
# global map of chlorophyll
import netCDF4
import numpy as np
import matplotlib.pyplot as plt
import matplotlib as mpl
from mpl_toolkits.basemap import Basemap
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   # find x,y of map projection grid.
   lon, lat = ds.variables['lon'][:], ds.variables['lat'][:]
   lons, lats = np.meshgrid(lon, lat)
   x, y = m(lons, lats)
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cbar.set_label("Chl a mg/m$^3$")
plt.tight_layout()
plt.savefig('example_out_chlorophyll.png', bbox_inches='tight', dpi=150)
plt.close("all")
```

Useful references

Essential OLCI (Copernicus Marine Data Service) links:

•CODA for download of data from last 365 days: https://coda.eumetsat.int
•CODAREP (Reprocessed historical data): https://codarep.eumetsat.int
•CODA user manual: https://coda.eumetsat.int/manual/CODA-user-manual.pdf
•Data centre (for older data): https://www.eumetsat.int/website/home/Data/DataDelivery/EUMETSATDataCentre/index.html
•Batch scripting for CODA download: https://coda.eumetsat.int/manual/CODA-user-manual.pdf (page 34)
•Video tutorial for CODA downloads: https://www.youtube.com/watch?v=l4oeRYj6_5U&list=PLOQg9n6Apif2Qw_gLhwzhJb3XUoAiUkoq&index=2
Video for OLCI data download and visualisation in SNAP: https://www.youtube.com/watch?v=V3NAuafvlFM&index=3&list=PLOQg9n6Apif2Qw_gLhwzhJb3XUoAiUkoq

Useful references

Useful links for other types of ocean satellite data you may want to use:

-CMEMS (Level 3 and 4, merged, model products): http://marine.copernicus.eu/

-NASA ocean colour (for MODIS and VIIRS, and other historical sensors, plus some in situ data): https://oceancolor.gsfc.nasa.gov/

-Ocean colour CCI (Global merged sensor product for climate studies): **http://www.oceancolour.org/**

Useful general Python links:

-Beginners (general) python tutorials: https://wiki.python.org/moin/BeginnersGuide/Programmers

-Working with marine data: https://oceanpython.org/

For those who work with/wish to work with more GIS based applications, consider

-GDAL: https://pcjericks.github.io/py-gdalogr-cookbook/

-Installing Jupyter notebooks (comes with Anaconda) http://jupyter.org/install.html

-Installing netCDF4: type 'conda install -c anaconda netcdf4' in to the command line (if you have used anaconda install)

Any questions?

谢谢

Thank you for you time and I hope that you have learned something.

Any questions then please ask now or come and find me this week.