Essential Ocean Variable (EOV): Ocean Colour

Background and Justification

The term 'ocean colour' broadly refers to the spectral radiance emanating from the sun that is backscattered off the upper part of the oceanic water column, and which contains information on the properties of the water and its constituents. The phenomenon of colour is the result of absorption and scattering, as light interacts with the water and materials suspended or dissolved within it (i.e., the optically active 'constituents'). Ocean colour encompasses a multitude of biological, biogeochemical, and ecological properties of the ocean, and is an EOV because changes in the colour of the ocean can be related to changes in the presence and magnitude of living and non-living particles and of dissolved materials in the water.

The measurement of ocean colour enables differentiation and classification of different water bodies because the colour of any particular ocean region depends on the proportion, type, and vertical distribution of different dissolved or particulate materials and the depth of the water. Ocean colour is useful for evaluating the health of an ecosystem and to inform resource management, such as fisheries and recreation, in the coastal and open ocean but also in lakes and other inland water bodies. It is also useful to estimate water quality and the amount of heat that accumulates as the ocean absorbs sunlight. In order to fully use the ocean's optical properties to conduct broad ocean science and applications, it is critical for users to understand what type of waters are being observed, and also understand the limitations and possible errors in what are called 'ocean colour products'. These products include the Ocean Colour sub-variables and derived products shown in Table 1.

Measurements of ocean colour (Table 1) include the intensity and spectral variability of light backscattered from below the ocean surface, vertical profiles of the colour of water, and measures of inherent optical properties like the absorption or scattering coefficient. Current methods to observe the ocean's optical properties include underwater optical sensors as well as airborne and satellite observations. These sensors passively measure sunlight backscattered from the upper layers of the ocean. Active sensors equipped with various light sources, including lasers of different colours and filters, are also used to probe the vertical distribution and composition of dissolved and particulate matter and the depth of coastal waters.

Ocean Colour Remote Sensing (OCRS) encompasses radiometric techniques that are continuously evolving. Radiometers measure the solar energy backscattered by the ocean looking at the sea surface from a variety of platforms (satellites, suborbital manned aircraft, unmanned aerial systems (UAS). The water-leaving radiances at different wavelengths contain information on the ocean albedo and the in-water constituents. Water leaving radiances by remote sensing from satellites or high-altitude aircraft are derived from the top-of atmosphere (TOA) radiances after accounting for the atmospheric contribution to the remotely-sensed ocean colour signal, a process referred to as 'atmospheric correction'.

Products derived from OCRS include phytoplankton chlorophyll a concentration, biogeochemical and ecological indices including water quality measures, metrics to gauge phytoplankton physiology, and indicators of ecosystem status and health. Environmental variables such as bathymetry, dissolved organic carbon, and suspended sediment concentration can be derived from OCRS. Additional products useful to model light propagation through the water are derived and used to estimate surface ocean primary productivity, and to model the heating of the surface ocean. While the link between ocean colour and biogeochemistry is most often statistical, it is grounded in mechanistic understanding of the underlying phytoplankton physiology, biogeochemistry, ecology, and optics of the ocean.

The derivation of OCRS products from aircraft and satellites involves complex modelling of required ancillary measurements including solar illumination, atmospheric conditions to estimate radiance reflected and absorbed by gases, aerosols, clouds, and reflections of light off the ocean surface (sun glint). Radiance reflected back to space by the atmosphere contributes generally between 90-95% of the top-of-atmosphere signal. The atmospheric correction process leads to another series of data products including but not limited to aerosol type and aerosol optical thickness.

To date, sustained ocean colour remote sensing observations are obtained routinely from polar-orbiting and geostationary satellites, AERONET-OC stations, and airborne sensors. Ships, buoys, and automated platforms, including gliders, Argo floats, and other various specialized sensors deployed at various sites (including calibration/validation sites, e.g., MOBY, BOUSSOLE), provide complementary in-water optical observations which are used for vicarious calibration of the on-orbit satellite sensors and validation of remotely-sensed data products. The algorithms used for the various products are themselves based on data collected by the international scientific community and shared through various open databases (Table 5).

While the majority of current applications involve passive (sun is the light source) radiometry of light without regard to polarization, promising future application of active (Lidar) remote sensing and of remote sensing of polarized light have been demonstrated. These new methods, combined with advanced radiometric methods, hold the potential to expand and improve the current suite of ocean biological, biogeochemical, and ecological data products to examine the magnitude, range, health, status and trends of life in the ocean, and to address complex ocean biogeochemistry, ecological, and physical processes.

To date, ocean colour sensors have focused on measuring in the visible spectrum of light including PAR (Photosynthetically Available Radiation, or between 400 and 700 nm). However, there is a clear need for ocean colour sensors to observe from the ultraviolet (UV) to the short-wave infrared (SWIR), with high spectral resolution (hyperspectral), and with more sensitive sensors (signal to noise) to enable more precise atmospheric correction over turbid waters, as well as to enable development of new products and revision of existing products, including suspended and dissolved matter in turbid waters, bathymetry, plankton functional types, and other products. It is also clear that there are applications in coastal and inland waters that in addition require higher spatial resolution (i.e., pixels of order of metres to tens of metres) compared to the requirements for global ocean assessments (spatial resolution of hundreds of metres to kilometres).

Table 1: EOV Information	
Name of EOV	Ocean Colour
Sub-Variables	- Top-of-atmosphere (TOA) radiance - Remote sensing reflectance (Rrs(λ)) - Downward spectral irradiance (Ed)* - Upward spectral radiance (Lu)*
Derived Products	- Water-leaving radiance and normalized water-leaving radiance [spectral *L(λ)* and *nL(λ)*] - (Incident) Photosynthetically Available* Radiation (PAR) - Chlorophyll-a concentration Inherent Optical Properties (IOPs): - Total absorption coefficient-a; - Absorption coefficient due to phytoplankton pigments (a_{ph}) - Absorption coefficient due to coloured dissolved and detrital organic matter (a_{dg}) - Absorption coefficient due to coloured detrital organic matter (a_d) - Absorption coefficient due to coloured dissolved organic matter (a_g) - Backscattering coefficient (b_b) - Backscattering coefficient due to particles (b_{bp}) Apparent Optical Properties (AOPs): - Diffuse attenuation coefficient [K_d, typically for blue-green light at 490 nm and for PAR] Water quality, Ecological (phytoplankton community), Biogeochemical, and other properties: - Total Suspended Solids [TSS, *also referred to as Total Suspended Matter and Particulate Matter*] - Fluorescence Line Height (FLH) - Net Primary Production *[for example, modelled using PAR and Sea Surface Temperature]* - Plankton (including Phytoplankton) Functional Groups and community structure - Water quality/Harmful algal bloom indices, including Harmful Algal Events - Floating algae and floating macrophyte indices - Concentration of Particulate Organic Carbon - Concentration of Particulate Inorganic Carbon - Carbon stocks (sources and sinks) and fluxes
Supporting Variables	Some of these are referred to as ancillary variables as they are used in atmospheric correction models and in the derivation of some products: *https://oceancolor.gsfc.nasa.gov/docs/ancillary/* - Sea surface temperature EOV - Sea ice EOV

	- Sea surface height EOV - Ocean surface stress EOV - Sea surface salinity EOV - Meteorological data (surface pressure, relative humidity, cloud cover) - Concentrations of atmospheric gases (water vapour, ozone, nitrogen dioxide) - Bathymetry - Normalized differential vegetation index (NDVI) Algorithm development and calibration/validation variables: - In situ radiometry observations and bio-optical/biological/biogeochemical observations - Phytoplankton biomass and diversity EOV - Particulate matter EOV: particulate organic matter concentration [for biomass/productivity], total suspended organic matter concentration [for biomass/productivity] - Coloured Dissolved Organic Matter (CDOM) concentration or visible light absorption - Bio-optical variables (remote sensing reflectance, absorption coefficients) - HPLC pigments
Responsible GOOS Panel	GOOS Biogeochemistry Panel Contact: ioccp@ioccp.org The Ocean Colour EOV Specification Sheet is developed and jointly maintained by members of the International Ocean-Colour Coordinating Group (IOCCG), GOOS Biogeochemistry Panel and GOOS Biology and Ecosystems Panel.

*Naming convention after:

- Morel, A., & Smith, R. C. (1982). Terminology and Units in Optical Oceanography. Marine Geodesy, 5(4), 335–349.
- Mueller, J. et al. (2003). Ocean Optics Protocols For Satellite Ocean Color Sensor Validation, Revision 4, Volume I: Introduction, Background and Conventions. NASA Technical Report NASA/TM-2003-21621/Rev-Vol I. Goddard Space Flight Space Center Greenbelt, Maryland 20771, USA.

Table 2a: Requirements Setting				
GOOS Themes	This EOV is needed to deliver against the requirements of all three themes of GOOS: (i) Climate, (ii) Operational services, (iii) Marine ecosystem health			
Applications (as defined by GOOS)	This EOV delivers essential information for the following applications as considered by GOOS: Operational ocean data and forecasting; Climate prediction and projection; Climate analysis and assessment, (incl. fundamental understanding of ocean processes); Hazard response/early warning systems (incl. oil spill, water quality monitoring); Sustainable management (incl. aquaculture management, water quality assessment); Environmental assessment and outlook; Biodiversity analysis and assessment			
Readiness Level **(as defined in the FOO)**	Mature - 8 - “Mission Qualified”			
Phenomena to Capture	**1** **Trends in primary production**	**2** **Phenology**	**3** **Eutrophication**	**4** **Calcification**
Temporal Scales of the Phenomena	seasonal and annual to decadal	seasonal	weekly to decadal	monthly
Spatial Scales of the Phenomena	tens of kilometres to basin and global scale	tens of kilometres to basin and global scale	coastal zones 1-100 km	1-250 km
Magnitudes/Range of the Signal to Capture	0-2500 g-C/m^2/yr	0.01-100 mg-Chl/m^3	10-100 mg-Chl/m^3	0.00001 - 0.02 mol-PIC/m^3
Current Uncertainty Relative to the Signal	max(70%)	max(0.03 mg-Chl/m^3, 30%)	30%	
Target Uncertainty Relative to the Signal	50%	same	30%	

Table 2b: Requirements Setting (continued)					
Phenomena to Capture	**5 Sediment resuspension and transport**	**6 Land sea/riverine fluxes**	**7 Algal blooms (incl. Harmful Algal Blooms)**	**8 Biogeographical shifts**	**9 Water quality**
Temporal Scales of the Phenomena	hourly to weekly	weekly	hourly to weekly	seasonal to decadal	hourly to weekly
Spatial Scales of the Phenomena	<1 km - 100's km	<1 km – 100's km	10-100 km	100-10,000 km	<1 km - 100 km
Magnitudes/Range of the Signal to Capture	1-100 g TSS/m^3	0-500 µmol-DOC/L POC TSS	Presence/absence	Geographic shifts and change in surface area	Attenuation (K_d) & absorption (a_{ph}, a_g) vary depending on wavelength: K_d (490) 0.02-5 m^{-1}; a_{ph} (443) 0.01-2m^{-1}; a_g (443) 0.01-10 m^{-1}; Turbidity: 1-100 gm^{-3}; Functional types: presence/absence
Current Uncertainty Relative to the Signal	30%	50%	Application-specific	50%	Quantified to individual characteristics
Target Uncertainty Relative to the Signal	30%	30%	Uncertainty is in identification of the species responsible for blooms	30%	30%

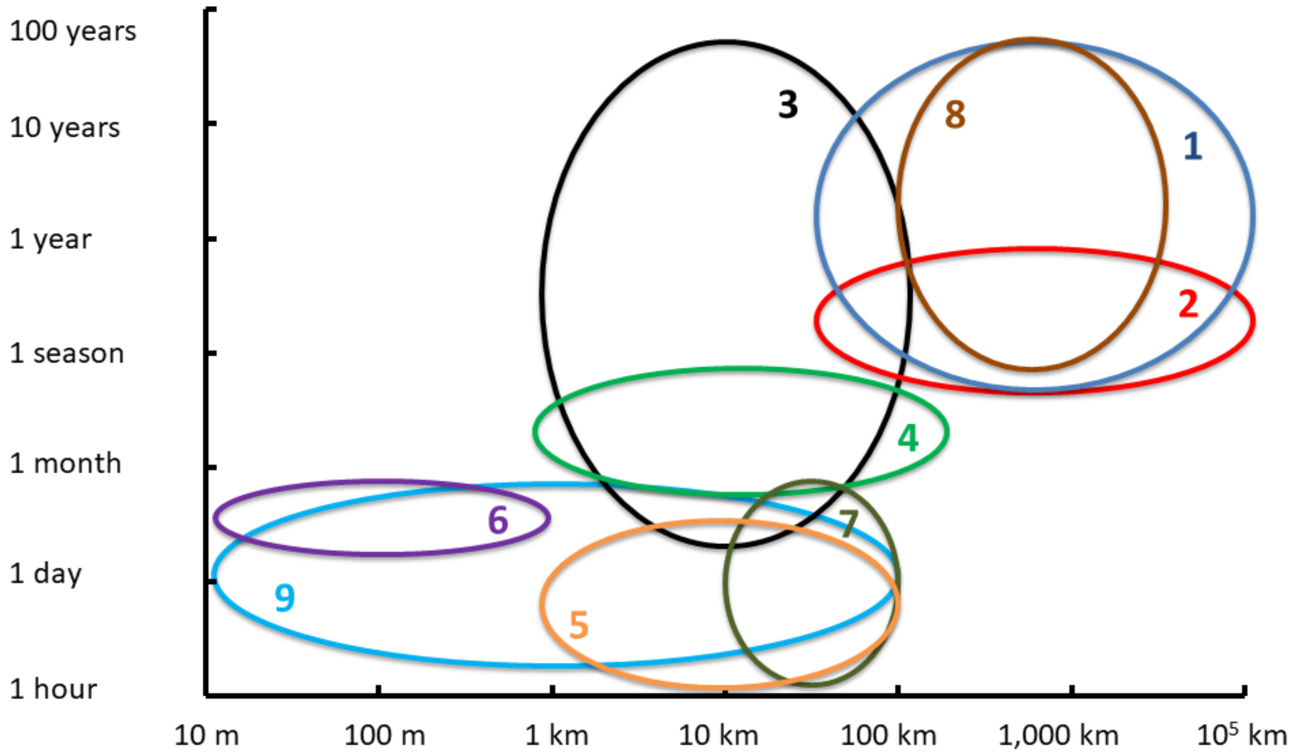

Figure 1: Spatial and temporal scales of phenomena (as colour-coded and listed in Table 2 above).

Table 3: Current Observing Networks			
Observing Approach	**Moored Fixed-Point Observatories**	**Tower Fixed-Point Observatories**	**Satellites**
Readiness Level of the Observing Approach for this EOV	Mature	Mature	Mature
Leading Observing Network(s)	MOBY/BOUSSOLE + other	AERONET-OC	Ocean Colour Radiometry Virtual Constellation + other as on http://ioccg.org/resources/missions-instruments/
Readiness Level of the Observing Network	Mature	Mature	Mature
Phenomena Addressed	**1, 2, 3, 7, 9**	**1, 2, 3, 5, 7**	**1, 2, 3, 4, 5, 9**
Spatial Scales Currently Captured by the Observing Network	Horizontal coverage: Single point Vertical coverage: Surface + two or three depths Footprint: 1 -100 m^2	Horizontal coverage: Single point Vertical coverage: Surface Footprint: 1-100 m^2	Horizontal coverage: Global Ocean with polar orbiting, lower latitude with geostationary. Vertical coverage: Surface Footprint: 10 m^2 -> 1 km^2 (smaller near poles)
Typical Observing Frequency	3 times per day (MOBY). Every 15 min (BOUSSOLE).	Hourly, real time. Number of stations varied in time, currently 17.	Daily->16 days. More near poles

Supporting Variables Measured	CTD, fluorometry, Sometimes IOPs		Profiles of CTD, IOPs and radiometry
Sensor(s)/ Technique	Upward and downward looking radiometers. Radiometers at several fixed depths. HyperSpectral	Upward and downward looking radiometers. Hyper and multi spectral	Downward looking Multi spectral radiometers (varied band width)
Accuracy/Uncertainty Estimate (units)	Better than 5% radiometric accuracy*	Better than 5% radiometric accuracy (~7% at 667nm)*	
Reporting Mechanism(s)	Reports to funding agencies		

*Accuracies as expected by NASA. PIs encouraged to provide separate estimates of errors.

Table 4: Future Observing Capacity				
Observing approach	**Profiling floats**	**Satellites**	**Moored Fixed-point observatories**	**Tower Fixed-point observatories**
What is the novel aspect of this observing approach?	In-situ, profile used to extrapolate to surface; Provides possibility to extrapolate Ocean Colour measurements to depth as well as to validate Ocean Colour products.	Hyperspectral, global, $1km^2$ (PACE) Hyperspectral, local, $30m^2$ (EnMap, PRISMA, Landsat/Hyspiri/SBG-type) Polarimetry (Active) Lidar	Evolution of in situ capacity through: - HARPOONS, HyperNAV, MOBY-NET. - A new Lampedusa (Italy) and other European sites	New hyperspreptral capacity for an evolution of AERONET-OC (through EU HyperthNET)
How does this novel aspect impact our observing capacity?	Ability to vicariously calibrate new missions within a short period of time using multiple floats. Ability to observe the vertical structure.	Ability to measure non-chlorophyll pigments, better separate CDOM from Chl, likely to provide information on (phyto)plankton functional types (taxonomy). Ability to detail ocean particle types and profiles, export carbon fluxes; Ability to follow aquatic biochemistry into ecosystems in coastal regions, estuaries, tidal wetlands and lakes. Ability to potentially characterize hydrosols (particles suspended in the water). Simultaneous retrieval of remote sensing reflectance (Rrs) and aerosol properties, enhancing traditional methods of atmospheric correction with radiometry, particularly in challenging situations near coastlines and inland water bodies, getting at particle complex refractive index and absorption characteristics.		

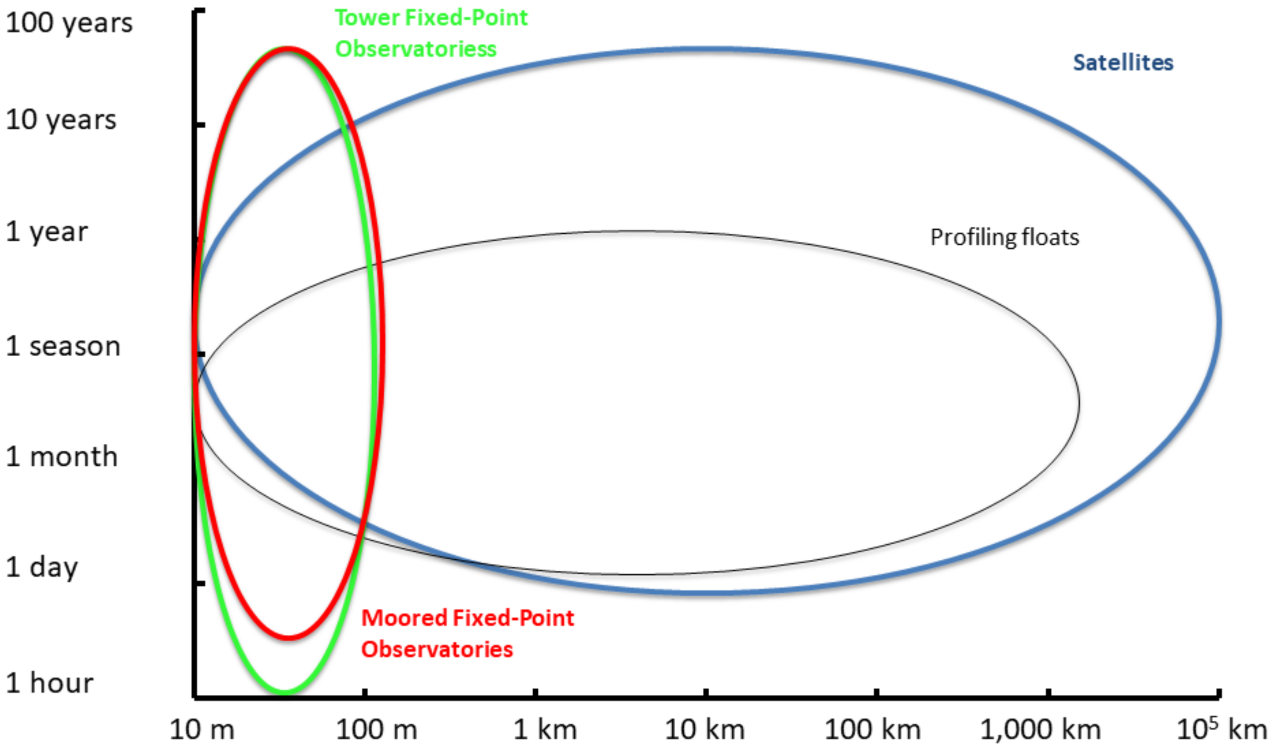

Figure 2. Spatial and temporal observation scales of component networks listed in Table 3 (thick coloured circles) and in Table 4 (thin black circles).

Table 5: Data & Information Creation					
Observing Approach	**Oversight & Coordination**	**Data Quality Control**	**Near Real-Time Data Stream Delivery**	**Data Repository**	**Data Products**
Fixed-Point Observatories (Tower and moored)	AERONET-OC MOBY BOUSSOLE Kavaratti Western Channel Observatory (L4) Fisheries and Oceans Canada buoys network	AERONET-OC MOBY BOUSSOLE Western Channel Observatory (L4) Fisheries and Oceans Canada buoys network	BOUSSOLE Web Fisheries and Oceans Canada buoys network	AERONET-OC web SeaBASS, NOAA NESDIS, NCEI BOUSSOLE Web Western Channel Observatory (L4) Web Mermaid	NASA Ocean Colour Ocean Color Climate Change Initiative CMEMS Ocean Color Thematic Assembling Center GlobColour
Satellite Remote Sensing	OCR-VC	Space Agencies	NASA, NOAA, ESA/EUMETSAT, JAXA, ISRO	NASA Ocean Color Web, NOAA NESDIS/Star, ESA/EUMETSAT Copernicus, JAXA G-Portal	
Ship-based	NASA OBPG AMT	PIs deliver to data centres		SeaBASS BODC PANGAEA	

Profiling floats	Biogeochemical Argo	Biogeochemical Argo	Argo GDACs: US GODAE, CORIOLIS	Argo GDACs: US GODAE, CORIOLIS	

Table 6: Links & References	
Best Practices, Guides and Other Background Documentation	Best practices & guides: IOCCG technical report series: http://ioccg.org/what-we-do/ioccg-publications/ Background documents: International Ocean Colour Coordinating Group (IOCCG). 2008. IOCCG Report Number 7: Why ocean colour? The societal benefits of ocean-colour technology. In: Reports and Monographs of the International Ocean-Colour Coordinating Group. Platt, T., N. Hoepffner, V. Stuart, and C. Brown (Eds.). IOCCG, Dartmouth, Nova Scotia, Canada. International Ocean Colour Coordinating Group (IOCCG). 2012. IOCCG Report Number 13: *Mission Requirements for Future Ocean-Colour Sensors.* Charles R. McClain and Gerhard Meister, (Eds.). IOCCG, Dartmouth, Nova Scotia, Canada. IOCCG Protocols: http://ioccg.org/what-we-do/ioccg-publications/ocean-optics-protocols-satellite-ocean-colour-sensor-validation/ NASA Technical Memorandum, Ocean Optics Protocols for SeaWiFS validation: https://archive.org/details/NASA_NTRS_Archive_19950016254 http://www.oceanopticsbook.info/view/light_and_radiometry/introduction
Links for Contributing Networks	MOBY: https://www.star.nesdis.noaa.gov/sod/moby/ BOUSSOLE: http://www.obs-vlfr.fr/Boussole/html/home/home.php AERONET-OC: https://aeronet.gsfc.nasa.gov/index.html OCR-VC: http://ioccg.org/group/ocr-vc/

Links for Near-Real Time Data Stream Delivery	https://earthdata.nasa.gov/earth-observation-data/near-real-time/download-nrt-data https://coastwatch.noaa.gov/cw_html/OceanColor.html https://www.eumetsat.int/website/home/Data/CopernicusServices/Sentinel3Services/OceanColour/index.html http://www.eorc.jaxa.jp/en/distribution/monitoring/
Links to Data Repositories	https://seabass.gsfc.nasa.gov https://www.bodc.ac.uk https://www.pangaea.de http://mermaid.acri.fr/home/home.php http://biogeochemical-argo.org/# http://www.obs-vlfr.fr/Boussole/html/home/home.php http://www.westernchannelobservatory.org.uk https://oceancolor.gsfc.nasa.gov https://coastwatch.noaa.gov/cw_html/index.html https://www.eumetsat.int/website/home/Data/CopernicusServices/Sentinel3Services/OceanColour/index.html https://gportal.jaxa.jp/gpr/ https://earth.esa.int/web/guest/data-access/browse-data-products/-/article/meris-full-resolution-full-swath-6015 http://www.esa-oceancolour-cci.org http://hermes.acri.fr
Data Product Links and References	Satellite weighted Lw's: https://www.star.nesdis.noaa.gov/sod/moby/gold/ Hyperspectral Lw's and Es: https://www.star.nesdis.noaa.gov/sod/moby/filtered_spec/ https://aeronet.gsfc.nasa.gov/index.html & ocean colour page at: https://aeronet.gsfc.nasa.gov/new_web/ocean_color.html Zibordi et al., 2009: AERONET-OC: A network for the validation of ocean color primary products. J. Atmos. Oceanic Technol., 26, 1634–1651, doi:10.1175/2009JTECHO654.1. Bélanger, S., Carrascal-Leal, C., Jaegler, T., Larouche, P., & Galbraith, P. (2017). Assessment of radiometric data from a buoy in the St. Lawrence estuary. Journal of Atmospheric and Oceanic Technology, 34(4), 877–896, doi: 10.1175/JTECH-D-16-0176.1

Glossary of terms

A **Framework for Ocean Observing (FOO)** is a guide for the ocean observing community to establish an integrated and sustained global observing system that addresses the variables to be measured, the approach to measuring them, and how their data and products will be managed and made widely available. FOO is available from: http://www.ioccp.org/index.php/foo

A **GOOS Essential Ocean Variable** is a sustained measurement or a group of measurements necessary to assess state and change at a global level, and to increase societal benefits from the ocean on scales from global to regional.

Sub-variables are components of the EOV that may be measured, derived or inferred from other elements of the observing system and used to estimate the desired EOV.

Supporting variables are other EOVs or other measurements from the observing system that may be needed to deliver the sub-variables and/or derived products of the EOV.

Derived products are calculated from the EOV and other relevant information, in response to user needs.

A **phenomenon** is an observed process, event, or property, with characteristic spatial and time scale(s), measured or derived from one or a combination of EOVs, and needed to answer at least one of the GOOS Scientific Questions.

A **footprint** is here defined as the area over which given EOV measurements performed by a single observing element (as a transect, station, track, etc.) are representative of a broader region.

List of abbreviations

AERONET-OC	AERONET Ocean Colour
AMT	Atlantic Meridional Transect
AOP	Apparent optical property
BODC	British Oceanographic Data Centre
BOUSSOLE	BOUée pour l'acquiSition d'une Série Optique à Long termE *[the current European system vicarious calibration field site]*
CDOM	Coloured Dissolved Organic Matter
CTD	Conductivity temperature depth
DOC	Dissolved organic carbon
EOV	Essential Ocean Variable
FLH	Fluorescent line height
FOO	Framework for Ocean Observing
GDAC	Global Data Assembly Centre
GOOS	Global Ocean Observing System
GO-SHIP	Global Ocean Ship-based Hydrographic Investigations Program
HPLC	High Performance Liquid Chromatography
IOCCG	International Ocean Colour Coordination Group

IOP	Inherent optical property
MOBY	The Marine Optical BuoY *[the current US system vicarious calibration field site]*
NASA	US National Aeronautics and Space Administration
(n)Lw	(Normalized) water leaving radiance
OCRS	Ocean Colour Remote Sensing
OCR-VC	Ocean Colour Radiometry – Virtual Constellation
OBPG	NASA Ocean Biology Processing Group
PAR	Photosynthetically Available Radiation
PI	Principal investigator
PM	Particulate matter
Rrs	Remote sensing reflectance
TSS	Total suspended solids
TOA	Top-of-atmosphere

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