International Ocean Colour Science Meeting 2025

SUBMITTED ABSTRACTS - Alphabetical Order by Theme

Continuous Research in ocean colour science

Continuous research that is not theme-specific

Current Status of the GOCI-II Atmospheric Correction and Its System Vicarious Calibration

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The Geostationary Ocean Color Imager series (i.e., GOCI and GOCI-II) has advanced ocean color remote sensing by providing synoptic regional observations of coastal and open ocean phenomena in the Northeast Asian Seas. As the first spaceborne ocean color sensor capturing daytime imagery with unprecedented temporal resolution, it has been particularly valuable for studying short-term variability in biological and physical processes. Atmospheric correction is a critical step in retrieving accurate ocean color information, as it compensates for atmospheric scattering and absorption in top-of-atmosphere radiance. The GOCI-II atmospheric correction algorithm builds upon the previous GOCI method, with enhancements to improve accuracy, especially in turbid waters. This is achieved through the addition of two new spectral bands at 620 nm and 709 nm, which help to better characterize in water suspended sediment types in optically complex coastal and estuarine regions. System vicarious calibration (SVC) gains are derived following the SeaWiFS heritage approach, using VIIRS R_{rs} datasets processed by NASA/OBPG. The most recent atmospheric correction, after SVC application, has been rigorously validated with *in situ* radiometric data from both clear and turbid waters, the MarONet system deployed in support of PACE calibration, and the AERONET-OC site at Socheong-cho Station.

Coastal Monitoring Service: A Regional Approach from Copernicus LAC Chile

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Copernicus LAC Chile, the Regional Copernicus Center for Latin America and the Caribbean, aims to meet regional needs in the storage, processing, and distribution of Earth observation data. Among its strategic developments is the Coastal Monitoring Service, designed to adapt Copernicus global marine products into solutions for the specific environmental and societal challenges of coastal areas in Latin America and the Caribbean.

This service integrates satellite data from the Copernicus Marine Service with in situ measurements of key biophysical variables such as chlorophyll, sea surface temperature, salinity, sea level, currents, sea ice, nutrients, carbon, transparency, turbidity, and wave conditions. These in situ data are collected in collaboration with regional institutions.

The initiative's main goal is to calibrate and validate machine learning models, enhancing the spatial and temporal resolution of regional marine products. Additionally, it fosters open access to data, supporting coastal development and evidence-based decision-making in the region.

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Hyperspectral radiometry on BGC-Argo floats: first steps and challenges towards FRM status.

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The BioGeoChemical-Argo (BGC-Argo) program is progressively implementing a global network of profiling floats equipped with biogeochemical and bio-optical sensors, including measurements of downwelling irradiance (Ed) at three wavelenghts : 380, 412 and 490 nm. Since 2022, as part of the ERC-REFINE project, a subset of these floats have been equipped with ruggedized hyperspectral TriOS-RAMSES radiometers, enabling the collection of both Ed and upwelling radiance (Lu) profiles. About fifteen of these floats are currently operational, delivering near real time profiles and surface data every 10 days for various open ocean regions representative of the ocean's bio-optical diversity.

This study evaluates the potential of BGC-Argo floats to meet Fiducial Reference Measurement (FRM) standards for ocean color radiometry satellite validation. To this end, we explore various methods to determine hyperspectral remote sensing reflectance (Rrs) from BGC-Argo floats data. We focus in particular, on the characterization TriOS-RAMSES radiometers and the quantification of platform-specific uncertainties (calibration, light extrapolation, dark offset, temperature dependency, tilt, self-shading, etc.). Our objective is to determine the uncertainty associated to each Rrs measurement obtained from hyperspectral BGC-Argo floats. The approach follows the methodology outlined by Bialek et al. (2020) for the BOUSSOLE buoy and relies primarily on sensor characterizations conducted by the Tartu Laboratory. This study concludes by identifying key gaps that need to be addressed to elevate the current array of hyperspectral BGC-Argo floats to a fleet of FRM-grade platforms.

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Performance assessment of Satellite Chlorophyll-a products and abundance-based models in the coastal waters off-Kochi, Southwest coast of India

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Abstract

Chlorophyll-a(Chl-a) concentration is a major indicator of phytoplankton biomass and has been widely used for assessing phytoplankton abundance and primary productivity in marine environments. Over the past decade, ocean-colour imagery has provided a synoptic-scale assessment of phytoplankton dynamics and their role in marine biogeochemistry and global carbon cycle. This study primarily concentrates on the coastal waters off-Kochi along the southwest coast of India. These optically complex waters are strongly influenced by the southwest monsoon, which promotes nutrient-rich upwelling, primary productivity and phytoplankton growth. Additionally, high riverine discharge and anthropogenic activities further contribute to fluctuations in phytoplankton abundance and size classes in this region. Surface water samples were collected on selected dates over a five-year period (2018-2023) from five different stations of varying bathymetry (5, 10, 20, 30, and 40 m) and sequential filtration methods were employed for estimation of individual phytoplankton size classes (PSC).

The *in-situ* data collected were used to evaluate the performance of satellite derived Chl-a from MODIS-Aqua, Sentinel-3 and Ocean colour climate change initiative (OC-CCI) V6.0 product. Following this, three widely used abundance-based models: Brewin et al. (2010), Sahay et al. (2017) and Shunmugapandi et al. (2021) were used for phytoplankton size class (PSC) estimation. Abundance based models are used to classify satellite ocean colour derived fields of phytoplankton biomass observable as Chl-a, into three size classes, i.e. microplankton (> 20 µm), nanoplankton (> 2 to < 20 µm) and picoplankton (< 2 µm). Our study provides valuable insights in addressing the limitations and improving the performance of these existing algorithms and abundance-based models in optically complex coastal waters. This work also underscores the critical role of satellite remote sensing in improving our understanding of phytoplankton ecology.

Keywords: Chlorophyll-a, Phytoplankton, Upwelling, Phytoplankton size class, Abundance-based models.

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Detecting Floating Plastic Debris in Inland Waterbodies using Sentinel-2 Imagery

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The increasing prevalence of plastic pollution in aquatic ecosystems has necessitated the development of remote sensing tools to monitor and mitigate its impact. Several spectral-based algorithms have been developed based on the spectral characteristics of artificial plastic targets in marine environments. However, their effectiveness in detecting naturally floating plastic debris in inland waters remains unexplored. This study, therefore, assessed two commonly used plastic detection indices, i.e., the Floating Debris Index (FDI) and the Plastic Index (PI), using Sentinel-2 multispectral imagery. Results were validated using high spatial resolution Planetscope-SuperDove imagery and aerial photos captured on the same dates. The findings revealed that FDI and PI effectively detect and differentiate floating debris from water based on spectral characteristics with maximum separability. However, they could not differentiate between plastic materials visible in the captured aerial images and other types of floating litter, such as vegetal material, wood, or organic matter. Although this could be linked to the spectral and spatial resolution of Sentinel-2 imagery, these indices were initially designed and optimized to detect specific plastic targets. This study, therefore, highlights the need to refine these indices further for use on mixed floating materials common in freshwater environments.

Assessing the Ocean Color Capabilities of an Airborne Atmospheric Lidar

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Lidar can help us overcome many of the limitations faced by passive remote sensing, allowing the study of the ocean's biogeochemistry during both day and night, in the presence of absorbing aerosols, and at high solar angles, while also providing information on the vertical structure of the ocean. However, most progress so far has been made using instruments and algorithms developed for atmospheric applications, and there is a growing need to develop new processing schemes for the ocean. To address this gap, the present study investigates the capabilities of the French Lidar Aerosols Nouvelle Génération (LNG) for profiling the upper ocean's optical properties. LNG is a three-wavelength (355 nm, 532 nm, and 1064 nm, with polarization and High Spectral Resolution Lidar, HSRL, at 355 nm) atmospheric airborne lidar. Nine flights were made as part of the CADDIWA campaign in Cabo Verde (September 7th to 22nd, 2021), during which in situ measurements were taken, including profiles of the diffuse attenuation coefficient (K_d) and the particulate backscattering coefficient (b_{bp}). The lidar signal at 355 and 532 nm is pre-processed and corrected for its transient response. Then it is calibrated using bio-optical models and ocean color estimates of chlorophyll-a (from MODIS and OLCI). Following calibration, the lidar signal is inverted to estimate K_d and b_{bp} using common algorithms for 532 nm (Klett, 1981; Churnside and Marchbanks, 2017) and 355 nm (HSRL), and match-ups with the in situ and ocean color data are used to evaluate these estimates. An initial analysis indicates that the subsurface contribution can be identified in the LNG data, with the cross-polarized signal presenting a deeper peak and a wider distribution in comparison to the co-polarized signal. Future results are expected to showcase LNG's potential for ocean color applications and help advance the processing of lidar data for the ocean.

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Quality Analysis of GOCI Series Remote Sensing Reflectance over the East China Sea

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The global ocean color missions, NASA's SeaWiFS to MODIS and VIIRS, has provided continuous Remote Sensing Reflectance (R_{rs}) records for more than 20 years since 1997, thereby establishing an framework for studies on global marine ecosystem changes and variability. Ensuring the continuity and consistency of satellite observations during mission transitions is critical for constructing long-term Climate Data Records (CDRs).

The objective of this study is to insure the continuity of R_{rs} from the Geostationary Ocean Color Imager (GOCI) series (GOCI and GOCI-II) through comparative analysis, which serves as a fundamental dataset for the long-term assessment in the East China Sea (ECS). For this purpose, we used GOCI series data collected during the overlap period (September 2020-March 2021), excluding the In-Orbit Test phase, over the ECS domain (27-36°N, 119-130°E). GOCI-II data were binned to 500 m spatial resolution, and GOCI data were optimally interpolated onto the GOCI-II geolocation grid to achieve spatial consistency between the two datasets. Subsequently, linear trends and correlation analyses were performed to examine the consistency of the GOCI series.

The analysis of R_{rs} during the overlap period shows that, despite the high turbidity in the coastal ECS, the two dataset exhibited strong consistency, with correlation coefficients exceeding 0.97 and RMSE values below 0.02 for most bands except in the shorter wavelengths. These results demonstrate that GOCI series data can reliably support long-term and continuous monitoring of water quality and marine environmental variability, where in situ measurements from ships or buoys are limited. Furthermore, this study highlights the potential of the GOCI series as a robust global-scale mission for future investigations aimed at accurate analysis and prediction of rapidly changing marine phenomena, such as low-salinity water intrusion and marine heatwaves.

Marine Heatwaves Drive Shifts in Phytoplankton Phenology and Seasonal Cycles

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Marine heatwaves (MHWs) are prolonged periods when sea surface temperatures (SST) remain significantly above the climatological mean for at least five consecutive days. Their frequency and intensity have increased in recent decades due to climate change, producing cascading effects on marine ecosystems. As primary producers, phytoplankton are central to the global carbon cycle, and shifts in their seasonal timing (phenology) can disrupt trophic interactions and alter biogeochemical processes.

This study examines phytoplankton phenological responses to MHWs across the North Pacific (100°E–135°W, 18°N–60°N) using MODIS-Aqua Level-3 chlorophyll-a (CHL) data at 4 km resolution, reprocessed to match the 25 km resolution of the Optimum Interpolation Sea Surface Temperature (OISST) dataset. We reconstructed CHL time series for 2003–2023 to evaluate changes in bloom curves during MHW events.

The analysis shows clear regional differences. In the Yellow Sea, higher SST during MHWs leaded the onset of the spring bloom. In the broader North Pacific, bloom initiation occurred slightly earlier, but bloom magnitude declined sharply. These findings indicate that MHWs-induced warming can alter both the timing and intensity of phytoplankton blooms. Such region-specific responses may be indicative of future ocean conditions under continued climate change and emphasize the need to account for local variability when assessing marine ecosystem responses to a changing climate.

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New uncertainty visualisation features in HyperInSPACE Community Processor (HyperCP)

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HyperInSPACE Community Processor (HyperCP) is an open-source processing software for in situ above water radiometry. It is designed to provide hyperspectral support for the PACE mission but also multispectral missions such as Sentinel-3 by processing automated and manually acquired, above-water, hyperspectral ocean color radiometric data using state-of-the-art methods and protocols for quality assurance and control, uncertainty estimation/propagation, sky/sunglint correction, convolution to satellite wavebands, and ocean colour product retrieval. Currently, HyperCP supports Sea-Bird Scientific, TriOS, and IMO radiometers with and without robotic sun-tracking platforms such as SolarTracker, pySAS, So-Rad, and DALEC.

Uncertainties are propagated using Community Metrology Toolkit (CoMet) toolkit developed by NPL. This is an open-source software that provides a means to store and propagate uncertainty and error-correlation information. Depending on the level of information about an instrument calibration and characterisation, uncertainties within HyperCP are handled differently. Correction factors for instrument related effects are used if an individual instrument was fully characterised and the residual uncertainties of that corrections are propagated. For the cases where that knowledge is not available the uncertainties are assigned to a given instrument manufacture-model class based on the results of intensive laboratory testing of several different radiometers from the same class.

Recently implemented development in HyperCP includes visualisation of individual uncertainty contributors allowing users to understand the main drivers of uncertainty in their product of interest, such as remote sensing reflectance. Examples will show spectral dependence in effects of uncertainty contributors on products of interest and how they depend on instrument characteristics and measurement conditions such as cosine diffuser imperfections and varying solar zenith angle.

Finally, we will discuss challenges in the wavelength region below 400 nm both in terms of correction for instrument related effects and uncertainty propagation.

NPL contribution to HyperCP takes place in the frame of the NASA – EUMETSAT – Copernicus FRM4SOC collaboration.

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The autonomous profiling HyperNav system radiometric data processing, quality control, corrections and derivations of water-leaving radiance.

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Ocean color satellite missions require post-launch calibration adjustments known as system vicarious calibration (SVC). The SVC process is used to evaluate and adjust the calibration factor of visible to NIR bands of the ocean color satellite sensor. The SVC method utilizes in-situ water leaving radiance measurements propagated to the top of the atmosphere using the same atmospheric correction functions as in operational processing of ocean color satellites. A new hyperspectral radiometric sensor, HyperNav, is being used to finely and accurately resolve the in-situ upwelling radiance spectrum needed for SVC of the PACE mission OCI sensor and is producing a high number of SVC quality measurements across several ocean locations. The HyperNav is an instrument composed of two hyperspectral upward radiance sensors and is mounted on an autonomous float. In this work, we outline the calibration and characterization processes being used to insure high quality and low uncertainties in the in-situ radiance measurements. We also describe the processing steps applied to the measured upward radiance, including propagating the upwelling radiance measurements from 10 cm deep to above the surface, reconciling the independent radiance measurements from the two radiometric sensors to improve the estimated water-leaving radiance to further constrain uncertainties, and performing quality control, such as flagging shading of a radiometer by the float. Finally, we discuss ongoing work to further reduce uncertainties including corrections for Raman scattering and for BRDF corrections.

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PANTHYR in WATERHYPERNET – investigating calibration stability over time of an automated above-water hyperspectral radiometric sensor

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A network (WATERHYPERNET) of automated hyperspectral radiometers has been set up to provide water reflectance measurements in the visible and near-infrared bands for the purpose of multi-mission satellite validation and water quality monitoring. The PANTHYR (PAN-and-Tilt HYperspectral Radiometer) system discussed here, one of the two autonomous systems in the WATERHYPERNET project, consists of two TriOS RAMSES hyperspectral radiometers (one radiance and one irradiance) making measurements over a range of azimuth and zenith angles, using a sun-tracking instrument pointing package. Data is transmitted to shore daily, then processed and web-distributed automatically in near-real time for integration in satellite mission validation analyzes.

In order to ensure the quality of this data the TriOS sensors at field sites are swapped annually and calibrated at Tartu Observatory (Estonia) for radiometric accuracy, as well as having instrument response characterised for elements such as temperature and cosine effects. This work will investigate changes in these radiometric calibrations over time, to determine whether in-situ data is adversely affected by factors such as instrument drift or environmental degradation of the sensor. This information will be presented in the context of the system's (and network's) relevance to both current and future satellite missions for the purpose of radiometric data validation.

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Towards marine bioluminescence detection by satellite ocean colour

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Marine bioluminescence in the upper layers of the water column presents a threat to surface and underwater naval vessels, which could be visually detected during night-time. One objective of the project called BIOLUMOPS is to develop a predictive map of marine bioluminescence based on satellite imagery, complemented by in situ data collected with gliders. Marine bioluminescence occurs typically at night and is often produced by dinoflagellates and, to a lesser extent generally, by zooplankton, and many other organisms at higher trophic levels. Here, the main focus is first to identify dinoflagellates using daytime satellite images.

The area of study is the Gulf of Lion (Mediterranean Sea). Preliminary studies are based on Landsat-8/9 imagery acquired in March 2025 during a sea survey involving an oceanographic ship and 3 gliders. Satellite images reveal structures consistent with dinoflagellate blooms. For that, atmospheric correction was applied without land masking to preserve potential pixels of emerged dinoflagellates. No glint correction was performed as it might attenuate useful near-infrared signals. Several spectral indices were computed and incorporated in a database as pixel descriptors.

Based on this database, the final aim is to develop a machine learning technique identifying the filamentous structures characteristic of dinoflagellate blooms and their related bioluminescence potential based on the mean individual light signal found in the literature. The three SEAEXPLORER gliders were notably equipped with a UBAT bioluminescence sensor along with a chlorophyll-a fluorescence sensor, CTD and ADCP probes, and an Underwater Vision Profiler (UVP6); all of these give us a broader view of the physical context and type of organisms present during the satellite acquisitions, not only in the surface waters but also in the water column.

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Sentinel 2 Ground Segment Water Processor Sen2Water

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Abstract:

The Sentinel-2 Level 2A product currently provides surface reflectances over all land as well as coastal and inland and water surfaces. However, due to the physics of the problem, a land atmospheric scheme as included in the Sen2Cor atmospheric correction method is not optimal for atmospheric correction over water surfaces, and although the resulting surface reflectance spectra are reasonably good, they do not meet the quality requirements of water quality applications in general, and those of the Copernicus Services for inland and coastal product in particular.

In order to meet the requirements from the community and the Services, a second atmospheric correction scheme has been implemented that delivers aquatic reflectances for all water surfaces, called Sen2Water. The processing chain elements in Sen2Water are identical to the ones used by Copernicus Land Monitoring Service and the Copernicus Marine Monitoring Service, namely the pixel identification IdePix, the atmospheric correction processors Acolite, C2RCC and Polymer, and the merging procedures based on water optics.

The aquatic reflectances from Sen2Water will become part of the Level 2A product by 2027. In the meantime, a stand-alone version of Sen2Water is available and integrated into SNAP, similar to Sen2Cor. The validation done by the Copernicus Services is directly applicable, and it was part of the implementation activity to perform an own validation independently.

The documentation of Sen2Water includes an Algorithm Theoretical Basis Document (ATBD), a Verification and Validation Report and technical software documentation, and we will briefly present key results from the Verification and Validation Report. By 2027, Sen2Water atmospheric correction scheme is expected be implemented as an integral part of the operational ground segment processor. In this implementation, the output of Sen2Water will be merged with that of Sen2Cor.

As the aquatic reflectance will become an additional data layer within the Level 2A product, a continuous validation of aquatic reflectances will be required. Those should follow established practices and protocols, e.g. by IOCCG or by Eumetsat (Sentinel 3 OLCI ocean colour products). However, Sentinel 2 will be used a lot for inland waters where additional complexity exists, and only few FRM quality reflectances measurements are available.

Hyperspectral Drone-based system for above-water Radiometric Acquisitions (HYDRA)

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Unmanned Aerial Vehicles (UAVs), commonly referred as drones, offer unique alternative to in situ measurements performed by fixed structures or ships.
Within such a general framework, this work presents a UAV system named "Hyperspectral Drone-based system for above-water Radiometric Acquisitions" (HYDRA), proposed for above-water radiometric measurements specifically supporting the validation of ocean color data products.
By relying on consolidated measurement methods and a class of widely used hyperspectral radiometers, HYDRA comprises the drone platform allowing to quantify the radiance from the sea L_T, and a complementary ground-station to measure the sky radiance L_i and the downward irradiance E_s.
Measurements aiming at evaluating the performance of the system were carried out in the northern Adriatic Sea in the vicinity of the "Acqua Alta Oceanographic Tower" (AAOT) with almost ideal conditions determined by sun clear from clouds, and additionally sea state, cloud cover and wind speed lower than 2, 2 oktas and 4 m s^{-1}, respectively.
During these tests, HYDRA L_T measurements were complemented by independent and concurrent L_T measurements performed at the AAOT using a hyperspectral radiometer belonging to the same class of that operated on the drone.
Matchups of HYDRA and AAOT L_T showed mean spectral differences generally ranging between 0 and +1% in the 400-580 nm interval, and within $\pm$1% in the 580-700 nm interval. The same differences affected the R_{RS} spectra as a consequence of the fact that the same L_i and E_s values were applied to determine HYDRA and AAOT radiometric products.
The work summarizes HYDRA measurement method, technical solution, and results from field tests, as well as their assessment through concurrent measurements performed from the fixed deployment platform.

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SuperDove radiometric data assessment in coastal and inland waters

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The use of high-resolution (HR) data in aquatic applications increased significantly in the last decade with the launch of decametre-scale optical sensors. More recently, commercial very-high resolution (VHR) sensors, offering finer spatial and temporal resolutions, have been showing the potential of complementing data from high-resolution missions. Among VHR instruments, Planet SuperDoves (SD), with a band-setting similar to Copernicus Sentinel-2 MSI one, a 3-m spatial resolution and quasi-daily revisiting time, show potential for widening the application of optical remote sensing to smaller water basins and to phenomena characterized by fine temporal and spatial scales.

However, the uncertainties in SD products need to be quantified, to assess their fitness-for-purpose to water monitoring applications. Moreover, considering the higher monetary costs of commercial data purchase and environmental costs of data storage, an evaluation of their added value and a meticulous cost-benefit analysis should be carried out.

This work aims to provide uncertainty estimates for SD-derived aquatic reflectance in different water types, benefitting of radiometric measurements from AERONET-OC. Atmospheric-corrected products distributed by Planet and ACOLITE-derived remote sensing reflectance (R_{RS}) data were both evaluated.

The compatibility between SD and Sentinel-2 products was also assessed comparing R_{RS} and Rayleigh-corrected reflectance (R_{RC}) from these satellite sensors.

Results showed quite low performances at all bands for both R_{RS} products, excepted for more turbid waters, with mean relative difference values above +67% (and up to ~ +780%). They highlight a lack of a publicly available robust atmospheric correction processor for SD data for a variety of optical water types. Comparison with Sentinel-2 products showed promising results only when comparing R_{RC} values, mainly for bands at 560, 665 and 705 nm (r^2=0.9). Still, the results of R_{RS} products comparison suggest the need of a harmonization strategy for SD and S2 products, indispensable to consistently merge these data in multi-source monitoring systems.

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Identifying and tracing the journey of volcanic ash in the marine environment: Using the January 15, 2022, Hunga eruption as a case study

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The January 15, 2022, eruption of Hunga volcano produced a modest volume of ashfall (0.1–0.2 km^3 DRE) relative to its plume size (55 km in height, 400-km-wide umbrella) and compared to eruptions of similar intensities (e.g., Pinatubo, 3 km^3 DRE). In addition to the relatively limited volume of ashfall, a significant portion was dispersed across open ocean, hindering sampling efforts. Limited work has been done to trace the subsequent sinking and dispersal of volcanic ashfall in an ocean setting following an explosive eruption. The 2022 eruption of Hunga volcano provides a unique opportunity to examine such submarine transport of ashfall through the ocean, with ample satellite imagery and proximal samples collection available. Here we use ocean color algorithms to detect initial ash at the ocean's surface and then apply a 3D Lagrangian particle tracking model to study the submarine dispersion and settling rates of the 2022 Hunga volcano ashfall in the Pacific Ocean. True color satellite imagery of the discolored water plume is finally used as verification within the model. The biological effect of volcanic ash to "fertilize" the ocean remains an open-ended question and the variables that effect the fertilization potential are still contested. The approach used here to trace volcanic ash at the ocean's surface can be directly inputted into a phytoplankton bloom model, thus shedding light on the potential marine-biological effects of a set volcanic eruption. This remote approach supersedes the need for opportune water column sampling directly after an eruption and can be applied to both historical and future eruption scenarios. With an extension of the model to the seafloor, ashfall units within cores can be retraced to their respective surface location. Such applications could greatly benefit efforts to improve volcanic ashfall mapping in the open ocean.

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IHMSC: A novel iterative hybrid multiple scattering-corrected retrieval method for enhancing accuracy in ocean Lidar profiling inversions

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Ocean lidar technology, an emerging active remote sensing method, excels at revealing the vertical structure of subsurface ocean layers, addressing challenges in carbon flux, phytoplankton analysis, and biogeochemical monitoring. Current lidar inversion methods, however, rely on empirical formulations for homogeneous waters and overlook photon multiple scattering, which introduces significant uncertainties, especially in complex coastal ecosystems. To overcome this, we present an iterative hybrid multiple scattering-corrected retrieval method (IHMSC) based on 117,456 vertical profiles (2017–2024) in the South China Sea. The model combines the optimization of backscatter–attenuation ratios, lidar ratios, and semianalytical simulations of multiple scattering effects integrated with XGBoost machine learning to relate lidar-derived optical properties (Kd, bbp) to biogeochemical parameters (Chl, POC). Compared with the in situ and satellite ocean color products, the results of the validation against multisource data strongly agree: Kd (R=0.84, RMSE = 0.0055 m^{-1}, MAPD = 4.25%, N = 14,019), bbp (R = 0.52, RMSE = 0.0001 m^{-1}, MAPD = 11.71%, N = 12,818), Chl (R = 0.61, RMSE = 0.0055 μg/L, MAPD = 32.82%, N = 113,746), and POC (R = 0.88, RMSE = 20.55 μg/L, MAPD = 18.14%, N = 115,490). These results bridge active and passive remote sensing. This study also reveals the dynamic three-dimensional characteristics of the subsurface phytoplankton layer (SPL) in the South China Sea, revealing spatial and temporal heterogeneity influenced by environment factors. The nearshore SPL shows diurnal variations in thickness and intensity driven by tidal processes: it thickens and ascends during the day and thins and descends at night. Larger tidal amplitudes are linked to shallower layers and higher chlorophyll-a concentrations. These findings demonstrate the potential of lidar technology for large-scale, long-term monitoring of subsurface ocean profiles, offering a valuable complement to in situ and passive satellite remote sensing data.

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Practice and Application of Integrated Satellite-Earth Calibration for China's Ocean Color Satellite

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The integrated satellite-earth calibration performs preliminary calibration of ocean color satellite sensors through onboard solar calibration, and further reduces the uncertainty in the solar calibration and atmospheric correction processes by using system vicarious calibration. This article provides a detailed introduction to the methods and processes of integrated satellite-earth calibration, key issues identified and targeted solutions. It covers aspects such as the periodic influence of the solar beta angle during calibration and the correction of the anisotropic degradation of the solar diffuser. Through practical application on China's ocean color satellites, the accuracy of integrated satellite-earth calibration and the consistency of data products have been analyzed and validated. The results show that the integrated satellite-earth calibration accuracy of China's ocean color satellite meets research requirements, and the data products exhibit high consistency with international mainstream satellites. Through high-precision integrated satellite-earth calibration, the China's ocean color satellite can provide accurate observational information for ocean monitoring and environmental protection, and provide a solid foundation for independently generating climate data records.

Submesoscale Eddy Detection in the South China Sea Based on Satellite-Derived Sea Surface Temperature

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Submesoscale eddies significantly influence ocean energy cascades and material transport, yet their detection remains challenging due to limited spatial resolution of conventional satellite altimeters. Here, we present Sub-Eddy-Net, a novel deep learning algorithm based on an enhanced YOLOv8 framework, designed to detect submesoscale eddies from MODIS Sea Surface Temperature (SST) data in the South China Sea. Our algorithm achieved 0.959 detection accuracy and identified 20,443 submesoscale eddies during 2015–2024. Analysis revealed that cyclonic eddies occurred at higher frequency than anticyclonic eddies, with mean radii of 13.1 and 13.7 km, respectively. Eddies concentrated in coastal regions and the Luzon Strait, with distinct seasonal variability. Cross check with SWOT data revealed 64.3% feature correspondence, 27.1% spatial displacement, and 8.6% SST-exclusive detections, demonstrating superiority over Chla-based methods. Sub-Eddy-Net provides an effective tool for investigating submesoscale ocean dynamics, offering new insights into their contribution to ocean circulation, mixing processes, and climate variability.

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Validation of Satellite Chlorophyll-a products using data collected during the ESA Ocean Training Course 2025

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The ESA Ocean Training Course 2025 (OTC 2025) combined hands-on student training with data collection relevant to satellite ocean colour validation. Aboard the 111-year-old Norwegian tall ship *Statsraad Lehmkuhl*, students and lecturers from 28 nations sailed three cruise legs from April to June 2025, covering the diverse environments of the Norwegian Sea, North Atlantic, and Mediterranean, and in the process generating a valuable in situ dataset.

During the cruise, a continuous spectral inline absorption system (WET Labs AC-S) recorded chlorophyll-a line-height, a proxy for phytoplankton biomass and an Essential Climate Variable due to its role in the global carbon cycle. Continuous underway measurements provide advantages over sparse point sampling, capturing mesoscale variability and improving matchup potential with satellite products. Additional CTD profiles with fluorometric chlorophyll estimates (SBE 19plus V2) complement the dataset.

In this study, we apply standard matchup protocols (e.g., Werdell et al. 2013; Brewin et al. 2016, Pramlall et al. 2023) to compare the inline chlorophyll record with daily L3 satellite chlorophyll products, including multi-sensor GlobColour, OLCI, PACE and MODIS-Aqua. We also evaluate the Copernicus GlobColour L4 product, which is particularly relevant for the data collected in the Norwegian Sea, where persistent cloud cover limits direct L3 matchups.

This preliminary analysis aims to (i) demonstrate the scientific value of data collected during OTC 2025 for satellite validation, (ii) provide an initial assessment of L3 and L4 chlorophyll-a retrievals across contrasting oceanic regions, before later improving matchup accuracy with lower-level satellite products, and (iii) lay the groundwork for future incorporation of HPLC-derived chlorophyll for more rigorous calibration of the inline system. Beyond this first comparison, the study highlights how training initiatives such as the OTC enhance synergies between in situ observations and satellite ocean colour, while educating the next generation of ocean scientists.

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Enhanced Continuity of Ocean Colour Observations from Sentinel-3 Next Generation Optical

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The Sentinel-3 Next Generation Optical (S3NGO) mission will enable a major advancement in ocean colour monitoring, building upon the foundation of the current Sentinel-3 constellation. Central to these improvements is the Advanced OLCI (AOLCI) instrument, which introduces several key enhancements. Firstly, the spatial resolution is doubled, moving from 300 m in the first-generation OLCI to 150 m in AOLCI. This finer resolution enables more detailed observation of oceanic features and coastal processes, supporting a broader range of scientific and operational applications.

Secondly, AOLCI maintains the high signal-to-noise ratio (SNR) characteristic of the first-generation OLCI, even with the increased spatial resolution. This ensures that the improved detail does not come at the expense of radiometric performance, preserving the quality and reliability of ocean colour data for downstream Copernicus services and user communities.

Most notably, the spectral capabilities of AOLCI should be dramatically expanded. The S3NGO Mission Advisory Group has recommended the downlink of 408 hyperspectral channels, a substantial step forward from OLCI's 21 bands. These channels span 340–1040 nm with fine spectral sampling, enabling hyperspectral observations that will revolutionise the retrieval of ocean colour products, including phytoplankton functional types and ocean primary production. ESA is currently examining the feasibility and trade-offs associated with this recommendation.

Enhancements to the other main instrument onboard, the dual-view Advanced SLSTR (ASLSTR) are the resolution of 500 m for all channels (including those in the thermal infrared) and three additional bands at 440 nm, 1.24 µm and 8.7 µm that wil enable new applications and improved synergy with AOLCI.

Collectively, these enhancements mean that S3NGO will continue and strenghten Sentinel-3 role as the European reference mission for ocean colour, offering unprecedented spatial and spectral detail, improved radiometric performance, and continuity for Copernicus operational services. The mission will support advanced monitoring of marine biodiversity, ecosystem dynamics, and climate-relevant processes in the coming decades.

The S3NGO mission is currently entering Phase B of development (preliminary definition), with the first of two satellites expected to be launched in 2034.

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Beach litter detection: from Laboratory-based analyses to remote sensing detection

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Marine litter is one of the most pressing global challenges, with significant negative impacts on coastal ecosystems and human health. In-situ sampling, remote sensing, and hydrodynamic modelling are useful tools to address the issue of marine litter (Bellou et al., 2021).

Remote sensing offers several advantages for detecting plastic litter, such as efficiently mapping large or inaccessible areas like dunes and lakes (Manfreda et al., 2018; Andriolo et al., 2022). However, the lack of standardized protocols for monitoring techniques, combined with technological limitations, makes the detection of marine litter complex.

Additionally, laboratory experiments aimed at creating spectral libraries are often carried out without standardized protocols, producing heterogeneous data across different scientific groups and limiting the replicability of the measurements.

In this framework, this research activity aims to address these gaps.

Following a beach litter monitoring campaign, a subsample of collected beach litter was spectrally characterized using two different experimental setups primarily differing in the illumination conditions: direct light inside a black box and diffuse light inside a white box. The analyses highlighted the main differences between the two experimental setups and provided useful insights for defining a standardized protocol.

The possibility to detect litter on sandy background was evaluated by identifying the promising spectral bands for debris detection. The spectral angle mapper (SAM) index was applied, showing that visible and near infrared wavelengths are suitable for effective litter detection.

Future developments of this research will focus on identifying currently operating satellite sensors that show the greatest potential for detecting litter on sandy beaches.

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Integrating TriOS RAMSES Hyperspectral Data with Satellite Ocean Colour to Monitor the Northeast Atlantic.

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The detection and monitoring of phytoplankton functional types (PFTs) are critical to understand marine ecosystem dynamics and assess the impacts of climate change on ocean biogeochemistry. Recently, Ireland's capability to monitor ocean colour in NE Atlantic waters has advanced through a project called "Integrating remote sensing into ecosystem change and marine management processes" funded by the European Maritime, Fisheries and Aquaculture Fund (EMFAF). This project aims to enhance Ireland's capacity in the use of remote sensing data from satellites providing policy relevant data and evidence. Implemented technical advancements include continuous hyperspectral measurements with in-air TriOS RAMSES hyperspectral sensors installed on the Irish national research vessels, the RV Celtic Explorer and the RV Tom Crean. Hyperspectral sensors are mounted on a newly acquired autonomous platform called the Solar tracking radiometry platform or So-Rad (Plymouth Marine Laboratory). This system provides high-resolution, FRM (Fiducial Reference Measurements) quality datasets that are essential for validating satellite products while also supporting the development of region-specific algorithms, specifically for the North-East Atlantic region. In concert, a Data Management - Quality Management Framework (DM-QMF) approach exists, with workflows for procedures, data processing, quality control, and integration into global databases such as NASA's SeaBASS.

Here, we will present the project framework, including methods for ship-based radiometric sampling, initial insights from data collection and the workflow involved for data processing.

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Hyperspectral radiometry on BGC-Argo floats: A Quality-Control Procedure for Bio-Optical Applications of Hyperspectral Radiometric Upwelling Radiance and Downwelling Irradiance Profiles.

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Since 2012, the BioGeoChemical-Argo (BGC-Argo) program has included measurements of downwelling irradiance (Ed) at three wavelengths on autonomous profiling floats. Between 2022 and 2024, a dedicated array of about fifteen BGC-Argo floats equipped with TriOS-RAMSES hyperspectral radiometers measuring Ed and upwelling radiance (Lu) was deployed across open-ocean regions characterized by diverse bio-optical conditions. To date, these floats have acquired 698 profiles of both Ed and Lu from 300 m up to the surface every 10 days around local noon, independently of weather conditions. Therefore, robust quality control is essential, especially for downstream applications such as ocean color remote sensing reflectance validation or diffuse light attenuation coefficients (Kd/KL) computation.

This study proposes an automated Quality Control (QC) method for hyperspectral Ed and Lu profiles measured by BGC-Argo floats, building upon previous QC procedures developped for multispectral radiometry. The method identifies and flags perturbations in the light field, such as those caused by atmospheric clouds, wave focusing, spikes, and applies correction for dark current. The procedure consists of two main steps: first, at five key wavelengths (380, 443, 490, 555, and 620 nm), the quality of individual data points is assessed throughout each vertical profile, resulting in wavelength-specific QC flags. Then, these flags are synthetisized to assign a global QC classification (*Good*, *Questionable*, or *Bad) for* the full spectral profile. This study is associated with a Python code which offers the ocean optics community a robust, standardized and computationally efficient approach to quality control hyperspectral BGC-Argo data, facilitating its use for further bio-optical applications.

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Spatio-temporal distribution of Coloured Dissolved Organic Matter on the Scotian Shelf, Eastern Canada.

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Colour dissolved organic matter (CDOM), as quantified by its absorption properties, plays a crucial role in the underwater light regime, impacting primary production and satellite ocean colour products if not properly accounted for. Therefore, information on its spatio-temporal dynamics contribute to our understanding of marine ecosystems function. In the current study, we used data collected during six cruises occurring in spring (2) and fall (4) on 10 transects distributed over the Scotian Shelf and in the Gulf of Maine (eastern Canada) between 2021 and 2023. Samples were collected within 10 m of the surface, immediately filtered on board and stored in amber bottles at 4^{o}C until processing in the laboratory on an Ultrapath UV-visible spectrometer within a month of collection.

In general, CDOM absorption at 443 nm had higher variability in the fall relative to spring, with a seasonally independent south-north gradient increasing from about 0.09 m-*1* in the Gulf of Maine to about 0.15 m-*1* at the entrance of the Gulf of Saint-Lawrence. The more southern transects (~ <45 N) had 10-20% lower average absorption in fall relative to spring, with the northern transects being upwards of 40% higher in fall than in spring on average.

One also observes a across shelf gradients with higher values close to shore. When compared to phytoplankton and detritus absorption at 443 nm, CDOM absorption contributed between 20% (off shore stations in Fall) and 95% (Spring coastal station of the Cabot Strait, entrance of the Gulf of Saint Lawrence). Our results hypothesis a main source of CDOM from the Gulf of Saint-Lawrence that travel along the coastal Scotian Shelf, and second source in the Gulf of Maine, while local production on the Scotian Shelf remains small.

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Satellite Detection of Volcanic Ocean Discolouration Events: Insights from MODIS and Sentinel-2 Observations

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Although submarine volcanism is estimated to account for over 75% of global volcanic activity, playing a critical role in carbon cycling, influencing ocean geochemistry, and supplying nutrients to marine ecosystems, these events remain poorly documented - particularly in shallow arc settings.

Due to their remote locations and unpredictable nature, submarine eruptions are challenging to detect in near real-time. However, one of their most recognizable surface manifestations - especially in shallow-water environments - is the formation of discolouration plumes, formed by the interaction of hot volcanic fluids with cold seawater. These plumes, which vary in colour depending on the concentration of elements such as iron, aluminium, and silica, offer a valuable opportunity for detection via ocean colour remote sensing.

This study investigates the surface reflectance signatures of shallow submarine eruptions and their impacts in the Tonga-Kermadec region, using a combination of MODIS and Sentinel-2 imagery processed through Google Earth Engine. Preliminary analysis suggests that discolouration plumes associated with these types of events exhibit distinct spectral signatures, which can be differentiated from other optically similar oceanic features such as chlorophyll blooms. A possible outcome is the fertilization of surrounding waters following an eruption, driven by volcanic nutrient input, which can enhance local phytoplankton productivity - a reaction that has already been observed, such as at Home Reef in 2006.

These results will serve as the foundation for the development of a classification tool capable of detecting and tracking submarine volcanic eruption impacts in near real time. Future work will expand the workflow to include other surface manifestations, such as pumice rafts, and integrate additional sensors and data products. Beyond detection, this approach will also help advance our understanding of how submarine volcanism affects local water quality and marine biogeochemistry in remote and under-observed ocean regions.

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Advanced training to support the use of fiducial reference measurements for satellite ocean colour validation

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In 2024 and 2025 advanced training courses were held to promote the outputs of the Copernicus FRM2SOC2 project led by EUMETSAT in support of the EU Copernicus programme, and related initiatives from NASA. The goal of the FRM4SOC2 project has been to establish complete radiometric traceability for Ocean Colour products through validation with fiducial reference measurements (FRM), i.e. a radiometry quality stamp on the Ocean Colour data. FRM4SOC2 produced radiometer characterisations and calibrations, developed measurement procedures (complementing those from the IOCCG), and provided tools allowing the full radiometric uncertainty propagation.

The "FICE" (Field Instrument Comparison Exercise) trainings took place in Venice. In parallel to the trainings, radiometer comparisons took place to understand the instrument differences and validate the developed protocols and software tools. The trainings aimed to share this experience and resources with the wider community, whilst also taking advantage of both the present expertise, and the opportunity to show cutting edge research in action.

The two week courses featured:

- Expert lectures from the project team
- Practical experience collecting field measurements, including at the Acqua Alta Tower
- Hands-on tutorials for working with Copernicus Sentinel-3 OLCI and PACE data
- Introduction and practical exercises for working with the HyperCP processor and ThoMaS matchup toolkit
- A group project phase, where participants processed data they had collected themselves and conducted real validation against multiple satellites. Participants presented their results and reflections to consolidate their learning.

The participation in the course included students from Europe the USA, European, South America and Asia. This poster will present the structure of the course, the resources used, outcomes of the training, and plans for the future to maintain and expand the community who are capable of making such measurements to the benefit of all satellite ocean colour data producers and users.

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Validation of PACE water products based on So-Rad *in situ* data collected onboard the R/V Gaia Blu in the Mediterranean Sea

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Satellite-derived Ocean Colour (OC) products are essential for monitoring marine ecosystems and climate-relevant parameters, including phytoplankton biomass and optically active constituents. The accuracy of these products relies on rigorous calibration and validation protocols supported by high-fidelity in-situ measurements.

A So-Rad system was installed onboard the Italian national oceanographic vessel RV Gaia Blu in May 2025. The So-Rad system comprises three TriOS Ramses hyperspectral radiometers performing automated above-water radiometric measurements to derive Apparent Optical Properties (AOPs). Radiance measurements (L_i, L_t) and downwelling irradiance (E_s) are processed to compute Remote Sensing Reflectance (R_{rs}), facilitating direct comparisons with satellite-derived OC products.

This study reports the first validation results of the hyperspectral PACE mission OCI utilizing the So-Rad system onboard RV Gaia Blu, targeting the Mediterranean Sea region.
Multiple radiometry processing schemes and matchup methodologies are evaluated to determine their efficacy under diverse optical conditions, optimizing protocol selection based on environmental variability.
As NASA introduced the V3.1 near-real-time processing in July 2025 and stopped the V3.0 processing in August, we will also present a comparison of the V3.0 and V3.1 performance for the May–August data.

Continuous in-situ data acquisition combined with standardized matchup protocols ensures high data quality and frequent spatiotemporal collocations. The mobility of Gaia Blu enables sampling across a broad spectrum of optical and trophic regimes, from coastal to oligotrophic open-ocean waters. This spatial heterogeneity enhances the dataset's representativeness and strengthens the assessment of hyperspectral R_{rs} retrievals across diverse Mediterranean conditions.

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Hierarchical Bayesian Modeling for Robust Estimation of SVC Gains across Multiple Sites

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Accurate ocean color remote sensing requires precise radiometric calibration of satellite sensors. A key step is post-launch system vicarious calibration (SVC), where top-of-atmosphere (TOA) radiance is adjusted using in situ measurements of water-leaving radiance (Lw). For sensors like the PACE Ocean Color Instrument (OCI), this involves comparing satellite TOA radiances with simulations based on high-quality Lw matchups at several reference sites. SVC gains, defined as the ratio of measured to simulated TOA radiance, are typically averaged across sites or matchups to derive a global correction. However, standard averaging approaches have limitations. They often overlook site-specific factors such as environmental variability, aerosol properties, and differences in instrument configuration or matchup quality. This can introduce biases, especially when the number and quality of matchups vary across sites, and makes it difficult to incorporate auxiliary covariates or quantify uncertainty in a rigorous way. To address these issues, we developed a hierarchical Bayesian model that treats site-level gains as samples from a shared global distribution, while capturing site-specific effects through random terms and covariates. This framework supports partial pooling of information across sites, improves robustness when data are sparse or noisy, and yields principled uncertainty estimates at both global and site levels. We applied the model to PACE OCI SVC data from MOBY, MARONET, and HyperNav sites, incorporating aerosol properties and instrument identity as covariates. The model is implemented using Markov Chain Monte Carlo sampling to obtain posterior distributions of global and site-specific gains. Results show that the hierarchical approach produces more stable gain estimates, with better uncertainty quantification and improved handling of inter-site variability, highlighting its potential for enhancing calibration strategies in upcoming ocean color missions.

Estimation of particulate organic nitrogen and phosphorus from satellite observations using neural network-based algorithms

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In the context of anthropogenic perturbation to the nitrogen and phosphorus cycles, determination long-term trends and budget of all nitrogen and phosphorus chemical species in the global ocean remain a significant challenge. This study explores the potential of neural network-based algorithms applied to satellite ocean color observations for estimating surface concentrations of particulate organic nitrogen (PON) and phosphorus (POP) at the global scale. A large training dataset was compiled, combining satellite-derived remote sensing reflectance, $R_{rs}(\lambda)$, inherent optical properties (IOPs), including absorption coefficients of particulate matter, and phytoplankton, particulate backscattering coefficient, as well as chlorophyll-a concentration, sea surface temperature, mixed layer depth, and photosynthetically available radiation. These IOPs were derived from $R_{rs}(\lambda)$ using different available inverse methods.

Validation was conducted using extensive matchup datasets of concurrent in situ measurements of PON and POP. The neural network retrievals showed good agreement with in situ observations across a wide range of environments, from oligotrophic open-ocean waters to coastal regions (*MdAPD* = 23 and 11 % for PON and POP, respectively). When applied to MODIS-Aqua observations, the algorithms reproduced the expected global distribution of PON and POP: elevated concentrations were observed in turbid shelf and coastal regions and in upwelling areas, while low concentrations were found in oligotrophic regions.

Overall, the proposed neural network-based algorithms provide a promising tool to investigate long-term trends and budgets of PON and POP at the global scale, as well as in specific regions impacted by anthropogenic perturbations affecting nitrogen and phosphorus cycles.

Detection of floating marine plastic debris and Phaeocystis globosa foam with a convolutional neural network (U-Net), combining multispectral satellite images and environmental data

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My PhD thesis aims to improve our understanding of the fate of floating plastic debris, its distribution and sources, as well as the increasing threat posed by harmful foam following *Phaeocystis globosa* blooms. High spatial resolution multispectral images from Sentinel-2 coupled with Machine Learning techniques have recently shown to be very promising tools for the detection and classification of plastic debris and floating organic matter, however their similar spectral characteristics make them difficult to discern. These uncertainties make prevention and clean-up projects less efficient. My project proposes an innovative approach that exploits the vast amount of data available today. A convolutional neural network with the architecture of a U-Net will be trained with Sentinel-2 data and additional spectral bands, an extended spatial and temporal context for classification, as well as environmental data that provide hitherto under-exploited information on the presence of debris and foam. Once the detection algorithms have been trained on plastic and foam separately, joint detection of plastic debris and foam will be investigated. A study of the long-term trend of the presence of plastic debris and foam in three specific regions will also provide a better understanding of their behavior and the factors that explain their evolution. Quantifying their past presence will provide a better understanding of the current situation and future scenarios. Ultimately, it will contribute to the scientific basis for an approach to reducing the amount of plastic released into the oceans, and a better understanding of the evolution of plastic debris and foam.

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Satellites as critical national assets for monitoring post fire hazards in coastal waters: a demonstration study following the early 2025 Los Angeles Fires

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In January 2025, Southern California experienced catastrophic wildfires, including the Palisades and Eaton Fires, followed by a succession of intense rain storm events in February 2025. The debris runoff caused coastal plumes that included heavy metals and excess nutrients, which have health implications for the public and marine life. This work leverages multiple remote sensing datasets (i.e., Landsat-8, 9, Planet, PACE, Sentinel-1,2,3), including multispectral, hyperspectral, and radar measurements. Changes in turbidity and surface roughness are visible in satellite imagery post-fire.

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Assessing changes in the processing chain of Sentinel-3/OLCI using reference measurements from fixed autonomous hyperspectral radiometers in four Italian sites.

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The calibration and validation (Cal/Val) of satellite data products using measurement networks and reference sites are fundamental to evaluate the sensor performance during the missions and to assess data quality and integrity. Autonomous in situ radiometer systems can provide extensive, representative and high-quality reference datasets to perform reliable radiometric Cal/Val activities based on match-up analysis.

Four autonomous hyperspectral radiometers have been established at four aquatic sites across diverse optical regimes in Italy: two HYPERNETS/HYPSTAR systems deployed at the Acqua Alta Oceanographic Tower and in Lake Garda in May 2021 and June 2022, respectively; the RESTO station equipped with a WISPStation in Lake Trasimeno since 2018; and the series of Satlantic hyperspectral underwater radiometers installed close to the Lampedusa Island in June 2022.

In this work, we perform a validation analysis using the hyperspectral radiometric datasets acquired at these sites to assess the changes in the processing chain of the Sentinel-3/OLCI WFR product from collection 3 to collection 4. Changes are evaluated by comparing the validation results derived from the match-up datasets including co-collocated in situ and satellite radiometric (i.e., remote sensing reflectance) measurements. Satellite and in situ quality control are based on the recommendations of EUMETSAT and site managers.

Results include a coverage analysis to evaluate flagging differences, as well as metric comparisons based on a common set of match-ups. The results presented in this work show that fixed autonomous hyperspectral radiometer systems are becoming mature and capable of acquiring regularly good quality data to support space agencies for assessing new satellite products as well as changes in processing chains.

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Main pathways transport patterns of plankton communities in the Black Sea

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The main pathways transport patterns of plankton communities in the Black Sea are extracted from climatologic coherent structures (cLCS). The cLCS are derived from daily velocity climatology provided by the Copernicus Marine Service. The present study employs the cLCS to examine and illustrate the horizontal dispersion pattern of algal bloom patches. A comparative analysis is conducted between the spatial patterns of cLCS and the distribution patterns of satellite-derived surface chlorophyll. The findings of this study demonstrate the efficacy of the reconstruction process in elucidating the specific impact of horizontal stirring on oceanic patterns. In addition, the impact of horizontal transport on the distribution of surface chlorophyll is discussed.

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Development of the operational atmospheric correction algorithm for the COCTS2 onboard the Chinese new-generation ocean color satellite

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After the two operational polar-orbiting ocean color satellites HY-1C and HY-1D launched in 2018 and 2020, respectively, China launched the new-generation ocean color observation satellite (named as HY-1E or HY-3A, hereafter called HY-1E) on 16 Nov. 2023. The second-generation Chinese Ocean Color and Temperature Scanner (COCTS2), one of the major payloads onboard the HY-1E, can daily observe global ocean color and sea surface temperature. In this study, we developed operational ocean color retrieval algorithms for the HY-1E/COCTS2 and preliminarily examined their performances. Firstly, the operational atmospheric correction algorithm was established based on look-up tables generated by vector radiative transfer model for coupled ocean-atmosphere system (PCOART), and cross-calibrated by the SNPP/VIIRS-retrieved ocean color products. Then, we proposed a cross-calibration method for correcting the radiance response difference along the viewing angles and obtained the viewing correction functions for each channel. The results showed that the determination coefficient of the linear relationship between cross-calibration simulated radiance at the top-of-atmosphere and HY-1E/COCTS2 measured radiance was larger than 0.95, indicating the good linear response of the HY-1E/COCTS2. Based on the established atmospheric correction algorithms, the HY-1E/COCTS2 data were processed to generate the daily global products of remote sensing reflectance (*Rrs*) and chlorophyll-a concentration (*Chl*) and were validated by the in-situ data and the synchronous products from Aqua/MODIS and SNPP/VIIRS. The mean absolute percentage errors referring to the in-situ data from AERONET-OC were 14.287% (412 nm), 13.341% (443nm), 8.0623% (490 nm), 9.1882% (520 nm), 17.836% (565 nm), 58.474% (620 nm), 63.229% (665 nm) and 61.552% (681 nm), and the ocean color products derived by HY-1E/COCTS2 were consistent with the products from Aqua/MODIS and SNPP/VIIRS, indicating the good performance of HY-1E/COCTS2 to monitor global ocean color environment.

Enhanced Coral Reefs Classification from Remote Sensing with Spatial Information

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Coral reefs represent one of the most biodiverse marine ecosystems on earth; however, they are increasingly threatened by human activities and climate change. Accurate mapping of benthic substrate types such as coral, algae, sand, and rubble is essential for ecological assessment, change monitoring, and conservation planning. Traditional remote sensing approaches, which typically rely on bottom reflectance inversion from multispectral imagery combined with pixel-based classification, often yield fragmented outputs in optically complex shallow waters and are subject to uncertainties in atmospheric correction. To address these challenges, this study proposes a substrate pre-classification model based on Unet++, using global benthic habitat data from the Allen Coral Atlas together with in situ measurements. This model directly employs Rayleigh-scattering-corrected reflectance as input and leverages a multi-scale convolutional architecture that incorporates spatial neighborhood and texture features to enhance spatial awareness. Our results show that the proposed model achieves overall accuracies over 87% for substrate classifications across multiple regions and consistently outperforms the conventional pixel-based classifiers, particularly in areas with fragmented coral structures. Notably, this spatially aware classification framework significantly enhances the continuity and reliability of coral reef habitat mapping, offering an effective pathway for high-resolution benthic monitoring. Moreover, it provides a more efficient approach for substrate mapping that bypasses full atmospheric correction.

Keywords: coral reefs, benthic classification, remote sensing, optically shallow waters, Unet++

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Using SVP drifters and Ocean Color products to directly assess rates in the ocean

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While the use of satellite-derived ocean color products has successfully increased our understanding of and ability to predict stocks in the ocean, it is still challenging estimate rates. For example, traditional satellite-based primary production algorithms are based on combining biomass or chlorophyll with auxiliary properties to indirectly estimate growth rates of phytoplankton and carbon fluxes. These approaches have been highly successful when integrated over long time scales (seasonal -- decadal) but are of less use when resolving shorter. For example: while NPP is highest in the early or mid-phase of a bloom event, a stock-based estimate would report the highest production at the end, when biomass is the highest but actual production is minimal due to nutrient depletion.

We address these shortcomings by following the evolution of satellite-derived properties in specific water masses using a Lagrangian frame. We do this by combining OC-CCI and PACE products with In-Situ SVP drifters drogued at 15 meters depth to explore the rate of change in Chl and phytoplankton community structure at different regions of the ocean. We also assess the frequency of bloom events and how episodic phytoplankton growth is in the global ocean.

Enhancing GOCI-II Inherent Optical Properties Algorithms via Machine Learning

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Inherent Optical Properties (IOPs) are fundamental for understanding the physical and optical characteristics of the ocean, as they govern the absorption and scattering of light in water. Accurate estimation of IOPs is crucial for monitoring marine ecosystems, detecting biogeochemical changes, and managing coastal and open-ocean environments. Satellite observations provide an efficient and large-scale means to monitor IOPs, offering high temporal and spatial coverage that is unattainable through in-situ measurements alone. Traditional quasi-analytic algorithms (QAA) have been widely used to derive IOPs from satellite-derived remote-sensing reflectance (R_{rs}), yet they rely on empirical coefficients and mathematical formulations that may limit accuracy, especially in optically complex waters. In this study, we propose a hybrid machine learning (ML) approach that integrates QAA algorithms with ML, replacing empirical coefficients and functions with data-driven models. This method allows the estimation of total absorption (a_total) and total backscatter (bb_total) across all GOCI-II spectral bands from simulated R_{rs} datasets generated by the HydroLight radiative transfer model. Results show that the proposed approach improves the accuracy of both absorption and backscattering coefficients across all bands. These findings demonstrate the potential of combining traditional optical models with machine learning for enhanced IOP retrieval from GOCI-II, providing a promising avenue for advancing marine environmental monitoring.

Multi-mission observations unveil fine-scale biogeochemical coupling on the East Greenland Shelf

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Mesoscale processes such as oceanic eddies play a crucial role in shaping the physical and biogeochemical dynamics of the ocean, with impacts to processes varying from heat and nutrient transport to primary productivity. In the Arctic, these features occur at smaller spatial scales (10–60 km) than at mid-latitudes (50–100 km), making them difficult to resolve with conventional satellite altimetry. As part of the ESA Polar Cluster project Fresh4Bio, we investigate mesoscale dynamics in the Nordic Seas, with a focus on the East Greenland Shelf—an important exchange region between the North Atlantic and the Arctic where sea ice complicates observations. We show how the high-resolution Surface Water and Ocean Topography (SWOT) satellite, combined with conventional nadir altimetry, can significantly improve the detection of fine-scale ocean features in this region. We created 2-km resolution maps of ocean topography, geostrophic currents, and relative vorticity from April 2023 to October 2024 by interpolating SWOT and nadir altimetry data in space and time. These maps reveal mesoscale processes (20–100 km) that were previously unresolvable. To explore biophysical interactions, we identified a 20-km anticyclonic eddy and examined its associated phytoplankton bloom. We analyzed co-located sea surface temperature (SST; L3 AVHRR OSI SAF, 5-km resolution) and Chlorophyll-a (Chl-a; L3 CMEMS GlobColour, 4-km resolution) to assess the physical–biological coupling within the eddy. Our results highlight strong environmental modulation of the bloom by mesoscale dynamics. Next steps include tracking the eddy over time while monitoring SST and Chl-a to better understand the processes driving phytoplankton variability in this complex and under-observed region.

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Structure perturbations in above-water radiometry: the AAOT case study

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The Copernicus Earth Observation (EO) programme, established by the EU, produces and delivers satellite products for monitoring the aquatic environment. The assessment of satellite products relies on field radiometry to ensure compliance with EO requirements. Over the last decades, this action has been supported by an increasing number of in situ radiometric measurements acquired with autonomous above-water systems deployed on offshore structures. The aim of the present work is to support the quality assurance of in situ measurements through Radiative Transfer (RT) simulations of the perturbing effect induced by the deployment structures (structure perturbations, SP).

The Acqua Alta Oceanographic Tower (AAOT) in the north Adriatic Sea was selected for this investigation given former SP experimental studies at this site, as well as a comprehensive characterisation of its environmental properties. A detailed SP analysis based entirely on in situ data, however, would be limited by the difficulty in addressing the variety of potential measurement conditions. Conversely, RT simulations can, in principle, account for any field measurement setting and environmental case.

The versatility of the RT-simulation approach, as well as the overall agreement between selected SP experimental and simulation results, are presented in this work. Results document the SP dependence on the measurement geometry, illumination conditions, and reflective properties of the deployment structure. In addition to the distance between the deployment structure and the sensor footprint at the sea surface, a marked SP dependence on the sun zenith angle is evidenced.

This work also shows that SP affecting measurements performed with the AERONET-OC system operated at AAOT are overall negligible when applying strict quality assurance criteria. These findings highlight that measurements taken with above-water systems deployed on offshore towers, as well as research vessels, would benefit from SP analyses equivalent to those presented here for the AAOT.

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A major cyanobacteria bloom in the Baltic Sea region in summer 2025 observed using multiple methods

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A cyanobacteria bloom with an unusually large geographical extent was observed in the Baltic Sea region in summer 2025 when comparing to years 2002–2024. The maximum extension of the bloom coincided with a heat wave and low wind speeds. We investigated the distribution and the dynamics of the bloom using a multiple methods approach. Satellite remote sensing of ocean colour showed that the bloom occurred not only in the Baltic Proper and the Gulf of Finland, but also in the Bothnian Sea. Sentinel 3-OLCI and Sentinel 2 -MSI were used to address different geographical scales. The hyperspectral sensor on PACE-OCI provided insight in spectral signatures from the cyanobacteria and from other types of phytoplankton communities. An ocean glider equipped with bio-optical sensors was used to investigate depth distribution of the cyanobacteria. Phycocyanin fluorescence, a proxy for cyanobacteria biomass, indicate that the bloom extended from the surface to 20 m depth. Results from automated imaging flow cytometry and light microscopy show that the dominating taxa were *Nodularia spumigena*, *Aphanizomenon flos-aquae* and *Dolichospermum* spp., and these taxa were observed also in the relatively higher saline waters of the Kattegat and the Skagerrak. To provide early warning to the public, tourism, aquaculture and desalination industries, a combined approach integrating observations of cyanobacteria, their toxins and ocean modelling is under development.

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Onboard Radiometric Calibration of GOCI-II Using Solar Diffuser and Long-Term Monitoring of Diffuser Stability

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The Geostationary Ocean Color Imager-II (GOCI-II) conducts onboard radiometric calibration through the Solar Diffuser (SD) and monitoring devices that track its long-term stability. The SD provides absolute gain measurements, while the monitoring system assesses changes in diffuser properties under the space environment exposure. These instruments maintain radiometric stability over the mission.

This study utilizes monitoring data from June 2020 to the present, with weekly SD acquisitions and periodic monitoring observations. Sensor performance was evaluated using the current radiometric correction (RC) model, which applies both an angle correction model and a long-term trend correction model. Results show that inverse normalized gain derived from SD and monitoring measurements consistently captures diffuser degradation patterns. Long-term monitoring also provides additional information on the environmental effects influencing the diffuser, which helps to identify gradual performance loss and to refine calibration accuracy. The integration of monitoring data with SD-based calibration enhances the stability of radiometric calibration and supports the production of reliable ocean color observations from GOCI-II.

Keyword: GOCI-II, On-board Radiometric Calibration, Solar Diffuser, Ocean Color Remote Sensing

Phytoplankton Phenology and Physical Forcing in the Pemba Channel: Disentangling Their Roles in Small Pelagic Fish Dynamics

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Abstract

Small pelagic fish play a crucial role in food security and livelihoods for coastal communities in Tanzania; however, their distribution and abundance are closely linked to plankton dynamics and environmental fluctuations. This study examines the influence of phytoplankton phenology and key physical drivers on the distribution and abundance of three important small pelagic fish groups (mackerel, sardines, anchovies) along the Pemba Channel using satellite-derived and modelled datasets including chlorophyll-a concentration, sea surface temperature (SST), wind, ocean currents, and mixed layer depth (MLD) spanning from 2011 to 2022. Our results demonstrate that temporal shifts in phytoplankton phenology relate to small pelagic fish catches along the eastern Pemba Channel. In particular, the peak in phytoplankton biomass has a partial but significant impact on mackerel and sardine groups in June and November. This indicates a bottom-up trophic link between primary producers and the above trophic levels. In contrast, anchovy, appears to be less influenced by phytoplankton timing, but more responsive to physical forces such as SST and seasonal winds. Moreover, the three groups also peak at different times of the year, which suggests an inverse relationship which could be attributed by resource competition. Overall, productivity is higher during the southeast as compared to the northeast monsoon season. This study demonstrates the complex interplay between biological and physical drivers in shaping small pelagic fish dynamics along the Pemba Channel and the Tanzanian coastal waters. These findings are essential for informing fisheries management strategies in Tanzania, particularly under the threat of climate change.

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Unveiling the Relationship between Phytoplankton and Particulate Organic Carbon in the Global Ocean via Satellite Data

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Phytoplankton communities proliferate in the surface layer of the global ocean and represent the primary source of particulate organic carbon (POC) in open waters. Understanding the link between phytoplankton biomass and POC is essential for quantifying the marine carbon cycle, yet this relationship remains variable across space and time. In this study, we assessed global patterns in the POC-chlorophyll-a (Chl-a, a proxy of biomass) relationship using MODIS-Aqua remote sensing data from 2002 to 2025. POC concentrations were derived using bbp values as described in Loisel et al. (2018), while Chl-a served as a proxy for phytoplankton abundance. To evaluate the potential role of community structure, we incorporated satellite-derived phytoplankton community structure data from El Hourany et al. (2019, 2024). We focused on the POC/Chl-a ratio, a diagnostic indicator of carbon accumulation, potentially providing insights into the biogeochemical roles of different phytoplankton groups. Our results reveal a complex and non-uniform relationship between POC and Chl-a, with variability expressed across temporal and spatial scales. These findings suggest that differences in phytoplankton community composition may help explain the observed diversity of POC-Chl-a relationships in the global ocean.

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In-situ multispectral inherent and apparent optical properties data set for bio-optical modelling and ocean color remote sensing products validation in the European Arctic.

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A multispectral data set of inherent and apparent optical properties collected in the Fram Strait in summer seasons from 2013 to 2016 is presented. Field work was carried on across the Fram Strait, in West Spitsbergen Current (WSC) waters carrying saline and warm Atlantic Water and in the East Greenland Current (EGC), that carries fresher and cold Polar Water, which properties are modulated by fresh water input from rivers, sea ice melt and melt of Greenland ice sheet. These two major water masses thus have distinct water properties. Optical properties of the WSC are mostly controlled by phytoplankton life cycle, while those in EGC are controlled by CDOM absorption. This data set is composed of more than 400 upper ocean vertical profiles of spectral absorption and attenuation measured with the ac-9 submersible spectrometer and DOM fluorescence measured at three spectral excitation/emission channels, that enabled to observe spatial distribution of different DOM fractions. Discrete water samples were collected for measurements of absorption spectra of CDOM and particulate absorption and chlorophyll-a concentration, Chla. The radiometric measurements with the use of the a hyperspectral TRIOS radiometer mounted on the floating system were conducted to derive remote sensing reflectance. Vertical profiles of spectral downwelling irradiance were measured with a C-OPS radiometer to characterize the underwater light field. The phytoplankton pigments line height absorption $a_{LH}(676)$, derived from ac-9 measured absorption spectra, was found to be the most reliable optical proxy for determination of Chla, while the fluorescence intensity of the humic-like DOM component was identified as a strong predictor of CDOM absorption coefficient.

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Long-Term variability of surface Chlorophyll in the North Indian Ocean: Role of Ocean-Atmosphere Forcings

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Abstract:

Surface chlorophyll *a* concentration (Chl-a) in the North Indian Ocean (NIO) exhibits substantial spatial and temporal variability, driven by a complex interplay of oceanic and atmospheric processes. This study investigates the long-term variability in Chl-a across different upwelling and winter cooling regions of the NIO, using satellite-derived Chl-a data spanning from 1997 to 2024, in conjunction with oceanographic and atmospheric reanalysis products. The NIO is divided into five subzones based on coastal upwelling and winter cooling - NAS, SEAS, SUR, OUR, and SDR. Seasonal and inter-annual variabilities in -a was analyzed in relation to key physical drivers such as sea surface temperature (SST), thermocline depth (D26), upper ocean stratification, wind stress curl, and Ekman pumping velocity. SST exhibits a semi-annual seasonal cycle, peaking in Apr-Jun and Oct–Nov, and reaching minima during Jan-Feb and Aug. Long-term (1960-2024) trends indicate a statistically significant warming in SST across all regions, with the most rapid increases observed in SDR (0.0119°C/year) and SEAS (0.0093°C/year), while the lowest SST trend was observed in SUR (0.0051°C/year), followed by OUR(0.0067°C/year). Long-term wind speed showed an overall increasing trend in all the sub domains except in NAS and SEAS. However, post 1997, all regions showed declining trend. Chlorophyll-a concentrations display strong seasonal variability, with maxima during the southwest monsoon (Jun-Sept) and minima during pre-monsoon months (Mar–May). From 1997 to 2024, declining trends in chlorophyll-a were observed in NAS, SUR, and OUR, with NAS showing the steepest decline. In contrast, SEAS and SDR showed increasing trends in chlorophyll a, possibly associated with changing monsoonal winds and increasing ocean stratification under a warming climate. These findings enhance our understanding of biophysical coupling and provide insight into the potential impacts of climate variability productivity and economically vital region.

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Mapping Mediterranean River Plumes with ADG443: A Remote Sensing Approach

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River plumes are crucial drivers of coastal biogeochemistry, transporting sediment, nutrients, and organic matter from land to ocean. Therefore, they have a wide range of impacts on various aspects of coastal environments, such as for instance: primary production and biodiversity, coastal morphology, water quality. For an accurate plume detection, the use of satellite-derived ocean colour observations is highly advantageous, as it provides a high temporal resolution synoptic view and a cost-effective monitoring of dynamic properties in optically complex coastal waters. Specifically, Copernicus Marine products are very suitable for these studies. Among the optical properties tested for detecting river plumes, the absorption coefficient of colored dissolved organic matter (CDOM) and non-algal particles (NAP) at 443 nanometers (ADG443) has not yet been widely explored. As an Inherent Optical Property (IOP), ADG443 is a particularly valuable tracer for freshwater and particulate matter, since both CDOM and NAP exhibit strong absorption in the blue light spectrum.

This study tests the efficacy of ADG443 obtained from the Copernicus Marine Service operational multi-sensor dataset as an indicator of Ebro and Rhône river plume dynamics. Our initial observations from the operational long-term time series of satellite-derived ADG443 imagery in the Western Mediterranean are promising. The data show that ADG443 can effectively delineate the extent and dynamics of the Ebro River plume under diverse hydrological and oceanographic regimes including extreme flood conditions. A further analysis with the Rhône River plume during the same period further supports the robustness of this approach. These results indicate that ADG443 can be an effective tool for enhancing our understanding and monitoring of river plumes.

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Evaluation of Total Column Ozone from AMI and GEMS for Atmospheric Correction of GOCI-II

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Accurate atmospheric correction is essential for generating reliable ocean color products from the Geostationary Ocean Color Imager-II (GOCI-II). Total column ozone (TCO) is a crucial parameter for correcting gaseous absorption, particularly in the UV and blue spectral bands. Since GOCI-II does not provide its own TCO data, external datasets from co-orbiting geostationary satellites must be employed. This study evaluates TCO products from the Advanced Meteorological Imager (AMI) and the Geostationary Environment Monitoring Spectrometer (GEMS), using ECMWF ERA5 reanalysis as a reference. Statistical analyses, including correlation coefficients (R), root mean square error (RMSE), and bias, were conducted to assess the performance of both datasets. The results show that both AMI and GEMS TCO products are highly correlated with ERA5 (R = 0.986 and 0.991, respectively). Although GEMS exhibits a slightly higher correlation, AMI shows lower RMSE (~9 DU) and a near-zero bias (~+1 DU), while GEMS presents a larger RMSE (~19 DU) and a consistent negative bias (~–3 DU). Spatially, AMI demonstrates lower RMSE and bias across the study domain. Temporally, AMI maintains stable performance throughout the year, whereas GEMS exhibits stronger seasonal fluctuatio... To investigate the practical impact of these differences, the TCO products from both AMI and GEMS will be applied to GOCI-II gaseous absorption correction, and the derived remote sensing reflectance (Rrs) will be analyzed. Preliminary results suggest that AMI provides more consistent and accurate Rrs products, while the fusion of AMI with GEMS may effectively complement data gaps.

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Improvements of GOCI-II gas absorption correction through via fusion with GK-2A/B data

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Atmospheric correction is a fundamental step in ocean color remote sensing, aiming to obtain accurate sea surface reflectance by removing the effects of atmospheric scattering and absorption. The precision of this process is critical, as it directly influences the reliability of derived ocean color products. Therefore, the continuous improvement of atmospheric correction techniques is essential to maximize the scientific and practical utility of satellite ocean color data. With the launch of new ocean sensors, algorithms have advanced in aerosol correction, cloud masking, and turbid water adjustment (Ahn et al., 2020). However, as international standards for remote sensing reflectance (Rrs) accuracy have become more stringent, there is an increasing demand to enhance all components of atmospheric correction. Mélin et al. (2022), for example, demonstrated that uncertainties in auxiliary data used during atmospheric correction can introduce substantial variability in Rrs, emphasizing the importance of high-quality ancillary information.

This study focuses on improving the accuracy of GOCI-II Rrs by refining gas absorption correction through integration with AMI/GK-2A and GEMS/GK-2B. These geostationary instruments, co-located with GOCI-II, provide near real-time atmospheric gas concentration data with higher spatial and temporal resolution than the currently used NCEP forecast fields. As observation-based datasets generally offer better fidelity than model forecasts, incorporating AMI and GEMS data reduces uncertainties arising from auxiliary inputs and the spatiotemporal variability of gases.

The gas transmittance of GOCI-II bands derived from AMI and GEMS integration showed closer agreement with ECMWF reanalysis compared to NCEP forecasts. At 412 nm, correlation improved, though the mean absolute percentage difference (MAPD) slightly increased, likely due to ECMWF's coarse resolution missing localized NO_2 hotspots. For Rrs, the combined use of AMI and GEMS produced results more consistent with ECMWF across all bands, while daily MAPD variability was substantially reduced, demonstrating the effectiveness of multi-sensor integration in atmospheric correction.

Hyperspectral radiometry on BGC-Argo floats: Technical Perspective and integration into one-argo

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Since 2012, the BioGeoChemical-Argo (BGC-Argo) mission of the One-Argo program has revolutionized the global-scale acquisition of six key biogeochemical and bio-optical variables throughout the water column. This success is due not only to the strong coordination and support provided by the One-Argo framework, but also to the technological maturity and capability of Argo profiling floats, which have proven to be highly efficient autonomous platforms for hosting a wide range of sensors. A new generation of Argo float, the Provor CTS5, has been developed since 2011 by nke in collaboration with the Laboratoire d'Océanographie de Villefranche, to accommodate increasingly complex sensors. This platform was selected in 2020 to integrate two ruggedized hyperspectral TriOs-RAMSES radiometers as part of the ERC-REFINE project, in order to measure vertical profiles of both downwelling irradiance (Ed) and upwelling radiance (Lu).

In this work, we discuss the advantages and challenges of using this platform for radiometric measurements within the One-Argo framework. Following a technical presentation of the float, we will highlight its capabilities in terms of sampling frequency, programming flexibility, and operational deployment at sea. We will also present its ability to carry additional sensors to complement radiometric data with other biogeochemical measurements. Questions related to vertical stability in the water column and potential shading effects on the sensors will also be addressed. Finally, we will discuss the integration of these floats into the One-Argo program, with a particular focus on leveraging the Argo data infrastructure for the distribution of radiometric data and float's metadata.

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Resolving near-coastal remote sensing signal into contributions by bottom, water column, glint and the adjacency effect

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All waterbodies are changing in the variable climate conditions. Monitoring of these changes over large areas is possible only by using remote sensing. The near-coastal zone is extremely important because many biological processes take place there e.g. most of carbon reaching waterbodies from land is processed there. However, interpreting the signal from littoral zone is complicated as it consists not only of the radiation from the water column, but also from shallow water benthic habitats, sun and sky glint as well as from nearby land (adjacency effect). Moreover, there are often many mixed pixels. Therefore, the most typical approach in remote sensing is excluding the near-coastal pixels from further analysis. This is not a feasible option if we want to study near costal processes. Moreover, in the case of small and medium size lakes there are no pixels not affected by the adjacency effect or other issues.

The main reason, why there are no good solutions to correct for these issues, is the lack of in situ data with sufficient auxiliary information. In our study we collected data from across lakes starting from the shore. Remote sensing reflectance, reflectance not containing clint, water depth and water quality data was collected together with video. This data should enable to resolve the contribution of the adjacency effect, lake bottom, sun and sky glint and the water column itself and to propose algorithms for removing the adjacency effect and glint from Sentinel-2 imagery.

We have carried out experiments in lakes with different optical water properties (clear, eutrophic, high-absorbing) and coastal areas (agricultural, urban, natural forest, mountains) during different seasons.

This poster will introduce our approach for the fieldwork; the comparison between different Sentinel-2 products; and our proposals on how to handle the targeted issues.

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When Land Meets Water:
A Review of the Adjacency Effect in Aquatic High-Contrast Environments

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Inland and coastal waters pose significant challenges for accurate reflectance retrieval in optical remote sensing. This is mainly due to their optical complexity, resulting from high turbidity, bottom influence, and proximity to land surfaces. Atmospheric scattering combined with these factors causes spectral blending and distortion of the target spectrum. This phenomenon is known as the adjacency effect (AE) and introduces significant biases in satellite-based quantitative retrievals, affecting areas several kilometers in extent. Our review presents current understanding of the emergence and impact of AE, and summarizes methodological advances in the field. Moreover, we highlight tools available to quantify and correct AE in optical satellite imagery. Recently, the open-access tools RAdCor and T-Mart have shown promising results for AE correction. We applied both methods to a Sentinel-2 MSI case study of the Osterseen Lake District south of Munich (Germany). The results demonstrate that while both algorithms effectively correct AE in the near-infrared, there is potential for future improvement in the visible wavelengths. These findings align with the broader trends emphasizing operational applicability and suggest that future research should focus on algorithm refinement and AE quantification in diverse environments.

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Using ocean colour products as tracers for surface currents reconstruction, an approach using a neural network

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Ocean colour has been used to monitor phytoplankton biomass and ecosystem processes; thanks to its sharp gradients it can also provide a reliable source of data as a tracer for surface dynamics. The growing availability of high-resolution products (e.g. Sentinel-2, Sentinel-3), offers the potential of capturing processes at different spatial scales, from large scale oceanic processes to eddies and filaments, resolving meso- to submesoscale features, complementing the information extracted from other established tracers as sea surface temperature. While traditional methods for estimating surface currents from remote sensing rely on altimetry and the geostrophic approximation, these approaches face limitations in resolving finer scales.

In this study, we explore the capabilities of a neural network to reconstruct ocean surface currents based on the advection visible in ocean colour tracer fields and auxiliary variables such as altimetry products. We implemented a convolutional encoder-decoder architecture trained with a cost function that minimizes the difference between advected tracer fields and their observed distributions, with additional constraints to fit physical boundaries (coastal boundaries) and flow properties (divergence). This approach aims to overcome limitations such as sparse along-track sampling and revisit times, often observed in traditional altimetry products, by exploiting the finer spatial and temporal resolution of ocean colour data.

In this first stage we used model fields from the Irish-Iberian Biscay (IBI-MFC) reanalysis and non-assimilative biogeochemical hindcast, testing chlorophyll, temperature and salinity as input fields. Preliminary results indicate that chlorophyll fields capture variability associated with mesoscale, while salinity provides more stable reconstructions. The next stage involves using multiple tracers as input fields to exploit the merged ocean colour products and obtain finer scale outputs for ocean surface processes.

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Characterizing oil spills using deep learning and spectral-spatial-geometrical features of optical satellite images

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Marine oil spills cause pollution to the environment, where timely information on the oil characteristics (i.e., oil types, concentration, thickness) is essential for spill response and post-spill assessment. Existing remote sensing models (including deep learning (DL)) have been applied to both synthetic aperture radar (SAR) and optical remote sensing images, which are primarily for presence/absence detection. Here, we propose a framework to take advantage of data richness (i.e., multi-band observations under different viewing conditions) of optical sensors to characterize oil spills beyond simple detection. The framework includes a 2-step DL model to account for the spectral-spatial-geometrical features of optical images to achieve the simple detection, and a spectral model to characterize oil type and estimate oil quantity. The framework led to a relatively comprehensive "ground truth" dataset including all possible scenarios to account for various oil types and observing conditions, which can be used in the future for model development. Application of the framework to HY-1C/D CZI images between December 2018 and April 2023 revealed substantial oil spills in the marginal seas off China, with quantified spatial distributions and oil characteristics. We found that oil spill incidents are primarily from ship discharges (85.8 %), while platform leaks lead to more oil emulsions (58.6 % compared to 13.1 % from ships), highlighting the drilling oils are the main source of oil spill pollution in China Seas. The spilled oils correlate with major port locations, including offshore Qingdao and Rongcheng, Bohai Bay, the adjacent areas of Beihai, and Hue and Da Nang in Vietnam.

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Ocean Colour Data for Reducing Uncertainty in Biogeochemical Model Simulations

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Ocean biogeochemical (BGC) models are important instruments for investigate global carbon cycle and other ocean biogeochemical processes. In such models, many parameters are not well known and often they are keep fixed in time and in space, which is not always representing reality because these parameters can change with season and location. In this work, we try to overcome this limitation by estimating both spatial and temporal variations of parameters in the Regulated Ecosystem Model version 2 (REcoM2) by assimilating satellite ocean colour data with ensemble Kalman filter method. We focused on nine sensitive BGC parameters and performed optimisation experiments. The simulations with the optimised parameters show about 26 % decrease in root mean square error of surface chlorophyll-a compared to runs with uniform parameters. The spatial patterns of the estimated parameters also show good agreement with known distributions from observations. This result demonstrate that ocean colour data are very useful for improving model skill and for better representation of biogeochemical variability in the ocean.

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Ensemble Bathymetry Product (EBP): A satellite-derived shallow water mapping system using Sentinel-2

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Abstract

Coastal areas are dynamic ecosystems, driven by ocean processes and human activity, making them highly vulnerable to climate change. Detailed and timely information on bathymetry is crucial in conservation and climate risk management efforts as it helps describes coastal vulnerability, sea level rise, and tidal habitat loss. Bathymetry also aid in mapping blue carbon ecosystems such as mangroves, seagrasses, and coral reef extents which inhabit specific depth ranges. Traditional survey methods can be challenging and costly especially in shallow areas. Remote sensing provides a more efficient and cost-effective way for mapping these vulnerable areas at a high spatial resolution with the Sentinel-2 Multi-Spectral Imager (MSI). We have developed the Ensemble Bathymetry Product (EBP) that is a combined output from two approaches: the spatial homogeneity method (SHM) that assumes deep and shallow water pixels have the same optical properties up to a specific distance, and the reflectance separation method (RSM) based on Stumpf's ratio transform model. Both methods resolve water depths from a physics-based inversion model. Calibration was done by referring the satellite-derived water depths to Electronic Navigation Charts (ENC), bathymetry maps, and tidal harmonics data. To assess the performance and robustness of the EBP model, 11 sites across the South-east Asian region were chosen with the ENCs taken as ground truths. The model has an overall accuracy R^2 of 0.88 and the median relative difference across the sites fall below 30%. The EBP model outputs had been used for mapping intertidal zone extents and show consistency in areas with existing coastal resource maps. Aside from marine and coastal research applications, the maps can be beneficial for planning further hydrographic surveys in shallow coastal areas and remote islands that may not have been surveyed yet.

Keywords: remote sensing, bathymetry, intertidal zones, sentinel-2

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Wavelet-based Analysis of the Hyperspectral Signatures of Marine Plastic Litter

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Current approaches to analyzing hyperspectral signatures of marine plastic litter typically focus on identifying discrete absorption features at specific wavelength regions. Techniques such as the Spectral Angle Mapper (SAM) are often employed to compare spectra and produce an overall similarity score. While some existing methods may account for broader signal characteristics in an implicit fashion, to the best of our knowledge, there have been no prior studies that explicitly focus on the frequency content of hyperspectral signatures.

Our work introduces the first application of the Continuous Wavelet Transform (CWT) to the domain of hyperspectral remote sensing of marine plastic litter. By analyzing the signal structure through the CWT, we introduce a frequency-domain perspective that offers insights into the spectral information content. We propose that this approach can aid in estimating sensor requirements; for instance, if specific features in the CWT scalogram are identified as relevant, the Nyquist–Shannon sampling theorem can be applied to infer the necessary spectral resolution to capture those features effectively.

We also introduce a novel technique - CWT Gradient Matching (CWTGM) - which leverages the gradient of CWT scalograms to derive a frequency-based similarity metric.

While substantial room for improvement remains, our results show that the CWT can be used to identify features that may otherwise prove difficult to analyze, and can inform the design of hyperspectral and multispectral sensors.

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Tailoring Copernicus Operational Products for Coastal Ocean Applications: The Case of Internal Island-Trapped Waves in the Adriatic Sea

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Internal island-trapped waves (ITWs) are generated around Lastovo Island (South Adriatic Sea) in the summer, causing vertical displacements of the thermocline up to 30 m and altering the stratification of the water column. ITWs can influence primary production by facilitating the transport of nutrients from deeper layers of the water column to the euphotic zone, and by distributing phytoplankton toward surface waters where light availability is higher. Field campaigns in July 2022 and 2023 provided a valuable *in situ* high-resolution dataset, including temperature, PAR, currents, nutrients, chlorophyll *a*, zooplankton and phytoplankton communities, as well as experimental primary production measurements. Whereas effects of ITWs have been thoroughly investigated at a single station near Lastovo Island, their broader spatio-temporal impact, particularly on primary production, remains poorly understood. This study explores the potential of leveraging the Mediterranean operational products released by CNR-ISMAR for the Copernicus Marine Environment Monitoring Services (CMEMS) to investigate ITW-related variability in primary production around Lastovo Island. Physical and biogeochemical products were assessed and adapted for coastal applications through upscaling to 1 km spatial resolution and integrating *in situ* observations to refine primary production estimates. Preliminary analyses suggest spatial heterogeneity in primary production, with increased production on the southern side of Lastovo Island. The case highlights both the opportunities and limitations of applying regional-scale operational products to study localized coastal processes. It underscores the need for tailored approaches in algorithm development and integration with *in situ* data to improve the monitoring of biodiversity and productivity, especially in coastal systems, such as the Adriatic Sea, which are increasingly affected by rising sea surface temperature and prolonged stratification due to climate change.

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SWIR-band Atmospheric Correction and S3NGO Requirements for OLCI-SLSTR Synergy

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This work, conducted for EUMETSAT in collaboration with ESA, contributes to the requirement definition of the future Copernicus Sentinel-3 Next Generation Optical mission (S3NGO). Under its mandate for operational satellite oceanography, and more specifically Ocean Colour Radiometry, EUMETSAT needs to ensure that the future Advanced-OLCI (AOLCI) and Advanced-SLSTR (ASLSTR) onboard S3NGO meet strategic users' requirements for complex coastal and inland waters. The main challenge is to produce water reflectance over such targets because of the lower performance of the atmospheric correction (AC), as the detection of aerosols is affected by backscattering of suspended matter. With current OLCI's radiometry in the VIS-NIR (400 nm -1020 nm), the decoupling between aerosol and water turbidity requires a marine model; however, this approach is inherently inefficient over strongly turbid waters where the flattening of the marine spectrum in the NIR becomes ambiguous with the shape of the aerosols.

This limit can be overcome thanks to measurements in the SWIR, where the water absorption is so high that aerosols are detected unambiguously, assuming enough radiometric quality. On S3NGO, the full spectral range from UV to SWIR can only be achieved by combining the measurements from AOLCI and ASLSTR, i.e. from two subsystems with different viewing geometry and slight time difference, what questions their usage for ocean colour AC.

The purpose of this study is twofold:

1. Demonstrate the feasibility and benefit of a synergy SWIR-band AC with the current S3 mission;
2. Refine the technical requirements of AOLCI, ASLSTR and the Level-1 synergy product (SYN L1C) of S3NGO so that the SWIR-band AC can reach the performance required by users.

The poster will focus on the SYN-SWIR-AC processor developed for existing SYN L1C products generated by EUMETSAT. We will present advantages against the standard OLCI processor and summarise limits related to differences in geometry.

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Understanding Optical Water Types (OWT) in Coastal USA Regions

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Using an Optical Water Type (OWT) classification model, we assessed the distribution and variation of optical water types in the ecologically and economically important coastal regions of the United States. The OWT model identifies 23 water types on a continuum from open ocean blue water with low chlorophyll to high turbidity waters in coastal regions. Daily OWT classifications were derived using remote sensing reflectance data from the Ocean Colour Climate Change Initiative (OC-CCI) at 4km resolution from 2000-2023. A comparison between *in situ* chlorophyll point data and the OWTs, as well as broad regional OWT analyses were conducted to understand how OWTs vary in time and space. All 23 water types are present in the U.S. coastal regions (0-80 km from shore), however the dominant OWT varies between regions. As expected, there is a notable onshore to offshore gradient in OWTs with Case 2 OWTs occurring more frequently closer to shore and "blue water" Case 1 OWTs occurring in offshore waters (> 80 km). The western regions (Hawaii, Alaska, Western U.S.) tend to have more occurrences of lower OWTs (1-11), while the East Coast regions (Gulf Of America, Eastern U.S.) have greater variability and more instances of higher OWTs (11-23). *In situ* point location evaluations show that eastern U.S. regions also have higher fine scale OWT variability than western regions. Increasing our understanding of the variability of OWTs in optically complex regions can assist in the development of dynamic remote sensing algorithms and improved products such as chlorophyll *a* concentration. More than 90% of U.S. Fisheries occur in the coastal regions, thus there is a critical need for more accurate ocean color products to better understand how changes in phytoplankton biomass, productivity and composition affect the coastal marine ecosystems.

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Verification of GOCI-II Remote-Sensing Reflectance Using the MOBES Buoy and HYPSTAR

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GOCI-II, the follow-on to GOCI, has continued observations over Northeast Asia since February 2020; together the two missions now span roughly 15 years (2010–2025). It features improved spatial (~250 m), spectral (13 bands spanning ~380–900 nm across UV–VIS–NIR), and temporal resolution (hourly daytime imaging, ~10 images per day). Additional bands at 380, 520, 620, and 709 nm introduced on GOCI-II enhance sensitivity to chlorophyll-a, suspended sediments (TSS), and CDOM, and also support more robust atmospheric correction (e.g., UV constraints on absorbing aerosols/CDOM). To validate the GOCI-II data, a marine optical buoy was developed and a platform-based observing system was established for Rrs. The MOBES (Marine Optical Buoy in the East Sea) was designed using MOBY as a benchmark. It uses RAMSES hyperspectral radiometers to measure in-water Ed and Lu at depths of 1 and 5 meters. These radiometers have a wavelength range of approximately 320–950 nm and a sampling range of approximately 3 nm. Furthermore, environmental measurements were obtained through the utilization of a fluorescence, backscattering, and CT sensor, a weather sensor, and a GPS. For surface Rrs observations, the HYPSTAR system developed through the HYPERNETS project was introduced. This system uses the RAMSES sensor to observe Ed, Lsky, and Lw, enabling the derivation of Rrs. MOBES underwent its preliminary testing and operations from August to October 2024 prior to its retrieval. Following modifications and enhancements, the system was reinstalled in the East Sea in July 2025 and has been in operation there ever since.The Rrs observations obtained through the MOBES and HYPSTAR systems were compared and validated against GOCI-II Rrs products, including those from other ocean color sensors such as VIIRS and OLCI.

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Study on shape classification of ocean remote sensing reflectance spectra measured in seawater around the Korean Peninsula in 2022 and 2023

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The composition of seawater and the resulting ocean color are the primary factors determining ocean remote sensing reflectance (Rrs) measured by hyperspectral optical instruments. The Rrs spectrum is shaped by these elements. Therefore, the phenomenon of Rrs can be attributed to the inherent optical properties of seawater composition. This provides a very important theoretical foundation for developing remote sensing reflectance models.

Therefore, this study aims to classify the spectral shapes of Rrs measured using the RAMSES above system in the waters around the Korean Peninsula in 2022 and 2023 based on their morphology. Additionally, we aim to analyze the correlations between the seawater inherent optical properties (such as the absorption coefficient (a) and backscattering coefficient (bb)) derived from this classification and chlorophyll concentration (CHL) and total suspended matter (TSM) concentration. This correlation analysis is expected to provide the basis for the classification based on the shape of the Rrs spectrum. We will then assess the suitability of these classified spectral shapes by evaluating their a, bb, CHL, TSM, and the WASI model provided by the IOCCG. This should help determine whether the Rrs spectra measured by hyperspectral optical instruments can be used as reference values for validating and calibrating satellite data.

Keywords: ocean remote sensing reflectance, Classification, Spectral shape, Optical Properties, Ocean Color

Assessing bottom reflectance contributions to inversion schemes within optically complex coastal systems.

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Retrieval of bio-optical variables from remote sensing imagery in shallow coastal are sensitive to errors stemming from contributions of light from benthic reflectance. Algorithms designed for these conditions must account for the bottom reflectance by incorporating their effects into the bio-optical model. However, in many cases it is unknown when bottom reflectance is a contributing factor to the surface-exiting remote sensing reflectance. Existing schemes for identifying optically-shallow pixel conditions commonly utilize bathymetric tests in combination with spectral light level tests to distinguish "optically deep" conditions in geometrically shallow conditions. These criteria however are not universally applicable to all regions, particularly very shallow waters prone to conditions that render them optically deep. To improve ocean color models in optically complex systems, benthic contributions must be further explored in these environments.

In this work, we aim to assess schemes for flagging optically-shallow conditions, and the impacts of benthic signals with the shallow water inversion scheme known as the Hyperspectral Optimization Processing Exemplar (HOPE; Lee et al. 1999) in the Indian River Lagoon (IRL) - a shallow water estuary that is 250km long with 4m maximum depth located on the eastern-central coast of Florida. We collected inherent optical properties (IOPs) and remote sensing reflectance measurements throughout the IRL from 2021 to the present, along with measurements of benthic reflectance. We tested methods to improve an existing shallow flagging scheme and assessed HOPE inversions with various bottom types to identify their impacts on IOP retrievals. Aside from improving IOP retrievals in HOPE inversion schemes, the development of this project has potential to aid in future seagrass restoration efforts within the lagoon.

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Planetary Diagnosis of Phytoplankton Iron Stress

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Iron limits phytoplankton growth across vast ocean areas, particularly in high-nutrient, low-chlorophyll regions. Yet, the global dynamics of iron stress remain poorly understood. Here, we integrate satellite-derived chlorophyll fluorescence, diverse field observations, and a biogeochemical model to quantify global phytoplankton iron stress over the past two decades. Satellite, field, and model observations show strong agreement and half of the ocean experiences significant iron stress, extending well beyond traditionally recognized regions. We identify climate-driven trends, with rising temperature associated with iron stress intensifying in mesotrophic and easing in oligotrophic regions. These contrasting trends are linked to shifts in co-limiting resource availability. Consequently, iron stress varies out of phase between the core upwelling zone and the broader equatorial Pacific during El Niño/Southern Oscillation cycles. Our findings suggest that future climate change will have opposing effects on iron limitation in nutrient-rich versus nutrient-poor marine biomes.

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Optical Spectral Features and Variability of Thornton Bank Site: Insights from the WATERHYPERNET Network.

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Satellite optical remote sensing plays a crucial role in monitoring the quality of coastal and inland waters by measuring parameters like chlorophyll-a and suspended particulate matter. The reliability of this satellite data hinges on robust validation, which is supported by in situ measurements of water-leaving radiance reflectance. The WATERHYPERNET, an innovative international network of automated radiometers with zenith and azimuth pointing systems, offers in situ hyperspectral validation across a spectral range of 400-900 nm. This range is adequate for all visible and near-infrared bands utilized by current and future satellite platforms, including Sentinel-3/OLCI, MODIS, ENMAP, PACE, and CHIME.

Building on over 20 years of experience from AERONET-OC, which demonstrated the effectiveness of radiometric validation through a network of automated radiometers, the PANTHYR (PAN-and-Tilt HYperspectral Radiometer) System is part of the WATERHYPERNET. Successfully installed at the C-Power Windfarm Offshore Transformer Station (OTS), located 30 km off the Belgian coast in the Thornton sandbank, it collects measurements every 20 minutes from sunrise to sunset, primarily for satellite validation.

Additionally, the high-frequency and long-term hyperspectral water reflectance data can enhance various applications in Belgian water monitoring, including phytoplankton dynamics, turbidity, and diatom blooms. Since the launch of MERIS in 2002, Belgian waters have been pivotal for validating satellite ocean color radiometry. The simultaneous operation of the WATERHYPERNET - PANTHYR and an AERONET-OC CIMEL-SeaPrism on the same platform facilitates a comparative analysis between multi- and hyperspectral sensors. This work focuses on the optical spectral features and variability of the water at this site, examining both temporal and spatial aspects, which is essential for validating new satellite missions and understanding local water dynamics.

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Quantification and correction of adjacency effects in optical remote sensing products of Swiss lakes

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The influence of surrounding land surfaces on top-of-atmosphere satellite measurements is one of the typical challenges in remote sensing of inland waters. This so-called adjacency effect (AE) can significantly increase at-sensor radiance leading to inaccuracies in atmospheric correction, and consequently affect reflectance calculations and thus air and water constituent retrieval. AE is particularly critical near shorelines, in low reflectance lakes and high reflectance catchments, under high aerosol loadings and in rugged topography. Despite its relevance, the quantification and correction of AE in lakes has been neglected until new methods were developed in recent years. Their application still requires a thorough examination regarding the improvement of satellite-derived water quality products.

To address this gap, we present results from field campaigns on four Swiss lakes with diverse geomorphological features, namely Lakes Biel, Constance and Zurich, and Walensee. These campaigns provide a unique dataset of continuous above-water hyperspectral radiometry (320–950 nm) acquired along multiple littoral-pelagic transects concurrent with Sentinel-2 and/or Landsat-8/9 overpasses. We also collected measurements of Inherent Optical Properties (IOPs), Specific IOPs, Total Suspended Matter (TSM), and Secchi depth at selected locations along the transects. Measurements were further complemented by ancillary information, e.g., bathymetry, and continuous 360° fisheye imagery. To assess AE correction on the level of remote sensing reflectance, we evaluate established atmospheric correction (AC) algorithms such as ACOLITE and POLYMER in combination with recent AE-specific correction approaches like RAdCor and TMART. Preliminary results show significant radiometric biases attributed to AE, with implications for Aerosol Optical Thickness (AOT) estimation and reflectance accuracy. We assess the performance of each AC-AE pair by comparing the obtained satellite reflectance with corresponding in situ measurements.

Our analysis reveals a clear distance-to-shore dependency of AE magnitude and highlights the potential of AE correction for improving optical remote sensing in Swiss lakes. Ultimately, these findings can support the development of more reliable operational down-stream water quality products in lakes across the perialpine region.

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Satellite observations of phytoplankton blooms in the Western part of the Black Sea

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Monitoring phytoplankton blooms and studying the factors associated with their occurrence and development is of utmost importance due to the adverse effects on marine ecosystems and coastal resources. They lead to increased water turbidity, formation of hypoxic and anoxic zones, mortality of marine species. Most used for registration of such events are satellite observations because of their availability and good spatial and temporal resolution. The aim of this study is to evaluate the reliability of satellite observations (level L3 and L4 data) in comparison to in-situ measurements, and to identify periods of intense phytoplankton development in the Bulgarian part of the Black Sea (42°–43.7°N and 27°–29°E) for the period 2015-2024. Satellite products for concentration of chlorophyll-a were obtained from the Copernicus Marine Service, while in-situ data were collected by the Institute of Oceanography at the Bulgarian Academy of Science.

The comparison of the satellite and in-situ data was done for different regions: close to shore, along the shelf and in the open sea. Mean value, RMSD and correlation coefficients were calculated. The comparisons showed that the largest deviations from in-situ measurements occur near the coast and decrease towards the open sea. Satellite L3 values demonstrate smaller error and higher correlations than L4. Therefore, further analysis of chlorophyll-a variability was based on these data.

A 10-year time series (2015-2024) of spatially averaged daily values of chlorophyll-a revealed a mean concentration of 0,72 mg/m^3 with a standard deviation of 0,54 mg/m^3. Thus, a threshold of 1,3 mg/m^3 was defined as indicative of anomalously high concentrations of chlorophyll-a, i.e. bloom. No clear trend was identified in the yearly distribution of days with bloom events. The monthly distribution showed that blooms peak in late autumn (November), winter (January) and spring (May), while minimal occurrence was observed during the summer months.

During the spatiotemporal analyses four categories of blooms were identified: (1) north-to-south spreading blooms likely influenced by Danube or other rivers' nutrient input; (2) large-scale blooms along the entire Bulgarian coast linked to northward currents and coastal upwelling; (3) localized events in the bays of Burgas and Varna, possibly from anthropogenic sources; and (4) blooms south of Burgas, associated with mesoscale eddies concentrating phytoplankton.

Satellite observations proved to be a reliable source for studying chlorophyll-a variability in the western Black Sea. However, careful interpretation of the spatiotemporal evolution of blooms and circulation patterns along the western coast is essential.

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Detection and Dispersion Analysis of a Small-Scale Oil Spill off Jeju Island Using Sentinel-2

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Even small-scale oil spills can impose serious ecological threats on pristine coastal environments, regardless of the limited volume discharged. Here, we examine a diesel spill that occurred on 4 July 2022 along the coast of Jeju Island, Korea, following a fire on moored fishing vessels. High-resolution Sentinel-2 imagery was employed to establish a remote sensing-based framework for detecting, quantifying, and tracking the dispersion of the spill. Non-ocean pixels such as land, ships, and clouds were removed through spectral thresholding, after which a spectral unmixing algorithm was applied to isolate endmembers representing oil and seawater. The Spectral Angle Mapper (SAM) technique was then used to delineate the oil slick, and a two-beam interference model was adopted to estimate both thickness and volume. The resulting oil-covered area and volume showed good agreement with reported values. A striking feature of this event was the bifurcation of the slick into two branches as it exited the harbor. Hydrodynamic simulations combined with near-surface wind data demonstrated a strong and statistically significant correlation between current direction and oil advection. Furthermore, bathymetric information extracted from Sentinel-2 imagery revealed two small seamounts near the harbor outlet, which likely guided the divergence of the slick's trajectory. Overall, this study highlights the capability of high-resolution optical satellite data to detect thin oil sheens and underscores the combined roles of wind, currents, and local bathymetry in shaping oil dispersion in shallow and environmentally sensitive coastal waters.

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Continuous Optical Measurements from a Tall Sailing Ship: Early Results from the ESA Ocean Training Course 2025 Expedition

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Ocean colour remote sensing requires robust in-situ measurements for satellite validation, particularly in under-sampled regions. This poster will present early-stage findings from the ESA Ocean Training Course 2025 (OTC25) expedition aboard the tall ship *Statsraad Lehmkuhl*. The six-week voyage (Tromsø–Reykjavik–Nice, April–June 2025) spanned Arctic, North Atlantic, and Mediterranean waters, providing a rare opportunity to collect high-resolution optical datasets using a non-traditional research platform.

A continuous inline system combined a WET Labs AC-S spectral absorption and attenuation meter with a Sequoia Scientific LISST-200X particle size analyser, enabling continuous underway measurements of spectral absorption, beam attenuation, and particle size distribution along the 6,200-nautical-mile route. For closure and validation, discrete CTD-rosette water samples were collected and will be analysed for particulate absorption (filter pad method), colour dissolved organic matter (CDOM), particulate organic carbon (POC), and suspended particulate matter (SPM). Together, these datasets enable cross-validation between continuous and discrete measurements, and satellite observations.

This presentation will outline the dataset collected and demonstrate, for the first time, the spatial and environmental context of the cruise track. It will also describe the approach for cross-comparing continuous and discrete sampling methods, forming the basis for assessing measurement consistency across platforms.

Operating advanced optical systems on a tall sailing vessel required adaptations to address constraints such as limited laboratory space, inlet water quality, and vessel motion. Lessons learned from these operational challenges will be discussed in the context of future ship-of-opportunity programmes.

This work will provide new bio-optical datasets for lesser-observed regions and directly support the validation of current and forthcoming hyperspectral ocean colour satellite missions. It also offers practical insights into leveraging heritage sailing vessels as valuable platforms for modern ocean optics research and global-scale satellite validation efforts.

Operational Ocean Colour Services with Sentinel-3: Applications in the Marine Ecosystem and Fisheries Monitoring

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Abstract:

This study presents the development and implementation of operational ocean colour services using Sentinel-3 OLCI and SLSTR data for ecosystem and fisheries monitoring. The workflow covers the complete chain from satellite data acquisition to processing, analysis, and decision-making for delivering timely information products. The complete automatic data processing chain (ADPC) is built using SNAP-GPT and Python, enabling efficient, repeatable, and rapid generation of outputs. Core applications include algal bloom detection, coral bleaching alerts, potential fishing zone (PFZ) forecasts, and other satellite-based environmental services. Multi-sensor satellite observations are integrated with in situ measurements and laboratory-based water sample analyses to improve data accuracy and validation. The combined approach enhances the reliability of ocean colour products by addressing challenges such as cloud cover and bio-optical algorithm performance in optically complex waters. The processed datasets, offering improved temporal by one day and spatial resolution by 300 meters and 1 km, are tailored to support operational services in the Indian Ocean and Pacific Island countries compared with other open-source satellite data. By merging Sentinel-3 satellite data with ground-truth observations, this work provides actionable insights for marine ecosystem health assessment and sustainable fisheries management. The integration of Sentinel-3's advanced capabilities into regional operational frameworks demonstrates significant potential for strengthening coastal monitoring, climate impact assessment, and resource management in data-limited regions

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‘Ocean Glow’: Detecting phytoplankton nutrient limitation via above water radiometry

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Phytoplankton productivity in the open ocean is strongly influenced by nutrient availability, yet nutrient limitation patterns remain challenging to monitor at basin and global scales. *Ocean Glow* is a five-year project designed to investigate the effect of nutrient limitation on the photophysiological response in phytoplankton and the resulting influence on sun-induced chlorophyll fluorescence signatures. A major part of the project is dedicated to integrating high-resolution ship-based radiometry measurements with simultaneous sampling of phytoplankton pigment composition, photophysiological parameters, nutrient concentrations, and nutrient limitation status in order to bridge the gap between ship-based measurements and remote-sensing approaches.

One of *Ocean Glow’s* core objectives is to link and deconvolve the relationship between optical signatures in above-water radiometry and key biochemical indicators of nutrient limitation. To address this, six large field campaigns have been conducted since 2023, spanning diverse biogeochemical regimes showing both iron and nitrogen limitation, including subtropical oligotrophic waters, highly productive Southern Ocean fronts, and high-latitude seasonal blooms.

Results from the first campaign, in South Atlantic nutrient-rich filaments and oligotrophic waters, showed a threefold increase in sun-induced fluorescence response from waters with iron limitation compared to waters with nitrogen limitation, substantiating previous similar findings in the equatorial Pacific Ocean and supporting the relationship between passive fluorescence and nutrient limitation. Further initial results from other campaigns also indicate consistent spectral features associated with nitrogen and iron stress, providing early evidence that optical detection of nutrient limitation may be feasible at large scales.

By determining whether and how these fluorescence-based optical signatures relate to nutrient stress, *Ocean Glow* is establishing the basis for the development of quantitative models linking radiometric signals to nutrient limitation status. While operational detection from space remains a longer-term goal, the insights gained here will be essential for determining the feasibility, accuracy, and potential biases of such approaches.

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An Improved Ocean Colour Algorithm to detect Chlorophyll-*a* using Sentinel-3 OLCI for the Western Antarctic Peninsula

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The Western Antarctic Peninsula (WAP) has been particularly vulnerable to climate change in recent decades, and it is considered one of the most rapidly warming regions in the Southern Ocean. Remote sensing is a crucial tool for passively monitoring phytoplankton biomass and multiple biophysical processes in the ocean. However, current global algorithms often struggle by underestimating the chlorophyll-*a* (Chl−*a*) concentration and have a reduced accuracy in higher latitudes and more optically complex waters. Specialized algorithms for the Southern Ocean and the WAP already have been proposed by previous studies for other satellite missions and initiatives with a coarser spatial resolution in comparison to Sentinel-3 Ocean and Land Colour Instrument (OLCI).

The novel Chl-*a* algorithm proposed was specially calibrated for the WAP using Sentinel-3 OLCI. The algorithm was derived by a compiled dataset of *in situ* measurement and Sentinel-3 images, that were atmospherically corrected using the Case 2 Regional Coast Colour (C2RCC) processor to account for the terrain and water complexity of the region. An optimization routine was used to fit and compare existing algorithms to the dataset, and to define a region-specific algorithm. Additionally, different machine learning (ML) approaches were applied to retrieve Chl-*a* concentrations and to define a region-specific model. The proposed model significantly improves satellite Chl-*a* retrieval, enabling a more accurate monitoring of phytoplankton biomass at a finer spatial resolution than previous works.

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Hyperspectral is not just multispectral with lots of bands – use of WATERHYPERNET for validation of hyperspectral satellite missions

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A new generation of hyperspectral satellite missions raises the potential for measurement of new aquatic processes and parameters, including phytoplankton groups, i.e. more than just chlorophyll *a*. Algorithms that exploit spectral curvature/derivatives/anomalies are promising and many hyperspectral algorithms have been proposed for phytoplankton groups. However, truly hyperspectral algorithms may be quite different from multispectral algorithms in their sensitivity to satellite measurement errors. For example, spectrally smooth errors (aerosol correction, broadband calibration, sunglint) have negligible impact on the second derivative of reflectance, whereas spectrally rough errors (wiggles, random noise, interband calibration) are greatly amplified in the second derivative of reflectance. This is a new paradigm for algorithm design, atmospheric correction and radiometric validation since accuracy for the second derivative of reflectance may be more important than the reflectance itself.

The WATERHYPERNET component of HYPERNETS delivers hyperspectral water-leaving radiance reflectance measurements continuously at multiple sites for validation of satellite missions, both multispectral and hyperspectral. Satellite validation by WATERHYPERNET will be demonstrated here for hyperspectral missions (ENMAP, PRISMA, PACE, etc.) with specific focus on the new challenges of hyperspectral algorithms, including the potentially huge impact of spectrally rough errors.

The status of the WATERHYPERNET network will be updated, including recent improvements made in data processing, quality control and distribution.

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Bio-fouling detection of moored inherent optical sensors

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Bio-fouling on optical sensors is the main limiting factor determining measurement accuracy and a significant challenge for medium-range coastal ocean deployments lasting more than two weeks. This is the case for the continuous inherent optical observations collected at the Australian Integrated Marine Observing System (IMOS) Lucinda Jetty Coastal Observatory (LJCO, http://lucinda.it.csiro.au/). Despite best efforts to reduce bio-fouling using copper tubing and copper tape, data degradation due to bio-fouling can be observed frequently in the Sea-Bird Scientific ac-s beam attenuation and absorption measurements and the SeaBird Scientific BB9 scattering observations at this site. Maintenance at the LJCO is usually at 2-3 week intervals and post-deployment photos provide evidence of the type and extent of the bio-fouling on optical lenses and tubing. The fouling can be highly variable depending on the season, ranging from thin almost transparent bio-films to significant barnacle growth (sticky little crustaceans). We tested different detection methods using copper-shuttered reference instruments such as the SeaBird Scientific ECO Triplet-w and WQM devices that are presented in this study. The best performing detection method based on time series correlation has been implemented for operational data processing and reprocessing of version v2025.0, which is available from the Australian Ocean Data Portal (https://portal.aodn.org.au/). This data version now provides an additional bio-fouling flag for improved quality control of the IMOS-LJCO ac-s and BB9 observations, ensuring high quality, consistent datasets in an extended time series.

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Suspended sediment budget and its relation with the submerged mudbanks dynamics along Suriname's coastal area

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Suriname has a 390 km-long coastline characterized by the presence of large, dynamic submerged mudbanks. They are primarily sustained by sediment transported from tributaries in this coastal area, such as the Marowijne and Suriname Rivers. Nonetheless, the sediment supply from the Amazon River also plays a significant role. These dynamic features migrate westward over decadal time scales (10–15 years), influencing sediment deposition, coastal erosion or accretion hotspots and the mangrove forests development. A comprehensive understanding of the impact of sediment transport patterns on mudbanks' spatio-temporal evolution is relevant for coastal management and ecosystem conservation.

This study is focused on a satellite-based approach for detecting, mapping, and analyzing the sediment dynamics that govern submerged coastal mudbank behavior in Suriname. It integrates low resolution (e.g. Sentinel-3 and MODIS) ocean color observations to derive suspended particulate matter (SPM) concentrations. This allows a comprehensive assessment of regional sediment transport pathways and the long-term feeding mechanisms of migrating mudbanks. High-resolution optical imagery from the Landsat (5, 8, 9) and Sentinel-2 missions is used to map the seasonal spatio-temporal evolution (2003 - present) of the submerged mudbanks, assessing their long-shore migration and offshore extent.

The results show the monthly and seasonal SPM spatio-temporal variability (between 2003 - present) over an extended region (±200 km beyond Suriname's coastline) and the long-shore and offshore extent analysis of submerged mudbank migration and its correlation with SPM dynamics. All these are correlated with the identified erosion and accretion sectors and mangrove forest expansion and retreat areas, for an overall assessment of the coastal vulnerability patterns.

The presented service was developed under the Further Expansion of EO Uptake Supporting International Development Banks Projects (FEOSID), financed by the European Space Agency, which aims to extend the thematic and geographic coverage of the Earth Observation demonstration services developed in Latin America.

Validation of remote sensing reflectance derived with WASI from EnMAP L2A land data using AERONET-OC data

Ian Somlai-Schweiger[1,*], Thomas Schroeder[2], Peter Gege[1]

To retrieve remote sensing reflectance, R_{rs}, from satellite images of water bodies, it is necessary to subtract the surface reflections of the sun and sky (glint), R_{rs}^{surf}. A newly introduced Rrs tool from the software WASI allows to simulate R_{rs}^{surf} for bottom of atmosphere reflectance images, which are affected by glint and minor path radiance errors from atmospheric correction. This work presents examples of R_{rs} spectra obtained with WASI for eight EnMAP scenes, which were atmospherically corrected using EnMAP's L2A processor for land, PACO. For each EnMAP scene, atmospheric parameters (ozone column, AOT, water vapor) are input into WASI and the user optimizes the processing parameters individually. Then, a pixel-wise glint correction estimates the sky radiance reflected at the water surface in sensor direction as fractions of three components originating from direct solar radiation (sun glint) and diffuse components caused by molecular and aerosol scattering (sky glint). The generated glint image is subtracted from the input L2A image, resulting in a glint corrected R_{rs} image. Two scenes each are chosen at four AERONET-OC sites: Venice Lagoon (AAOT), Bahia Blanca, Chesapeake Bay and Lucinda. The in-situ data that is timely closest to each EnMAP acquisition is chosen to validate the R_{rs} results, which are also compared with EnMAP's standard water L2A product.
A strong correspondence between the WASI derived R_{rs} and AERONET-OC measurements is achieved for all scenes and sites. The aquatic R_{rs} spectra obtained from the EnMAP land product closely resemble those from the standard water product. In the case of Bahia Blanca, the high concentration of total suspended matter leads to a glint overestimation below 500 nm. Further investigation is needed to determine if additional fine-tuning of the WASI processing parameters might compensate this effect. Overall, the results validate the glint correction method implemented in the new Rrs tool.

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Practice and Reflections on the Construction of China's Ocean Satellite Marine Calibration and Validation Sites

Qingjun Song[1], Chaofei Ma[2], Hailong Peng[3], and Zhou Wu[4]

Optical remote sensing signals from ocean satellites are influenced by multiple factors, such as sea surface noise and atmospheric interference. Therefore, obtaining high-precision, traceable in situ "ground truth" data (high-quality field observation data) is crucial for satellite calibration and the validation of remote sensing products. Internationally, the construction of marine calibration and validation sites has formed a relatively well-developed network layout, providing continuous access to multi-parameter, long-term time-series in situ data. Based on an investigation of the observation technology systems and primary tasks of global marine Cal/Val networks, this study systematically analyzes the status and development trends of these networks. Considering the operational needs of China's ocean satellites and the environmental characteristics of China's coastal seas, this paper summarizes the practical experience and application outcomes of building China's marine Cal/Val network. At present, eight fixed stations have been established, covering representative marine areas such as the Bohai Sea, Yellow Sea, East China Sea, and South China Sea. These stations carry out year-round continuous observations of key marine environmental parameters (e.g., water color, hydrographic conditions, and air–sea fluxes) and meteorological variables, forming a supporting validation system in conjunction with domestic ocean satellite data. The network has already achieved a rational spatial layout, stable operational capability, and reliable data quality, providing strong support for the radiometric calibration accuracy assessment of domestic satellites, the validation of remote sensing product authenticity, and the improvement of retrieval algorithms. In the future, with the implementation of development plans, the Cal/Val network is expected to generate a long-term time-series, high-spatiotemporal-resolution "spatiotemporal cube" dataset of in situ observations covering major types of China's coastal waters. This dataset will support cutting-edge research in marine bio-optical modeling, ocean geophysical modeling, and ocean remote sensing inversion algorithms, while promoting deeper cooperation and academic exchange between Chinese and international scientists in the field of ocean satellite calibration and validation.

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Oil spill detection and potential for thickness estimation by combining ultraviolet and optical remote sensing

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Abstract:

The GOCI-II ocean color sensor, mounted on the GK-2B geostationary satellite, features 13 spectral bands ranging from ultraviolet (380 nm) to near-infrared (865 nm) with a spatial resolution of 250 meters. The inclusion of the ultraviolet band presents a novel opportunity for detecting oil spills and estimating oil thickness in marine environments. This study utilizes GOCI-II data from two reported oil spills along the coast of China to assess the capability of the 380-nm band for oil spill detection. Our findings indicate that the 380-nm band exhibits the highest positive contrast for identifying oil slicks among all GOCI-II spectral bands. The GOCI-II's one-hour revisit time during daylight further enhances oil spill monitoring, making it particularly valuable during emergency response situations. An oil detection algorithm was developed by integrating the ultraviolet and optical bands to accurately delineate the extent of oil slicks. Additionally, the potential for estimating oil thickness was explored by leveraging the combined data from ultraviolet and optical bands. The results demonstrate the effectiveness of using ultraviolet bands for oil spill detection and highlight the promising potential for oil thickness estimation. These findings underscore the value of emerging ocean color sensors with ultraviolet capabilities, such as PACE/OCI and HY-1E/PMRIS, in advancing oil spill remote sensing.

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Rrs-meters: A Floating Optical Buoy System (FOBY) for Direct Measurement of Remote-Sensing Reflectance Based on the Skylight-Blocked Approach (SBA)

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Accurate determination of remote-sensing reflectance (Rrs) is fundamental for quantitative ocean colour applications, yet conventional Rrs measurement approaches are affected by systematic uncertainties introduced by skylight reflection and correction algorithms. To address these challenges, we developed the Rrs-meter, a floating optical buoy system (FOBY) based on the Skylight-Blocked Approach (SBA). SBA employs a geometric shading configuration to physically suppress sky-glint contamination, thereby reducing systematic uncertainties in Rrs derivation.

The instrument architecture integrates a tripod-based floating platform that minimizes self-shading while maintaining optimal geometry under dynamic sea states. Its modular design allows rapid deployment (<5 minutes), lightweight operation (<5 kg), and supports interchangeable payloads including hyperspectral radiometers, CTD instruments, and optical sensors for chlorophyll-a, coloured dissolved organic matter (CDOM), and backscatter. Integrated attitude detection and GNSS receivers provide real-time attitude tracking and geospatial referencing. Two operational configurations are available: a portable system for cruise-based measurements, and a disposable version capable of year-long drifting observations.

Data processing algorithms incorporate automated filtering (>5° exclusion), shadow-depth correction, and statistical averaging using confidence-interval methods to remove outliers and enhance spectral stability. Radiometric calibration is traceable to NIST standards, ensuring measurement accuracy and comparability across platforms. Field campaigns in inland and coastal waters demonstrate strong agreement with benchmark systems (TriOS RAMSES), with Rrs deviations typically <5% across 400–700 nm.

The Rrs-meter has been successfully applied to satellite vicarious calibration, algorithm validation, and long-term ocean colour monitoring, offering a robust, scalable, and efficient platform to advance global aquatic remote sensing.

PCA-Driven Atmospheric Correction of PACE Hyperspectral Ocean Color Imagery

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Atmospheric correction (AC) of ocean color imagery faces significant challenges in regions with absorbing aerosols, adjacency effects, and optically complex waters, conditions frequently encountered in coastal and inland areas, but also occasionally present in the open ocean. Traditional algorithms, which extrapolate the atmospheric signal from near and shortwave infrared to shorter wavelengths, often fail in these conditions. To overcome this, the top-of-atmosphere (TOA) signal undergoes principal component (PC) decomposition, retaining only PCs sensitive to water signals, which allows for precise non-linear mapping of TOA to water reflectance. This methodology is tailored for PACE OCI imagery with a 5 nm resolution across 340 to 895 nm. The algorithm excludes OCI observations affected by strong gaseous absorption, but maps TOA PCs to water PCs defined across all spectral bands, enabling water reflectance estimates over the entire 340-895 nm range. A direct mapping of the selected TOA PCs to chlorophyll-a concentration is also implemented. Ensembles of TOA reflectance are generated using in situ observations and Hydrolight simulations to support the PC mapping and quantify pixel-level uncertainties. The algorithm's performance is theoretically assessed under various angular and environmental conditions. Application to OCI imagery over diverse oceanic and coastal regions demonstrates the method's effectiveness in complex atmospheric and optical settings. It yields realistic water reflectance spectra and does not exhibit artifacts such as negative or anomalously low values at short wavelengths. Preliminary validation using co-located in-situ measurements of hyperspectral water reflectance and chlorophyll-a concentration indicates acceptable agreement, though additional matchup data are needed to fully assess accuracy.

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A spectral unmixing approach for chlorophyll-a retrieval from Sentinel-3 OLCI top-of-atmosphere spectra in optically complex fjords

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We propose a new method of retrieving chlorophyll-a and ocean color remote sensing reflectance (R_{rs}) simultaneously from Sentinel-3 OLCI top-of-atmosphere radiance spectra in optically complex coastal areas. Using a database of inherent optical properties, including measured volume scattering functions and hyperspectral particulate and dissolved absorption coefficients from Norwegian fjord water samples, we have identified local endmembers representing water with high colored dissolved organic matter (CDOM) absorption, weakly absorping but highly scattering glacial meltwater, and highly scattering water from coccolithophore blooms. These three types of water often co-occur in Norwegian coastal environments, leading to a high degree of optical complexity. Using a gradient descent method and the ocean-atmosphere coupled radiative transfer model AccuRT, we identify the best mixture of these three endmembers as well as atmospheric variables to match top-of-atmosphere radiance spectra. We can then retrieve corresponding values of chlorophyll-a through linear mixing of the endmember chlorophyll-a concentrations, and model remote sensing reflectance by linear mixing of the optical properties of these endmembers. This unmixing approach shows similar and in some metrics, better performance than other R_{rs} and chlorophyll-a retrieval methods we tested (BAC, ACOLITE, and POLYMER, paired with band-ratio, neural network and red-edge algorithms for chlorophyll-a retrieval). We conclude that this is a novel approach for regional chlorophyll-a retrieval algorithms in optically complex environments, which can be adapted for new regions with appropriate endmember water optical properties.

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Global assessment of merged multi-sensor ocean-colour chlorophyll-a products.

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Abstract.

With the availability of global ocean-colour chlorophyll-a (chl-a) estimates that now span 28 years, there has been a concerted effort to produce merged data products from different satellite sensors to assess changes in chl-a, over the global ocean for the past three decades. To date, the performance of these merged chl-a products has not been thoroughly assessed, which is the objective of this paper. We assembled a large global in-situ dataset resulting in >13000 in-situ chl-a satellite match-ups. A comprehensive suite of merged ocean-colour chl-a products was assessed including two OC-CCI data streams (OC-CCI v5 and OC-CCI v6), two GlobColour data streams and the Copernicus Marine Environment Monitoring Service (CMEMS) GlobColour L3 and L4 and CMEMS-CCI products. All of these data products exhibited consistent results with the in-situ chl-a data with a mean relative percentage difference of 15%.

Biology dominates seasonal carbon uptake at high latitudes in Antarctic coastal waters

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The Southern Ocean plays a vital role in global CO_2 uptake, but the magnitude and even the sign of the flux remain uncertain. Physical mechanisms for carbon uptake are emphasized, with the role of biology in surface ocean carbon uptake potentially underestimated in coastal high latitude systems, and the influence of phytoplankton phenology is underexplored. This study focuses on the West Antarctic Peninsula, a case study region experiencing rapid climate change, to examine shifts in seasonal surface ocean carbon dioxide uptake. We used 20 years of in situ air-sea CO_2 flux data from research vessels and satellite-derived Chlorophyll-a data from OC-CCI as a proxy for phytoplankton biomass. OC-CCI was used for the Chlorophyll-a record because the OC-CCI atmospheric correction approach (POLYMER) results in more representative spatial distributions of coastal phytoplankton biomass than other approaches due to adjacency effects along bright icy coastlines in polar regions. We observed that the seasonal cycles of both air-sea CO_2 flux and Chlorophyll-a concentration intensified poleward. The amplitude of the seasonal cycle of the non-thermal component of surface ocean pCO_2 increased with increasing latitude, while the amplitude of the thermal component remained relatively stable. These results suggest that pronounced biological uptake occurs over the shelf in austral summer despite reduced CO_2 solubility in warmer waters, which typically limits carbon uptake through physical processes. Chlorophyll-a concentrations and air-sea CO_2 fluxes were tightly coupled across all years, especially when phytoplankton biomass was high. These results suggest that an ocean-color-based air-sea CO_2 flux algorithm may be developed to estimate surface ocean carbon uptake from space.

Validation of satellite water reflectance products with WATERHYPERNET/PANTHYR

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In this poster we present the pan-and-tilt hyperspectral radiometer (PANTHYR) system design, its standard acquisition protocol, data processing, and quality control. The PANTHYR was developed for the autonomous measurement of water-leaving radiance reflectance with the goal of providing validation data for any optical satellite sensor. PANTHYR consists of custom electronics, a pair of TriOS radiometers (irradiance and radiance) mounted on a pan-and-tilt head, so it can automatically adapt to favourable geometries for above-water radiometry, and park its sensors to minimise fouling between measurements. A PANTHYR measures multiple times per hour, at different relative azimuth angles to the sun, and can generally provide a matchup for any cloud free visible to near-infrared satellite imagery over the deployment site, if the sensor resolution and site location are compatible. Sites with PANTHYR deployments are integrated within the WATERHYPERNET network and their quality controlled data are distributed through the WATERHYPERNET data portal. Through radiative transfer modelling, we investigate avenues for improving the PANTHYR processing and quality control, and evaluate calibration tracking during long unsupervised deployments. Finally, the use of PANTHYR measurements for validation of several satellite missions is demonstrated, including public and commercial metre-scale missions not specifically designed for water quality remote sensing, as well as traditional coarser resolution ocean colour sensors. We evaluate retrievals of hyperspectral ocean colour data from the PACE/OCI mission in terms of reflectance magnitude and spectral continuity. We show reasonable performance in terms of reflectance magnitude, but large spectral discontinuities that will impact pigment retrievals.

Next-generation PANTHYR system: enhanced reliability and deployability for autonomous ocean colour validation

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Autonomous hyperspectral radiometer systems are essential tools for validating satellite-derived water reflectance. Based on the existing PANTHYR system and building on field and production feedback, we present the updated design with major hardware and software upgrades aimed at improving reliability, ease of deployment, and environmental resilience.

The upgraded system integrates temperature and humidity monitoring, expanding diagnostic and monitoring capabilities. A redesigned housing in fiberglass reduces weight, eliminates corrosion risk, and incorporates stacked component mounting to reduce size requirements and detachable cabling for easier setup and transport. Enhanced internal cable management and improved documentation further simplify assembly and replication.

Robustness in harsh marine conditions is improved through advanced waterproofing, including pressure equalisation valves, better cable glands, and an additional backplate for rigidity.
Together, these features extend reliability, operational lifetime and reduce maintenance needs.

Software enhancements include automated disk-space checks, external storage of RGB images, and system uptime monitoring, further facilitating stable long-term deployments with minimal intervention requirements.

This revised system represents a step forward in autonomous validation instrumentation, addressing practical challenges of deployment and operation while safeguarding high-quality ocean colour measurements. It is now better positioned for integration within sustained observation networks such as WATERHYPERNET.

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Hyperspectral radiometry on BGC-Argo floats: first exercise of Ocean Color Satellite Validation.

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The BioGeoChemical-Argo (BGC-Argo) program is expanding the global network of autonomous profiling floats equipped with biogeochemical and bio-optical sensors. Since 2012, standard floats have measured downwelling irradiance (Ed) at three wavelengths (380, 412, and 490 nm). In the context of the ERC-REFINE project, an enhanced array of about fifteen BGC-Argo floats has been deployed between 2022 and 2024 across several open-ocean regions with distinct bio-optical characteristics.

As satellite missions such as NASA's PACE or the upcoming ESA's CHIME begin delivering unprecedented spectral resolution, the availability of spectrally resolved, high-quality in situ data becomes essential. This new generation of BGC-Argo floats provides a unique response to this need, capturing radiometric observations across 140 wavelengths between 320 and 780 nm, in a wide range of optical regions. Indeed, these floats are equipped with ruggedized TriOS-RAMSES hyperspectral radiometers capable of measuring both Ed and upwelling radiance (Lu) from 300 m to the surface. Observations are collected every 10 days around local noon with a denser 5 day sampling during a 4-month intensified sampling phase (mid-March to mid-June 2024) designed to optimize matchups with the initial phase of the PACE satellite mission. To date, 698 hyperspectral profiles have been collected and transmitted in near real time.

Following extensive characterization of both the sensors and the measurements platforms, we are now able to deliver qualified remote sensing reflectance and its associated uncertainty, from hyperspectral BGC-Argo data. This study presents thee first results of a comparison exercise between quality-controlled in situ hyperspectral BGC-Argo data and coincident observations fromOcean Color satellite missions, including PACE and Sentinel-3.

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INVESTIGATING METOCEAN EFFECTS ON FLOATING OFFSHORE WIND PLATFORM POSITIONAL OFFSET USING SENTINEL-2 IMAGERY

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Floating offshore wind farms are expanding into deeper and more dynamic environments, demanding scalable monitoring solutions to ensure safe and efficient operations. This study explores the use of Sentinel-2 optical imagery to track the positional offset of semi-submersible floating wind platforms and assess their response to wind and wave forcing.

A convolutional neural network (U-Net) was trained to segment platforms in satellite imagery, achieving 98.8 % pixel-level accuracy and 88.7 % mean Intersection over Union. Extracted platform centroids were combined with wind and wave data from Copernicus Marine Service and ECHOWAVE hindcasts for August 2021–July 2024. Statistical analyses included linear regression, multivariate regression, and k-means clustering.

Results show a moderate but statistically significant global correlation ($R^2 = 0.12$) between wind speed and displacement magnitude, increasing to $R^2 = 0.71$ for westerly winds when directionality is considered. Multivariate models indicate both wind and wave parameters contribute to motion, with anisotropic behaviour linked to mooring geometry and environmental exposure. Clustering revealed four distinct displacement regimes, each associated with characteristic wind patterns.

The methodology also demonstrated value for anomaly detection, identifying two potential mooring line failures based on displacement thresholds and supported by Sentinel imagery showing concurrent vessel activity.

Despite spatial resolution and temporal coverage limitations, this approach provides a cost-effective, wide-area monitoring layer that complements in-situ systems. It can support real-time tracking, operational state classification, and early warning of anomalies, contributing to the resilience of floating offshore wind operations.

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Denoising VIIRS and Sentinel-2 MSI ocean color imagery for improved floating algae monitoring using noise-simulation-aided deep learning

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The floating algae index (FAI) images derived from Visible Infrared Imaging Radiometer Suite (VIIRS) and Sentinel-2 Multispectral Instrument (MSI) have been widely used to monitor open ocean and coastal floating algal blooms, but they often suffer from complex and variable noise with different strengths, orientations, and distributions. While deep learning methods are effective at reducing noise, adapting them to sensor-specific noise variations remains challenging. Such adaptation typically requires large-volume and high-quality training data to adjust models across different satellite sensors. Here, we propose a two-step denoising process: 1) simulating noise using spatial frequency domain information to generate customized representative training data from limited samples, and 2) training the state-of-the-art MIRNet denoising module, which integrates multi-scale residual learning and attention mechanisms, for optimal performance. The method was tested on medium-resolution VIIRS FAI data, degraded by stripe noise, and high-resolution Sentinel-2 MSI FAI data affected by glitter noise. By applying noise simulation, 4,320 training data were prepared from 91 real VIIRS samples, and 11,200 training data from 58 real MSI samples. The optimized MIRNet denoising model effectively reduced various types of noise while preserving the spatial details of ocean surface algae features. The average peak-signal-to-noise ratio (PSNR) and Structural Similarity Index (SSIM) of denoised VIIRS and MSI FAI images significantly improved over the original noisy images. Noise intensity on FAI and biomass values were estimated for VIIRS and MSI images, showing that noise on MSI FAI led to ~10 % biases in biomass estimates, whereas the effect on VIIRS biomass estimates is negligible. The MIRNet was also tested on VIIRS Color Index images and improved the image quality even without retraining. Overall, the proposed noise-simulation-aided deep learning method can effectively enhance ocean color image quality, enabling more accurate ocean colour remote sensing.

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Diurnal Variability of Sub-Mesoscale Chlorophyll-a Fronts
Revealed by Geostationary Ocean Color Observations

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Ocean fronts are fundamental components of ocean circulation, the climate system, and marine ecosystems. Taking advantage of the unprecedented spatiotemporal resolution (250 m, hourly) of the geostationary ocean color satellite GK-2B/GOCI-II, we refined and implemented an optimized algorithm to detect sub-mesoscale chlorophyll-a (Chl-a) fronts. For the first time, this dataset allowed us to investigate the diurnal variability of sub-mesoscale biological fronts. Our results show that Chl-a fronts form richer and more coherent sub-mesoscale patterns than physical fronts derived from sea surface temperature (SST). During the spring bloom season, both the number and area of Chl-a fronts exhibited a dome-shaped diurnal cycle, peaking around local noon. The fronts also underwent clear horizontal displacements: under strong currents they closely followed surface advection, whereas under weak currents their propagation speeds diverged from current velocities, pointing to the growing influence of biological processes. These findings highlight dynamic behaviors—particularly the diurnal variability in speed and the directional mismatch with currents—that had not been recognized in previous studies. In contrast to the historical emphasis on mesoscale physical fronts, our assessment reveals the importance of capturing sub-mesoscale biological fronts to better understand oceanic variability.

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Highest Quality Remote Sensing Reflectance Database Compiled from 20+ years of MODIS-Aqua measurements

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Remote sensing reflectance (R_{rs}) is a fundamental property in satellite ocean color remote sensing, which is critical for retrieving optical-biogeochemical properties and data-driven atmospheric correction algorithms. In this study, we compiled a database of the highest quality R_{rs} (HQ_{MODISA}-R_{rs}) based on 20+ years of ocean color measurements by the Moderate Resolution Imaging Spectroradiometer (MODIS) onboard the Aqua satellite, where three main criteria were employed to screen the highest-quality R_{rs}. Our evaluation showed that the criteria for the highest-quality R_{rs} (CHQR) improved MODIS R_{rs} data consistency with benchmark in situ R_{rs} datasets, such as those from MOBY and AERONET-OC. After applying CHQR, analysis of imagery products in the South Pacific Ocean revealed that the coefficient of variation (CV) of R_{rs} among pixels reduced from 0.042 (standard quality control) to 0.030, along with enhanced temporal consistency, which indicates that this approach effectively filters abnormal data products. While such a dataset played a key role in the development of the cross-satellite atmospheric correction algorithm (Lee et al., 2024), we here further demonstrate that applications of HQ_{MODISA}-R_{rs} have ~21.0% of oceanic areas between 50°S and 50°N showing reversed long-term trends of R_{rs} compared to the trend based on the standard R_{rs} product. We anticipate that this highest-quality R_{rs} database would not only improve our evaluation and understanding of long-term changes in various R_{rs}-derivative bio-optical properties of the global ocean, but also help to obtain consistent products among various satellite ocean color missions.

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Obtain Consistent Remote Sensing Reflectance between Hyperspectral PACE OCI and Multi-band NPP VIIRS

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Atmospheric correction (AC) is a critical factor limiting the accuracy of ocean color remote sensing and the consistency across satellites. NASA's PACE mission, launched in 2024 with the hyperspectral Ocean Color Instrument (OCI), provides new opportunities for cross-mission continuity. We present $CSAC_{OCI}$-H, a hybrid framework that combines a neural-network-based cross-satellite AC approach with the heritage AC scheme to generate hyperspectral remote sensing reflectance (R_{rs}) from OCI, with consistent R_{rs} obtained for common wavelengths between OCI and VIIRS. For paired OCI–VIIRS data used in this study, the model shows markedly improved spectral consistency, particularly reducing biases in the ultraviolet and blue bands. Validation against MOBY in situ data demonstrates higher accuracy than heritage algorithms, while comparisons with AERONET-OC in coastal waters indicate more robust performance under challenging atmospheric conditions. Applied to satellite imagery, $CSAC_{OCI}$-H mitigates cloud-edge artifacts and yields smoother spatial patterns. This framework provides a practical pathway for harmonizing hyperspectral and multispectral ocean color records, supporting long-term climate and ecological studies.

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Ocean colour applications to carbon and the climate

Spatiotemporal Dynamics and Drivers of Surface Ocean pCO_2 in Polar and High-Latitude Regions

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Polar and subpolar oceans play a pivotal role in regulating the global carbon cycle, accounting for the majority of oceanic uptake of anthropogenic CO_2. However, uncertainties remain high due to observational challenges under extreme conditions. Understanding the distribution of surface-ocean CO_2 partial pressure (pCO_2w) and its underlying drivers is critical for improving assessments of high-latitude carbon dynamics. We present a machine learning framework that integrates spatiotemporal classification and supervised learning to reconstruct and quantify the processes controlling the variability of pCO_2w from satellite-observable and reanalysis-modeled environmental variables. First, Self-Organizing Maps were applied to environmental variables (such as sea surface temperature, salinity, ice concentration, chlorophyll-a, absorption by colored detrital matter and wind speed) to cluster the Arctic and Antarctic into bioregions with distinct seasonal and biogeochemical regimes. Within each bioregion, Random Forest regression models were developed separately for sea-ice and open-water conditions to predict pCO_2w at 8day timeframe using SOCAT database and the variables cited above, between 1997 and 2022. This two-step framework allows us to explicitly assess how much of the observed pCO_2w variability can be explained from accessible variables. Model performance was high across regions ($R^2 \approx 0.96$, RMSE = 6–14 µatm). Analysis revealed that pCO_2w is primarily controlled by sea surface temperature (11–33%), salinity (15–35%), and sea ice (2–18%). Importantly, the framework captured seasonal cycles of pCO_2w, with summer minima and winter maxima consistent with in-situ observations, reflecting both thermal and non-thermal controls. Last, the analysis of spatio-temporal changes in bioregions' boundaries within the studied period highlights potential regime shift within the pCO_2w dynamic. By combining bioregional classification with supervised learning, this approach provides new insights into the drivers of surface-ocean CO_2 variability, advancing the integration of satellite data into high-latitude carbon cycle studies.

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Bayesian Estimation of Photosynthesis Irradiance Parameters for Marine Phytoplankton

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Quantifying marine primary production is essential for understanding oceanic carbon cycling and its role in regulating climate (Kulk et al., 2020). Accurate estimation of the photosynthesis–irradiance (P–I) relationship is central to this, yet uncertainty in key parameters — initial slope α^B, assimilation number P_m^B, respiration rate R and photoinhibition term β — is often underreported. We present a Bayesian modeling framework to estimate distributions of P–I parameters from replicated in situ incubations for both photoinhibiting and non-photoinhibiting datasets. The hierarchical structure will allow pooling of information across experiments while retaining experment-specific estimates, improving inference where data are sparse (Sivia & Skilling, 2006). We have tested the method to two datasets and conducted posterior predictive checks to evaluate model fitness. Finally, the parameter distributions are propagated through a primary production model to estimate daily water-column primary production along with quantified uncertainty. This approach aims to provide a statistically rigorous pathway for incorporating parameter uncertainty into primary production models.

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Towards Operational Large Scale Seagrass Mapping Using Sentinel-2 Time Series: Insights from the ESA Coastal Blue Carbon Project.

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As part of the ESA Coastal Blue Carbon project, we aim to map Mediterranean seagrass meadows using EO data and a simplified, transferable habitat typology. The objective is to develop robust and generic approaches for large-scale habitat mapping based on Sentinel-2 time series.

We designed a large-scale experiment covering six Sentinel-2 tiles along the Mediterranean coasts of Spain and France, representing a diversity of ecological, geomorphological conditions. The focus is on benchmarking methods for constructing bi-monthly image composites, which are essential to generate homogeneous and temporally consistent time series suitable for supervised classification.

These compositing strategies and temporal configurations are evaluated through their classification performance. We implement multiple evaluation levels, including cross-validation within tiles and transfer testing across tiles, to assess the generalization potential. This allows us to measure the predictive power of each method on unseen Sentinel-2 tiles, a critical aspect for scaling up seagrass mapping.

In addition, this framework also allows testing the benefits of correcting the impact of the water column. In optically shallow areas, water surface reflectance is a depth-dependent combination of contributions from the bottom reflectance and from the optically active constituents of the water column. Using Lee's QAA equations and EMODNET's high resolution bathymetry product, it is possible to correct these contributions to derive depth-invariant bottom reflectance. Maximum optical depth on seagrass meadows in Mediterranean coastline is roughly 8 to 10 m. First results show an improvement in the generalization potential of the method by integrating the physical properties of the water column.

This work provides a solid foundation for the development of scalable, transferable, and operational workflows for the mapping of seagrass habitats across the Mediterranean region. It supports long-term monitoring strategies and contributes to the broader goal of improving our understanding and management of coastal blue carbon ecosystems.

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Assessing satellite estimates of particle backscatter in the Mediterranean Sea using the first array of Biogeochemical-SVP Lagrangian drifters

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Satellite-derived particulate backscattering (b_{bp}) provides key insights into large-scale ocean biology and biogeochemistry, serving as a proxy for phytoplankton biomass and particulate organic carbon. These data underpin estimates of carbon stocks, fluxes, and productivity in coupled physical–biogeochemical models. However, the paucity of in situ multi-band b_{bp} measurements limits robust uncertainty assessment of satellite products (Brewin et al., 2023). To address these observational gaps, Surface Velocity Programme (SVP) drifting buoys, historically used to validate SST and SSS, have been equipped with bio-optical and oxygen sensors, defining the Biogeochemical-SVP drifters. The high sampling frequency combined with a Lagrangian approach enables it to overpass numerous pixels in a single day, thus providing large in situ datasets for validation activities of b_{bp}, not achievable by other in situ platforms. Here, we present for the first time a comparison of satellite and in-situ b_{bp} using observations from Lagrangian drifters which provide b_{bp} at 470 and 532 nm. To this aim, we tested different algorithms (e.g. QAA, GSM) and satellite sensors (e.g., PACE/OCI, Sentinel-3/OLCI) to quantitatively evaluate the performance of the retrievals. The in-situ data derived entirely from the first BGC-SVP drifter array deployed in the Mediterranean Sea during the ITINERIS'EYES cruise performed in July 2025. In the next future, a coordinated array of BGC-SVP drifters, BGC-Argo floats, and other autonomous platforms working in synergy could provide the required surface and subsurface data at the temporal, spatial, and spectral (e.g., multi- or hyperspectral resolution) scales of interest to future satellite missions.

Enhancing Ocean Color Observations' Description of Surface Carbon Compounds using Diffuse Attenuation Products in the UV and Bue from Sentinel-5P TROPOMI

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Light reflected from the ocean surface encodes essential information about phytoplankton, coloured dissolved organic matter (CDOM) and underwater light, relevant for estimating primary productivity or other biogeochemical processes. The atmospheric sensor TROPOMI on Sentinel-5P resolves as opposed to former atmospheric sensors the ocean's mesoscale dynamics of the underwater light attenuation (Kd) in the UV and short blue with its nearly daily coverage and 3.5 km by 5.5 km pixel size. The retrievals are based on identifying the strength of the vibrational Raman scattering (VRS) signal in the spectrally high resolved TROPOMI data and then converting it via a look-up table (LUT) based on coupled atmospheric-oceanic RTM calculations of Kd in the specific wavelength region corresponding to the excitation of the VRS. We present our novel operational products (https://data-portal.s5p-pal.com/products/kd.html) which contain pixel-by-pixel uncertainties based on the sensitivities of the retrievals' parametrizations to atmospheric and oceanic parameters. We show validation of the TROPOMI Kd products to the multispectral data set of Kd available from the global BGC-ARGO program. In particular, for the Mediterranean Sea, we explore the capabilities of the TROPOMI Kd products to improve classifying DOM properties which enables describing in more detail the CDOM dynamics. We further use these data together with other ocean color products, such as chlorophyll-concentration of specific types of phytoplankton (PFT), CDOM and the 4D-products of the ESA project 4DMedSea on the overall chlorophyll concentration (CHL), sea surface temperature and salinity to differentiate ecoregions in these waters. We aim to improve previous regionalization approaches of the Mediterranean Sea through a better incorporation of fluxes between the various phytoplankton groups, particulate organic matter to depth and dynamics and storage of dissolved organic carbon and its colored fraction CDOM. Our study shows the first exploitation of these TROPOMI products in relation to the ocean's carbon pool.

***The next level*: Quality metrics and metrology of climate indicators and derived datasets**

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While recent years have seen much progress in the application of metrological principles and uncertainty analysis to satellite data, there is a gap in the propagation of this knowledge and standardisation to derived (level 3+) datasets. These include climate indicators derived from lower-level observational data (satellite / in-situ), climate projections, reanalyses, etc. that are provided by the Copernicus Climate Change Service (C3S). Examples are marine biogeochemistry, sea level, and surface wave indicators derived from ERA5 reanalysis and CMIP6 projection data. These are popular for applied research, industry, and policymaking across diverse sectors (energy, fishery, flood management, etc.) because they provide use case-oriented data on standard, gap-filled spatial and temporal grids. These use cases require reliable access to good quality, trustworthy, and reproducible data. However, the uncertainties in these datasets are often not provided in a complete or standardised manner. This ultimately limits their appropriate usage and the interpretation of resulting information upon which decisions will be made.

Here, we present an overview and gap analysis of current approaches (strengths and weaknesses) for uncertainty estimation across a range of climatological indicators and derived datasets, with a focus on ocean datasets. We provide recommendations on an initial set of metrology-based uncertainty estimation methods and metrics and documentation that should be included with these datasets as well as the further research necessary to address knowledge gaps. This is conducted in consultation with dataset producers and users spanning competency from domain experts to novice. Our goal is to provide users with confidence that data they acquire through the C3S are credible and enable them to establish the utility of the data with respect to their needs and requirements. This is an interactive process and we encourage input from this community to further shape a standardised, user-oriented approach.

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Optimizing Lagrangian drifter deployment for ocean color validation coupling kinematical models, remote sensing, and in situ data

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Satellite observations of particulate backscattering (b_{bp}) have greatly enhanced our understanding of ocean biology and biogeochemistry on large scales, serving as proxies for phytoplankton biomass or particulate organic carbon. b_{bp} is essential for estimating organic carbon stocks and fluxes and ocean productivity, which is subsequently incorporated into coupled physical-biogeochemical models. However, the paucity of in situ multi-band b_{bp} data hinders efforts to quantify uncertainties in satellite b_{bp} and its derived products. To address these gaps, Surface Velocity Programme (SVP) drifting buoys have been equipped with bio-otical and oxygen sensors, defining the Biogeochemical (BGC)-SVP drifters. The high sampling frequency combined with a Lagrangian approach enables it to overpass numerous pixels in a single day, thus providing large in situ datasets for validation activities, not achievable by other in situ platforms. Here, we present a novel Observing System (OS) to validate satellite b_{bp} products, integrating remote sensing, Lagrangian modeling, and in situ data, for the Mediterranean Sea. Main innovations are: integration of Lagrangian simulations using a sub-grid kinematic model applied to ocean currents datasets, and the constraing of simulated trajectories with gapped satellite b_{bp} data to assess variability and identify optimal deployment sites and time for BGC-SVP drifters, maximizing match-up opportunities. Different criteria are established as the beachtime time, the total potential and bin-specific matchups. Preliminary results suggest the Ionian Sea as the best site to reduce drifter beaching but also to capture low-mid b_{bp} values over the entire year. Higher b_{bp} values could be captured during winter and spring in the northwestern Mediterraean Sea. The development of an OS is a foundational step from research to sustained operations. The OS framework here developed can be extended to global ocean and has potential applications for validating other ocean color variables across ongoing (e.g., Sentinel-3/OLCI, PACE/OCI) and future satellite missions (e.g., ESA CHIME).

Retrieval of Particulate Inorganic Carbon in the North Sea with the MTG/FCI geostationary sensor

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Particulate Inorganic Carbon (PIC) is an important component of the marine carbon cycle, due to its dual role in carbon sequestration and release. In the pelagic environment, PIC is produced by calcifying plankton, particularly coccolithophores. Mapping of coccolithophore bloom areas and monitoring PIC concentration have been performed from space using multispectral ocean colour satellite since the SeaWiFS mission. Here we provide a first evaluation of the geostationary Meteosat Third Generation (MTG) Flexible Combined Imager (FCI) data to map areas where PIC is the dominant source of scattering and to retrieve PIC concentration. In situ data were collected during a field campaign in the North Sea in June 2025, when several water types were sampled, including a coccolithophore bloom (PIC concentration between 10 and 80 mg m^{-3}). PIC was measured via ICP-OES from discrete water samples, and continuously during ship transit with a prototype LISST-PIC optical sensor. Previously published waveband difference algorithms were adapted to the FCI wavebands. The classification method confidently detected areas with PIC above 40 mg m^{-3} (3.3 mmol m^{-3}), while correctly excluding areas with a high non-coccolithophore particle load (e.g. the East Anglian plume). The PIC retrieval algorithm showed a Mean Absorlute Percentage Deviation (MAPD) of 40 % against discrete samples (N = 7) and 55 % against the continuous PIC measurements (N = 84), with most of the deviation arising from estimation bias (overestimation). While these results were obtained from a single campaign and a single cocccolithophore bloom, they suggest that the FCI can be used to detect areas where PIC is the main scatterer and for PIC quantification, warranting additional work to improve algorithm design. The high temporal frequency of FCI can potentially provide better coverage of areas with frequent cloud cover, as well as resolve tidal variations in coastal environments where coccolithophores are known to occur (e.g. English channel).

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Enhanced Reconstruction of Satellite-derived Monthly Chlorophyll a concentration with Fourier Transform Convolutional-LSTM

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Chlorophyll a (Chl a) concentration, a vital indicator of water quality and crucial for assessing the health of marine ecosystems, presents significant challenges for satellite remote sensing due to various interferences, such as cloud cover, sun-glints, and adjacency effects. These impediments limit our understanding of marine ecosystems and hinder sustainable management practices. This study proposes a novel approach to overcome these challenges: the Fourier Transform Convolutional Long Short-Term Memory (FTC-LSTM) framework. Integrating Fourier Transform Convolution (FTC) and Long Short-Term Memory (LSTM) layers, the FTC-LSTM model aims to estimate cloud-free Chl a, improving the accuracy and robustness of the inpainting process. Evaluation of the FTC-LSTM model across the South China Sea (SCS), along with two other state-of-the-art deep learning models (DINCAE and Conv-LSTM), reveals its consistent superior performance across regions with distinct characteristics. Notably, the FTC-LSTM model achieved the highest scores with impressive values: 0.95 for determination coefficient (R^2), 47.57 for peak signal-to-noise ratio (PSNR), 0.99 for structural similarity index measure (SSIM), and 0.01 for root mean square error (RMSE). Temporal analysis demonstrates the model's ability to accurately capture the temporal variability of Chl a in the SCS. Furthermore, comparison of spatial patterns indicates that the FTC-LSTM model excels in reliably reconstructing Chl a distribution within the SCS, outperforming other models, particularly in tropical and subtropical regions significantly impacted by clouds.

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A Tropical Cyclone-Induced and Satellite-Detected Chlorophyll a Elevation Accompanied by Phytoplankton Biomass Decrease

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Abstract

Satellite observations have traditionally associated tropical cyclones (TCs) with phytoplankton blooms through elevated chlorophyll-a (Chla) concentrations, yet this relationship masks complex underlying ecological processes. Through a integration of satellite data and in-situ bio-optical measurements, we reveal a counterintuitive ecological response to TC "Chaba" in 2022 that challenges conventional understanding. While satellite-detected Chla concentrations increased and phytoplankton division rates accelerated following TC passage, we surprisingly documented simultaneous declines in phytoplankton biomass and carbon-to-chlorophyll (C:Chl) ratios. Our analysis demonstrates that physiological regulation, rather than biomass accumulation, dominated high-Chla zones during and after TC disturbance, with C:Chl anomalies contributing over 60% to elevated Chla areas. This research presents a paradigm-shifting scenario: phytoplankton biomass began accumulating initiated pre-TC, yet increased loss rates during/after TC reduced phytoplankton biomass despite enhanced division rates. The fundamental decoupling between TC-induced Chla enhancement and phytoplankton biomass dynamics we document has profound implications for oceanic carbon cycling models and climate predictions, necessitating a recalibration of how we interpret satellite Chla signals in storm-affected marine ecosystems.

Capturing the variability within the Particulate Organic Carbon Flux: A Bayesian approach

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Mapping Particulate Organic Carbon (POC) flux and its spatiotemporal variability is key in understanding the mechanisms of the biological carbon pump. Current modelling methods that try to predict flux from environmental drivers struggle to capture the variability present in POC flux within estimates. This is because the distribution of POC flux is thought to be log-normal, meaning it has high variability and is positively skewed. This means the variance can obscure the relationships to underlying drivers if it is not explicitly considered. We hypothesise that this omission leads to the differences in current total POC flux estimates, with inverse models resulting in higher global estimates because they implicitly account for variability. By using a newly compiled sediment trap database and a hierarchical Bayesian regression model, we describe the distribution of POC flux, explicitly accounting for its skewness. We demonstrate that patterns in the log-mean and log-variance of the log-normal POC flux distribution can be captured by just three explanatory variables: satellite derived chlorophyll-*a* concentrations, sea surface temperature and POC flux measurement depth. In this approach, satellite derived chlorophyll-*a* explains the largest amount of POC flux distribution and the second-most on the variance. This model reproduces the observed distribution of POC flux, allowing for a spatial and temporally varying POC flux estimate. Our global POC flux estimate is larger than similar statistical methods where variance is ignored, which supports our hypothesis. These results not only increase our understanding of spatiotemporal changes in POC flux but also enhance our knowledge of how environmental variability influences it. Overall, this will improve global estimates of POC flux and predict changes in response to climate related environmental variability.

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Optical water type classification for better estimation of aquatic carbon in the ocean, coastal, and inland waters

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Consistent monitoring of water quality across freshwater-marine systems remains challenging due to the different orders of magnitude of concentrations of optically active water constituents. We provide an overview of the novel atmospheric correction A4O and water algorithm ONNS for Sentinel-3 OLCI data from different world regions. The aim is to overcome fragmentation in water quality monitoring along the aquatic continuum from lakes, rivers to the sea by applying an optical water type-specific and neural network-based processing scheme for Copernicus satellite data. Emphasis of our work is on analysing the optical complexity of remote-sensing reflectance of diverse water bodies. Results of a new optical water type classification show that almost all (99.7%) remote-sensing reflectance delivered by A4O are classifiable and that for example the North Sea-Baltic Sea region exhibits the full range of optical water diversity. Moreover, we show a way for inherent optical properties-based and water type-specific estimation of dissolved and particulate organic carbon in water. The processing chain offers many additional links to estimate the various pools of aquatic carbon and phytoplankton groups from space.

Seasonal variability in the bio-optical properties of the central Iceland Basin: implications for the regional modelling of primary production

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The central Iceland Basin (CIB) is a key region of the subpolar North Atlantic, where phytoplankton blooms drive substantial fluxes of carbon and nutrients, playing a critical role in regional biogeochemical cycles. In this study, we tuned a spectrally-resolved primary production (PP) model using multi-platform datasets from the CIB. Measurements of phytoplankton pigment biomass, light absorption coefficients, and photosynthesis–irradiance (P–E) parameters were obtained from several cruises of the CIB that covered various phases of the seasonal cycle, characterised by different levels of nutrient and light limitation. Matchups between in situ chlorophyll-a measurements and Level-3 satellite ocean colour data products reveal sensor-specific differences. To obtain detailed information on changes in the vertical structure of the biomass field, CTD and BGC-Argo profiles of chlorophyll-a fluorescence, corrected for non-photochemical quenching, were fitted with a Gaussian function to characterise the shape and magnitude of the biomass profile. The chlorophyll profile parameters and phytoplankton absorption measurements were incorporated into the radiative transfer model, and modelled profiles of photosynthetically active radiation (PAR) and downwelling irradiance at 412 and 490 nm were compared with measured irradiance profiles obtained from ship-based deployments and floats. Using the regionally-tuned primary production model, profiles of instantaneous production, integrated over the day, were computed. Estimates using global versus regional bio-optical parameterisations were compared, and the relative importance of productivity below the mixed layer was also assessed. We discuss the implications of our findings for regional estimates of remotely-sensed primary production.

Assessing Greening and Blueing Patterns over the Arctic Ocean under Climate Change

Hyun-Cheol Kim[1] and Joo-Eun Yoon[2]

Ocean color data provide key insights into the biological and biogeochemical state of the ocean by capturing variations in optically significant constituents such as phytoplankton and dissolved organic matter, which are fundamental components shaping marine ecosystems. Recent observations show regionally varying trends in ocean color, with some areas experiencing “greening” due to increased phytoplankton productivity, while others exhibit “blueing” linked to decreased biomass or shifts in species composition. The Arctic Ocean, one of the fastest-warming regions on Earth, is undergoing rapid environmental changes that significantly impact its marine ecosystems. However, such ocean color changes have yet to be clearly documented in the Arctic, revealing a gap in our understanding of ecosystem responses to these shifts. Therefore, this study investigates patterns of greening and blueing—reflected in changes in chlorophyll concentration and optical properties—across the Arctic Ocean using satellite-based data. We analyze long-term ESA Ocean Colour Climate Change Initiative (OC-CCI) data from 1998 to 2024, focusing on three key variables: chlorophyll-a concentration, hue angle, and remote sensing reflectance (Rrs). By examining spatial and temporal trends over this 27-year period, we identify emerging signals of both greening and blueing in distinct Arctic regions, indicating heterogeneous ecosystem responses to climate change. These findings highlight the complexity of Arctic marine ecosystem dynamics and underscore the value of ocean color data for continuous environmental monitoring. We will conclude with a discussion on the ecological implications of these trends and the potential of ocean color as a valuable tool for long-term Arctic monitoring.

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PhytoBLOOM: Phytoplankton Biogeochemical Laboratory Observations and Optical Measurements — Experiment Design and Initial Analysis

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Inherent optical properties (IOPs) of phytoplankton are fundamental parameters in ocean optics, providing essential input for bio-optical models, remote sensing algorithm development, and interpretation of phytoplankton dynamics. Despite their importance, species-specific IOP datasets remain scarce, particularly for harmful algal bloom (HAB)–forming taxa that exert profound ecological and socio-economic impacts. Earlier studies have analyzed phytoplankton IOPs, but these efforts were often scattered and limited in scope. A major advance was made by Neely et al. (2022), Lomas et al. (2024), which for the first time compiled a large-scale dataset encompassing over 50 phytoplankton species, linking hyperspectral IOPs with biogeochemical and physiological variables under controlled laboratory conditions.

Our study builds on prior research by utilizing bloom-forming phytoplankton species and by incorporating state-of-the-art optical instruments. A custom flow-through system was configured in which AC9/ACS, Hyper-a, Hyper-bb, and LISST-200X were integrated into a pump-driven loop, enabling hyperspectral characterization of absorption, scattering, and beam attenuation. Complementary measurements of backscattering and volume scattering functions were carried out with two SC6 and an ECO-VSF3 in a dedicated tank, while hyperspectral reflectance was recorded with a TriOS RAMSES spectroradiometer. In parallel, discrete samples were collected and analyzed for biogeochemical properties, including pigment composition (via HPLC), particulate and dissolved organic carbon (POC/DOC), colored dissolved organic matter (CDOM) absorption, and particulate inorganic carbon (PIC), with pigment-specific absorption further resolved using the filter-pad technique.

By resolving species-specific optical signatures at hyperspectral resolution, this dataset provides a fundamental basis for advancing the detection and quantification of HABs through remote sensing. In particular, this dataset will serve as a valuable resource for the development and validation of next-generation algorithms designed for recently launched and forthcoming hyperspectral satellite missions such as PACE and GLIMR, thereby enhancing our capacity to discriminate among bloom-forming taxa and to monitor their spatiotemporal dynamics with unprecedented accuracy.

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Bridging the gap between surface and subsurface optical estimates of particulate organic carbon concentration: Evaluating multivariable algorithms for global satellite ocean color and BGC-Argo applications

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Particulate organic carbon is central to oceanic carbon export and biogeochemical cycling, yet robust global observations of its mass concentration (POC) remain challenging due to limitations in remote sensing and in situ techniques. The expanding BGC-Argo float array can support integration of surface POC estimates from satellite remote-sensing reflectance R_{rs} with subsurface observations, but consistent algorithms are essential to avoid platform-induced biases. This study evaluates the performance of a multivariable POC algorithm, referred to as Model-B (Koestner et al., 2024), that uses the particulate backscattering coefficient b_{bp} and concentration of chlorophyll-a (Chla) as inputs, and is applicable to both BGC-Argo float and satellite observations with a 2-step approach. Three matchup datasets are explored: in situ R_{rs} and in situ POC (N = 509), satellite R_{rs} and in situ POC (N = 223), and satellite R_{rs} and BGC-Argo b_{bp}(700) and Chla (N = 4448). For estimating POC from R_{rs}, the Model-B input of b_{bp}(700) is derived using QAA-v5 using either MODIS-Aqua or in situ R_{rs}, and the Chla input is estimated with the OCI algorithm. Independently, POC is also derived from Model-B using vertically-resolved b_{bp}(700) and Chla from scattering and fluorescence sensors on BGC-Argo floats. Initial results show that the multivariable Model-B performs comparably across both in situ and satellite matchup datasets to the R_{rs}-based hybrid POC algorithm developed for global satellite applications (Stramski et al., 2022). Some positive biases for Model-B at low POC occur which are likely driven by uncertainties in b_{bp}(700) and Chla inputs. For the MODIS–BGC-Argo matchups, Model-B estimates from BGC-Argo floats in the surface layer show promising consistency with satellite hybrid POC algorithm results, particularly when satellite-derived Chla is used instead of float-based fluorescence estimates of Chla. Further evaluation is ongoing to assess regional and temporal agreement, refine BGC-Argo Chla fluorescence corrections, and explore merging satellite and BGC-Argo data into a 3-D POC product.

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Towards analysis ready primary production data

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In the literature, there have been several initiatives aimed at consolidating primary production measurements from different oceans and seas into a unified dataset. A notable recent contribution is by Mattei & Scardi (2021), who compiled more than 6 000 in situ primary production profiles from across the globe, building on the dataset from Behrenfeld & Falkowski (1997). Another recent global dataset of photosynthetic parameters was published by Bouman et al. (2018). Historically, one of the pioneering and most influential efforts was led by Trevor Platt and collaborators, resulting in an extensive archive of photosynthesis versus depth and photosynthesis versus irradiance measurements. These datasets provided the foundation for many mathematical models of primary production and to this day continue to serve as a critical resource for model development. Additional valuable sources of primary production data include long-term time series of primary production at oceanographic stations, such as the Hawaii Ocean Time Series (HOT), Bermuda Atlantic Time Series (BATS), and Cariaco Ocean Time Series (CARIACO), among others. These stations are particularly important for testing models and identifying long-term trends in primary production. Here, we present ongoing efforts to unify existing data sets under one framework. As a primary effort, we are building a new global dataset of photosynthesis parameters recovered by inverse modelling from production profiles. As a secondary effort, we are working on constructing time series of photosynthesis parameters at BATS, HOT and CARIACO. And as a third effort we are digitizing archived data on photosynthesis irradiance experiments. The overarching goal of the work is to generate analysis ready primary production data, in line with the FAIR principles and to provide the oceanographic community with freely available codes for data analysis.

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SwedCoast-BlueCarb project: mapping eelgrass extent in optically-complex waters

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In support of efforts to protect eelgrass beds, halt biodiversity loss, and promote recovery, the SwedCoast-BlueCarb project applies satellite Earth Observation (EO) to Swedish coastal waters. Funded by the Swedish and UK Space Agencies, the project combines EO and in situ data to assess the impacts of climate-change mitigation in contrasting test areas: the CDOM-dominated Baltic Sea around Kalmar and the Swedish west coast, where optical conditions are also strongly influenced by Baltic outflow via the surface current.

Initial activities established collaborations with academic partners and monitoring programmes, and laboratory analyses have characterised the absorption and reflectance spectra of submerged vegetation.

EO processing focuses on generating consistent, high-quality datasets. Atmospheric correction methods are tested, and a modelling approach has been developed to retrieve both water optical properties and submerged vegetation from surface reflectance. Copernicus Sentinel-2 imagery (20 m) is used to map eelgrass (*Zostera marina*) and bladderwrack (*Fucus vesiculosus*) extent—together with uncertainty estimates—where vegetation occurs within detectable depths. Sentinel-3 data (300 m) provide complementary information on water optical status, a key factor for light availability and ecosystem health. In parallel, commercial WorldView-2 imagery (2 m) is being evaluated to demonstrate the potential of very high-resolution mapping.

Now the initial modelling approach is working, the ongoing work is using the benefits of a machine learning model to speed up the modelling so whole Sentinel-2 scenes can be run systematically, enabling systematic monitoring across large spatial and temporal scales.

Ultimately, an automated processing chain will deliver EO-based products openly through a GIS-style portal. These products will help local authorities and conservation groups track eelgrass condition, identify restoration priorities, and evaluate the effectiveness of management measures. By quantifying vegetation extent and water optical properties, the project supports blue-carbon conservation goals and strengthens the evidence base for climate-change mitigation in coastal ecosystems.

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Satellite-based observations of carbon in the ocean: Pools, fluxes and exchanges (SCOPE)

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Quantifying the ocean carbon budget and understanding how it is responding to anthropogenic forcing is a major goal in climate research. The ocean has absorbed around a quarter of CO_2 emissions released anthropogenically, and this uptake of carbon has increased relative to CO_2 emissions. Yet, our understanding of the pools of carbon in the ocean, the processes that modulate them, and how they interact with the land and atmosphere, is not satisfactory enough to make confident predictions of how the ocean carbon budget is changing. Improving our understanding requires a holistic and integrated approach to ocean carbon cycle research, with monitoring systems capable of filling the gaps in our understanding. Satellite observations can play a major role in this. The ESA SCOPE project aims to provide the best possible characterisation of the ocean carbon budget from satellite observations and further the understanding of its variability in space and time. We present the development of an internally consistent dataset of carbon pools, fluxes and exchanges that are observable from space, including dissolved inorganic and organic carbon, particulate inorganic and organic carbon, phytoplankton carbon, primary and export production, and air-sea CO_2 exchange. This satellite-based ocean carbon dataset is harmonised in space and time, based on climate-quality input data from ESA's Climate Change Initiative and fully error-characterised. This allows us, for the first time, to address both the physico-chemical and biological processes that drive the ocean carbon cycle in a consistent manner. We use the newly developed dataset to analyse trends in each component of the ocean carbon cycle since the start of the continuous ocean-colour data record in 1997. This will provide insight into how satellite observations can aid in the assessment of the ocean carbon budget in a climate context and provide useful information to evaluate and improve climate models.

Observing the Coupling of Biological and Microbial Carbon Pumps in the North Atlantic Subtropical Gyre

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Understanding ocean carbon cycling and its sensitivity to climate change requires integrating diverse observations to resolve the roles of multiple carbon pumps, including the biological and microbial carbon pumps (BCP and MCP, respectively). While BCP exports organic carbon from surface waters to the deep ocean via sinking particles (biological gravitational pump) and actively mediated transport driven by physical and biological processes (physical and migration pumps), the MCP transforms labile dissolved organic carbon into refractory forms, contributing to long-term carbon storage. Despite their shared roles in regulating carbon fluxes, the coupling between these two pumps remains poorly understood, particularly in most oligotrophic areas, the subtropical gyres.

This study is conducted under the European Space Agency's Ocean Carbon pillar, within the framework of the "Satellite-based observations of Carbon in the Ocean: Pools, fluxes and Exchanges" (SCOPE) project, which aims to improve observation-based estimates of carbon pools and fluxes and to support the development of satellite products for ocean carbon cycling. Focusing on the core North Atlantic Subtropical Gyre (NASTG), we investigate the coupling between BCP and MCP by integrating satellite Ocean Color observations, in situ BioGeoChemical-Argo (BGC-Argo) float profiles, and 4D observation-based reconstructions. To this aim, we compare BCP efficiency derived from satellite-based export production (EP) and primary production (PP)—SCOPE products—with instantaneous particulate organic carbon (POC) fluxes from BGC-Argo profiles. We also assess the contributions of different BCP pathways, —particularly the physical injection pump, to their coupling with the MCP. We find a significant correlation between the downward export of particles from the BCP in the productive layer and the intensity of the MCP, with a discernible half-month time lag between the two processes. This synergic approach helps to "connect the puzzle" of carbon export and transformation in one of the ocean's most nutrient-poor regions, offering new insights into the biogeochemical functioning of the NASTG .

Retrieving Dissolved Organic Carbon Concentrations in Coastal Waters Using Google Earth Engine and Machine Learning

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Monitoring dissolved organic carbon (DOC) concentrations in coastal waters is essential for understanding carbon dynamics in these ecosystems and their role in the global carbon cycle. Ocean color remote sensing offers an effective means for large-scale DOC measurements but faces challenges in coastal waters due to the complex water optical properties and atmospheric conditions, particularly when DOC is optically inactive. In this study, we used Google Earth Engine to compile a large training dataset with matched radiometric measurements from Sentinel-2 and ground-truth DOC measurements. We then trained a machine learning-based model, termed AutoGluon-DOC, using 70% of the randomly selected training data to estimate DOC from Rayleigh-corrected top-of-atmosphere reflectance ($\rho rc(\lambda)$), along with auxiliary data such as the date and time of image acquisition. Validation with the remaining 30% of the data demonstrated the robust performance of AutoGluon-DOC, with the median absolute percentage error of derived DOC around 10% across different satellite-field matchup criteria. Applying AutoGluon-DOC to Sentinel-2 images over Dongshan Bay (DSB) revealed a clear spatial gradient of decreasing DOC from the bay head toward the bay mouth and a seasonal cycle characterized by higher DOC in summer and lower levels in winter. An analysis of the relationships between DOC and precipitation, riverine discharge, and tidal height suggested that tides predominantly govern the spatial-temporal distribution of DOC within the bay, while runoff and precipitation more likely contributed to its seasonal variations. These results underscore the potential of AutoGluon-DOC for high-resolution monitoring of DOC in coastal waters, with its framework adaptable to monitoring DOC dynamics and other optically inactive constituents in diverse coastal environments.

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Carbon from earth Observation between Ocean and Land (COOL)

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The coastal ocean plays a critical role in the ocean carbon cycle, yet our current understanding of the different pools and fluxes of organic carbon is limited by strong local dynamics, which requires high spatial and temporal resolution of observations covering relatively large areas across the shelf seas. Satellite remote sensing of carbon pools and fluxes at high spatial resolution and daily frequency can cover this gap in observations, but new algorithms need to be developed and validated.

In the ESA project "Carbon from earth Observation between Ocean and Land (COOL)", we aim to estimate carbon pools and fluxes for which algorithms are relatively mature, and hence we can have some certainty in their application in the coastal ocean at the global scale in the near future. These include Particulate Organic Carbon (POC), Particulate Inorganic Carbon (PIC), Dissolved Organic Carbon (DOC) and Primary Production (PP). Using data from Sentinel-3 OLCI at 300 m resolution and Sentinel-2 MSI at 60 m, we aim to produce an internally consistent coastal ocean carbon satellite dataset in selected European coastal regions. We make use of *in situ* datasets for evaluation and validation of these satellite products. We then use the newly produced Earth Observation datasets in the Baltic Sea and in the upwelling areas of the western Gallican coast, northwest Spain to investigate the temporal and spatial changes on carbon pools and fluxes.

Estimating and Monitoring Dissolved Organic Carbon (DOC) from Space across the Global Ocean, with a Focus on the Northwest European Shelf

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Effective monitoring of Dissolved Organic Carbon (DOC) from space is crucial for tracking carbon stocks and understanding fluctuations in both coastal and open ocean environments. As part of the OCROC project, founded by the Copernicus Marine Service, we have enhanced the existing Ocean and Land Color Instrument (OLCI) DOC algorithm, designed to leverage data from both historical and current ocean color sensors. This algorithm initially used four key inputs: the absorption coefficient of Colored Dissolved Organic Matter (a_{cdom}), chlorophyll-a concentration (CHL), Sea Surface Temperature (SST), and Mixed Layer Depth (MLD), each at varied time lags to account for water mass dynamics.

Two optimized Artificial Neural Network models, along with a specialized approach for coastal areas influenced by terrestrial inputs, were adapted for the MODIS and VIIRS missions using wavelength adjustments to ensure accurate acdom estimation. The resulting weekly DOC product, spanning 1998–2022 at 4 km resolution, has been validated with a Mean Absolute Percentage Difference (MAPD) of 12.92%. Further validation using in situ time series, including the Bermuda Atlantic Time-Series Study (BATS) and the Hawaii Ocean Time-Series (HOT-DOGS), confirms a robust reconstruction of seasonal variability. Specific regions, such as the North Atlantic and Arabian Sea—known for distinct DOC patterns driven, for example, by CHL blooms and strong river outputs—have been analyzed and cross-validated with various published studies.

Furthermore, a first example of application at 1 km² spatial resolution, using GlobColour data spanning 1998–2022, is presented for the Northwest European Shelf—a region characterized by elevated DOC levels strongly influenced by phytoplankton blooms and terrestrial inputs. This higher resolution enables a more detailed understanding of DOC dynamics in the area, particularly near river mouths and along the coast.

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Integrated Autonomous Monitoring of Carbonate chemistry, Marine reflectance, and Bio-optics during ship transit

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Integrating measurements of carbonate chemistry, marine reflectance, and bio-optical properties is essential to capture and understand the coupled physical–biogeochemical processes driving CO_2 dynamics and to link in situ observations with satellite remote sensing. This is particularly so in coastal shelf seas, comprising optically-complex waters with strong spatial and temporal variations in biological activity and carbonate chemistry.

We build on the observational capacity of RV Simon Stevin, a Flemish ICOS (Integrated Carbon Observation System) Ocean Station operating in the North Sea, equipped with state-of-the-art sensors for continuous measurement of carbonate system parameters on pumped surface water, including the partial pressure of CO_2 (pCO_2). We expanded the vessel's underway system with a flow-through Autonomous uNderway near-real-Time HYperspectraL Optical Properties PackagE (ANTHYLOPE), measuring hyperspectral backscattering (Sequoia hyperBB), attenuation, and absorption (Seabird AC-S), single wavelenght backscattering, fluorescence of CDOM and Chlorophyll-a (RBR Tridente), UV fluorometry (Seapoint SUVF), particle size distribution (Sequoia LISST-200X), red light attenuation (LISST-Tau) and Particulate Inorganic Carbon (prototype optical sensor, developed in collaboration with Sequoia Scientific), complemented by a thermosalinograph (Seabird TSG). Lastly, an autonomous hyperspectral radiometry system for the measurement of above-water reflectance (R_{rs}), (IMO DALEC) was mounted on a pole on the bow of the vessel.

Our integrated monitoring system was first put in operation in May 2024 and has been tested and improved during several measurement campaigns. Here, we present the data processing and quality control pipelines and discuss the challenges associated with the operation of the ANTHYLOPE and DALEC systems. We present preliminary results on the mulitple uses of the integrated dataset. First, we show that the characteristics of the particle assemblage (particle concentration, composition, and size) can be retrieved from inherent optical properties. Next, we show the improved retrieval of biogeochemical variables by leveraging the hyperspectral nature of the signals. We also test and (re-) calibrate commonly used remote sensing algorithms for the retrieval of SPM, POC, and Chlorphyll-a from R_{rs}. Lastly, we investigate the spatio-temporal dynamics of pCO_2 and examine its physical, chemical, and biological drivers.

Comparison of CO2COAST's satellite-derived CO_2 fluxes with CMEMS's product and uncertainty associated with choice of gas-transfer velocity parameterization

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Abstract: The CO2COAST project generated high-spatial-resolution satellite-derived pCO_2 water and air-sea flux of CO_2 products over global coastal water. We compare this product with an existing one maintained by the European Copernicus Marine Environment Monitoring Service (CMEMS) (Chau et al., 2022) over 45 wide coastal ocean zones (defined in Resplandy et al. (2023)). The CO2COAST's product (currently at 4km resolution) has been downscaled to match CMEMS's 0.25° x 0.25° grid and the CO_2 flux rate has been estimated using the FluxEngine (Shutler et al., 2016) software and the same gas-transfer velocity (k) parameterization (Wanninkhof, 2014) as CMEMS's, albeit using different inputs except for wind speed and surface pressure (ERA5). Additionally, we evaluate the uncertainty in the CO_2 flux products associated with different k parameterization methods (included in FluxEngine) using data (pCO_2 water, SST, etc.) from CO2COAST project. Over the 2007-2020 period, the net coastal CO_2 flux rate between 50°S and 70°N according to CMEMS is roughly two third that of CO2COAST (-0.66 and -0.98 $molC.m^{-2}.y^{-1}$, respectively) while pCO_2 water is similar (8 µatm gap). Analysis of the regional-area-average monthly flux rate shows only 15 zones with good correlation (coefficient of correlation ≥ 0.7). Underestimation of pCO_2 by CO2COAST compared to CMEMS over higher range can also be observed in zones with weak flux correlation. Such gap in flux rates will be further investigated in relation to the different inputs of each flux product (k, pCO_2 air, and, solubility). For instance, our results indicate that the choice of k parameterization method has only minimal impact on flux when only wind data (ERA5) is used, while methods using radar backscatter produce substantially different flux. The wind-based parameterizations rely on polynomial relationships, and comparing cubic and quadratic formulations yields MAPD values of 7.5-18%. Linear formulation deviates more, but still remains within a maximum MAPD of 30%.

Keywords: air-sea CO_2 flux, pCO_2, gas transfer velocity parameterization, CO2COAST

Acceleration of Ocean Warming and Diverging Productivity Trends in the Northeast Atlantic: A Satellite-Based Assessment

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Since the post-industrial era, sea surface temperature (SST) has shown a consistent warming trend at a global scale, while chlorophyll-a (Chl-*a*) concentrations and net primary production (NPP) have generally exhibited declining trends in the open ocean. Some recent studies suggest that intensified coastal upwelling, driven by increased alongshore winds, may locally counteract these negative trends enhancing biological productivity. This study aims to assess the evolution of long-term trends in SST, Chl-*a*, NPP, meridional wind stress, and aerosol in the Northeast Atlantic, focusing on both open-ocean and upwelling regions. We applied the methodology developed by Siemer et al. (2021), using the same satellite and *in situ* datasets, updated to include the most recent data, and also defined additional subregions to distinguish smaller open-ocean areas of interest. Our findings reveal a significant acceleration in SST warming across the entire study area in the last six years. In open-ocean regions, this acceleration is accompanied by a stronger negative trend in Chl-*a*, suggesting a continued decline in phytoplankton biomass. Conversely, in coastal upwelling zones, particularly the Northwest African upwelling system, the decline in Chl-*a* and NPP appears to be slowing down, indicating a potential mitigation effect. Furthermore, we observed that both the reduction in productive area and the decline in the number of highly productive days per year have slowed in these upwelling regions, suggesting a potential buffering effect against oligotrophication.

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Chlorophyll Dynamics at Agulhas Fronts: Ocean-Colour Observations

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The Agulhas Current—a western boundary current—flows along southern Africa before retroflecting to form the eastward Agulhas Return Current near the Subtropical Front. This eddy-rich system transports heat, salt, and nutrients and brings oligotrophic subtropical waters into contact with subantarctic fronts, creating sharp biogeochemical gradients that modulate phytoplankton biomass. Phytoplankton biomass in the Agulhas Current system regulates regional carbon cycling, yet its long-term variability and drivers remain unclear. We analyse monthly chlorophyll-a data from the Ocean Colour Climate Change Initiative (OC-CCI) to quantify seasonal and interannual change and associated physical controls. Missing data were reconstructed with DINEOF; trends were assessed using the Mann–Kendall test with Sen's slope; dominant variability and drivers were diagnosed with EOFs and multiple linear regression using sea-surface temperature, mixed-layer depth, wind speed, sea-level anomaly, and stratification.

We identify two persistent chlorophyll hotspots—along the Agulhas Return Current and at the Agulhas Retroflection—showing significant upward tendencies and distinct sensitivities to physical forcing. In the Return Current, periods of cooler surface temperatures, deeper mixed layers, and stronger winds coincide with enhanced vertical exchange and higher chlorophyll, consistent with intensified westerlies. At the Retroflection, the signal is weaker and more variable, reflecting stabilisation by warm inflow and mesoscale recirculation. These results reconcile regional contrasts in productivity and highlight where and why ocean-colour signals are changing, with implications for forecasting ecosystem responses and Southern Ocean carbon uptake. We also outline uncertainty arising from gap-filling and sensor harmonisation and emphasise the need for sustained satellite–in situ synergy in this eddy-dominated system.

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Concerted carbon system observations in the Baltic Sea as asset for verification and algorithm development for remote-sensing-based carbon data products

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Assessing the surface ocean carbonate chemistry is of great importance to quantify the ocean uptake of anthropogenic CO_2. The efforts to compile ground-based observational data lead to global products like the Surface Ocean CO_2 Atlas (SOCAT) and data-derived estimates as part of the annual Global Carbon Budget. New demands steadily emerge, such as providing baseline and monitor success of marine Carbon Dioxide Removal (mCDR) in a reliable monitoring, reporting and verification (MRV) concept.

Recent developments to derive carbon system parameters (total inorganic carbon - CT, total alkalinity - A_T, and pH) of surface waters from space are promising, but rely on robust observational data for algorithm testing and verification. The Baltic Sea has always raised high interest for remote-sensing-based environmental research, due to the large interest in its ecosystem state and its immense importance for the people living in the pan-Baltic area. Yet, the Baltic Sea has also proven to be a difficult environment for remote sensing based observations due to complex optical properties and boundary effects, often requiring local solutions.

At the other hand, the Baltic Sea region is currently covered with an unusual high density of high quality observational surface carbon system data. Three ship of opportunity (SOOP) lines are covering large parts of the Baltic Sea as part of the European Integrated Carbon Observations System (ICOS RI) and a fixed station near the Archipelago Sea, providing year-round data coverage. Linking observations from this network with efforts aiming to develop remote-sensing based products for carbon system parameters in the demanding area of the Baltic Sea provides a unique opportunity to advance the field further. Our presentation, introducing the network of operational ground-truthing carbon system observations and showing some of the derived data products at the IOCS 2025 meeting, is an attempt to stimulate this linkage.

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Scale-Dependent Relationships Between Ocean Color and Physical in-situ in the North Atlantic Spring Bloom: Validation Using Gap-Filled Satellite Products

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High-resolution transect observations (n=5,110) were conducted across the North Atlantic during the spring transition (April-May 2025), spanning Arctic-Subpolar (70°N-56°N) and Temperate-Subtropical (56°N-36°N) regions. The study quantifies the scale-dependent link between ocean color (chlorophyll-a) and physical fields (SST, SSS) by integrating in-situ measurements with satellite observations to reveal how hierarchical controls on biological patchiness are serious for carbon export estimates. In situ chlorophyll a fluorescence and particulate organic carbon were measured continuously alongside physical parameters. Satellite validation employed CMEMS Level-4 gap-filled ocean color products (4km, daily), achieving 100% spatial coverage, with logarithmic correlation r=0.744 (RMSE=0.40). In addition, GHRSST SEVIRI SST validation yielded r=0.97 despite 33% coverage limitations. Five biogeochemical clusters were identified through hierarchical classification. The high-scale separation is observed where physical fields maintained consistency over ~400km, while ocean color decorrelated at 54km due to submesoscale biological patchiness. Chlorophyll-a shows strong spatial clustering (I=0.89, p<0.001). According to frontal zones, the results show that ~100km is the critical separation scale between SST and chlorophyll-a. However, cluster analysis showed matched physical-biological scales (~145km) only at fronts. The findings demonstrate that gap-filled Level-4 ocean color products capture biological variability at scales relevant to frontal dynamics and carbon export. The three-fold scale mismatch between physics and biology implies that regional carbon models must accurately resolve submesoscale processes to represent spring bloom heterogeneity. The work provides quantitative metrics for validating next-generation ocean color missions and highlights the value of integrated multi-sensor approaches for understanding biogeochemical-physical coupling in productive ocean regions.

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Monitoring Phytoplankton Biomass and Diversity from Space: The ESA PHYTO-CCI and OC-CCI Perspective

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Phytoplankton are at the heart of the ocean's carbon cycle, driving carbon fixation and forming the base of the marine food web. Their biodiversity, including the variety of functional types, plays a crucial role in marine ecosystems and biogeochemical processes. Satellite-based monitoring of these microscopic organisms is essential for understanding their dynamics and impacts. Ocean colour remote sensing provides a powerful way to do this. Both phytoplankton and ocean colour remote sensing are considered an Essential Climate Variable (ECV) by the Global Climate Observing System (GCOS), highlighting their global importance.

We will present an overview of the ESA 'PHYTOplankton biomass and diversity Climate Change Initiative' (PHYTO-CCI) project, which aims to develop two satellite-based ECV data products: phytoplankton carbon biomass and pigment diversity. The project integrates and compares satellite-retrieval algorithms using optical water classification, producing products with uncertainty estimates and validating them with *in situ* and model data.

We will also present recent and planned improvements to the Ocean Colour CCI (OC-CCI) dataset, including a shift of the base mission from MERIS to OLCI and an expansion from 6 to 11 spectral bands. The new bands, covering blue-edge to near-infrared, will open the door to implementing a wider range of algorithms, ultimately improving both ocean colour and phytoplankton ECV products for climate and ecosystem research.

An algorithm for a global assessment of coastal dissolved organic carbon

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Dissolved organic carbon (DOC) plays a crucial role in ecological and biogeochemical processes. Many models have been developed to estimate DOC in coastal waters at a local scale using ocean-colour remote-sensing data. However, there is currently no global algorithm capable of addressing the variability and complexity of DOC dynamics in coastal waters. In the Satellite-based observations of Carbon in the Ocean: Pools, fluxes and Exchange (SCOPE) project, funded by the European Space Agency (ESA), we aim to address this gap by developing a global DOC satellite retrieval algorithm for coastal waters by using daily, 4-km resolution data from the European Space Agency (ESA) Ocean Colour Climate Change Initiative (OC-CCI) from 1997 to 2023, combined with sea surface salinity (GLORYS12v1) and temperature (ESA SST-CCI, version 3.0). For model development, we matched these satellite datasets with *in situ* DOC concentration data from the CoastDOM v1 database. Multiple statistical methods, including multiple linear regression (MLR), random forest regression (RF), and extreme gradient boosting (XGBoost), were tested, with the best performance achieved by a RF model using sea surface salinity and temperature, the remote sensing reflectance at 560 nm and total absorption at 412 nm. Although the developed algorithm showed high performance, the relatively coarse resolution of OC-CCI poses challenges, as it may fail to resolve sharp DOC gradients in dynamic coastal zones such as river plumes and estuaries, potentially reducing accuracy in those areas. Still, OC-CCI offers climate-quality data for a longer period of time compared to individual ocean-colour sensors. Expanding *in situ* observations, especially in underrepresented areas, will further enhance model accuracy and applicability. This work contributes to a better understanding of carbon dynamics in coastal ecosystems and provides a robust tool for future satellite-based assessments of DOC in global coastal waters.

Estimating coastal carbon fractions with Sentinel-2 MSI and Sentinel-3 OLCI to support large-scale carbon cycle studies

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A thorough understanding of the global carbon pools and cycle is essential to understand and predict the effects of climate change. Coastal waters play a key role in the global carbon cycle but remain poorly understood due to their optical complexity, high spatial variability, and sensitivity to climate change. Satellite remote sensing data can provide high spatial and temporal resolution for carbon monitoring at local, regional, and global scales. However, existing sensors are not optimised for dynamic coastal zones. Sentinel-2 MSI (S2) offers high spatial resolution, while Sentinel-3 OLCI (S3) provides better spectral band configuration, temporal resolution, and radiometric sensitivity, though its spatial resolution may be insufficient for highly heterogeneous coastal waters. In the ESA CoastalCarbonMapper project, we tested the applicability of both S3 and S2 for mapping carbon fractions—Total Organic Carbon (TOC), Dissolved Organic Carbon (DOC), Particulate Organic Carbon (POC), and Dissolved Inorganic Carbon (DIC)—in coastal waters. We aimed to develop and validate algorithms using *in situ* data and S2 and S3 imagery, addressing: (1) What are the optical proxies for different carbon fractions in coastal waters? (2) Which algorithms are most suitable for coastal carbon mapping? Bio-optical and physical water parameters were measured directly in the field, and water samples were collected to analyse carbon fractions and optically active water constituents in the laboratory. Measurements at the test sites were taken four times during the ice-free season of 2023–2024. Based on the collected data, potential optical proxies were identified, and retrieval algorithms for carbon fractions were developed and validated. The study represents a step forward in the remote sensing of coastal waters and Earth observation science. If adopted, the proposed carbon fraction products could allow for significant progress in different fields, from research to monitoring and policy making.

Ocean colour from sea and space: A partnership of in-situ chlorophyll proxy measurements with ocean colour remote sensing data to investigate frontal system primary productivity

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Keywords: Remote Sensing, Ocean Colour, Chlorophyll, Primary Productivity, Frontal System, Shelf Sea

High primary productivity found in shelf seas supports 80% of global wild seafood capture, highlighting their importance to the survival of ecosystems and humanity. Understanding how offshore wind infrastructure influences these dynamic systems is critical for sustainable marine management. Our research focuses on satellite ocean colour analysis to assess the impact of offshore wind infrastructure on the Flamborough Frontal System, a key hydrodynamic feature in the western North Sea. Satellite observations are central to up-scaling these findings and identifying cross-frontal variability over time.

Here we present Sentinel-3 chlorophyll-a, sea surface temperature, and turbidity data, retrieved for the Yorkshire coastal frontal system, and for offshore windfarms: - monopile-based (Hornsea One) and floating (Kincardine, Hywind). Frontal gradients were mapped, and the seasonal variability, and spatial patterns of algal blooms in these regions was analysed. Our results provide insight into surface productivity and stratification processes over broad spatial and temporal resolutions. These findings have been combined with in situ measurements of CTD, optical measurements (fluorometry, spectrophotometry) and HPLC pigment analysis to provide fine-scale vertical and horizontal gradients of chlorophyll, temperature and salinity. Further analysis of Sentinel 1 Interferometric Wide Swath, and Sentinel 2 imagery allows visualisation of sediment wakes, and the tidal variation associated with offshore wind infrastructure.

By integrating in-situ oceanographic measurements with remote sensing data we can enhance our understanding of phytoplankton dynamics across mixed and stratified waters, in coastal waters and those adjacent to offshore wind infrastructure, improving the detection of subtle shifts in primary productivity and water clarity linked to offshore wind infrastructure induced hydrodynamic alterations.

Overall, this work highlights the pivotal role of Earth observation in advancing marine ecosystem assessment and hydrodynamic monitoring. Therefore, contributing to future offshore wind development, supporting marine spatial planning, and reinforcing the relevance of ocean colour science for environmental and societal needs.

A Novel Deep Learning Framework for Retrieving Key Ocean Biogeochemical Parameters in Polar Regions from Spaceborne Lidar

Zhenhua Zhang[1], Siqi Zhang[1], Peng Chen[1], Delu Pan[1]

Passive ocean color remote sensing is severely limited in polar regions by low solar elevation and extended polar nights, resulting in significant data gaps that hinder a comprehensive understanding of Arctic and Antarctic marine ecosystems. To overcome this observational challenge, we leverage the unique, sunlight-independent capabilities of spaceborne lidars, utilizing a multi-mission dataset from CALIOP/CALIPSO and ATLAS/ICESat-2. We have developed a suite of innovative deep learning models, including a Two-Branch-Two-Step (TBTS) framework, to retrieve key biogeochemical parameters from lidar signals. This data-driven approach combines features extracted directly from the attenuated backscatter waveform with physically derived parameters, such as the depolarization ratio, to invert for surface concentrations of Particulate Organic Carbon (POC), Particulate Inorganic Carbon (PIC), Chlorophyll-a (Chl), and the particulate backscattering coefficient (bbp). By training the models on co-located daytime MODIS data, our framework successfully extends these critical ocean observations into the polar winter. The methodology circumvents the uncertainties inherent in traditional physics-based algorithms, which rely on fixed assumptions for optical conversion factors. Validation against independent in-situ data from BGC-Argo floats confirms the accuracy and robustness of our retrievals. This work provides the first-ever estimates of PIC from spaceborne lidar and delivers a continuous, year-round view of polar ocean biogeochemistry. By filling critical observational gaps, this novel application of spaceborne lidar provides an unprecedented opportunity to quantify the full annual cycle of carbon stocks and phytoplankton dynamics in the world's most rapidly changing marine environments.

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Diurnal Global Air-sea CO_2 Flux Reconstructed from Spaceborne LiDAR Data

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Oceans play a crucial role in mitigating climate change by absorbing a substantial amount of carbon dioxide (CO_2) from the atmosphere. Despite this vital function, our understanding of oceanic CO_2 dynamics remains incomplete. This study aimed to elucidate daily variations in oceanic CO_2 levels and the air-sea CO_2 exchange through the application of a novel technique. Leveraging LiDAR technology, renowned for its ability to provide continuous measurements day and night, we conducted a comprehensive assessment of global oceanic CO_2 absorption spanning 23 years. Our model effectively replicated existing CO_2 data, revealing a notable phenomenon: oceanic CO_2 absorption rates are approximately 10-30% higher during nocturnal hours compared to diurnal periods. This variance can be attributed to a myriad of factors, including temperature differentials, wind patterns, as well as biological processes such as photosynthesis and respiration. Recognizing and comprehending these daily oscillations are pivotal for refining predictions of oceanic CO_2 uptake and addressing discrepancies observed in current carbon budget estimations. By shedding light on this intricate interplay, our pioneering investigation underscores the indispensable role of LiDAR technology in furnishing unparalleled day-night coverage of oceanic data. Furthermore, our findings significantly contribute to advancing our comprehension of oceanic CO_2 cycles and their pivotal role in climate regulation. Emphasizing the imperative of integrating day-night variability into assessments of the ocean's carbon sequestration capacity, this study underscores the urgency of holistic approaches in confronting climate change.

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Whiting Events in pre-Alpine Lake Constance:
Integrating *In-situ* and Remote Sensing Data to Monitor and Quantify Calcite Precipitation

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The global carbonate cycle plays a crucial role in shaping short-term carbon dynamics, particularly in inland waters where calcite precipitation, or 'whiting events', visibly mark the transformation of catchment-derived alkalinity into atmospheric CO_2 [1]. Despite their importance, the occurrence and intensity of lake whiting remain poorly monitored and quantified across time and space. From 2022 to 2024, we conducted a multi-platform monitoring campaign in Lake Constance, combining *in-situ* observations with remote sensing. Biweekly *in-situ* observations included vertical profiling with a multiparameter probe to measure turbidity (FNU), temperature, pH, conductivity, and chlorophyll-*a* fluorescence. POC and PIC were quantified using glass-fiber filters and a combustion module coupled to a total carbon analyzer. Sentinel-3 OLCI imagery was used to estimate lake-wide PIC by correlating reflectance with *in-situ* data. Temporal changes in PIC were mapped to identify the timing and extent of calcite precipitation in Lake Constance. Results show that both turbidity and PIC peaked at 7–10 m water depth, with PIC values determined with the combustion module closely matching the turbidity profile recorded by the multiparameter probe. *In-situ* data also showed that PIC peaks occurred after chlorophyll-*a* maxima in late May and were followed by a pH rise in early June. Among spectral bands, Rw665 showed the strongest correlation with PIC ($R^2 = 0.58$), outperforming conventional bands like Rw650 ($R^2 = 0.47$). Additionally, the regression showed overestimation at high chlorophyll-*a* and low PIC levels, and consistent underestimation when PIC exceeded 40 µg/L across the top 20m water column (integrated water sample). Averaged satellite-derived PIC values from all the pixels for Lake Constance captured a similar seasonal trend to *in-situ* measurements, with a clear peak in July–August. By integrating turbidity measurements and remote sensing, this study provides two practical tools for tracking calcite precipitation events.

Reference:

[1] Gaël Many et al. (2024) Calcite precipitation: The forgotten piece of lakes' carbon cycle. Sci. Adv.10, eado5924. DOI:10.1126/sciadv.ado5924

Improving validation of satellite particle backscatter estimates to support climate research: the INSPIRE project

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The particulate backscattering coefficient (b_{bp}) is an indicator of phytoplankton biomass, particulate organic carbon, and particle size distribution in the ocean. It serves as input for modeling net marine primary production and net community production. Since b_{bp} can be estimated through satellite imagery, it plays a fundamental role in quantification primary production on a global scale and evaluating its spatial patterns. Therefore, accurate satellite-based b_{bp} is required to constrain coupled physical and biogeochemical models, thereby improving climate projections. To date, most of the European Space Agency (ESA) Ocean Science Cluster-funded projects that utilize b_{bp} have relied on global operative products (i.e., ESA OC-CCI). However, these products lack associated uncertainty compared to in situ measurements, limiting out understanding of their impact on ocean productivity and organic carbon export.

The ESA INSPIRE project aims to address this gap by developing an advanced Observing System (GOS) specifically tailored for validating satellite b_{bp} products, integrating remote sensing, Lagrangian modelling and in situ data. This involves using a new generation of Surface Velocity Programme (SVP) drifting buoys equipped with bio-optical and oxygen sensor, named Biogeochemical (BGC)-SVP drifters. Designed for extended deployment periods, they offer a promising solution for collecting data in challenging marine environments by the combination of the Lagrangian approach and a high sampling frequency. This project seeks optimize drifter deployment locations to maximises the number of in situ observations usable for match-up activities. Lastly, satellite b_{bp} products will be validated with in situ measurements collected using BGC-SVP drifters deployed both the global ocean with a particular focus in the Mediterranean Sea. The drifters launched in the Mediterranean Sea were acquired through the ITINERIS (Italian Integrated Environmental Research Infrastructures System) project.

The present study and the use of BGC-SVP drifters could be impactful in relation to the next generation of altimetry (e.g., NASA SWOT), hyperspectral ocean color satellite missions (e.g., NASA PACE, NASA GLIMR, ESA Sentinel Next Generation, and ESA CHIME), and future lidar mission (e.g., ASI CALIGOLA) for the detection of ocean processes from fine to larges scales both in space and time.

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Ocean colour applications to water quality

Oceanographic Threats and Water Quality: The First Digital Operator Agent LLM for Proactive Water Quality Management in Desalination — Initial Insights from Northern Chile

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In the hyper-arid Atacama Desert, Chile anticipates a 350% increase in seawater desalination capacity by 2030 (38,766 L s^{-1}). However, operational continuity is threatened by episodic oceanographic events such as harmful algal blooms (HABs/red tides), upwelling-driven turbidity, hydrocarbon contamination, and swell-induced sediment resuspension, all of which can trigger unplanned shutdowns and increase operational costs.

We present a multi-source database integrating in-situ hyperspectral measurements from RAMSES TriOS radiometers (processed with the SBA method) with PlanetScope and Sentinel-3 OLCI imagery to characterise spectral signatures of critical water quality anomalies. These data support the calibration of remote sensing algorithms for early detection and classification of ocean colour anomalies impacting desalination intake water.

A key innovation is the Digital Operator Agent LLM, the first AI system designed specifically for desalination water quality management. This retrieval-augmented generation (RAG) agent incorporates over 300 validated Q/A pairs from plant operators, connects directly to alert systems, and provides real-time, context-aware assessments of swell events, upwelling, and HABs. Using LangChain as its interface, the agent queries vectorized ocean colour datasets to interpret anomalies and recommend preventive operational actions.

Preliminary deployments indicate a 60% reduction in unplanned plant shutdowns, avoiding losses estimated at USD 5M and preserving more than 50,000 m^3 of freshwater that would otherwise have been lost due to oceanographic threats. These results highlight the potential of coupling ocean colour remote sensing with AI-driven operational intelligence to strengthen the resilience and efficiency of desalination infrastructure.

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From Ports to Pixels: Satellite Monitoring of Coastal Change in the Offshore Energy Era

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The expansion of offshore renewable energy is anticipated to increase activity in coastal and estuarine harbour areas through the enlargement of port facilities, greater use of onshore space for component storage, and expanded use of submerged areas for in-water storage. Such developments have the potential to alter water quality and affect coastal ecosystems. This study presents WavEC's efforts to develop and validate methodologies for monitoring these environments using multispectral satellite data, with a focus on detecting and tracking potential changes associated with increased harbour activity.

The monitoring framework targets key oceanographic and ecological parameters, including chlorophyll-a concentration, suspended sediment concentrations, and the spatial distribution of seagrass and saltmarsh habitats. These indicators, in combination with other relevant parameters, contribute to assessing water quality, evaluating ecosystem health, and supporting sustainable coastal management in the context of growing industrial pressures.

The approach integrates open-access datasets from Copernicus Sentinel missions, valued for their broad coverage, high temporal frequency, and spectrally rich observations, with higher-resolution imagery from commercial satellite providers such as GEOSAT. This combination enables a comparative evaluation of the potential benefits and measurable gains offered by commercial high-resolution data in specific monitoring applications. A comprehensive review of existing literature and methodologies was undertaken to identify the most suitable spectral indices and retrieval algorithms for each parameter in coastal and estuarine contexts.

Monitoring methodologies are being refined to improve the detection of key environmental indicators and enhance the temporal analysis of changes within these dynamic systems. In parallel, workflows are being developed to facilitate the processing and visualisation of satellite-derived information, enabling continuous monitoring of harbour areas and supporting timely, evidence-based decision-making for environmental management.

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Challenges and limitations in satellite-based estimation of suspended particulate matter concentration in the narrow branches of the Danube Delta

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Understanding the dynamics of suspended particulate matter (SPM) concentration in aquatic ecosystems is essential for assessing water quality and ecosystem health. While remote sensing provides valuable capabilities for monitoring this parameter over wide spatial and temporal ranges, its application to inland waters, particularly narrow river branches such as those in the Danube Delta, remains challenging.

In this region, channel widths vary significantly along their course, and SPM levels can change rapidly over short distances. Some important issues include the identification and correction of adjacency effects from surrounding land and vegetation. Uncertainties associated with the atmospheric correction step (some due to highly variable aerosol conditions) are also difficult to account for. Other major constraints refer to the availability of good quality in-situ measurements and proper match-ups between satellite reflectance data and biogeochemical variables for regional algorithms calibration. The acquisition of adequate in-situ data can be affected by flow dynamics and rapid changes along the river course, potentially leading to differences between satellite observations and field data.

This study applies and compares different processing approaches for high-resolution Sentinel-2 and Landsat 8 imagery to reduce these limitations while also identifying where and under what conditions they occur along the branches. The analysis tests multiple atmospheric correction methods, different image processing techniques and integrates in-situ measurements with satellite data to improve the accuracy of SPM estimations.

Comparative examples are presented to highlight effective strategies for improving SPM concentration estimation in narrow inland water systems.

An Iterative Multi-Target Framework for Inland Water Quality Retrieval Using Multispectral and Hyperspectral Satellite Data

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1. Background

Retrieving multiple inland water quality parameters (WQPs) from remote sensing reflectance is challenging because spectral features often overlap and are influenced simultaneously by multiple optically active WQPs, such as chlorophyll-*a* (Chl-*a*), total suspended solids, and coloured dissolved organic matter (CDOM). Single-target machine learning approaches model each WQP independently, which can lead to misattribution of spectral features when multiple parameters interact. Multi-output approaches, such as Mixture Density Networks (MDNs), model multiple WQPs simultaneously, helping to assign spectral features to the correct parameters. However, for training, they rely on complete datasets that contain coincident measurements of all relevant WQP, or on imputed values when some measurements are missing. This can reduce their performance when such training data are not available.

2. Methods

We developed an iterative multi-target learning framework that allows the integration of incomplete training datasets without relying on imputations. Separate random forest models are first trained for each WQP to generate proxy estimates for missing parameters. These estimates are then incorporated as additional features for subsequent iterations. The process continues until convergence, measured via a weighted harmonic mean of R^2 values, enabling the model to capture parameter interactions and reduce spectral interference.

3. Data

The framework was tested using the global GLORIA dataset and a local case study on the St. Lawrence River, Canada, with Sentinel-2, Landsat 8/9, Pléiades, and, for the first time, Wyvern hyperspectral imagery. In situ measurements of Chl-*a*, turbidity, and CDOM were collected in summers 2024–2025.

4. Results

The iterative framework achieved high retrieval accuracy for all target WQPs, performing on par with or exceeding MDNs while demonstrating greater robustness to incomplete datasets. Wyvern hyperspectral imagery was effective for Chl-*a* and turbidity mapping. Sentinel-2 and Landsat 8/9 also provided good results, whereas Pléiades imagery showed lower accuracy, likely due to its limited spectral resolution.

5. Conclusions

The multi-target learning framework successfully disentangles overlapping spectral signals, delivering reliable WQP estimates across diverse optical conditions, and represents a practical framework for enhanced multi-parameter water quality monitoring in inland and coastal waters.

Monitoring bio-optical and radiometric properties of shelf waters off Western Australia.

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In 2017, the Curtin University's Remote Sensing and Satellite Research Group (RSSRG) initiated a monitoring of bio-optical and radiometric properties of coastal waters off Perth, Western Australia. A moored Thetis profiler was deployed and collected sequences of various durations of daily profiles of temperature, salinity, chlorophyll fluorescence, particulate backscattering, hyperspectral absorption and attenuation, and hyperspectral downward plane irradiance and upwelling radiance at nadir. This data set provided insights into the dynamics of these properties and allowed matchups with satellite ocean colour observations. The Thetis was decommissioned in 2023 and replaced from March 2024 by a ship-based monthly monitoring of the same quantities, plus absorption of coloured dissolved organic matter (CDOM). These activities are developed in the frame of, and under funding from, the Australia Integrated Marine Observing System (IMOS). In September 2024, the coastal site was complemented by the deployment of the Marine Optical Network (MarONet) system in clear waters further offshore, as part of the vicarious calibration program of the NASA PACE mission. MarONet is funded by NASA and is a joint effort from University of Miami, San-José State University, Moss Landing Marine Laboratories (SJSU-MLML), the National Institute of Standard and Technology (NIST, US) and Curtin University. We will present example outputs from these activities, in terms of bio-optical variability including CDOM absorption, optical closure and satellite matchups.

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Drivers of Coral Reef Health in the Florida Keys (2011–2025): A Spatio-Temporal Analysis of Water Quality and Thermal Stress Using Landsat 5/8/9 imagery

Coral reefs in the Florida Keys have experienced repeated bleaching events and declining health in recent decades, making it critical to understand the environmental factors driving these changes. Using Landsat 5/8/9 imagery complemented by coral monitoring data from the Florida Reef Resilience Program (FRRP), we evaluated the role of water quality in coral bleaching across the Florida Keys from 2011 to 2025 during peak bleaching season (August–October). Time series of water quality parameters, including Kd490, colored dissolved organic matter (CDOM), chlorophyll-a, total suspended sediments (TSS), and turbidity, were derived from satellite imagery. We explored how these variables, along with sea surface temperature anomalies, related to observed bleaching patterns and examined which factors most strongly contributed to coral stress. To address uncertainties in shallow water remote sensing, regions with depths less than 4 meters were masked using NOAA bathymetry data (topobathy lidar DEM). Missing or cloud-affected data were filled using Data Interpolating Empirical Orthogonal Functions (DINEOF), enabling complete spatial coverage and robust time series analyses. This integrated approach enabled the identification of key environmental drivers of coral bleaching and validation of satellite-derived water quality data with field measurements. By combining long-term remote sensing with in-situ observations, these results inform management strategies and support improved monitoring of coral reef health in the Florida Keys.

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Inline optical systems reveal spatiotemporal gradients of phytoplankton community variability in the Laurentian Great Lakes

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The Great Lakes represent one of the most optically diverse and environmentally significant freshwater systems on Earth. Traditional discrete sampling methods, while valuable, fall short in capturing the full spatial and temporal variability of these vast and complex water bodies. To address this gap (and to support the NASA PACE satellite validation efforts), MTRI developed an optical flow-through system for the USEPA R/V Lake Guardian which provides continuous underway measurements of inherent optical properties (IOPs), including hyperspectral particulate absorption, attenuation, and backscattering (a_p, c_p, b_{bp}). This system, piloted in 2024 and fully deployed in 2025, enables near-continuous underway optical sampling, dramatically improving spatial resolution across water bodies and allowing for improved characterization of water optical properties.

Variability in phytoplankton community structure can be observed through IOPs in myriad ways. For this study, we focused on two indicators: phytoplankton pigments and particle size. Different phytoplankton communities contain unique pigment combinations, each of which absorbs light at different wavelengths, allowing them to more effectively harness solar energy for photosynthesis. Using these known absorption wavelengths, pigment composition can be estimated from a_p measurements using Gaussian decomposition. Particle size is also indicative of phytoplankton community and ecosystem health, with larger microplankton typically dominating in more nutrient-rich waters and smaller pico- and nanoplankton thriving in more oligotrophic waters. While our flow through system does not utilize an instrument to explicitly measure the phytoplankton size distribution, we can use the b_{bp} spectral slope (γ) as a proxy, with higher γ indicating smaller particle sizes.

This analysis investigates derived pigments and γ from three different cruises in Lake Michigan (in April, June, and August 2025) to investigate shifts along nearshore/offshore gradients, between basins, and across a temporal range when stratification was developing. These results will fill existing knowledge gaps that are crucial for existing Great Lakes monitoring programs while also providing useful data for validation and calibration of satellite-derived products.

CONNECT Tagus - Integrating ocean colour, in-situ and model data to support a water quality operational service

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Abstract

The Tagus Estuary is one of the largest and most important estuaries in Europe. It is a tide-dominated transitional system, located near Lisbon (Portugal). It is surrounded by a large metropolitan area, supporting 2.3 million people in its margins, which contribute to several water quality problems. It forms a transitional system characterized by a wide bay and a deep, long and narrow inlet that connects the Atlantic Ocean to the interior of the estuary. Water circulation is driven by semidiurnal tides, with additional influence from river discharge and storm surges, yielding strong marine to riverine gradients.

The CONNECT Tagus service (Rodrigues et al., 2024) aims to address the need for an operational service to evaluate water quality in the Tagus estuary. It combines observations, both from satellite and in-situ sondes, with model-based forecasts. The service integrates: i) Earth Observation (EO) data, mainly on sea surface temperature and chlorophyll concentrations; ii) real-time physical and biogeochemical data acquired from in-situ observation networks (Castellanos et al. 2021); and iii) shelf-to-estuary quality operational modelling with SCHISM (Zhang et al., 2016) to produce daily forecasts of local physical and biogeochemical variables. The observational data (satellite and in-situ sondes) are provided by CoastNet RI (http://coastnet.pt). The operational circulation and water quality models are operated by WIFF and OPENCoastS (Oliveira et al., 2020; Rodrigues et al., 2021) and downscale CMEMS predictions of the Iberia-Biscaya regional model. A set of water quality indicators are computed and made available at a dedicated webGIS portal (http://connect-portal.lnec.pt), enhancing the management, monitoring and forecasting of the water quality in the Tagus estuary.

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Smartphone-Based Digital Imaging via the TurbAqua App for Forel-Ule Water Colour Index Determination

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The explosive growth of smart phone usage, together with the increasing capabilities and sophistication of its camera sensors has enabled the collection of high-quality digital imagery for *in situ* water colour characterization. Since 2018, trained participants have collected water surface images of Lake Vembanad using the in-app photo capture tool of the TurbAqua mobile application, as part of a citizen science programme by ICAR-Central Marine Fisheries Research Institute. In this study, the digital images are processed using the WAter COlour from Digital Images (WACODI) algorithm to derive Forel–Ule (FU) indices, which were then compared with Sentinel-2 MSI observations. Preliminary analysis indicates that FU values derived from images using WACODI algorithm tend to cluster in the Forel-Ule Index range 10-13, corresponding to Greenish waters. A three-tier validation approach is envisaged involving *in situ* FU readings, image-derived FU values, and Sentinel-2 MSI-based FU observations. This multi-source validation aims to identify the influence of surface reflectance, ambient lighting, suspended sediment load, and other optically active substances on perceived water colour across different platforms and scales. Once calibrated, and refined to regional conditions, the algorithm can be integrated into the TurbAqua app to support real-time water colour classification from digital images contributed by citizen scientists. This study highlights how the link between community-based monitoring and satellite ocean colour validation can bi-directionally serve both scientific objectives and societal needs.

Key words: Forel-Ule Index, Ocean Colour, Citizen Science, WACODI, TurbAqua application

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Optimising 6S-based atmospheric correction for PRISMA and EnMAP hyperspectral imagery over inland waters

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Keywords: EnMAP, PRISMA, 6S, atmospheric correction, hypertrophic and oligotrophic inland waters.

Abstract

In aquatic remote sensing, accurately retrieving water quality parameters from hyperspectral data is a significant challenge due to the complex interaction of light with both the atmosphere and the water column. The primary obstacle is the weakness of the water-leaving radiance, which is easily masked by atmospheric influence, especially in the blue spectrum. Atmospheric correction is therefore the most critical step to obtain the water's true spectral signature.

This study addresses atmospheric effects in Level 1 hyperspectral imagery from the PRISMA and EnMAP satellites over inland water bodies. Our objective is to introduce an efficient atmospheric correction method using a radiative transfer modelling (RTM) approach based on the Second Simulation of the Satellite Signal in the Solar Spectrum (6S) model.

Despite RTM models like MODTRAN offering greater performance and thinner spectral bandwidth, the 6S model was selected for its balance of simplicity and accuracy. This makes it an efficient and suitable solution for solving the complex inverse problem of atmospheric correction. We simulate atmospheric parameters using 6S and incorporate them into the radiative transfer equation to convert the top-of-atmosphere (TOA) radiances to remote sensing reflectance *(Rrs)*.

The effectiveness of our approach is evaluated by comparing the derived *Rrs* with in situ spectroscopy measurements. We quantify the uncertainty, imprecision, and inaccuracy of our method over both oligotrophic and hypertrophic inland waters across the visible to near-infrared (VNIR) wavelength range. The results, reported using key statistical metrics such as Bias (inaccuracy), standard deviation (imprecision), and confidence interval (uncertainty), show that all these statistics are below 0.01 sr^{-1} for every spectral band within the VNIR wavelength range.

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Enhancing RADIALES time series: Evaluating C2X-Derived Chlorophyll Products in the Optically Complex Waters of the Golfo Ártabro (NW Spain)

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Obtaining accurate estimates of water quality from satellite observations remains particularly difficult in coastal areas, where both organic and inorganic particles significantly influence the water's optical properties. This complexity demands highly precise atmospheric corrections as well as adjustment of existing global and regional chlorophyll-a (Chl-a) algorithms, including the development of specific ones to improve the Chl-a estimation. Over the past few decades, numerous atmospheric correction methods have been introduced to address this challenge. However, their effectiveness can vary based on specific environmental conditions and geographic locations and validation efforts are still essential across diverse water types to fully utilise these tools. The objective of this study was to assess the accuracy of the chlorophyll derived products of the C2X-Nets processor using Sentinel-2 imagery (10 m) in the Golfo Ártabro (NW Spain). Validation was performed using data from the RADIALES time series, a long-term monitoring program initiated in 1988 by the Oceanographic Centre of A Coruña (IEO-CSIC). A total of 269 matchups were analysed in three sampling stations distributed perpendicular to the coast, taking into account measurements between 0 and 5 m depth. Overall, the C2X-Nets algorithm did not yield reliable Chl-a estimates across the full dataset ($R^2 = 0.10$, MAE = 0.9, RMSE = 1.3, Bias = -0.3). However, performance improved when stations were evaluated individually, with the poorest results observed at the innermost station in the Ría de A Coruña bay. This underperformance may be partly attributed to the combination of local environmental factors (e.g., frequent swell) and the 10 m used in the resampling. Future work will explore coarser spatial resolutions (20 m, 60 m) on the accuracy of C2X-derived Chl-a estimates as well as the evaluation of alternative algorithms to improve regional Chl-a retrievals.

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Satellite-Derived Monitoring of Faecal Contamination in Coastal Waters Using Sentinel-2: A Novel Approach to support Recreational Water Safety

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Abstract:

Monitoring faecal indicator bacteria (FIB) in recreational waters is essential to safeguard public health and comply with environmental regulations. However, current monitoring practices rely heavily on in-situ sampling, which is resource-intensive and spatially limited. In this study, we present for the first time, a novel satellite-based approach for direct surveillance of *Escherichia coli* (*E. coli*) and *Enterococcus* bacteria in coastal waters, leveraging Sentinel-2 reflectance data across 20 beaches in Calvia, Mallorca, Spain.

Two empirical models were developed using ordinary least squares regression, incorporating spectral features from SWIR and visible bands (notably Rrs1614, Rrs2202, and Rrs443). These models achieved strong predictive performance (R^2 of 0.79 for *E. coli* and 0.74 for *Enterococcus*), accurately identifying contamination hotspots and capturing spatial-temporal variability during both routine monitoring and known pollution events. The models successfully distinguished faecal contamination from traditional water quality indicators such as chlorophyll-*a*, turbidity, and suspended matter, enhancing interpretability and robustness.

The results reveal that aggregated bacterial colonies and associated organic matter influence surface reflectance in SWIR-visible band ratios, enabling detection. Validation using in-situ measurements confirmed the models' capacity to detect contamination, including a confirmed leakage event traced to a septic source. While challenges remain in reducing uncertainties from atmospheric corrections, sampling mismatches, and bottom interference, this study marks the first successful demonstration of direct FIB mapping using Sentinel-2 data in oligotrophic coastal waters.

This work advances the integration of Earth observation for microbial water quality assessment and underscores its operational potential for timely, scalable monitoring to support sustainable tourism and coastal health management.

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The Euclidean Distance Score (EDS): A Composite Score for Evaluating Aquatic Remote Sensing Retrieval Algorithms

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Objective and consistent evaluation of retrieval algorithms is critical for advancing ocean colour remote sensing. However, existing multi-metric approaches often suffer from statistical limitations, redundancy, and the need for dataset-specific normalization, factors that can bias interpretations and hinder broader assessments. To address this, we introduce the Euclidean Distance Score (EDS), a composite score that integrates five complementary performance metrics selected for their compatibility with the characteristics of bio-optical data. EDS quantifies retrieval performance as the Euclidean distance from an idealized point representing a perfect result, balancing three key aspects: regression fit, retrieval error, and retrieval robustness. We demonstrate the practical utility of EDS using a set of curated in-situ bio-optical data and two retrieval algorithms (2SeaColor and the Quasi-Analytical Algorithm). Applicability of the method is illustrated with use cases, such as evaluating a single algorithm across multiple variables, comparing algorithm performance on shared retrieved variables, and assessing performance across different water types. The proposed method offers an objective and interpretable framework for synthesizing algorithm performance, supporting more consistent evaluations and facilitating better-informed decisions in both research and applied aquatic remote sensing contexts.

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Field Validation of Satellite-Derived Rrs and Chlorophyll-a in a Coastal Setting: A Case Study from Nogas Island, Philippines

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Abstract

This study presents an exploratory field validation of satellite-derived remote sensing reflectance (Rrs) and chlorophyll-a (Chl-a) concentrations from Sentinel-2 Level-1C imagery, using in-situ measurements and collected samples around Nogas Island, Antique. Field measurements were conducted on June 19–20, 2024, and compared with Sentinel-2 data acquired on June 22, 2024. This effort represents an initial step in validating ocean color remote sensing products for coastal areas in the Philippines, where optically complex water properties and environmental conditions pose unique challenges.

In-situ Rrs was measured using an Ocean Optics Spectrometer and resampled using Sentinel-2 spectral response functions (SRFs) for compatibility. Satellite Rrs was derived from Sentinel-2 data processed with the Modified Atmospheric Correction for OLI-lite (ModAco). Independent Chl-a concentrations were measured using an AAQ-Rinko sensor.

Comparison between the resampled in-situ Rrs and Sentinel-2 Rrs revealed consistent underestimation by the satellite, particularly in the blue bands (443–560 nm), with maximum negative differences of up to -2.8 sr^{-1}. The correlation between satellite and in-situ Rrs was moderate (R^2 = 0.452, RMSE = 1.975 sr^{-1}, p = 0.214), though variability remains high. These discrepancies reflect uncertainties from both sources, including limitations in field measurements such as uncorrected glint and surface effects.

Chlorophyll-a was estimated using the OC3 algorithm applied to both satellite-derived and in situ Rrs. The comparison between OC3 Chl-a values from satellite and in situ Rrs was weak (R = 0.070, RMSE = 6.240, p = 0.746). However, comparison with direct AAQ-Rinko measurements yielded a stronger correlation (R = 0.570, RMSE = 3.13, p = 0.003), indicating the potential utility of satellite-based Chl-a estimates.

This exploratory validation highlights both the potential and current limitations of applying satellite ocean color algorithms in coastal areas in the Philippines, emphasizing the need for continued refinement and localized validation strategies in regions like Nogas Island.

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Variations in the optical and biogeochemical properties of phytoplankton, non-algal particles, and dissolved organic matter in European coastal waters based on two years of intensive field measurements (Tara-Europa/HyperBOOST project)

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25 years after the Coastlooc[1] project, the optical and biogeochemical properties of European coastal waters have been intensively documented based on two consecutive years (2023-2024) of field measurements carried out onboard the Tara research vessel[2]. These measurements will be used for the validation of products from ocean color satellites as well as for the development of new and validation of existing ocean color inversion algorithms based on in-board radiometers.

One of the generated datasets, soon to be published, combines continuous inline optical measurements[3] with laboratory analyses of surface water samples collected at more than 200 field stations along the European coasts. It includes hyperspectral measurements of the following inherent optical properties (IOPs): light absorption by phytoplankton, non-algal particles and colored dissolved organic matter (CDOM), light attenuation, scattering and backscattering. Biogeochemical analyses covered measurements of the concentrations of suspended particulate matter (SPM), SPM organic and inorganic fractions, phytoplankton pigments including chlorophyll-a (Chla), dissolved and particulate organic carbon (DOC and POC), particulate inorganic carbon (PIC).

This dataset provided for the comparison between inline (Wetlabs ac-s) and laboratory (spectrophotometer) light absorption measurements resulting in a novel scattering correction. Additionally, the spatial variations of the mass-specific light absorption, scattering and backscattering coefficients are documented over the wide diversity of European coastal waters. Relationships are established between CDOM, its fluorescent fraction (FDOM) and the DOC concentration. These preliminary results are analyzed and discussed in the scope of improving inversion algorithms used to derive IOPs and concentrations of colored water constituents from ocean color satellite data.

[1] https://essd.copernicus.org/articles/15/3529/2023/
[2] https://hyperboost.info
[3] https://ioccg.org/wp-content/uploads/2019/11/inline-protocols-4.0-nov2019.pdf

Optical classification and estimation of water quality parameters using OLI-2/Landsat-9 imagery in Puno Bay-Peru

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A methodology was developed to evaluate water quality in the bay of Puno, located on Lake Titicaca, the highest navigable lake in the world, using high spatial resolution satellite images, in order to support environmental monitoring and sustainable management. Four water classes were identified using Landsat-9 image spectral reflectance values, the classes have been grouped into two optical categories: "case 1" waters (classes 2, 3 and 4) associated with more transparent water bodies, and "case 2" waters (class 1) linked to coastal areas influenced by high concentration of chlorophyll-a (CHL), total suspended solids (TSS) and other optical constituents. The developed simple linear regression (SLR) and multivariate linear regression (MLR) models showed good performance in estimating CHL and TSS. The CHL5 model, based on the ratio of the red and blue bands, achieved a correlation coefficient R = 0.628, together with the APPEL model (CHL6) quantified the low concentration of chlorophyll-a (from 2.5 to 7. 5 mg/m^3) in case 1 waters and the high concentration (>10 mg/m^3) in case 2 waters. For TSS, the SST6 model, using the NIR band (865 nm), recorded concentrations above 20 mg/L in case 2 waters, compared to a range of 5-15 mg/L in general. These results validate the applicability of remote sensing techniques for monitoring eutrophic lakes with poor *in situ* data availability.

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Satellite-derived Chlorophyll in the California Coast

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Abstract

Satellite-derived chlorophyll-a products are widely used for marine ecological studies, and water quality monitoring, but their accuracy in coastal waters remains a critical challenge. In this study, we evaluate the performance of three ocean-colour chlorophyll-a products, those from the merged ocean-colour dataset of the Ocean Colour Climate Change Initiative (OC-CCI) and those from two single sensors processed using the standard NASA SeaDAS processor the Moderate Resolution Imaging Spectroradiometer (MODIS) and the Visible Infrared Imaging Radiometer Suite (VIIRS). These products are evaluated against *in situ* chlorophyll-a observations in the coastal region off California, USA, which is a highly dynamic region characterised by large phytoplankton blooms driven by equatorial upwelling. Using daily matched satellite and *in situ* data, we find that OC-CCI outperforms MODIS and VIIRS in nearshore waters. These results highlight the importance of algorithm selection in coastal satellite applications and demonstrate the value of multi-sensor, *in situ* validation for advancing ocean colour science.

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Hyperspectral Assessment of Water Quality using PRISMA, EnMAP, and HYPSO in the Forth Estuary, UK

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With River-Sea Systems research supported by DANUBIUS-RI (the International Centre for Advanced Studies on River-Sea Systems), three campaigns (08/07/2025, 17/07/2025 and 24/07/2025) were conducted at the Forth Estuary, UK. An in situ dataset was collected (n.records = 9, n.sampling sites = 4), including biogeochemistry, inherent optical properties (IOPs), apparent optical properties (AOPs) and physical parameters. Moreover, hyperspectral satellite imagery (PRISMA - 08/07/2025, EnMAP - 08/07/2025 and 12/07/2025, HYPSO - 07/07/2025 and 17/07/2025) and data from the Forth-ERA digital observatory were acquired synchronously to field campaigns. The analysis of in situ data shows that: 1) high water quality variability and complexity (TSM (total suspended matter) range is 0.97 - 22.15 g m^{-3}, Zsd (Secchi disk depth) range is 2.4 - 15 m, and CDOM (coloured dissolved organic matter) range is 0.11 - 0.98 m^{-1}); 2) TSM is strongly positively correlated with water depth (r1 = 0.73, r2 = 0.79) , and mainly consists of suspended particulate inorganic matter (SPIM) (r1 = 0.998, r2 = 0.999). For reflectance measurements collected from each point/transect with TriOS RAMSES spectroradiometer, three correction methods were applied to remote sensing reflectance (Rrs(λ), sr^{-1}) calculated by 3C (three-component reflectance model), then matched with PRISMA data atmospherically corrected with ACOLITE/DSF and Polymer. The result shows that: 1) Jiang et al (2020) correction performs better, especially in the near-infrared spectral range; 2) PRISMA data corrected with Polymer is more consistent with in situ data (N = 2, slope = 1.2779, intercept = -0.0001, r = 0.85, RMSE = 0.0017, MAE = 0.0014). This study represents the first comprehensive analysis of bio-optical parameters, hyperspectral satellite data, and the Digital Water Observatory in the Forth Valley. It highlights the exceptional capability of spaceborne imaging spectroscopy for coastal water quality monitoring, and provides an in-depth understanding of water quality dynamics in River-Sea Systems.

In-situ reflectance measurements and optical characteristics of waters in Zeebrugge/MOW1, Belgian coastal zone

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Abstract

Autonomous in situ radiometric measurement systems have been proven to be cost effective tool for long-term satellite ocean colour data validation and water quality monitoring. This study utilises the available radiometric data from multi-spectral (SeaPRISM) and hyperspectral (HYPSTAR®) sensors developed under AERONET-OC and WATERHYPERNET networks, respectively, to assess the optical characteristics of waters in Zeebrugge/MOW1, Belgium. These sensors are hosted on the MOW1 tower, which is a maritime offshore monitoring station located about 3.6 km off Zeebrugge and is an established site of international networks for ocean colour validation (radiometric validation). In this work, we will be describing the variability of turbidity and chlorophyll concentrations derived from water reflectance measurements of the site. In addition, matchup analysis between insitu and satellite observations will be performed. Temporal patterns of optical characteristics and matchup validation results from the datasets will be presented and discussed.

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Leveraging Earth Observation and Ground Measurements for Ecological Quality Assessment in Tropical Coastal Waters

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Coastal water quality assessment and monitoring are crucial for ensuring the sustainability of coastal ecosystems and human well-being. In Bangladesh, evaluating water quality has become a priority to ensure a reliable water supply and protect coastal environments. A synergy between field-based measurements and satellite data, such as Sentinel-2 and Sentinel-3, can provide valuable insights into coastal water quality dynamics. The aim of the present work is to (i) assess coastal water quality using field-based data and compare it with remote sensing-derived estimation and (ii) develop a long-term water quality monitoring tool using remote sensing estimation in the coastal area of Bangladesh. The study was conducted at different sampling sites in Cox's Bazar during May 2024. Field data from previous studies, November 2016 and December 2017, were also used to evaluate the results. For the determination of ecological quality, water temperature, Dissolved Oxygen (DO), conductivity, salinity, total dissolved solids(TDS), pH, nitrate-nitrogen (NO3-N), soluble reactive phosphorus (SRP), soluble reactive Silica (SRS),chl a, and phytoplankton abundance were determined. The available reference conditions of different quality elements enabled the assessment of ecological water quality. Physicochemical-based water quality index (WQI) showed good to impaired water quality, whereas Chl a showed the bad ecological condition of the study area. The field-based results were correlated with Sentinel-3-derived chlorophyll (chl a) content and phytoplankton biomass which ranges from 0.172 to 22.1 µg/L, whereas field-based data show 0.98 to 13.81 µg/L. In addition, the mean value of phytoplankton biomass was 28.8 mmol/m^3 from Sentinel-3 products, whereas the field data showed 23.5 mmol/m^3. These deviations occurred due to the spatial resolution of Sentinel-3 products (300 m). The present study suggests that high spatial resolution remote sensing products, such as Sentinel-2, may be helpful for long-term monitoring of coastal water quality in Bangladesh.

Assessing biophysical dynamics in Italian lakes using time-series satellite products

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The Lakes_cci (Climate Change Initiative) project delivers globally consistent satellite-based observations of the Lakes Essential Climate Variable (ECV) in terms of Lake Water Level (LWL), Extent (LWE), Surface Water Temperature (LSWT), Ice Cover and Water-Leaving Reflectance (LWLR). The latter has been improved with an upgraded atmospheric correction algorithm (Polymer v4.17) and associated recalibration of algorithms for the retrieval of chlorophyll-a (Chl-a), total suspended matter (TSM), coloured dissolved organic matter (CDOM) and the vertical diffuse attenuation coefficient (Kd) has resulted in several marked performance improvements. Together, these variables provide a comprehensive picture of both the physical state of lakes and their biogeochemical responses to environmental changes, such as climatic and physical forcing. The dataset is offering a 30-year time series of high-quality data. The products are provided at a 1 km spatial resolution and a daily temporal resolution, covering more than 2,000 large lakes worldwide. This long-term dataset is a valuable resource for climate monitoring, hydrological modelling, ecosystem research, and assessing the impacts of climate change on inland water bodies.

In this study, we highlight the contribute of the Lakes_cci dataset to the Italian National Biodiversity Future Center (NBFC), by analysing biophysical water parameters to understand potential drivers behind observed trends over 10 waterbodies distributed across the Italian peninsula. The lakes represent a variety of origins (e.g., glacial, volcanic), types (e.g., natural, regulated lakes, wetlands), morphologies (e.g., deep and shallow) and trophic status. The Theil-Sen trend slope was calculated annually and seasonally for parameters such as Chl-a and Kd. Phenological changes in phytoplankton dynamics were analysed in relation to meteorological and climatic variables derived from ERA5-Land reanalysis data, Lakes_cci products such as LWL and LSWT, and with freshwater biodiversity variables and indicators. In deep, oligo-mesotrophic subalpine lakes, a shift in phytoplankton phenology was observed, likely driven by warmer winter conditions and the consequent absence of winter overturn. In shallow mesotrophic lakes, longer periods of elevated temperatures have been associated with shorter bloom durations associated with potential harmful algal booms.

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Assessing Drought Impacts on Phytoplankton Dynamics in Lake Kariba Using Remote Sensing and 3D Hydrodynamic Modeling

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Drought is one of the most severe and complex natural hazards, causing changes in the water balance and impeding crucial water-dependent ecosystem services. 2019 saw the most extreme drought in 24 years in sub-Sahelian Africa, resulting in historically low water levels in Lake Kariba, world's largest artificial reservoir by volume.

This study utilizes a novel approach to understand the effects of high and low water level on the spatio-temporal evolution of phytoplankton blooms through integration of remote sensing, in situ measurements, and a 3D hydrodynamic model applied to the entire lake.

Five parameters were extracted from the European Space Agency's Lakes_cci project: Water Level, Surface Water Temperature, Water Leaving Reflectance (LWLR), and derived chlorophyll-a concentration and turbidity, covering 1992 to 2022. Water transparency, as the spatially resolved attenuation coefficient Kd, is derived from LWLR and included in the model for the first time.

For simulating Lake Kariba's hydrodynamics, a Delft3D flow model is set up with 1 km horizontal resolution and vertical layers from 0.5 m to 5 m. Atmospheric forcing from hourly ERA5-Land data and daily precipitation in the immediate catchment from CHIRPS are imposed. The water balance is satisfied by incorporating observed Zambezi River inflow, dam outflows, and a calibrated runoff coefficient applied to precipitation to represent minor ungauged tributaries. The modelled temperature field is validated against in-situ thermal profiles at the deepest point. Further calibration compares simulated and satellite-derived water level and surface temperature.

Preliminary model results show good agreement between simulated and observed data, providing a reliable water and heat balance. The time series of surface water temperatures show shifted peaks in low-water-level years, accompanied by changes in phytoplankton bloom phenology.
Integration of the lake's spatial heterogeneity allows the identification of vulnerable areas, underlining the necessity of such approaches for operational management of precious water resources.

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Nutrient Retrievals from In Situ Hyperspectral Reflectance in the Mississippi Basin

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We developed a neural network-based approach to estimate nutrient levels (nitrate plus nitrite) from in situ hyperspectral reflectance observations. The network architecture is designed to pick up on non-linear correlations between hyperspectral reflectance inputs and nutrients as target variable. The network was trained on two years of matching hyperspectral reflectance (350 to 900 nm, 3 nm spectral resolution) and matching USGS nutrient readings (1926 records, 0.25 – 3 g/m3) at Baton Rouge (Louisiana, USA). A season's worth of match-ups (1136 records) from a second site (De Soto, Kansas, USA) was used to validate prediction performance and assess model transferability. Performance for the test-split (data not used during training) at Baton Rouge was convincing (R2=0.87, $p<0.01$, MAPE=0.17) and only slightly degraded when applied directly to the validation data set collected at De Soto (R2=0.72, $p<0.01$, MAPE=0.41). Additional model parameter tuning and more training data will further improve performance and robustness of these approaches. We're actively seeking to validate against additional nutrient <> hyperspectral reflectance datasets. This is to expand applicability to a larger range of water types, nutrient concentrations, and bio optical conditions, in preparation for nutrient retrievals from satellite-borne hyperspectral reflectance observations.

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How can we improve the relationship between phytoplankton sun-induced fluorescence and chlorophyll-a remote sensing-based estimates?

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Sun-induced fluorescence (SIF) emission from chlorophyll-a pigments in phytoplankton have been used in many remote sensing (RS) studies as an indicator of chlorophyll-a concentration (chl-a). However, the results correlating SIF and chl-a can be challenging to interpret, often attributed to the elastic scattering interference and impact of quenching mechanisms. Despite this, quenching mechanisms are seldom studied from a RS perspective, especially in optically complex waters. In our investigation, we differentiated between dominant Photochemical Quenching (PQ) and Non-Photochemical Quenching (NPQ) cases, which improved the relationship between SIF and chl-a.

We used data collected by an autonomous profiler in Lake Geneva, Western Europe between 2018 and 2022. Fluorometric chl-a estimates influenced by NPQ were corrected to distinguish occurrences of PQ and NPQ-dominant cases. The relationship between SIF and chl-a estimates is weak when no differentiation between quenching mechanisms is considered (R^2=0.37; Median Absolute Percentage Difference (MAPD)=74%). This relationship strengthens when separating PQ cases (R^2=0.72, MAPD=49%) from NPQ cases (R^2=0.48, MAPD=68%). Considering only in-situ measurements during Sentinel 3 overpasses ±3 hours further enhanced the relationship for both PQ (R^2=0.82, MAPD=35%) and NPQ cases (R^2=0.43, MAPD=61%). Scaling the approach to Sentinel-3 OLCI data did not produce satisfactory results due to errors associated with remote sensing reflectance products despite applying several atmospheric correction methods. We recommend improving the correction in the red-NIR wavelength region to effectively demonstrate the findings from our in-situ measurements to satellite data, especially in oligo-mesotrophic lake applications. Doing so will not only make satellite-based SIF yield retrievals better but also provide opportunities to produce SIF-based phytoplankton physiology products.

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Evaluation of Satellite Ocean Color Products across the North Atlantic: Insights from the One Ocean Expedition 2025

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Abstract

Satellite ocean color helps us understand the physical and biogeochemical processes occurring in the ocean due to its high spatiotemporal coverage, essential to characterise the impacts of extreme events, and monitor trends and changes in water quality. We aimed to evaluate Level 2 Ocean Color products from Sentinel-3 Ocean Land Color Instrument (OLCI) and Phytoplankton Aerosol Cloud, ocean Ecosystem (PACE) Ocean Color Instrument (OCI) using *in situ* observations. Water samples were collected at the surface in 25 stations across the North Atlantic Ocean during the European Space Agency's Ocean Training Course aboard the One Ocean Expedition 2025. They were filtered onboard using GFF filters for chlorophyll-a (Chl-a) and suspended particulate matter (SPM) concentrations. *In situ* Chl-a and SPM samples were analysed according to standard procedures. Sentinel-3 OLCI Level 2 products for the campaign were obtained from the network-attached storage onboard, and PACE OCI products from the National Aeronautics and Space Administration Earthdata Search. Match-up protocols follow EUMETSAT's recommendations for Ocean Colour product validations. As for the drone data validation, a DJI P4 Multispectral with an integrated multispectral imaging system was used to collect data on the water surface. Analysis of the datasets is ongoing, and results will be available for presentation at the conference. The results of these validation efforts aid in determining which sensor provides better estimates for the North Atlantic Ocean and improving satellite estimates on the open ocean.

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COCOBRAZ: Two Decades of Chlorophyll-*a* Trends and Drivers Along the Brazilian Margin

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Ocean colour remote sensing provides a unique perspective for monitoring phytoplankton biomass, seasonal cycles, and long-term trends, which are key indicators of marine ecosystem health, biogeochemical cycles, and coastal management. This study, developed under the ANR–FAPESP COCOBRAZ project, evaluates the performance of two satellite chlorophyll-*a* (Chl-*a*) datasets: the multi-sensor Ocean Colour Climate Change Initiative (OC-CCI) product and the single-sensor COCOBRAZ product derived from MODIS-Aqua 1 km data, against an extensive compilation of *in situ* Chl-*a* measurements, primarily from Brazilian waters. Performance analysis was categorized by optical water type (OWT) classes to assess strengths and limitations across different water masses. While OC-CCI showed reduced accuracy in optically complex waters (OWTs 1 and 2), the COCOBRAZ product, generated using an adapted atmospheric correction and neural network approach, achieved improved retrievals in these coastal conditions. However, COCOBRAZ underestimated very low Chl-*a* concentrations in the South Atlantic Gyre. A 20-year trend analysis (2002–2022) using seasonal Mann–Kendall and Sen's slope tests, plus time-series decomposition, revealed distinct spatial patterns. Increasing trends in São Luís, Maceió, Aracajú, Sepetiba Bay, Paraty, and southern South Brazil Bight were likely driven by land use and land cover changes. Declines in northern and northeastern regions were associated with climate variability, including SST anomalies, ENSO events, and AMOC variability. In the south, SST, precipitation, and ENSO phases influenced increasing Chl-*a* trends in the inner shelf and Patos Lagoon. The COCOBRAZ Chl-*a* product has proven to be a robust tracer of marine ecosystem change along the Brazilian margin. Its continued development, alongside other biogeochemical parameters, will provide an essential basis for assessing the vulnerability of coastal ecosystems to both natural and anthropogenic drivers.

Development of ocean colour products using Meteosat Second and Third Generation geostationary satellites

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Satellite Ocean Colour observations have been conventionally performed from polar orbiting sensors, but the benefits of using geostationary satellites to monitor ocean essential variables such as chlorophyll concentration and sea surface temperatures are now well established. This includes the possibility to observe dynamic diurnal processes and to achieve a better coverage thanks to frequent daily observations.

In December 2022, the European geostationary program entered a new phase with the launch of Meteosat Third Generation. This latest generation of EUMETSAT meteorological satellites carries the Flexible Combined Imager (FCI) instrument. FCI scans the full Earth disc, centred over Africa every 10 minutes, and scans Europe, the northern part of the Atlantic Ocean, and the Mediterranean Sea every 2.5 minutes. While primarily dedicated to meteorological objectives, FCI possesses the necessary spectral bands, and is a good candidate for retrieving ocean colour products, enabling operational monitoring of ocean primary productivity and turbidity.

This study depicts the framework in which EUMETSAT has engaged to develop a dedicated pre-operational prototype processor for atmospheric correction and the derived water products from FCI. This builds upon and expands previous developments and results for the Spinning Enhanced Visible and Infrared Imager (SEVIRI) on Meteosat Second Generation, which will be presented here as well. Additionally, the study focuses on the development of a multi-mission module that helps in retrieving the highest-quality water products. It also outlines the potential outcomes and applications that will be conducted to validate and use the current processor.

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A Study on the Uncertainty Analysis of Diffuse Attenuation Coefficient for Downwelling Irradiance based on the Radiative Transfer Model

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The diffuse attenuation coefficient for downwelling irradiance (K_d) is an apparent optical property (AOP) that describes the exponential decrease of light with depth due to scattering and absorption by constituents in the seawater. K_d used to study of ocean turbidity, primary production, and other bio-optical processes and, is typically estimated from remote-sensing reflectance (R_{rs}) derived from ocean color satellite. Recently, semi-analytical models based on radiative transfer theory have been developed to estimate K_d from inherent optical properties (IOPs), but may not fully account for environmental conditions, leading to errors. In this study, we used HydroLight simulations to evaluate the impact of four major environmental variables—solar zenith angle (SZA), wind speed, aerosol type, and aerosol optical depth (AOD)—by setting their minimum and maximum values across three water types (clear, moderate, and turbid conditions). The impact of each variable was analyzed by comparing the K_d derived from a semi-analytical model using IOPs obtained from the simulation. The results showed that SZA had the most significant impact across all water types, with the error rate from 10.21% in clear waters to 28.17% in turbid waters. While AOD had a relatively smaller effect, its influence increased with turbidity, up to 17.93%. The wind speed and aerosol type showed minimal impact, with maximum error rate differences of 2.75% and 0.05%, respectively. In particular, significant error rate occurred due to SZA, despite it being already accounted for in the semi-analytical K_d model, demonstrates a limitation of the K_d model. It indicates that the turbidity has to consider as an additional factor. This study represents that SZA and AOD are major factors contributing to K_d errors, and that turbidity should also be considered, suggesting the need for improvement of the K_d algorithm.

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Atmospheric correction of coastal waters based on satellite-AERONET-OC matchups

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Abstract

Atmospheric correction (AC) is a critical step in ocean color remote sensing, particularly for coastal waters that still face challenges from high concentrations of suspended materials and absorbing aerosols. To address these limitations, this study presents a novel AC algorithm, termed ACA-SIM, based on extensive matchups between satellite measurements and *in situ* remote sensing reflectance (R_{rs}) from Aerosol Robotic Network-Ocean Color (AERONET-OC), with neural networks as the processing tool. Validations with independent AERONET-OC measurements demonstrate that ACA-SIM delivers superior accuracy of R_{rs} across all spectral bands compared to both the NASA Standard and the recently developed OC-SMART algorithms, while the latter employs a strategy similar to ACA-SIM but relies exclusively on simulated data. In particular, for the blue bands, ACA-SIM reduced the mean absolute percentage difference (MAPD) of derived R_{rs} to ~15%, compared to an MAPD of ~32% by OC-SMART, and maintained robust performance even under challenging conditions. Moreover, when applied to MODIS-Aqua images in highly turbid and dust- or smoke-affected regions, such as the Bohai and Yellow Seas, the West Coast of North Africa, and areas impacted by Australian bushfires, ACA-SIM demonstrated exceptional capability in minimizing striping effects and generating reliable R_{rs} products. This study advances AC techniques for coastal waters and reinforces the significance of the AERONET-OC network. Furthermore, it lays a foundation for extending ACA-SIM to other satellite sensors, enabling the generation of consistent and accurate ocean color products across multiple satellite platforms.

Keywords: Ocean Color; Atmospheric Correction; AERONET-OC; Neural Networks; MODIS-Aqua; Coastal Waters; Absorbing Aerosols

A Novel Hyperspectral Index for Chlorophyll-a Concentration Quantification in Productive Waters

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Hyperspectral remote sensing offers significant potential for monitoring chlorophyll-a concentration (Chla) in optically complex waters. However, existing hyperspectral indices for Chla retrieval in productive waters often suffer from limitations due to interference from other water constituents, imperfect atmospheric correction, and the constraints of discrete spectral bands. To overcome these challenges, we propose a novel spectral index—the Red-Edge reflectance Peak Width Index (REPWI) - defined as the horizontal wavelength distance between a fixed red reflectance valley (678 nm) and the intersection point on the right slope of the red-edge reflectance peak. First, we employed a bio-optical model to establish the theoretical basis and quantify the relationship between REPWI and Chla. Next, we calibrated and validated the REPWI-based Chla retrieval model using in situ remote sensing reflectance and Chla data from 57 globally distributed water bodies. The model demonstrated high accuracy, achieving a coefficient of determination (R^2) of 0.92, a mean relative error (MRE) of 26.5%, and a root mean square error (RMSE) of 13.7 mg/m³, significantly outperforming existing spectral indices. Furthermore, the REPWI maintained a robust correlation with Chla (R^2 = 0.87–0.90) when applied to simulated spectra from major on-orbit hyperspectral satellites. Finally, we successfully implemented the REPWI-based model on the China's ZY1-02D hyperspectral imagery, confirming its high retrieval accuracy and resilience to imperfect atmospheric correction. In conclusion, the REPWI represents a theoretically sound and operationally effective hyperspectral index for monitoring Chla in productive waters, offering substantial improvements over conventional approaches.

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Identifying potential optical indicators of HAB events using Sentinel-2/3 satellites

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Harmful algal blooms (HABs) have severe implications for aquatic ecosystems, human health, and coastal economies. However, effective monitoring remains challenging due to the diversity of bloom types and their complex environmental forcing. Satellite remote sensing has advanced HAB detection, as specific algal taxa exhibit unique spectral characteristics. However, most studies have relied on low-spatial and spectral resolution imagery and focused on a limited number of reported bloom events. This study aims to detect and discriminate blooms of key toxic phytoplankton taxa (*Pseudo-nitzschia* spp., *Gymnodinium catenatum*, and *Alexandrium* spp.) across different coastal and oceanic domains, using Sentinel-2 (S2) and Sentinel-3 (S3) data, at 10 m and 300 m resolution, respectively. S2 and S3 images were retrieved from the Copernicus Open Access Hub during selected HAB events, reported in the Harmful Algae Event Database and scientific literature. Top-of-atmosphere reflectance was processed into surface reflectance using ACOLITE, which was then used to characterize and discriminate reflectance spectra. Multiple radiometric indicators were applied to optimize bloom patch detection. Physico-chemical data during blooms were explored to identify potential drivers. Overall, all reflectance spectra from S2 data displayed peaks at 560 and/or 704 nm, with different primary and secondary peak patterns among taxa. More intense blooms presented a high reflectance plateau in the near-infrared region, from 740 to 865 nm. Most S3 data failed to differentiate bloom from non-bloom events, except during intense events. The normalized difference chlorophyll index successfully identified *Pseudo-nitzschia* spp. and *G. catenatum* blooms, whereas using the normalized difference *Noctiluca* index better identified *Alexandrium* spp. blooms. Sea surface temperature, water column stratification, and nutrient concentrations appeared as concomitant potential environmental determinants for bloom development. This study improved our understanding of HAB optical diversity across different marine domains and can support the use of satellite-derived optical properties as predictors in future HAB modelling approaches.

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Cross-Regional Detection of Harmful Algal Blooms Using GCOM-C/SGLI Ocean Color Data in Eutrophic Coastal Waters of Japan and Thailand

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Harmful algal blooms (HABs) can cause a significant loss to marine ecosystems, fisheries, and coastal communities worldwide. To mitigate the harmful impacts, we introduce a novel application of high-resolution ocean color data from the Second-Generation Global Imager (SGLI) on the Global Change Observation Mission-Climate (GCOM-C) platform for detecting various types of algal blooms in two eutrophic coastal systems—Tokyo Bay, Japan, and the Upper Gulf of Thailand (uGoT). These regions frequently experience HABs due to high nutrient inputs but differ in bloom composition: diatoms and dinoflagellates are predominant in both areas, while green *Noctiluca* occurs only in the uGoT and raphidophytes only in Tokyo Bay.

An empirical band-ratio algorithm utilizing remote sensing reflectance (Rrs)—specifically Rrs(490)/Rrs(565), Rrs(530)/Rrs(565), and Rrs(673)/Rrs(565)—was developed based on the *in situ* Rrs spectra and phytoplankton pigment data obtained in both algal bloom and non-bloom waters from the uGoT. The algorithm effectively identified green *Noctiluca*, diatoms, dinoflagellates, and mixed species blooms in the uGoT, and it successfully detected blooms dominated by diatoms and dinoflagellates in Tokyo Bay, demonstrating its applicability across different regions. Despite variations in bloom species and the limited availability of *in situ* Rrs data in Tokyo Bay, the results demonstrate the potential of GCOM-C/SGLI ocean color data to monitor bloom dynamics in eutrophic coastal waters, which has implications for early warning systems and cross-regional HAB management strategies.

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Optical Remote Sensing for the Assessment of Coastal Sewage Pollution: A data-driven modelling approach

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This study presents a satellite-based data-driven framework for monitoring coastal sewage pollution using Landsat OLI multispectral imagery and machine learning (ML) models. A dual classification approach was adopted: one based on satellite-derived spectral responses and the other on field-measured water quality, to examine their association. The reflectance-based model served as the primary classification, complemented by classifications from the field-measured water quality dataset. Pre-classification analysis with t-SNE revealed distinct groupings, and AP clustering generated two cluster sets of reflectance and water quality. With these cluster sets, ML models such as Random Forest (RF), Multilayer Perceptron Artificial Neural Network (MLP-ANN), and 1D Convolutional Neural Network (CNN), are trained for the classification of coastal waters under high tide (HT) and low tide (LT) conditions. All models successfully identified sewage-impacted areas such as outfalls, creeks, and drains, with CNN showing the most consistent performance across tidal conditions and sewage sources. The dual classifications derived from these cluster sets identified sewage-impacted zones in coastal waters and showed a statistically significant association ($p<0.001$). This demonstrated a robust linkage between satellite-derived spectral responses and corresponding water quality attributes indicative of sewage pollution. Application of reflectance- and water quality–based trained models to new satellite images further confirmed their close association across flooding, ebbing, and slack tides. The study also developed the Coastal Sewage Pollution Index (CSPI), which revealed sewage presence extending beyond outfall zones. Linear discriminant analysis highlighted blue–green bands during HT and the red band during LT as the most influential spectral features for distinguishing pollution levels. Overall, this study demonstrates a cost-effective, scalable, and data-driven integrated framework for coastal management using satellite multispectral data and ML.

First Phycocyanin Retrievals from NASA PACE: A Physics-Informed AI Approach for Cyanobacteria Biomass Estimation

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Timely estimation of cyanobacterial biomass is critical for effective water quality monitoring and public health protection. Phycocyanin (PC), a pigment specific to cyanobacterial harmful algal blooms (cyanoHABs), is a strong proxy for cyanobacterial biomass. However, existing models for estimating PC concentration from hyperspectral remote sensing reflectance (R_{rs}) often suffer from overfitting due to uncertainties in R_{rs} measurements and limited availability of globally distributed in-situ PC data. Additionally, models relying solely on R_{rs}-based features may yield inconsistent spatial patterns in estimated PC due to varying in-situ measurement protocols.

To address these challenges, we developed a Physics-Informed Iterative Framework (PIIF) using a 3-layer neural network architecture that integrates both R_{rs}-based features and inherent optical properties (IOPs) to estimate PC concentration. IOPs are derived via a hybrid quasi-analytical inversion of hyperspectral R_{rs}, and provide physically grounded constraints that improve model generalizability. PIIF is trained on a diverse dataset (N=1504) of in-situ R_{rs} and PC concentration. Iterative training approach helps quantify epistemic/spatiotemporal and data-split-based uncertainties.

We evaluate model performance using an independent, optically complex validation dataset (N=120) from seven U.S. inland lakes. Curated in Summer 2024, it comprises in-situ pigment and radiometry measurements coincident with overpasses of Ocean Color Instrument (OCI) onboard NASA's new Plankton, Aerosol, Cloud, ocean Ecosystem (PACE) mission. The trained PIIF is applied to atmospherically corrected hyperspectral OCI imagery to generate spatiotemporal maps of PC concentration and associated model uncertainty. Results suggest that including IOPs as features significantly improves PC estimation and spatial transferability of the model (R^2: 0.82, %NRMSE: 8% for R_{rs}+IOP; R^2: 0.75, %NRMSE: 13% for only R_{rs}). These results also represent one of the first demonstrations of PC retrieval from PACE OCI data over inland waters. With its daily revisit and global coverage, PACE-OCI can enhance cyanoHAB monitoring and freshwater ecosystem management across both regional and global scales.

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Implementation and Adaptation of the GRADHIST Algorithm for Ocean Front Detection in the Alboran Sea Using Satellite Chlorophyll-a Data

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Submesoscale dynamics in the Alboran Sea play a fundamental role in the distribution of nutrients and phytoplankton biomass. To characterize these processes, we implemented and adapted the GRADHIST algorithm (Kirches et al., 2016) to a time series of satellite-derived chlorophyll-a (CHL) images obtained through the COPERNICUS MARINE platform and processed with XCUBE. GRADHIST combines a gradient-based detection module with a histogram-based method (SIED), enabling the identification of both strong and weak oceanic fronts.

The procedure included: (1) computation of spatial gradients as described in GRADHIST, (2) non-maximum suppression to retain only the strongest gradient responses along the gradient direction, (3) double thresholding with hysteresis (T1 and T2) to classify strong and weak fronts and connect contiguous structures, (4) localized histogram analysis (SIED) to detect bimodal CHL distributions indicative of frontal zones, and (5) final fusion of gradient- and histogram-based detections to generate robust front maps.

Preliminary results show good agreement between detected frontal zones and known structures of the Alboran Sea, including the Northern Alboran Front and the transition zone towards the Strait of Gibraltar. The method enables quantification of seasonal and interannual variations in front intensity and location, providing a robust framework for biogeochemical and coastal dynamics studies.

This work demonstrates the feasibility of transferring front detection algorithms originally developed for physical variables (SST) to the analysis of biological variables (CHL), opening new opportunities for multivariable data integration in ocean front studies.

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Phytomix: A Novel Algorithm for Detection of Optical Phytoplankton Group from Imaging Spectroscopy

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We combine an extensive bio-optical model, optical water type (OWT) classification, and regional expert knowledge with machine learning (ML) to improve detection of optical phytoplankton groups and address the ambiguity problem by automatically constraining a generic inversion approach.

EnMAP L2A and PACE-OCI L2A observations over the North Sea and Baltic Sea are sampled and extracted by OWT and filtered with Quality Water Index Polynomial (QWIP). The full inversion of these spectra with an updated version of the bio_optics framework provides concentrations of up to eight phytoplankton groups, non-algal particles (NAP) and CDOM absorption at 440nm. Depending on the OWT, different sets of phytoplankton groups are retrieved and their concentration ranges constrained. Three sets of specific absorption spectra are used in the inversion to cover natural variability and specific summer bloom species like *Phaeocystis* and *Noctiluca*. From the three solutions per spectrum, the one with the best spectral fit is assigned to a training dataset, also regarding the fit error against the spectral noise of the original spectrum. Overall, the training data selection assumes that an inversion solution with the best spectral fit also provides the best estimate of concentration values despite possible ambiguities of the solution due to the underdetermined problem.

Based on the training data, satellite observations are translated into simulation space by ML allowing cross-sensor application. Significant wavelengths are selected based on the specific absorption spectrum for each phytoplankton group for training of several ML models to retrieve the concentrations of a specific groups, total phytoplankton and detritus, and CDOM absorption.

We present first results based on in situ data comparison and plausibility analyses.

Phytomix will be published as an ESA's SeNtinel Platform (SNAP) plug-in.

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On the use of citizen science measurements for the validation of EO products in nearshore areas

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Cost-effective Secchi discs and mobile phone applications open up new possibilities for acquiring reference measurements for remote sensing of surface waters. In collaboration with 150 citizen scientists and a local NGO, the Association pour la Sauvegarde du Léman (ASL), we have collected more than three thousand Secchi measurements across Lake Geneva over the past year (www.lemanscope.org). These data are particularly valuable, as their quantity and spatial distribution far exceed those of any other Secchi measurement series. But quality control of citizen science data is a well-known challenge, especially since large cohorts can only be marginally instructed in the proper execution of measurements.

Data quality was investigated first. 22% of invalid Secchi measurements were identified because their coordinates were outside the lake area, because the measured Secchi depth exceeded the local water depth, or because the measured values were clearly beyond the variations in verified Secchi depth data series. The individual measurements identified in this way were further used to identify a few users with unreliable measurement data. The pelagic measurements filtered in such manner agree even slightly better with Sentinel-3 products than the official monitoring measurements in the middle of the lake.

Various Sentinel-3 Secchi products were validated with the citizen science dataset, using Secchi depth algorithms with different atmospheric and adjacency effect correction algorithms. Matchup results in the main basin agree better than matchups in the small basin. Likewise, pelagic matchups agree better than littoral matchups, whereas those along the hilly northern shore agree still better than those along the alpine southern shore. RAdCor showed a great potential for improvement, although it still lacks full adaptation for large viewing angle sensors. Such insights can only be gained through citizen science projects and the numerous measurements they provide.

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Developing and Validating Sentinel-3 OLCI Water Constituent Retrieval Methodologies in the Baltic Sea, for the Assessment of Long-Term Environmental Processes

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The Baltic Sea region has long been recognised as a particularly optically complex waterbody. Globally speaking, it is also relatively well studied from an ocean optics and ocean colour perspective. This study will build upon the contemporary literature for the region in order to assess and validate the current state-of-the-art satellite-based water constituent retrieval methodologies in the NW Baltic Sea. It will do so by utilising the current Sentinel-3 OLCI-A and OLCI-B sensors. The intention of this initial study is to identify the most effective retrieval methodologies for optically active water constituents, such as Chlorophyll-a, Total Suspended Matter (TSM), and Coloured Dissolved Organic Matter (CDOM) in the region. Processors including the C2RCC, FUB-CSIRO, as well as novel machine learning retrieval approaches will be validated, along with the EUMETSAT standard water constituent products. This study is an important first step, as once these methodologies have been developed and validated in the region for OLCI, they can also be applied to the MERIS data catalogue. This is because the OLCI sensor was developed from the MERIS sensor, and therefore most of the OLCI-based methodologies will also be compatible with MERIS data. Applying the validated water constituent retrieval methodologies to both the MERIS catalogue (2002 to 2012) and the OLCI catalogue (2016 to present) will allow one to build a long-term dataset for the region. This dataset can then be used to assess the spatiotemporal changes of water constituents in the region, over a period spanning 23 years (with a four-year gap). It is hoped that such a temporally comprehensive dataset can be used to quantify the effects of global environmental processes, such as climate change, on the water constituents and the phytoplankton phenology in the NW Baltic Sea region.

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<u>Aquaverse</u>: An Aquatic Inversion Scheme for Remote Sensing of Fresh and Coastal Waters

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Harmful algal blooms (HABs) can produce toxins and cause hypoxia which have deleterious effects on fisheries, aquatic ecosystems, and public health. Due to practical limitations, the *in situ* measurements that water quality managers rely on to monitor the health of aquatic ecosystems cannot obtain the spatial and temporal resolutions required for global monitoring of fresh and coastal waters. Instead, water quality managers can use ocean color remote sensing to obtain the necessary spatial and temporal coverage, enabling them to better inform *in situ* sampling efforts and, in turn, make more effective management decisions. Aquaverse is an end-to-end machine-learning-based processing pipeline designed for global water quality monitoring of optically complex fresh and coastal waters. The first step within Aquaverse is atmospheric correction, where the ocean color remote sensing reflectance (R_{rs}) is derived from the top-of-atmosphere reflectance. The second involves retrieving water quality parameters and inherent optical properties (IOPs) from the ocean's color (R_{rs}). These water quality parameters include chlorophyll-a, phycocyanin, and total suspended solids, which serve as proxies for phytoplankton biomass, potentially toxic cyanobacteria, and nutrient availability. The IOPs include absorption due to phytoplankton, non-algal particles, and colored dissolved organic matter (CDOM), which can be used for phytoplankton functional type identification, as well as for determining the source and composition of both non-algal particles and CDOM. Each Aquaverse product (R_{rs}, WQPs, and IOPs) has associated uncertainties, which represent the model's confidence in their predictions. Water quality managers can access (view/download) high spatial resolution products from Aquaverse through our web interface: https://ladsweb.modaps.eosdis.nasa.gov/stream/. Currently Aquaverse supports a wide range of multi- and hyperspectral sensors (at varying levels of support) including MODIS, VIIRS, Sentinel-2-3, Landsat-5-9, HICO, PRISMA, PACE, EMIT, PACE. The full codebase, trained models weights, training notebooks for Aquaverse can be accessed at https://github.com/ryan-edward-oshea/MDN_tutorials.

Advancing GOCI-II Chlorophyll-a data: ***Through Sensor Calibration and Water Quality–Adaptive Algorithms***

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The Geostationary Ocean Color Imager-II (GOCI-II), launched in February 2020, observes a region characterized by highly diverse and dynamically changing water quality, spanning from turbid coastal zones and river plumes to oligotrophic offshore waters in the Northwest Pacific. Its unique hourly revisit captures rapid fluctuations as well as long-term trends that are often missed by conventional polar-orbiting sensors, providing an unprecedented opportunity to monitor spatiotemporal variability in regional water quality. To improve the accuracy and stability of GOCI-II chlorophyll-a (Chl-a) products, we implemented an advanced calibration framework, including on-orbit sensor calibration, updated atmospheric correction, and vicarious calibration, which has been fully applied in the 2024 reprocessing. This update substantially reduced previous Chl-a overestimation and enhanced the temporal consistency of GOCI-II data. Building on this progress, we are developing a water type–adaptive Chl-a retrieval approach by optimizing the OC4 algorithm separately for optically distinct waters. This will enable more accurate assessments of water quality and ecosystem variability, supporting sustainable marine management under changing climate conditions.

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Multi-Platform Hyperspectral Observations for Inland and Coastal Water Quality Monitoring: Insights from On-Water Radiometry with USV and SmallSat

Vishnu Perumthuruthil Suseelan, Kai Sørensen, Sivert Bakken, Joseph Landon Garrett, Tor Arne Johansen

Inland and coastal waters are optically complex environments due to their proximity to land and influence from various biogeochemical constituents. This complexity presents significant challenges for remote sensing–based retrieval of water quality parameters, including sediment discharge, colored dissolved organic matter (CDOM), and harmful algal blooms (HABs). To address these challenges, we combine hyperspectral radiometric observations from both in situ on-water radiometry and spaceborne platforms.

On-water hyperspectral measurements were acquired using the *Pamela* Uncrewed Surface Vehicle (USV), equipped with a Trios skylight-blocking radiometry system to enable direct measurement of water-leaving radiance (Lw). The USV includes a remotely operated orientation system, allowing dynamic adjustment of the sensor to minimize self-shading and sun glint—an advancement over traditional above-water methods. Data collected from diverse Norwegian lakes and coastal sites were processed using a Python pipeline to derive remote sensing reflectance (Rrs, sr^{-1}), and quality was evaluated using the QWIP scoring method. The resulting spectra span a range of water types, including phytoplankton-rich, CDOM-dominated, and cyanobacteria bloom waters.

Complementing the in situ observations, we leverage hyperspectral imagery from the HYPSO small satellite mission, developed by the Norwegian University of Science and Technology. HYPSO-1 and HYPSO-2 are 6U CubeSats equipped with push-broom hyperspectral imagers designed for ocean color applications. Calibrated top-of-atmosphere radiance is retrieved using a custom-developed processing pipeline, followed by atmospheric correction algorithms primarily using Acolite, Polymer, and the OC-SMART algorithm, to produce Level-2 Rrs and the donwstreaming water quality products. As a first step, we assessed the radiometric performance of HYPSO using co-located observations from Pamela, AERONET-OC, and water HYPERNETS sites. In addition, intercomparisons were conducted with the Sentinel-3 OLCI sensor to further validate HYPSO-derived products.

This study highlights the synergistic value of integrating dynamic USV-based in situ measurements with satellite hyperspectral observations for improved monitoring of optically complex waters.

A New AI Approach to Retrieving Ocean Color Products from Unoccupied Aircraft Systems (UAS)

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Keywords: AI; drones; multispectral; water quality; marine optics

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Unoccupied Aircraft Systems (UAS, or drones) are a powerful tool for repeatedly observing coastal and estuarine environments with fine spatial resolution. Despite their potential, accurately retrieving radiometric measurements from optically complex and dynamic water surfaces remains a challenge – particularly with standard multispectral sensors onboard UAS. This study introduces a new artificial intelligence (AI) algorithm to derive remote sensing reflectance (R_{rs}) from data collected by a MicaSense RedEdge-MX 5-band multispectral sensor over the Choptank River Estuary (Chesapeake Bay, U.S.). This approach reduces the impact of surface-reflected light across a range of sky and wind conditions by incorporating the angle of incident light at each image pixel, determined by reconstructing surface wave facets using Fast Fourier Transform (FFT) functions. Data collected with *in-situ* TriOS RAMSES radiometers, resampled to match the UAS sensor's spatial resolution, were used to validate the accuracy of the UAS R_{rs} retrievals. This study represents a significant advancement in the field of coastal ocean color remote sensing, enabling fine-scale environmental monitoring, beyond the reach of satellite or traditional field-based observations.

Clear and Turbid Waters from Orbit: Long-Term Sentinel-2 Assessment of Water Quality in the Dutch Randmeren Lakes

M.S. Salama[1], R. van der Velde[2]

This study analyzes seven years (2018–2024) of Sentinel-2-MSI data to assess water quality across six lakes of the Randmeren system in the Netherlands. A total of 500 atmospherically corrected, cloud- and shadow-free images were processed using a newly developed Water Quality Index (WQI). The index applies an Empirical Orthogonal Transformation to combine two dependent spectral indicators: a turbidity index, based on red-to-green reflectance ratios, and a chlorophyll-a index, derived from red and red-edge bands sensitive to phytoplankton.

Standardized anomalies of the WQI were then used to identify zones with persistently favorable water quality. 'Clear water' frequency, defined as the number of months in which the WQI exceeded the 7-year mean, provided a measure of above-average conditions and enabled the creation of maps delineating persistent good and poor water quality areas. The results showed marked spatial variability: deeper zones generally exhibited clearer conditions, while shallow margins, inflow areas, and shorelines were more prone to turbidity and algal blooms. Across the six lakes, clear-water frequency ranged from fewer than 20 to more than 70 months, highlighting both stable and degraded systems as well as strong within-lake contrasts.

Monthly climatologies revealed pronounced seasonal cycles, with clearer conditions in late winter–autumn and peaks in turbidity and algal blooms during spring–summer. Annual trends indicated stable, high water quality from 2018–2021, a marked decline in 2022–2023, and partial recovery in 2024, likely reflecting environmental or management factors.

Overall, these findings demonstrate the potential of Earth Observation (EO) to deliver reliable, scalable monitoring of inland waters. By capturing spatial and temporal dynamics and providing consistent indicators, EO-based approaches can support the Water Framework Directive, Sustainable Development Goal 6, and the operational needs of water utilities.

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PACE for Freshwater Quality Monitoring

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NASA's PACE (Plankton, Aerosol, Cloud, ocean Ecosystem) Earth observing satellite has unique hyperspectral data that allows for unprecedented observations of inland and coastal waters. PACE's Ocean Color Instrument (OCI) has near daily coverage with 1.2 km spatial resolution, which allows for a variety of water quality products capable of providing near real-time information to water managers. Harmful algal blooms (HABs) are one water quality issue that requires monitoring and response. PACE OCI data products, including chlorophyll and an estimation of cyanobacteria concentration, can be indicators for HAB events. The poster will highlight new PACE inland products with the goal of creating discussion and gaining feedback from the community. It is an exciting time with PACE's unparalleled hyperspectral data providing insightful products for inland waters.

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Can Optical Water Types be used as ecological indicators? Insights from a temperate estuary

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Monitoring water quality and understanding how estuarine ecosystems respond to environmental changes is essential to sustain their ecological integrity and associated ecosystem services. In this study, we demonstrate that Optical Water Type (OWT) classification from Sentinel-2 MSI can provide valuable insights for environmental monitoring, using the Tagus estuary as an example. In-situ measurements (Chl-*a*, temperature, salinity, pH, and dissolved oxygen) were employed to characterize ecological profiles associated with OWT classes and to analyse the spatio-temporal and tidal variability during the period 2017-2024. We identified distinct ecological profiles among groups of OWTs, which were associated with marine, transitional and riverine waters with different physico-chemical characteristics and they were related to different environmental drivers. Tides significantly influenced the distribution of OWTs, with high and neap tides favouring the occurrence of clearer marine waters. Specific OWT classes emerged as indicators for key environmental processes, including marine water intrusion, freshwater inputs and phytoplankton-rich waters. Time-series analysis revealed a trend of increasing marine waters inside the estuary alongside interannual variability driven by hydro-climatic forcings. Our findings highlight OWT classification as a valuable stand-alone ecological indicator, providing a powerful and scalable tool for estuarine science, policy, and management.

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Optimising feature engineering improves the remote sensing estimation of Chlorophyll-a concentration and Secchi disk depth in coastal waters

Edson Silva[1], Julien Brajard[2], Lasse H. Pettersson[3]

Machine learning (ML) is widely applied in ocean colour to estimate water quality from satellite-derived parameters. These ML models typically rely on input features generated through feature engineering (FE) techniques, including band selection, band ratio computation, and feature scaling. While considerable effort is devoted to optimizing the ML models themselves, optimization of the FE remains relatively little explored. In this work, we use Sentinel-3 OLCI observations (n>624) along the Norwegian coast to calibrate [Chl-a] and Secchi disk depth (Z_{sd}) models using Multi-Layer Perceptron (MLP), Support Vector Machines (SVM), and eXtreme Boosting trees (XGBoost). The FE choice impact is assessed by employing six FE found in the Sentinel-3 OLCI literature. Then, we employ the Tree-Structured Parzen Estimator (TPE) to optimise the FE choices (2592 combinations), including band selection, log scaling, spectral shape estimation, index extraction, principal component analysis, feature scaling, and zero to one scaling. Our main result is that accuracy varies more among the six FE found in the literature than among the ML models and optimising the FE choices using TPE leads to more accurate models. The R for [Chl-a] using the literature FE falls in 0.09–0.44 (MLP), 0.4–0.52 (SVM), and 0.37–0.46 (XGBoost), while reaching 0.52, 0.55, and 0.53 for optimised FE. Similar conclusions are reached with Z_{sd}. Nevertheless, optimised FE depends on the target and ML model. For example, at least 90% optimisation instances (n=30) remove the near-infrared (NIR) bands for [Chl-a] models, while more than 90% include NIR for Z_{sd}. For [Chl-a], log scaling of reflectance is the optimal choice for 93% of XGBoost models but only 56% for SVM and MLP models. Since the FE dependence on the target, ML model, and probably on the region, we propose that developing FE optimization in ocean colour is necessary for producing more accurate models.

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Enhancing GCOM-C/SGLI Optical Water Type Classification: Focus on Phytoplankton Bloom Types

Eko Siswanto

Classifying optical water types (OWTs) is essential for distinguishing phytoplankton bloom types, which strongly influence marine ecosystems and ocean biogeochemical processes. A recent OWT classification method for the Global Change Observation Mission-Climate (GCOM-C)/Second-Generation Global Imager (SGLI) was designed to separate dinoflagellate and diatom blooms in the waters southeast of Hokkaido. In this study, the method was tested using independent in situ data from *Karenia selliformis* (dinoflagellate) blooms southeast of the Kamchatka Peninsula and Skeletonema spp. (diatom) blooms in Tokyo Bay. The results show that SGLI-derived spectra during dinoflagellate blooms consistently display a trough at 490 nm, while diatom blooms exhibit a peak at this wavelength—supporting the robustness of the spectral criteria. This study also employed binary logistic regression to define statistically meaningful boundary lines among the OWTs. Employing binary logistic regression, the method improved classification accuracy and was able to identify waters dominated by coloured dissolved organic matter and different phytoplankton groups in mesotrophic environments. These findings confirm the potential of the updated OWT method, while highlighting the importance of region-specific tuning to further enhance performance.

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Sentinel 2 user-relevant water quality monitoring in small southern African water bodies

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Water sufficiency and quality is fundamental for the economic development of any country and is closely linked to human health. It is vital to efficiently and regularly monitor the quality and quantity of water resources to support their sustainable management and utilisation. In the semi-arid country of South Africa, freshwater is the most limiting natural resource, especially in the highly populated Western Cape province where the combined effects of a growing population, economic activities, and climate pressures have presented various stresses to aquatic ecosystems, resulting in environmental problems such as eutrophication, harmful algal blooms and water scarcity. While the efficacy of remote sensing for monitoring water quality has been demonstrated in South Africa's larger water bodies, existing monitoring programmes and long-term global datasets (e.g. ESA Lakes Climate Change Initiative) doesn't include the water bodies in Western Cape because the small surface area makes it difficult to be observed from MERIS and OLCI. In the current study we assess the capability of Sentinel 2 for water quality monitoring in several key waterbodies of the Western Cape. We evaluate several atmospheric correction models (C2RCC, C2X, Polymer, Acolite and Sen2Cor), as well as a variety of published algorithms for estimating chlorophyll-a and total suspended solids concentrations, and make recommendations regarding their application in operational water quality monitoring. The potential users of these satellite-derived products, including government departments and agencies, are kept informed and involved throughout the co-design process, which builds their confidence and trust in the resulting satellite-derived products and information, and enhances their capability to use remote sensing tools within the South African National Eutrophication Monitoring Programme, and to support the sustainable use of water resources in South Africa. This study is funded as part of the ESA EO Africa Research and Development Facility in collaboration with the African Union Commission.

Analysis of regional variation of water transparency in the Yellow Sea and East China Sea based on MODIS data

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Water transparency is an important optical parameter used to interpret various properties related to water quality. We investigated regional variation in water transparency in the Yellow Sea (YS) and East China Sea (ECS) by conducting linear regression and k-means clustering analyses based on satellite-derived water transparency data and satellite products including MODIS sea surface temperatures (SSTs) and chlorophyll a concentration (Chl), colored dissolved organic matter (CDOM), and total suspended matter (TSM) levels for the period 2003–2023. Water transparency showed seasonal variation, increasing in summer and decreasing in winter, with larger seasonal extremes observed in the central YS and around Jeju Island than in coastal waters of Korea and China. Decadal variation in water transparency was significantly higher in summer and autumn than in spring and winter throughout the study area, exhibiting an increasing trend that was strongly correlated with decreasing Chl, CDOM, and TSM levels. K-means analysis resulted in the selection of five regions in the YS and ECS, among which spatial and temporal variation in water transparency were related to different regional impact factors. Coastal waters of Korea and China and the southern YS displayed a weaker increase in water transparency, which was associated mainly with Chl, followed by TSM and CDOM. In contrast, water transparency tended to increase dramatically in the central YS, where decadal variation was associated mainly with changes in TSM, followed by Chl and CDOM levels. Thus, regional variation in water transparency in the study area was dependent on local water conditions. These findings will be useful for understanding regional water quality in the study area.

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Intercomparison of EnMAP water-leaving reflectance from five atmospheric correction methods using global hyperspectral and multispectral in situ data

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The German hyperspectral satellite mission Environmental Mapping and Analysis Program (EnMAP) is designed to monitor and characterize the Earth's environment on a high spatial resolution. The application of EnMAP delivering information at many spectral bands on the reflected radiation from inland and coastal waters is envisioned to improve our knowledge on these ecosystems' habitats, biodiversity, water quality and many more. To extract this information from satellite images, the water leaving reflectance must be derived from the radiance measured at the satellite sensor. Several atmospheric corrections (AC) have been expanded for their capabilities on hyperspectral satellite data:

(i) The physics based Module Inversion and Processing System (MIP, EOMAP GmbH) which is used by the EnMAP ground segment to produce the L2A water product.
(ii) The "polynomial based algorithm applied to MERIS" (Polymer, Hygeos) which uses spectral matching which atmospheric and aquatic signals simultaneously fitted using the fully available VNIR spectrum.
(iii) The "Atmospheric Correction for OLI" (Acolite, RBINS) which is based on the Dark Spectrum Fitting algorithm.
(iv) The processor hGRS which is a hyperspectral adaptation of the previous Glint Removal for Sentinel-2-like (GRS) (https://doi.org/10.1016/j.rse.2017.10.022)
(v) PACO-WASI (DLR) which refers to the postprocessing of the operational EnMAP land product (https://doi.org/10.3390/s20051428) with the software WASI (https://doi.org/10.1016/j.cageo.2004.03.005; https://ioccg.org/resources/software/) to convert surface reflectance to remote sensing reflectance.

We assess the quality and compare the EnMAP water reflectance products from 2022 to 2025 generated by these five AC processors by validation with multispectral and hyperspectral in situ measurements from 28 sites spanning from inland, coastal and open ocean waters. Results show consistent performance for the operational MIP product compared to previous assessment by Soppa et al. (https://doi.org/10.1364/OE.523813) and depending on the water type also similar or even superior performance for the alternative ACs.

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A Water Quality Service for the Coastal Zone - the Copernicus Marine High-Resolution Coastal Service

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High-quality satellite-based ocean colour products can provide valuable support and insights in the management and monitoring of coastal ecosystems. Today's availability of Earth Observation (EO) data is unprecedented including traditional medium resolution ocean colour systems (e.g. Sentinel-3/OLCI) and high-resolution land sensors (e.g. Sentinel-2/MSI). With the High-Resolution Coastal Service (HROC), the Copernicus Marine Service (CMS) provides high resolution ocean colour products based on Sentinel-2/MSI data for European coastal waters. Products are generated by applying two different atmospheric corrections depending on the water type and merging approaches for water constituents. The service offers 12 different products for the coastal waters (20km stripe for the coastline) of all European Seas in a 100m spatial resolution. The primary variable is the spectral Remote Sensing Reflectance, a spectral BBP product is generated from the RRS products using a quasi-analytical algorithm. The *transparency products* include turbidity and Suspended Particulate Matter concentration. The *geophysical product* consists of the Chlorophyll-a concentration retrieved via a multi-algorithm.

We will highlight the implemented and planned evolutions for the service including the de-striping of the Sentinel-2 data using the top-of-atmosphere glint correction (TGC) and the harmonization of the CHL product between Sentinel-2/MSI and Sentinel-3/OLCI using machine learning.

- Detector striping can be observed over water in Sentinel-2/MSI imagery, especially under sun glint conditions. One of the reasons for banding is the staggered positioning of the detectors, which causes differing viewing conditions for adjacent detectors. We developed the TGC algorithm, which models the pixel-wise spectral shape and intensity of the glint signal at Top of Atmosphere considering the windspeed, aerosol optical thickness using the OSOAA radiative transfer model. This TOA glint signal is then subtracted from the TOA observation removing the banding effect.

- Due to differences between Sentinel-2/MSI and Sentinel-3/OLCI sensors regarding spectral band sets and viewing geometry, chlorophyll algorithms often having diverging values between both sensors. A machine learning technique (LightGBM) was used to transfer the more complex CHL algorithms (e.g. band ratio algorithms, switching algorithms, other machine learning algorithms) from Sentinel-3/OLCI to Sentinel-2/MSI.

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FRM4Drones-AQUA: Building a Framework for Fiducial Reference Measurements in Aquatic Remote Sensing with UAVs

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Unmanned Aerial Vehicles (UAVs) are increasingly recognised as valuable tools for aquatic reflectance measurements, bridging the gap between in situ observations and satellite-based Earth Observation (EO). However, the lack of harmonised protocols and standards remains a critical challenge for robust satellite product validation and development.

The FRM4Drones-AQUA project aims to address this gap by adapting Fiducial Reference Measurement (FRM) principles from the FRM4SOC (FRM for Satellite Ocean Colour) and FRM4VEG (FRM for Vegetation) frameworks for UAV-based aquatic applications. The project has prioritised community-driven discussions through a series of interactive workshops focusing on measurement and processing protocols, uncertainty characterisation, traceability, and practical implementation challenges.

The FRM4drones-AQUA workshops have already drawn considerable attention across the aquatic EO and Cal/Val communities, with strong international participation from researchers, space agencies, and environmental stakeholders. Key outputs include the identification of priority topics such as the need for community-supported protocols, sensor and platform calibration, standardised workflows, and QA/QC procedures for drone-based measurements over water. These outcomes form the basis for a draft roadmap outlining research needs and practical steps to establish UAV-based aquatic reflectance as a robust component of future satellite validation activities.

In this contribution, we will present the main findings from the workshops, highlight the identified priorities for the community, and share the next steps for further roadmap development. We will also showcase, using Sentinel-2 as an example, how UAVs can support validation activities in highly spatially and temporally dynamic aquatic environments. Finally, we will discuss how this initiative complements ongoing global efforts to strengthen the aquatic Cal/Val infrastructure and highlight opportunities for broad collaboration within the EO community.

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Mapping floating macrophyte cover dynamics in Lake Vembanad, India

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Invasive floating vegetation, particularly water hyacinth *(Pontederia crassipes),* has become an environmental and socioeconomic challenge in many water bodies in India, including the Vembanad-Kol wetland system in Kerala. Water hyacinth rapidly forms dense interlocking mats that block waterways, adversely impacting water quality, native biodiversity and livelihoods such as fishing, tourism, and paddy cultivation. Additionally, water hyacinth can create habitats that harbour pathogenic bacteria, as well as mosquito larvae and gastropods, which are vectors of diseases. This indicates there may be a potential human health risk associated with the spread of water hyacinth. Traditional *in situ* monitoring of water weeds is time-consuming and limited by accessibility and resources, making it difficult to assess large areas like the Vembanad-Kol wetlands (>1500 km^2). Consequently, little information is available on the distribution of floating vegetation over time at the scale of the entire wetland system. Remote sensing offers a cost-effective solution for mapping invasive species over large areas at regular intervals. This study uses Sentinel-2 data to assess the temporal and spatial dynamics of floating macrophytes in Lake Vembanad from 2016 to mid-2024. The Floating Algae Index (Hu, 2009) was used to separate water and vegetation cover, and a scaling approach was used to calculate the percent cover of floating vegetation for each pixel. Monthly composites reveal trends and seasonal variations in vegetation cover across the lake. Initial findings indicate a significant increase in floating vegetation during the study period and highlight specific hotspots of weed accumulation at different times of the year. The findings from this study will aid future modelling of floating vegetation distributions, waterborne disease risk and inform vegetation management decisions.

Simultaneous Retrieval of Suspended Particulate Matter and Inherent Optical Properties in Sediment-Laden Coastal Waters Using a Red–NIR Semi-Analytical Inversion (MOSAIC)

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Retrieving inherent optical properties (IOPs) and water quality parameters from remote sensing reflectance (Rrs) in optically complex coastal and estuarine waters remains a significant challenge. This complexity arises from overlapping spectral features, high environmental variability, bottom visibility, or sensor saturation. Such factors are particularly critical for turbid environments, where accurate monitoring of suspended particulate matter (SPM) concentration and other inherent optical properties (IOPs) underpin coastal monitoring and management. Here, we present MOSAIC, a novel matrix-based semi-analytical inversion algorithm designed for robust retrieval of key optical properties and SPM. MOSAIC operates within the red-to-near-infrared (NIR) spectral range (650–850 nm), building upon established linear matrix inversion frameworks. The algorithm estimates phytoplankton absorption, colored dissolved organic matter absorption, particle absorption, and particle backscattering at reference wavelengths, while simultaneously estimating suspended particulate matter (SPM) using all available wavelengths within the red and near-infrared (NIR) regions of the spectrum. Additionally, when surface water temperature is not available, MOSAIC can provide a range of temperature estimates. Validation was performed using both in situ and satellite datasets, including hyperspectral sensors (PRISMA, HICO) and multispectral imagery (Sentinel-3) over diverse regions such as the Venice Lagoon, the Gironde Estuary, the Río de la Plata, and the Patos Lagoon. MOSAIC demonstrated accuracy comparable to or exceeding established algorithms, especially in highly turbid environments (from 1 to 3981 g.m^{-3}). Lastly, a consistent relationship was identified between the MOSAIC-derived power-law slope of particle backscattering and the mean particle size, as derived from Laser In-Situ Scattering and Transmissometry (LISST) measurements. These results position MOSAIC as a valuable tool for advancing the retrieval of water quality parameters and IOPs in challenging coastal and estuarine environments.

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Retrieving chlorophyll-a across diverse optical waters using HY-3A CZI: The integrated and machine learning approaches

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The launch of the second-generation Coastal Zone Imager (CZI) onboard the HY-3A satellite (November 16, 2023) offers new potential for monitoring water quality via optical remote sensing. To support chlorophyll-a (Chla) retrieval across optically diverse waters, we developed and validated two complementary approaches: an integrated algorithm and a machine learning (ML) framework. The integrated algorithm addresses the optical complexity of inland and coastal waters by first classifying water types using $R_{rs}(485)/R_{rs}(660)$ and then applying the most appropriate algorithms: the Ocean Color Index (OCI) for clear waters, a blended three-band index (TBI) and normalized difference chlorophyll index (NDCI) for turbid waters, and a weighted combination for transitional types. This integrated approach, calibrated on a global in-situ dataset (N = 4,950), achieved high accuracy (R^2 = 0.88 in log scale) and strong consistency with Sentinel-2 MSI observations, supporting its reliability for spatial Chla mapping. To further enhance retrieval accuracy and scalability, we introduced and evaluated five machine learning models, Random Forest (RF), Support Vector Regression (SVR), Extreme Gradient Boosting (XGBoost), Deep Neural Network (DNN), and Mixture Density Network (MDN) using a more extensive global dataset (N = 7,535). Among them, MDN performed best with MAPE values of 33.64% for Chla. ML models were applied to atmospherically corrected CZI data for both validation and spatial mapping, confirming their ability to capture complex water quality gradients across variable conditions. Together, these two strategies demonstrate the potential of HY-3A CZI for high-resolution, large-scale, and accurate water quality monitoring. The integrated method offers physically interpretable and regionally adaptable estimations, while machine learning models provide flexible, generalizable solutions for accurate retrieval of multiple water quality parameters.

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Evaluating Copernicus Marine products in Optically Complex Estonian Coastal Waters (Baltic Sea)

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The Baltic Sea, including Estonian coastal areas, is significantly impacted by eutrophication and pollution, which affect ecological balance and water quality. The European Union (EU) has implemented the Water Framework Directive (WFD) to address these challenges, with the aim of achieving “good” status for all European surface waters by 2027. This involves comprehensive monitoring and annual reporting of water status. In addition to *in situ* data, remote sensing is a complementary tool to monitor water quality indicators such as chlorophyll-a and transparency over large spatial and temporal scales.

The Cop4ESTCoast prototype web interface supports the reporting of WFD water statuses in Estonian coastal areas by complementing *in situ* data with Copernicus Marine products, which provide daily observations of transparency, chlorophyll-a concentrations, and surface-layer nutrient concentrations. Additionally, Copernicus CORINE Land Cover products from 2012 and 2018 were added to the prototype as two layers, along with an additional layer showing land cover changes between these years.

The current study aims to validate and analyze the suitability of the product containing chlorophyll-a concentration and transparency for Estonian coastal areas, where waters are optically complex and highly diverse, including clear, turbid, chlorophyll-rich, and colored dissolved organic matter-rich waters. Validation is performed using *in situ* data of chlorophyll-a concentration and transparency, measured during national monitoring campaigns and downloaded from the Estonian Environment Agency database (kese.envir.ee). Long-term trends since 2016 are also assessed to evaluate the reliability of Copernicus Marine products and their potential to complement traditional monitoring for effective water quality management. Additionally, land cover changes in the coastal areas will be analyzed to see if these can be linked with the dynamics of the water quality indicators.

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Copernicus for research, operational and assessment needs:
evaluation of Copernicus Ocean-Colour with in-situ data

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The Copernicus Marina Data Store contains a wealth of ocean-colour satellite data products which are of interest to scientific research, federal operational monitoring and official water quality assessments. In order to incorporate these data into research and operational workflows, their quality and fitness for purpose in German national waters and the wider North and Baltic Seas need to be well established. In this context, an evaluation of several satellite-based Copernicus water quality products is being carried out. In the Baltic Sea, both Sentinel-2 MSI L3 and L4 and the Sentinel-3 OLCI L3 Multi-Year Chl-a, turbidity and SPM products are compared to long-term monitoring data and modelled hindcasts carried out by the Leibniz Institute for Baltic Sea Research Warnemünde, with a particular focus on the region west of 14°E. In the North Sea, the OLCI Multi-Year L3 product is compared with in-situ data from cruises carried out by the German Federal Maritime and Hydrographic Agency. These cover the entire North Sea in mid-summer and the German Bight multiple times a year. The evaluation highlights some of the challenges working with Copernicus ocean-colour products. While a seamless global product is available, its coarse resolution (5 km) presents complications in areas where Copernicus regions border another and a higher resolution is needed. Currently, the higher resolution data sets (1 km or 300 m) covering the North and Baltic Seas are processed separately, leading to sharp gradients at the Skagerrak – Kattegat boundary where the two products meet. By establishing the quality of the regional Copernicus ocean-colour products, we can assess which product is more suitable, and how products are best merged, for these areas where regional products overlap and differ substantially.

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Applications of Ocean Colour Data to Aid in Forecasting Harmful Algal Blooms

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Harmful algal blooms (HABs) are a persistent issue globally, with certain phytoplankton species growing rapidly and then decaying, leading to hypoxic areas or producing toxins that harm marine life. Ocean colour data from multiple sensors, including MODIS, VIIRS, and Sentinel-3, can be applied to monitor bloom dynamics, identify key environmental drivers, and support forecasting systems. We use these data to estimate phytoplankton biomass, compare sensor accuracy using *in situ* match-ups, and select the highest-performing sensor for statistical modelling to examine the correlation with toxin concentrations and HAB biomass. Previous work focused on the east coast of Tasmania, Australia, where discrepancies between sensors made it difficult to assess the relationship between chlorophyll-a (chl-a) and toxin concentrations. However, temperature data from the blended Multi-scale Ultra-high Resolution Sea Surface Temperature (MUR SST) product revealed a strong link between high toxin levels and cooler waters, with a threshold below 12 °C strongly associated with high toxicity in *Alexandrium catenella*. Using a similar workflow, we focus on coastal Japan, collecting *in situ* chl-a data for sensor validation and phytoplankton images to identify HAB species in the region, including *Noctiluca scintillans*, *Karenia* mikimotoi, and *Skeletonema* spp. Remote sensing products, meteorological observations, and climate indices will be integrated to determine the main environmental drivers, or combinations of drivers, associated with bloom development. Once these drivers are identified, we will build a forecasting model to predict bloom occurrence. We will also apply the *N. scintillans* detection algorithm from Luang-on et al. (2024) using GCOM-C/SGLI data to investigate bloom dynamics from the start of the sensor's record. These applications of ocean colour data, combined with environmental driver analysis, show strong potential for mapping HAB spread, understanding bloom mechanisms, and supporting the development of a forecast model for coastal Japan.

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Remote sensing estimates of global sea surface nitrate

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Information about sea surface nitrate (SSN) concentrations is crucial for estimating oceanic new productivity and for carbon cycle studies. Due to the absence of optical properties in SSN and the intricate relationships with environmental factors affecting spatiotemporal dynamics, developing a more representative and widely applicable remote sensing inversion algorithm for SSN is challenging. Most methods for the remote estimation of SSN are based on data-driven neural networks or deep learning and lack mechanistic descriptions. Since fitting functions between the SSN and sea surface temperature (SST), mixed layer depth (MLD), and chlorophyll (Chl) content have been established for the open ocean, it is important to include the remote sensing indicator photosynthetically active radiation (PAR), which is critical in nitrate biogeochemical processes. In this study, we employed an algorithm for estimating the monthly average SSN on a global 1◦ by 1◦ resolution grid; this algorithm relies on the empirical relationship between the World Ocean Atlas 2018 (WOA18) monthly interpolated climatology of nitrate in each 1◦ × 1◦ grid and the estimated monthly SST and PAR datasets from Moderate Resolution Imaging Spectroradiometer (MODIS) and MLD from the Hybrid Coordinate Ocean Model (HYCOM). These results indicated that PAR potentially affects SSN. Furthermore, validation of the SSN model with measured nitrate data from different months and locations for the years 2018–2023 yielded a high prediction accuracy (N = 12,846, R2 = 0.93, root mean square difference (RMSE) = 3.12 µmol/L, and mean absolute error (MAE) = 2.22 µmol/L). Further independent validation and sensitivity tests demonstrated the validity of the algorithm for retrieving SSN.

Water transparency and color in large rivers observed by Sentinel-2 MSI and its implications for SDG 6.3.2 monitoring

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ABSTRACT

Rivers are vital to Earth's water cycle and human societies, yet their water quality are increasingly threatened by climate change and human activities. While satellite remote sensing has emerged as a powerful tool for large-scale water quality monitoring across diverse aquatic ecosystems, a systematic analysis of water optical properties in rivers remains limited, restricting its use in supporting Sustainable Development Goal (SDG) monitoring. This study presents the first comprehensive analysis of water transparency (Secchi disk depth, Z_{SD}) and color (Forel-Ule Index) in the five large rivers (Yangtze, Danube, Mississippi, Nile, and Amazon) using Sentinel-2 MSI data (2019–2021). Results reveal significant spatial-seasonal variations: Danube had the highest transparency (Z_{SD}) and bluest color (FUI), followed by Nile, Yangtze, Mississippi, and Amazon. These differences were primarily driven by basin-specific soil erodibility and precipitation. Spatially, the Yangtze, Mississippi, and Amazon exhibited decreasing Z_{SD} and increasing FUI from their upper to lower reaches, contrasting with different trends in Danube and Nile, highlighting the influence of large dams. Seasonally, two different patterns were observed in the five rivers, underscoring the hydrological influences on water optical properties. Furthermore, as two key optical water quality parameters, Z_{SD} and FUI were analyzed for their complementary roles in characterizing river turbidity across varying water conditions. By quantifying spatiotemporal patterns, this study establishes a global baseline for river optical properties and supports SDG 6.3.2 monitoring. Our findings offer new insights into large-scale river ecosystem dynamics under environmental change.

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Phytoplankton dynamics, bio-optical trends, and their implications for water quality in the Northern Patagonian Gulfs

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Inherent optical properties (IOPs) are key in understanding the biogeochemical processes of coastal marine waters by providing proxies for a variety of biogeochemical quantities, including phytoplankton pigments. The Northern Patagonian Gulfs (NPG) encompass the San Matías (SM), San José (SJ), and Nuevo (N) Gulfs and are one of the most important regions of the Argentine Continental Shelf, as significant economic activities occur in this area. This presentation summarises 20 years of research on phytoplankton dynamics and optical water properties using ocean colour satellite data, highlighting ecological patterns and implications for water quality assessment in NPG. These studies have shown that the chlorophyll-a algorithms of the MODIS, VIIRS, and OLCI sensors yield satisfactory results for assessing the spatiotemporal variability of this parameter. Phytoplankton annual cycles in the NPG follow patterns typical of temperate waters, with a primary peak in spring and a secondary one in autumn. Positive trends in phytoplankton absorption, diffuse attenuation coefficient and temperature were observed across the region. These trends may reflect changes in water quality, as well as in the phenology and composition of phytoplankton communities, with potential impacts on the entire food web and the ecosystem services of the NPG. We are currently working to identify the optical components that predominate in light absorption in coastal areas. Recent results in NG indicate that during spring, phytoplankton dominates the in-situ absorption of particulate matter (>80%). In spring 2022, phytoplankton composition showed a marked dominance of dinoflagellates, including a bloom of the toxigenic species *Alexandrium catenella*, while diatoms were more abundant in 2023, showing year-on-year variations. These investigations underscore the importance of advancing research on the optical characteristics of coastal waters to improve water quality and algal bloom monitoring, particularly in the context of upcoming hyperspectral satellite missions.

Key words: phytoplankton, optical properties, water quality, Patagonian Continental Shelf

Evaluation of atmospheric correction methods for satellite imagery over a highly turbid lake: A Case study of Lake Okeechobee, Florida, USA

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Atmospheric correction of satellite imagery is a critical preprocessing step for accurately deriving physicochemical water quality parameters. However, not all atmospheric correction algorithms perform equally, and some are better suited to specific environmental conditions. With recent advancements in atmospheric correction techniques, such as the Remote sensing Adjacency Correction (RadCor) developed by the Royal Belgian Institute of Natural Sciences (RBINS), we are motivated to evaluate the performance of multiple correction approaches for Lake Okeechobee, Florida, USA. Lake Okeechobee serves as an ideal case study due to long-term dataset of *in situ* radiometry (AERONET-OC station from 2020-2021), as well as its challenging optical conditions. The lake is characterized by extreme turbidity due to high concentrations of CDOM and suspended sediments, as well as cyanobacterial blooms of *Microcystis aeruginosa* which occur from late spring to fall.

In this study, we assess the accuracy of several atmospheric correction methods—SeaDAS L2gen (two-band NIR and MUMM), ACOLITE (DSF and RadCor), C2RCC, and POLYMER—across multiple satellite sensors including: MSI Sentinel-2A/B, OLCI Sentinel-3A/B, and OLI Landsat 8/9. Performance of atmospheric correction methods were evaluated by matchup of satellite imagery with AERONET-OC measurements. Further, we explored the impact of correction method on the retrieval of the water quality indicators turbidity, chlorophyll-a, and cyanobacterial index using a contemporaneous dataset of *in situ* measurements collected between May 2021 and February 2022 as part of the Harmful Algal Bloom Assessment of Lake Okeechobee (HALO) program.

Exploring the Relationship Between Water Transparency and Optical Properties in the Arctic Ocean

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Ocean color is widely used to monitor phytoplankton abundance and marine ecosystem health, as phytoplankton influence seawater color and transparency. However, regional differences in optically active substances—such as phytoplankton, colored dissolved organic matter, and suspended particles—cause subtle but important anomalies in ocean color. These anomalies complicate interpretation because similar color values do not always indicate equivalent phytoplankton abundance, potentially leading to errors in estimating biological productivity from remote sensing. This challenge is especially significant in the Arctic Ocean, where optical properties are complex due to ice melt, river discharge, and unique plankton communities. Understanding these anomalies is critical to improve the accuracy of ocean color assessments and to track ecosystem changes effectively. Building on this, our study examines spatial and temporal variations in water transparency and ocean color during summer in the western Arctic Ocean, focusing on the Bering Strait/Chukchi Sea and Canada Basin. Using in situ data collected between 2011 and 2024, we analyze the diffuse attenuation coefficient (Kd) as an indicator of water transparency alongside Forel-Ule color values derived from remote sensing reflectance (Rrs). Our findings reveal distinct regional trends and variations in optical properties reflecting complex interactions among optically active constituents. Notably, waters with similar Forel-Ule colors showed differing Kd values, highlighting regional heterogeneity in seawater composition. This summer-focused, field-based study emphasizes the need for integrating multiple optical parameters to better understand Arctic marine ecosystem dynamics and their response to climate change.

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A novel water optical types framework for Chinese inland waters with the application of multitype satellite sensor

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Optical Water Type (OWT) analysis is crucial for comprehending water composition and quality, key factors in assessing water quality over extensive areas. However, China's inland waters lack a standardized system for such analysis. To quantitatively analyze the classification results, our study compared three K-means clustering methods, for analyzing 1310 spectral data from various Chinese lakes and reservoirs, thereby addressing this gap. The innovative split-merge K-means method identified 13 distinct OWTs that more closely adhere to the principles of minimizing intra-class distance and maximizing inter-class distance. These were categorized into four groups: clear water, turbid water, eutrophic water, and special type water. Additionally, we developed a method based on Spectral Angle Distance (SAD) to evaluate the classification capabilities of 12 satellite sensors. The results show that Sentinel-3 OLCI (Ocean and Land Color Instrument), MERIS (Medium Resolution Imaging Spectrometer), and Sentinel-2 MSI (Multispectral Instrument) have the best water classification capabilities, making them well-suited for large-scale monitoring of OWT changes. Conversely, other sensors, such as the Sustainable Development Scientific Satellite-1 (SDGSAT-1), Landsat-8, GaoFen-6, GaoFen-1, GaoFen-2, Landsat-5, Landsat-7, Moderate Resolution Imaging Spectroradiometer (MODIS), and HuanJing-1, necessitate the consolidation of water types for effective categorization, indicative of their more limited classification capabilities.

Evaluation and Regional Optimization of Remote Sensing Retrieval Algorithms for Colored Dissolved Organic Matter in the Northern Adriatic Sea

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Abstract: Colored dissolved organic matter （CDOM） is one of the largest components of oceanic carbon storage and plays a vital role in the marine carbon cycle. However, remote sensing algorithms for retrieving the concentration of CDOM vary with different water environments and the limited availability of observational information. There are differences in the CDOM estimation of the same water area among these classic approaches due to different channel selection and algorithm designs. Empirical methods have been applied to operational satellites (e.g. MODIS and SeaWiFS), which are usually based on band statistics and utilize two or three visible channels. Compared to empirical methods, semi-analytical methods have the advantage of good robustness and providing physically meaningful spectral parameters. Additionally, machine learning methods are attracting more attention due to high accuracy and calculation efficiency. In this study, 10 algorithms, including empirical, semi-analytical and machine learning methods, were selected for the assessment of a_{CDOM} estimation and compared with data from a field ship-borne in situ campaign in the Northern Adriatic Sea in 2024. These algorithms were applied to remote sensing reflectance (Rrs) of the Mediterranean Sea, Bio-Geo-Chemical, L3, daily Satellite Observations and then matched with in situ CDOM measurement according to temporal and spatial matching criteria. To optimize the CDOM estimation in the Northern Adriatic Sea, we are also developing a novel algorithm based on a semi-analytical method and hyperspectral observations which incorporates more observational information. Additionally, the results will be compared with those of some classical algorithms above with in-situ measurements across the Northern Adriatic Sea by matchup analysis. The proposed algorithm will be applied to OLCI Rrs and potentially extended to the state-of-art hyperspectral instruments, such as PACE/OCI, EnMAP and PRISMA.

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Ocean colour applications to biodiversity

From Diatoms to Cyanobacteria: Decoding Lake Võrtsjärv's Phytoplankton with Hyperspectral Eyes

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Obtaining more information from satellite data about the phytoplankton community in water bodies is key to their wider adoption in environmental monitoring schemes. The launch of new hyperspectral satellite missions, such as the Copernicus Hyperspectral Imaging Mission (CHIME) and the Land Surface Temperature Monitoring (LSTM), would permit the exploitation of a wider range of wavelengths for these purposes. To prepare for these hyperspectral satellite missions, in situ validation efforts are needed. In this study, the goal is to analyse and obtain information on the seasonal pattern of the phytoplankton community in Lake Võrtsjärv. Võrtsjärv is a large shallow eutrophic lake in Estonia (average depth 2.8 m) with typically two dominant phytoplankton groups, which vary seasonally. On the shore of the lake, there is a hyperspectral radiometer (Hypstar) which has been collecting spectral data since 2023. The hyperspectral water-leaving data is collected every 15 minutes from May to November each year. In addition, bio-optical and community parameters have been collected monthly from the lake. An approach to detect the change in community composition, from diatoms to cyanobacteria, from the hyperspectral reflectance data is undertaken here. The approach relies on the second derivative analysis of the spectral data and is validated using the light microscopy data on community composition. Work on this is ongoing. This study is part of the ESA AQUATIME project seeking to validate the upcoming hyperspectral satellite missions CHIME and LSTM.

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Temporal Dynamics of Benthic Habitats in the Coral Reefs of the Abrolhos Bank (Brazil) Using WorldView-2 Imagery and Machine Learning

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The Sebastião Gomes reefs (SGOM), located in the Abrolhos Bank region on the eastern Brazilian continental shelf, constitute part of the largest and most diverse coral reef system in the Southwestern Atlantic Ocean. These turbid-zone reefs are characterized by high turbidity and sedimentation. In recent decades, climate variability and local anthropogenic stressors have driven significant ecological transformations in this area. This study investigates changes in benthic habitat between 2010 and 2024 using WorldView-2 imagery. The preprocessing steps included atmospheric correction with ACOLITE and sunglint correction. Bathymetry was derived using the Stumpf model. Textural features (mean and the variance) were calculated from the first principal component of the multispectral bands. Spectral bands, bathymetry, texture layers, and several spectral indices[1] were used as predictor variables within a Random Forest model. In situ benthic cover data were obtained from underwater photographs from 21 reef stations in 2012 and 38 in 2024, analyzed using CoralNet. Of the full dataset, 30% was reserved for the final accuracy assessment, while the remaining 70% was split into 49% for training and 21% for internal validation. The final bottom habitat maps for both years were evaluated using overall accuracy (OA) and the Kappa coefficient, and then compared to assess temporal changes. OA values were 0.92 for 2012 and 0.80 for 2024. Results indicate a decline in coral cover, particularly along the reef edges and central zones, with localized transitions from areas dominated by algae or zoanthids to coral. These differences were statistically significant (McNemar's test, $\chi^2 = 1051.4$, $p < 0.01$). These findings are consistent with those of previous studies, which reported elevated Phase Shift Index values in SGOM, indicating persistent phase shifts. This emphasizes the necessity for sustained monitoring and conservation efforts and the utility of satellite-derived spatial information in supporting the management of marine protected areas.

[1] The following spectral indices were used:
NDWI (Normalized Difference Water Index) = (Green band – Red-edge band / (Red-edge band + Green band)
MDI (Modified Difference Index) = (Green band – Yellow band) / (Green band + Yellow band)
CAI (Chromophoric Algae Index) = (Yellow band – Blue band) / (Blue band +Yellow band)
RE_Blue–REdge = (Blue band – Red-edge band) / (Blue band + Red-edge band)
RE_Green–Red = (Green band – Red band) / (Green band + Red band)

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Phytoplankton Community Shifts Across Southern Ocean Fronts in the Indian Sector: Interannual Insights

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Phytoplankton in the Southern Ocean are key drivers of primary productivity and biogeochemical cycling, yet their community structure varies across oceanographic fronts and between years. This study examines phytoplankton composition and chlorophyll-a (Chl-a) distributions across four major Southern Ocean fronts—the Subtropical Front (STF), Subantarctic Front (SAF), Polar Front (PF), and south of the Polar Front (SPF)—within the Indian sector during the austral summers of 2018 and 2020. Surface water samples were analyzed to quantify six key phytoplankton groups: diatoms, cryptophytes, dinoflagellates, haptophytes, green flagellates, and cyanobacteria. Community assemblages and Chl-a biomass varied across fronts. Diatoms dominated at PF and SPF, comprising 42–46% of total abundance, with Chl-a up to 0.57 µg/L. Cryptophytes peaked at STF and SAF, reaching 47% and ~0.5 µg/L Chl-a. Dinoflagellates occurred across all fronts (8–19%), while haptophytes, green flagellates, and cyanobacteria showed minimal spatial variability. Total Chl-a ranged from 0.76 to 1.23 µg/L. Principal Component Analysis (PCA) of 16 environmental variables revealed notable interannual differences. In 2018, the primary ecological gradient (PC1, 44.6% variance) separated warmer, saline surface waters from regions with deeper light penetration, higher oxygen, and elevated surface Chl-a. Mixed Layer Depth (MLD) had limited influence that year. In contrast, in 2020, MLD emerged as a stronger predictor of productive conditions, associated with deeper light penetration and higher phytoplankton biomass. Water column density also positively correlated with Chl-a. Shifts in environmental-ecological relationships between years suggested changes in bloom development and vertical structure. These findings reveal consistent interannual differences in phytoplankton communities and environmental drivers in the Indian sector of the Southern Ocean. The changing roles of MLD, water column density, and Chl-a underscore variability in bloom dynamics and ecological niches across fronts. Such insights from in-situ observations offer valuable context for interpreting surface ocean patterns observed at broader spatial and temporal scales, particularly in high-latitude environments undergoing rapid change.

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Shedding light on phytoplankton monitoring in the western Baltic Sea

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The Baltic Sea is characterised in large parts by low biodiversity, both naturally and due to human-induced pressures. Changing climate, intensive anthropogenic use and increased frequency of extreme events exert further pressure on this delicate ecosystem, leading to changes in phenology of phytoplankton communities and mismatches in food web interactions, with unclear consequences for trophic transfer and uncertainty about its future stability. The western Baltic Sea, where inflows from the North Sea influence water mass exchange and community composition, is an important transition zone in this context, and may be a harbinger of regime shifts in phytoplankton diversity. Monitoring these changes is challenging due to the dynamic and complex nature of phytoplankton. We need tools that are both sensitive and scalable to detect biodiversity changes early. Emerging tools and technologies such as hyperspectral in situ and ocean colour remotely sensed observations, coupled bio-optical-ocean circulation modelling, organismal data from eDNA, and lipid biomarkers for phytoplankton biomass, open possibilities to develop enhanced observing systems which build on established monitoring programmes. We present plans for an integrated optical observing programme in the western Baltic Sea which includes an above water radiometry reference platform, adaptive in situ sampling and modelling to support validation of current and upcoming multi – and hyperspectral ocean colour satellite missions. Our focus is on workflows which leverage reflectance-based approaches to develop indicators of change in phytoplankton biodiversity in response to climate change as well as anthropogenic influences (e.g., eutrophication, marine heatwaves). By including biogeochemical proxy records from past climate periods in our analysis, we connect across different temporal and spatial scales, and look to unravel drivers of past changes and how these may inform present and future changes. This represents a big step towards rapid detection of biodiversity changes in phytoplankton communities, including emerging invasive species and harmful algae blooms.

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Recent changes in the phytoplankton community structure in the Gulf of Alaska

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This research was conducted as part of the International Year of Salmon and focused on changes in the phenology and composition of phytoplankton in the subarctic Pacific Ocean, which is the winter residence region for Pacific salmonids. Given the extensive study area, we analyzed a time series of satellite-derived phytoplankton phenology metrics and functional groups from 2002 to 2022, within previously defined bioregions in the subarctic Pacific.

Our findings showed a decreasing trend in the contribution of diatom chlorophyll-a (Chl-a) relative to the Chl-a of smaller algae, including haptophytes, pelagophytes, green algae, and cyanobacteria. This decline was particularly pronounced in the Gulf of Alaska after 2018. Since diatoms are a key species that form blooms in this region, we also observed a decrease in the accumulated yearly bloom duration in recent years, with the exception of the waters surrounding the Kamchatka Peninsula. Analysis of environmental factors and climate indices indicated that changes in phytoplankton composition were likely driven by a combination of weaker currents associated with the North Pacific Gyre Oscillation (NPGO) and recurring marine heatwaves since 2014. It remains uncertain whether the decline of the diatom group is temporary or signals the start of a long-term shift in the phytoplankton community structure in the subarctic Pacific. Nevertheless, regular monitoring is crucial, and a bioregion-oriented remote sensing approach can be a valuable tool for tailoring regional fish stock management strategies in the coming years.

NEW IOCCG REPORT ON BENTHIC REFLECTANCE

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Benthic reflectance is an optical property quantifying how a bottom boundary reflects and absorbs incident light across the electromagnetic spectrum. It represents how the bottom boundary of a water body reflects and absorbs some fraction of impinging irradiance, spectrally from ultraviolet to shortwave infrared (350 to 2500 nm). A new IOCCG Report on Benthic Reflectance is in draft format for review by the ocean optics and broader scientific community. This report brought together experts in this topic for the first time to share experience, guidance, and potential pitfalls in measuring benthic reflectance. We start with the basic theoretical framework required to develop a physical understanding of bottom observations including effects of three-dimensional structures. The next part of the report cover he types of platforms, instruments and measurement techniques that have been commonly used to assess the reflectance of a variety of benthic habitats, along with techniques for data collection, recording metadata, and spectral processing. A chapter is devoted to providing examples of spectral reflectance measurements for a range of sub- and intertidal benthic habitats. Spectral examples are grouped by substrate and benthos types including: sediment, corals, minerals and rubble, submerged aquatic vegetation, macroalgae, detritus (wrack and debris), and shadows. The final chapters include applications involving benthic reflectance including shallow water remote sensing, deep sea mining, archeology, and plastic detection, and ecology and global change detection. We end the report with a chapter on emerging technology for quantifying benthic reflectance. This report consolidates the current knowledge about the theory and practice of quantifying the reflectance of bottom boundaries over the last few decades. We note that such measurements are not only useful for mapping of the benthos, but also for understanding the physiological characteristics and potentially the "health" of shallow and deep benthic ecosystems.

Investigation of the Variation of Ocean Color and Phytoplankton Functional Types in the Bay of Bengal

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The monthly and inter annual variability of Ocean color products and Phytoplankton Functional Types (PFTs) are examined in the Bay of Bengal (BoB) from satellite data (2000-2020). Monthly Chlorophyll-a, Color Dissolved Organic Matter (CDOM), Photosynthetic Active Radiation (PAR) and Suspended Particulate Matter (SPM) data of merged satellites are used in this study. Ten PFTs (Microplankton, Nanoplankton, Picoplankton, Diatoms, Green Algae, Dinoflagellates, Prymnesiophytes, prokaryotes, pico-eukaryotes, Prochlorococcus; 3 phytoplankton size classes (PSC), 7 phytoplankton taxonomic compositions (PTC) are derived from individual monthly Chlorophyll-a. All data are averaged over the BoB region. We have found that the average Chlorophyll-a was decreasing (0.35 mg/m3 to .25 mg/m3) from the year of 2000 to 2020; whereas CDOM shows a sinusoidal relation from the year of 2000 to 2020; PAR has showed a decrease until 2014 then increase; SPM shows a rapid exponentially increasing trend from 2013. The highest Chlorophyll-a is found in the monsoon season (August) due to the high load of river discharge, cloudy environment, and associated favorable conditions; the lowest Chlorophyll-a is found in summer (April) due to the increased sunlight and PAR. Diatoms are the most dominant group in the BoB, which is going to be replaced by smaller planktons like Prochlorococcus species. Chlorophyll-a has a strong relationship with CDOM whereas PAR has a negative relationship with Chlorophyll-a and CDOM. Prokaryotes and Prochlorococcus have showed negative correlation with other functional groups.

A Decade of Kelp Forest Dynamics in the Northeast Pacific Using Sentinel-2 Multispectral Imagery and Machine Learning

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Kelp forests, critical temperate coastal ecosystems, face significant threats from climate change, yet their dynamic nature challenges large-scale monitoring. This study leverages a decade (2015-2025) of high-resolution Sentinel-2 multispectral imagery to analyze kelp canopy dynamics across four latitudinal sites in the Northeast Pacific, from Mexico to Canada. We developed a robust classification workflow by training an XGBoost model on a comprehensive, manually-curated spectral library. The model achieved high accuracy (F1-score > 0.99) by effectively utilizing the sensor's red-edge and near-infrared (NIR) bands, which are highly sensitive to chlorophyll in surface canopies. Random Forest regression models were then used to correlate the resulting kelp area time-series with key environmental variables and large-scale climate indices to identify the primary drivers of change at each site. Our analysis reveals a distinct latitudinal gradient in ecosystem dynamics. Southern sites exhibited volatile "boom-and-bust" cycles and low resilience, with recovery from stress events taking more than double the time of their northern counterparts. These dynamics were strongly predicted by large-scale climate patterns, particularly the North Pacific Gyre Oscillation (NPGO) and the PacWarm index. Conversely, the more stable northern populations showed weaker correlations with these drivers, suggesting that unmeasured local biotic factors, such as sea urchin grazing, are a dominant control. This research demonstrates the power of the Sentinel-2 archive for moving beyond simple habitat mapping to serve Earth system science. By linking ocean colour data to ecological processes, we can disentangle complex, region-specific drivers of ecosystem health, providing a critical foundation for developing targeted management strategies.

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Linking hyperspectral ocean colour to plankton biodiversity: the PlanktoSpace project

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Understanding and monitoring marine plankton biodiversity at global scales remains a fundamental challenge in oceanography. Current satellite ocean-colour products provide valuable information on bulk properties such as chlorophyll-a, but they cannot resolve the complexity of plankton community composition. The European Space Agency-funded *PlanktoSpace* project addresses this gap by developing advanced machine learning (ML) algorithms that link hyperspectral and multispectral remote-sensing reflectances (Rrs) to eDNA-based biodiversity datasets. Our approach builds on a new standardized global in-situ dataset that combines DNA metabarcoding, quantifying amplicon sequence variants (ASVs) across the entire tree of life, with satellite observations from PACE hyperspectral mission and legacy multispectral sensors. We hypothesize that the plankton community structure introduces subtle, second-order variations in Rrs spectra that are detectable through advanced feature-extraction methods. We will use a hybrid ML framework: first, unsupervised classification to identify first-order spectral diversity and extract second-order features; then, supervised learning to predict biodiversity proxies, including community composition. The resulting models will generate satellite-derived experimental products describing spatial and temporal patterns of plankton diversity. *PlanktoSpace* lays the groundwork for operational biodiversity monitoring from space by linking planetary-scale standardized genomics with Earth Observation. This work will support the exploitation of future hyperspectral missions such as CHIME (Copernicus Hyperspectral Imaging Mission for the Environment), complement existing biogeochemical indicators, and enhance our ability to assess marine ecosystem states and their responses to climate variability and anthropogenic pressures.

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Investigating phytoplankton community composition in the Equatorial Atlantic

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The equatorial Atlantic is a highly productive and dynamic region with large seasonal and interannual variability. Although this is the best studied ocean in the world, scientific observations are skewed in time and space. The highest productivity occurs in the summer when upwelling causes the "cold tongue" and Tropical Instability Waves (TIW) propagate westward. We mined the SeaBASS, British Oceanographic Data Center, and Pangea for High Performance Liquid Chromatography (HPLC) data and found over 1000 phytoplankton pigment data in the Equatorial zone between 7ºN and 7ºS albeit distributed unevenly over the seasons. Phytoplankton were categorized into micro, pico, and nano size classes using the HPLC. We further investigated in detail data collected during a cruise in July 2011 that traversed through the Cold Tongue to test the conventional dogma that holds that upwelling zones would be dominated by microplankton. We found that microplankton seldom dominated the phytoplankton community but rather it was nanoplankton that most often dominated, even at locations with high chlorophyll concentrations in the core of the Cold Tongue. Our findings demonstrate that the phytoplankton community composition in this region is more complicated than previously thought. Furthermore, the in-situ HPLC data showed that the community composition changed as the TIW aged and propagated westward across the Atlantic.

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Advances in remote sensing of floating macroalgae physiological condition using observations from the NASA Biodiversity Survey of the Cape (BioSCape) campaign

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Satellite remote sensing of floating marine macroalgae supports global monitoring via dynamic distribution maps that reveal temporal oscillations spanning seasonal to decadal cycles and support investigations of long-term extent change. For example, a four-decade Landsat timeseries of bull kelp populations in northern California showed that the extent of regional kelp forest declines following a severe marine heatwave in 2014-2016 greatly exceed historical observations in terms of decline severity and weak post-heatwave recovery. Similarly, two decades of MODIS observations of the tropical and sub-tropical northern Atlantic Ocean reveal persistent annual increases in the biomass of pelagic sargassum, with 2025 showing the highest biomass observed so far. Despite advances in monitoring floating macroalgae extent, developing mechanistic understanding of the drivers underlying observed changes is not assured and would be better supported if physiological condition—in addition to extent—were likewise retrieved. Recently launched hyperspectral imagers—including OCI and sensors not commissioned for ocean color applications such as EMIT and Tanager—support new opportunities to augment extent maps with indicators of physiological condition, a capability first demonstrated with AVIRIS observations of floating giant kelp forests in southern California. Here we present initial hyperspectral algorithms for brown algae focusing on kelps with floating surface canopies. Unless dislodged, these taxa are tethered to the substrate and remain in place, which mitigates confounding effects of age versus nutrient or temperature stress, thereby supporting algorithm development. We map algorithms assessing physiological condition onto AVIRIS-ng airborne imagery of the Western Cape of South Africa collected during the 2023 NASA Biodiversity Survey of the Cape (BioSCape) campaign, wherein sea bamboo, or *Ecklonia maxima*, is the dominant surface taxon. We assess spatial patterns in remotely sensed physiological indicators and compare with sea surface temperature. We discuss the applicability to other brown algae taxa, including giant kelp and pelagic sargassum.

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Monitoring Salt Marsh and Seagrass Biomass with Field Data and Remote Sensing Multispectral Imagery in Eastern Canada

Brigitte Légaré [1,2,3], Christian Nozais [1,2,4], Simon Bélanger [1,2,5]

Intertidal and littoral vegetation in salt marshes and seagrass beds plays a crucial role in sustaining the primary production of coastal ecosystems. Above-ground biomass, a key biophysical attribute of these habitats, is fundamental for assessing ecological functions and the ecosystem services they provide. Although detailed habitat mapping has been conducted along the Estuary and Gulf of St. Lawrence, spatial quantification of above-ground biomass remains limited. The growing availability of remote sensing data offers new opportunities to estimate biomass at broader spatial and temporal scales.

In 2024, extensive field campaigns were conducted in collaboration with *Zones d'intervention prioritaire* (ZIP) committees across several administrative regions, including Côte-Nord, Charlevoix, and Bas-Saint-Laurent. In situ measurements included above-ground biomass, leaf area index, and plant allometry for key coastal species such as eelgrass (*Zostera marina*), smooth cordgrass (*Spartina alterniflora*), and seacoast bulrush (*Bolboschoenus maritimus*). Multispectral imagery from Sentinel-2 and Planet satellites, acquired during low-tide conditions between June and October 2024, was atmospherically corrected using ACOLITE. A range of published vegetation indices was applied to estimate biomass, revealing seasonal trends aligned with vegetation growth and phenology.

While the performance of individual indices for predicting biomass was moderate overall ($R^2 < 0.55$), some indices yielded better results for specific species. These outcomes informed the development of region-specific algorithms tailored to each vegetation type, enabling the production of spatially explicit biomass maps. In addition, Partial Least Squares Regression (PLSR) models were developed using a suite of vegetation indices. These models effectively captured the variability in above-ground biomass for each species, with R^2 values exceeding 0.75.

This study offers valuable insights into macrophyte biomass dynamics in cold temperate coastal ecosystems and demonstrates the potential of remote sensing for ecological monitoring and informed coastal management.

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Improving Coastal Bathymetry Accuracy from Optical Satellite Data Using a Spectral and Temporal Processing Technique

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ABSTRACT

Generating accurate bathymetric maps is essential for managing marine resources and protecting coastal ecosystems. Bathymetry maps must meet specific technical requirements regarding temporal and spatial resolutions and vertical accuracy.

Bathymetric datasets are available through several local, regional, or global portals. However, high spatial and temporal resolution data are often difficult to access due to security restrictions, national regulations, or economic constraints.

Bathymetric maps can be produced using various surveying techniques, each suited to physical conditions (e.g., depth, water transparency), desired spatial and temporal resolutions, and available budget.

Considering these technical and operational constraints, this study introduces a novel approach that could greatly reduce data collection costs and enable mapping of larger areas. The approach is based on the processing of high-resolution optical satellite imagery and requires calibration. The calibration could be achieved using accurate data, such as satellite lidar altimetry, shipborne echosounder, or unmanned surface vehicles' measurements.

In southern Sicily (central Mediterranean), we leveraged calibration depths from approximately 7 to 50 meters. Subsurface reflectances were calculated and integrated into a simplified radiative transfer model. Calibration and validation were performed over a homogeneous sandy bottom. The technique provided reliable depth estimates down to about 25 meters, with performance limited by optical saturation beyond that limit. The key innovation is the temporal and spectral averaging of images, which significantly improves estimation accuracy.

Satellite-Derived Bathymetry calibrated with multibeam data allowed achieving an accuracy of ±7% at 95% confidence. Variations were mainly due to heterogeneous seafloors or surface anomalies like glint and wave radiometric disturbances.

This remote sensing method offers a robust and reliable solution for bridging the shallow-water data gap, often called the "white ribbon".

Following this research, we aim to develop further the method by exploring the use of alternative calibration datasets.

Phytoplankton community diversity and Ecosystem function from Sentinels (Phytodiverse)

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The ESA funded Phytodiverse project aligns with several EC projects and aims to advance the science of phytoplankton diversity algorithms for Essential Biodiversity Variables (EBV) and derived indicators from space. The project (starting in September 2025) will develop innovative techniques to create a new remote sensing reflectance (R_{rs}) dataset with enhanced spatial resolution, while also developing algorithms to analyse functional and trait diversity of phytoplankton using hyperspectral satellite data, investigating both community diversity and ecosystem function class EBVs. In particular, the project will investigate the phytoplankton community diversity from their functional traits based on pigments and size (EBV community diversity class) and the ecosystem functional EBV class (phenology) and how these can be advanced by hyperspectral datasets when compared to multispectrally derived EBV relevant products from satellite.

Phytodiverse will construct and expand an in-situ dataset for calibration and validation purposes. The in situ part will contain two components, a hyperspectral reflectance dataset collection in open and coastal waters and a biological dataset collection focused on the diversity of phytoplankton. The project will generate satellite-derived datasets of new products and will work in synergy with other ESA projects. Phytodiverse will produce uncertainty quantification through comparisons with in-situ data, different satellite products, and models. Various indicators, including trends and extremes, will be connected to the products generated within Phytodiverse.

Three distinct science cases will utilize these products and indicators across different environments (supersites) to investigate phytoplankton diversity succession within and around blooms: an open ocean case study will examine long-term changes in plankton community and function in the NE Atlantic; a coastal case study will focus on phytoplankton bloom diversity in the Northern Adriatic; and a polar case study will investigate phytoplankton diversity in the Arctic. Each science case and its associated tools are integrated with ongoing EC projects.

Methods for Phytoplankton Functional Type Retrieval in the Mediterranean Sea

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In this project, we quantify the skill of satellite-based retrievals of phytoplankton functional types (PFTs) and phytoplankton size classes (PSCs) for the Mediterranean Basin, a semi-enclosed, nutrient-limited sea with steep west–east gradients. To improve the performance of the empirical method used operationally in the Copernicus Marine Service, we integrate multispectral ocean-color fields with colocated in situ PFTs observations and compare three statistical models for PFT-resolved chlorophyll-a: (i) EOF-only (leading empirical orthogonal functions of ocean color), (ii) EOF + sea-surface temperature (SST, additive), and (iii) EOF × SST (state-dependent interaction). To ensure out-of-sample credibility, we employ blocked spatio-temporal cross-validation—holding out sub-basins and seasons—combined with nonparametric bootstrap resampling to derive confidence intervals on skill. Performance is summarized with R^2, RMSE, mean bias error (MBE), and mean percentage difference, and consolidated with decision metrics. Residual diagnostics check heteroskedasticity and autocorrelation. Results show systematic, PFT-specific differences in predictability and a consistent gain from SST information. The EOF × SST interaction model, as well as the empirical operational method, outperform alternatives. EOF × SST exceeds EOF and EOF + SST at higher temperatures and during stratified periods. Crucially, the empirical model—direct ocean-color features without SST—often matches or surpasses the EOF approaches, including EOF × SST, especially in optically complex near-coastal domains, likely by retaining high-frequency, subregional variability that modal decompositions smooth. Radar plots and scorecards provide visualization of model ranks by PFT and sub-region, highlighting when the empirical baseline is preferred and when SST-informed EOF models add value. These findings deliver guidance for Mediterranean ecosystem state indicators, biogeochemical data assimilation, and early warning of PFTs community shifts. More broadly, the framework clarifies when and where thermal constraints add value to PFTs retrievals and offers a portable, uncertainty-aware recipe for operational monitoring and climate-change attribution in optically complex basins—with the Mediterranean as the primary proving ground.

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Multi- and hyperspectral remote sensing approaches for retrieving phytoplankton size structure in a tropical nearshore environment

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Cell size is a key feature of phytoplankton communities, providing crucial information on the composition of aquatic systems. Several biological and ecological processes are linked to it, including photosynthesis, nutrient uptake, growth rate, and light absorption. At first order, phytoplankton size structure (PSS) is a proxy for community structure, and it also modulates interactions with the light field, for example, through the packaging effect. This relationship enables the assessment of PSS via remote sensing, motivating several studies that retrieve it using ocean-colour models. These algorithms have been successfully applied in Case 1 waters, but optically complex areas (e.g., coastal and nearshore waters) remain challenging. Such regions may benefit from enhanced multispectral sensors such as the Ocean and Land Colour Instrument aboard Sentinel-3A/B (OLCI-S3), as well as from a new generation of hyperspectral sensors including the Environmental Mapping and Analysis Program (EnMAP), the Hyperspectral Precursor of the Application Mission (PRISMA), and the Plankton, Aerosol, Cloud, Ocean Ecosystem (PACE) missions. Building upon these advances, this study investigates different remote sensing approaches for retrieving PSS in the São Sebastião Channel, on the northern coast of São Paulo, Brazil. A dataset containing *in situ* remote sensing reflectance spectra and size-fractionated, fluorometrically-determined chlorophyll-a concentration is being used to calibrate and validate PSS algorithms for the region. An initial comparison of PSS retrievals from *in situ* data resampled to EnMAP and OLCI-S3 spectral resolution using Tikhonov regularization (Ridge regression) shows that the increased spectral information of EnMAP improves model accuracy compared to OLCI-S3. These regionally calibrated algorithms can provide a basis for operational monitoring of phytoplankton communities in the São Sebastião Channel.

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Seaweed Invasions from Space: Optimising Sentinel-3 OLCI for Sargassum Detection

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Since the emergence of the Great Atlantic Sargassum Belt (GASB) in 2011, satellite sensors have become crucial tools in the detection, monitoring and tracking of these now seasonally recurring seaweed invasions across the Tropical North Atlantic (TNA). Monitoring has been essential for island and coastal communities surrounding the North Atlantic, Caribbean Sea and Gulf of Mexico, and the largely negative environmental and socio-economic impacts of Sargassum inundations have been well documented. Formerly, monitoring and early warning reporting was based on optical data acquired primarily by MODIS and MERIS, and existing detection algorithms based on these sensors are still leveraged for newer sensors from the Copernicus Programme, including Sentinel-3 OLCI. With MODIS now active for over two decades and MERIS observations ending in 2012, OLCI provides a newer, more reliable solution for daily monitoring of Sargassum movement in the TNA at 300 m resolution - enhancing the need to develop a satellite specific algorithm for OLCI. This study presents a unique band or spectra-based algorithm for cloud masking and Sargassum detection in Sentinel-3 OLCI Level 1 data. To bolster this heuristic approach, we also present initial results from a deep learning model that will allow for more robust scalability across the TNA and improve the accuracy of monthly Sargassum composites. This novel approach will support our understanding of this 'new normal' in the TNA, offering insights into where, when, and how Sargassum invasions may be driving changes in biogeochemical and climate levels across the region.

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Global and operational estimation of the phytoplankton class sizes based on particulate backscattering, using neural network with Sentinel-3/OLCI and PACE/OCI

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Remote sensing provides global-scale observations of chlorophyll-a concentrations, which serves as a proxy for phytoplankton biomass in the ocean. While chlorophyll-a data is valuable, many applications require more detailed information about phytoplankton species composition, because different species play distinct roles in the marine food web and carbon cycle. Phytoplankton can be grouped into size classes— such as micro, nano, and pico—offering a first approximation about their functional types. Kostadinov et al. (2009) developed a model to estimate particle volume distributions across these size classes using SeaWiFS data, demonstrating promising global-scale results. In this study, we adapted Kostadinov's methodology for its application with Sentinel-3/OLCI and PACE/OCI sensors. The aim of the study is to establish an operational approach to generate global maps of phytoplankton size classes.

The adaptation involves selecting optimal parameters best suited to Sentinel-3/OLCI and PACE/OCI data and implementing an optimization process to best fit particulate backscattering measurements. This optimization process enables us to use more wavelength than the initial method, which reduces sensitivity to inherent noise. Using Sentinel-3/OLCI, validation against a global in situ matchup dataset shows limitations for nano-phytoplankton, like those reported by Kostadinov et al. (2010), but significantly improved correlation coefficients for micro- and pico-phytoplankton ($r > 0.8$ compared to $r < 0.4$ in the original study). A smaller dataset of available in-situ matchups was used for PACE/OCI and correlation coefficients appear to be close to those estimated in the original study, however PACE/OCI shows improved retrieval of the nano-phytoplankton. The optimization process took too long to be operationally conscious, so we created a representative database to train a neural network to have an operational methodology. This adapted methodology enables us to produce global maps of phytoplankton size classes, which could be a tool to improve phytoplankton specific species detection.

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Late Spring Phytoplankton Dynamics along the Equator in 2022

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The Equatorial Atlantic is a highly dynamic region with strong seasonal changes in winds and currents resulting in changes in nutrient supply and phytoplankton biomass. Here we describe the structure of the phytoplankton community of the Equatorial Atlantic using measurements of phytoplankton pigments using High-Performance Liquid Chromatography (HPLC), chlorophyll and phycoerythrin fluorescence using spectrofluorometry, and cell counts using flow cytometry made at 60 stations in April/May 2022. The HPLC pigments were used to calculated Phytoplankton Size Classes (PSC) and compared with satellite derived PSC. The water column in May 2022 had warm surface waters with strong stratification and a deepening of the thermocline and nutriclines towards the west. While the core of the Equatorial Undercurrent capped the mixing of nutrient-rich, cold water to the surface, mixing below the core entrained nutrients to form a well-defined Deep Chlorophyll Maximum layer at 50-70m depth. A surface diatom bloom, identified by HPLC pigments and microplankton imagery was encountered between 2ºE and 7°W. Satellite data revealed this bloom to have begun around the 14th April and lasts more than 45 days as it is advected northwestward to reach 20ºW before it dissipated. Results of these analyses will be presented.

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High-resolution SWOT altimetry and ocean colour observations of the island mass effect in the Kuroshio Current

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The Island Mass Effect (IME), in which ocean currents interact with island and seamount topography to drive upwelling and stimulate biological production, plays a key role in supporting fisheries in oligotrophic waters. IMEs are increasingly recognized as ecologically significant hotspots where fine-scale physical processes, including turbulent mixing, frontal instabilities, and topographic flow disruption, enhance lower trophic level productivity and may contribute to fish recruitment and localized fisheries yield. In the Tokara Strait, a dynamic region where the Kuroshio Current flows over a chain of islands and seamounts, we used SWOT satellite altimetry in combination with MODIS and Sentinel-3 OLCI chlorophyll-a data to examine the physical expression and biological signature of the IME. SWOT, the first satellite altimeter capable of delivering two-dimensional swath measurements of sea surface height at unprecedented spatial resolution (two 50 km swaths on either side of the nadir, with a native resolution of 250 m), provides a transformative capability for detecting submesoscale features and frontal structures previously unresolved by conventional altimetry. SWOT observations reveal intensified surface flow gradients and submesoscale activity downstream of topographic features, coinciding with SST cooling and elevated chlorophyll concentrations indicative of enhanced upwelling and biological response. This study provides one of the first demonstrations of how next-generation satellite observations can resolve fine-scale current-topography interactions that trigger localized phytoplankton blooms, offering a mechanistic pathway by which submesoscale physical processes may enhance biological productivity and influence fisheries productivity in western boundary current systems.

Modeling Pelagic Fish Habitat Suitability from Satellite Data to Support Sustainable Fisheries Management

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The abundance of anchovy, sardine, and other small pelagic fish is a key indicator of marine ecosystem capacity and biodiversity. As filter feeders, these species link the bases of the food web to higher levels and are the primary food for larger predators and marine mammals in the open sea. Monitoring their habitat is essential for fisheries management, allowing pressures on overexploited regions to be reduced through targeted measures. This study utilizes remote sensing data to calculate the Habitat Suitability Index (HSI) of target species using satellite derived Essential Oceanographic Variables (EOVs) from Sentinel-3 data and from Copernicus Marine Services. The EOVs include Chlorophyll-a concentration, Sea Surface Temperature, Turbidity, Photosynthetically Available Radiation (PAR), Salinity, Dissolved Oxygen concentration, Ocean Circulation data and Bathymetry. The data are fed into an ensemble model which identifies the HSI at a 1km spatial resolution on a monthly basis. Currently, the models are run for the European anchovy (*Engraulis encrasicolus*) and the European pilchard (*Sardina pilchardus*) in the Greek Seas, Eastern Mediterranean. The study will provide insights into the spatial and temporal variability of suitable habitats of the target species, relating to their feeding and migration patterns. Finally, this information is incorporated in a larger management strategy framework, that aims to support EU legislation implementation and help mitigate overexploitation. This study has been has been funded by Copernicus Marine National Collaboration Programme (2021-2025), Contract number 25339L01D-COP-NCP USER DEMO-8000 "Pelagic Fish Habitat Suitability Modeling through Satellite Remote Sensing (FishHAB)".

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Impact of Tropical Instability Waves on Phytoplankton Communities along the Equator in 2019

Ajit Subramaniam[1], Ana Fernández Carrera[2], Ina Schmidt[3], Claudia Giulivi[4], Peter Brandt[5], and Rainer Kiko[6]

The Equatorial Atlantic is a highly dynamic region with strong seasonal winds and currents resulting in upward supply of nutrient rich cold water between June and September and ultimately affecting the phytoplankton dynamics in this region. This is also the season for maximum Tropical Instability Wave (TIW) activity. Here we present the results of our analysis of TIW activity between 2012 and 2020 using satellite data that showed TIW activity extended from June through September each year, peaking in July and August, although anomalous cooler water events with higher chlorophyll concentrations are occasionally seen in other months. We found considerable interannual variability in both the number of TIWs and their phenology. We also describe the response of the phytoplankton using measurements of phytoplankton pigments by high-performance liquid chromatography and cell counts using a flow cytometer from measurements made at 54 stations in September /October 2019. The in-situ data showed that we encountered the remnants of the seasonal Equatorial Cold Tongue between 5ºW and 14ºW and two upwelling events around 7ºW and 27ºW induced by TIWs. These cooler nutrient rich waters were dominated by nanoplankton rather than microplankton. However, microplankton dominated the community at a third upwelling event caused by a TWI front generating buoyant plume around 35ºW.

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Operational water mass classification for the Northwest Atlantic continental shelf

The productive waters of the Northwest Atlantic continental shelf are highly dynamic and variable through space and time. Large scale circulation changes and rapid warming have led to changes in prevalence and location of spatially-explicit water masses on the continental shelf. Variations in water masses can alter plankton community composition, affect primary productivity, and shift essential fish habitat. Accurate characterization and classification of specific water masses in the region is necessary to quantify dominant water masses and develop fisheries relevant operational products. Current satellite-derived water classification products (i.e. Seascapes) do not accurately define the expected water masses of the Northwest Atlantic. Hyperspectral imagery from the new PACE OCI instrument provides an opportunity to improve optical water type and phytoplankton composition classification that can be combined with additional biophysical data to improve water mass identification. We created two regionally-tuned unsupervised clustering models that classify water masses on the Northwest Atlantic continental shelf using self-organizing map (SOM) and hierarchical agglomerative clustering (HAC) methods. The satellite model will be validated using a similar classification model trained with twenty years of *in situ* hydrographic data. The high spectral, spatial and temporal resolution satellite based product will be used to identify dominant water masses to better characterize and quantify their seasonality, interannual variability and changes over time. This new operational product will be incorporated into new and existing modeling efforts aimed at understanding the oceanographic drivers of lower trophic levels, commercial fisheries, and protected species.

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Exploring ocean colour and lidar data in relation to Calanus spp. distributions from glider-derived acoustic scattering layers

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Abstract

This study, conducted within the CliN-BluFeed project, investigates the potential of satellite-based ocean colour and lidar observations to provide new insights into zooplankton distributions in the North Atlantic. We focus on *Calanus spp.*, a key genus in marine food webs, whose vertical distribution is inferred from acoustic backscatter profiles of sound scattering layers (SSLs) collected by autonomous underwater gliders (Seagliders) and an unmanned surface autonomous vehicle (Sailbuoy). Ocean colour Level 2 data from Copernicus Sentinel-3 and NASA's PACE missions are co-located with SSL observations to examine whether distinct multispectral or hyperspectral features are associated with *Calanus*-rich waters. In parallel, we explore the potential of NASA ICESat-2's Advanced Topographic Laser Altimeter System (ATLAS) photon returns to detect subsurface ocean signatures associated with SSL observations. This work is exploratory and ongoing, aiming to identify wavelength regions or spectral metrics sensitive to Calanus presence, compare reflectance data from Sentinel-3 and PACE, and evaluate the capabilities of ocean colour and lidar measurements for three-dimensional ocean observation and the potential monitoring of *Calanus spp.* in Norwegian waters.

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Time series of phytoplankton groups in the Fram Strait under the changing Arctic Ocean

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Abstract:
In the Arctic Ocean, phytoplankton are highly influenced by sea ice conditions and brine release. Phytoplankton dynamics are subject to the timing of nutrient and light-dependent biological production. Fram Strait (located between Svalbard and Greenland) as an important gateway to the Arctic, is a region where the cold ice-covered Arctic water exits from the western side and the warm Atlantic water enters the Arctic Ocean through the eastern side of the Strait. The two contrasting water masses interact in the central Fram Strait leading to complex phytoplankton dynamics especially under a rapidly changing Arctic climate. Within the framework of the Copernicus Marine Service Evolution Program, we have generated global chlorophyll-a products of several phytoplankton groups (PGs) derived from multi-sensor ocean color data, for a consistent long-term monitoring of the surface ocean PGs. The two-decade observations enable us to study the inter-annual variation and analyze the trend of the surface phytoplankton community structure on different scales. Focusing on the Fram Strait, the satellite PFT data are evaluated with in situ data from AWI established LTER Observatory HAUSGARTEN area, which includes data sets of bio-optical properties, pigment composition, phytoplankton taxonomic data from expeditions in the past years. We further investigate the current state and the two-decade trends of the major PGs; present and interpret their phenological patterns, inter-annual changes and the potential connections between the PG shifts/trends and climate drivers in the Fram Strait.

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