

Blue-Cloud Virtual Labs in support of Sustainable Development Goals

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Abstract— What doors does FAIR data open? FAIR (Findable, Accessible, Interoperable, Reusable) data is revolutionizing marine research by enabling seamless access to vast and diverse datasets. The Blue-Cloud thematic Virtual Labs (VLabs) serve as real-life demonstrators of web-based open science, showcasing the tangible benefits of FAIR data. These interactive environments allow researchers to explore and analyze over 10 million datasets via the Data Discovery and Access Service (DD&AS) and leverage advanced computational tools within a Virtual Research Environment powered by D4Science. Each VLab integrates applications for data processing, result publication, and collaborative workflows, fostering a dynamic, open-science ecosystem. Five key thematic areas highlight the broad research potential of these resources: (1) Integration of coastal ocean observations across Europe, (2) Coastal currents from observational data, (3) Carbon-Plankton Dynamics, (4) Marine Environmental Indicators, and (5) Global Fisheries Atlas. These domains illustrate how FAIR data facilitates cross-disciplinary studies, supporting biodiversity research, environmental monitoring, and fisheries management. By breaking down data silos and providing interoperable digital research environments, the Blue-Cloud VLabs exemplify how FAIR data opens doors to new scientific discoveries, cross-sector collaborations, and innovative methodologies in marine and environmental sciences. Blue-Cloud 2026 is thus a key enabler in shaping the future of ocean research, demonstrating the power of FAIR data to drive scientific progress.

Keywords— EOSC, Virtual Labs, Big Data, Virtual Research Environment, Data infrastructures

I. INTRODUCTION

“You can only manage what you can measure” [1]. This statement underpins current efforts in marine science to enhance the understanding and protection of ocean ecosystems. Accurate measurement and comprehensive data are prerequisites for informed decision-making in the face of increasing challenges such as climate change, biodiversity loss, pollution, and unsustainable exploitation of marine resources. Given the inherent complexity of marine systems, addressing these challenges requires a collaborative, interdisciplinary approach.

By working closely with long-term EU marine data services (i.e., EMODnet), and research data infrastructures (i.e., EuroArgo, SeaDataNet, Ecotaxa and others), Blue-Cloud is introducing a federated model, offering e-infrastructure services (computing, storage, analytics, SSO, AAI, generic service), a data discovery service (10M+ datasets and products from European marine infrastructures), and research intensive virtual labs, embedded in a VRE open to any users with federated identity.

Blue-Cloud operates in the framework of the European Open Science Cloud (EOSC), and its Service platform features a variety of services that can be used for undertaking world-class science via the EOSC ecosystem, by featuring leading operational marine research infrastructures and e-infrastructures. In the Blue-Cloud federation, Blue research infrastructures (RIs) and other data and service infrastructures

and technological providers make their services available to the community via agreed, FAIR formats and technology and standards and best practices supporting data exchange and interoperability, that EOSC recommends or accepts.

The five Blue-Cloud Virtual Laboratories (VLabs) serve as demonstrators of the FAIR (Findable, Accessible, Interoperable, Reusable) data principles in practice and how these can support advanced marine research and policymaking. The five thematic areas are 1) Coastal Observations along European margins, 2) Coastal Current observations, 3) Carbon and Plankton Dynamics, 4) Marine Environmental Indicators and 5) Global Fisheries Atlas.

II. BLUE-CLOUD VIRTUAL LABORATORIES (VLABS)

A. VLab 1: “Coastal Observations along European margins”

VLab 1 was developed to facilitate user interaction with coastal ocean observation data across Europe. It offers a dedicated digital environment that supports the exploration, access, and analysis of diverse datasets related to the coastal ocean. Through the development of specialized tools, VLab 1 enables seamless access to various data types, supports data processing and quality control when required, and promotes both individual dataset exploitation and integrated multi-source analyses. The platform integrates observational data collected by the partners of the Joint European Research Infrastructure for Coastal Observatories (JERICO-RI) with complementary datasets available from international repositories, thereby offering a comprehensive view of coastal dynamics.

To address the broad spectrum of user needs, VLab 1 is organized around three Thematic Services. Thematic Service 1 focuses on transboundary processes and connectivity along European margins, supporting investigations into biological connectivity, the transport of contaminants, and the impacts of riverine outflows. Thematic Service 2 addresses extreme events, with a particular emphasis on the coastal consequences of major storms. Thematic Service 3 highlights the contribution of ocean gliders, demonstrating the added value of repeated glider sections for sustained monitoring and observation of coastal processes.

Among its core functionalities, VLab 1 provides mechanisms for the identification and access of relevant coastal ocean datasets across Europe. It supports transparent handling and management of data, including optional preprocessing, quality control, and reformatting in accordance with established Best Practices. Furthermore, the platform offers a suite of tools for data exploitation and integrated analysis, enabling users to extract meaningful information across multiple parameters and sources. Visualization capabilities are also tailored to the specific objectives of each Thematic Service, ensuring that outputs are both scientifically relevant and accessible to a range of users.

A central concept underlying the design and implementation of VLab 1 is the recognition of the multidisciplinary expertise required to fully utilize coastal ocean observations. The mere availability of datasets does not ensure effective use; rather, users must navigate diverse data formats, quality standards, and analytical requirements. VLab 1 addresses these challenges by providing an integrated and user-oriented environment that facilitates the transformation of raw

observations into actionable knowledge concerning the processes and impacts that shape the European coastal ocean.

B. VLab 2: “Coastal Currents from Observations”

Sea surface currents (SSC) are fundamental to understanding upper ocean dynamics and the interactions between physical and biogeochemical processes. Surface currents are responsible for the transport of heat and mass, contribute to the formation and evolution of upwelling and downwelling systems, and influence the distribution of primary oceanic variables such as oxygen and chlorophyll. As such, SSC directly impact primary production and, consequently, shape the biological interactions across the trophic chain. Beyond their ecological significance, surface currents also play a critical role in the dispersion of pollutants, making them essential for applications such as oil spill modeling and marine risk assessment.

Given their relevance, SSC are classified as Essential Ocean Variables (EOVs) by the Global Ocean Observing System (GOOS) community. This classification highlights their importance for both fundamental oceanographic research and the development of operational oceanographic services. Analyses conducted over extended spatial and temporal scales are essential for identifying variability, understanding seasonal or interannual patterns, and characterizing dominant modes of circulation in the coastal and open ocean.

Despite their importance, direct measurements of SSC remain limited, particularly at basin-scale resolutions. Observational coverage from in situ platforms is often sparse and uneven, which presents challenges for large-scale applications such as ocean modeling, data assimilation, or pollutant dispersion prediction. To address these limitations, interpolation and data fusion techniques are commonly employed to generate gridded representations of SSC fields from heterogeneous datasets.

In this context, the present approach introduces a method for combining indirect remote sensing observations with direct in situ measurements to reconstruct gridded SSC fields. The method is based on the Data-Interpolating Variational Analysis in n dimensions (DIVAnd) [2], a variational inverse technique that formulates the reconstruction as a minimization problem. The associated cost function is designed to penalize sharp spatial gradients in the reconstructed field, promoting smooth and dynamically consistent solutions.

The methodology further incorporates a set of physical constraints into the cost function to enhance the realism and fidelity of the reconstructed currents. These constraints account for the influence of coastlines, the typically low horizontal divergence observed in surface flows, the Coriolis effect, surface pressure gradients, and the temporal coherence of oceanic systems [3]. By integrating these dynamic considerations, the approach ensures that the resulting SSC fields are not only spatially complete but also consistent with the known physical behavior of the upper ocean.

VLab 2 presents a multi-source data integration framework for the study and reconstruction of surface currents using a variational inverse method. The implementation is provided through an interactive Jupyter Notebook environment and is developed in the Julia programming language, ensuring reproducibility, scalability, and adaptability. The primary objective of this VLab is to support the reconstruction of surface current fields in the Mediterranean Sea by merging diverse observational datasets. However, the structure of the notebook is designed to be flexible and modular, allowing

users to readily adapt the approach to other regional domains, provided that sufficient data coverage exists. This generalizability makes VLab 2 a valuable tool for both research and operational applications in coastal oceanography.

The methodology integrates three key types of observational data. The first dataset includes surface drifters, which are instrumental for the cross-validation of reconstructed currents due to their ability to directly capture Lagrangian motion at the ocean surface. The second source consists of satellite altimetry data, which offers broad spatial and temporal coverage and is used to derive geostrophic surface currents through sea surface height gradients. The third data type is provided by High-Frequency (HF) radar systems, which contribute direct measurements of surface currents in coastal regions with high temporal resolution.

By combining these complementary datasets within the DIVAnd framework, VLab 2 enables users to generate spatially continuous and dynamically consistent current fields. The approach also emphasizes the importance of validation, particularly using independent drifter data, to ensure the reliability and accuracy of the reconstructed current structures. This fusion of satellite, in situ, and coastal radar data exemplifies the power of integrated observation strategies for characterizing complex coastal circulation patterns.

Through this environment, VLab 2 offers users a practical and extensible platform to engage with modern variational analysis techniques, fostering improved understanding and monitoring of surface current dynamics in coastal and regional seas.

C. VLab 3: “Carbon-Plankton Dynamics”

A comprehensive understanding of phytoplankton dynamics—the foundation of marine food webs—requires the integration of multidisciplinary datasets spanning biology, biogeochemistry, and physical oceanography. This use case demonstrates the interoperability and analytical capabilities offered by the Carbon-Plankton Dynamics VLab, which enables the combination of diverse data sources to support advanced modeling approaches. Specifically, the VLab framework facilitates (i) the implementation of a mechanistic model to identify the drivers of phytoplankton abundance, and (ii) the application of a machine learning algorithm to estimate carbon sequestration.

This VLab introduces a workflow for executing mechanistic models of the Nutrient-Phytoplankton-Zooplankton-Detritus (NPZD) type, utilizing near real-time data to quantify the respective influences of bottom-up and top-down drivers on phytoplankton dynamics. NPZD models are widely used in marine ecosystem studies and describe key components of the marine biogeochemical system with varying levels of complexity. Two specific model implementations are included: a basic NPZD model with fixed elemental stoichiometry, adapted from the formulations of [4] and [5], and an extended NPZD model of the quota type, based on [6] and expanded following [7]. Both model configurations simulate carbon and nitrogen cycling within the pelagic ecosystem.

The basic NPZD model is employed to demonstrate a workflow for uncertainty assessment. It simulates phytoplankton dynamics based on nutrient concentrations and zooplankton biomass, using near real-time data to quantify the contributions of bottom-up drivers (nutrients, sea surface

temperature, and photosynthetically active radiation) and top-down controls such as zooplankton grazing. The carbon dynamics are modelled in alignment with the marine biological carbon pump. Photosynthetic uptake of atmospheric carbon by phytoplankton initiates a downward transport of organic material through trophic interactions and sedimentation. This particulate organic matter is remineralized at depth, returning carbon to the system as dissolved inorganic carbon (DIC), thus participating in global carbon regulation.

Model validation is conducted by comparing simulated outputs, such as phyto- and zooplankton biomass, with field observations. The Root Mean Square Error (RMSE) is used as a performance metric. Multiple simulations are run using varied parameterizations, and the best-performing 10% (those with the lowest RMSE) are selected to generate predictions and define confidence intervals. For efficiency, a reduced subset of the best 5% simulations may also be used to estimate the relative contributions of drivers while minimizing computational demands.

The extended NPZD model incorporates a one-dimensional vertical water column and a simplified benthic layer. It includes two distinct nutrient pools: reduced inorganic nitrogen (NH_4^+) and oxidized inorganic nitrogen (NO_3^-). These are assimilated by two phytoplankton groups, each exhibiting variable C/N ratios, while zooplankton maintains a fixed elemental ratio. Phytoplankton also releases dissolved organic matter through leakage and exudation, which is further partitioned into carbohydrate and non-carbohydrate fractions. The carbohydrate component is involved in marine snow formation, which sinks and is subject to remineralization processes. Both phytoplankton and zooplankton mortality contribute to a detritus pool, which also undergoes vertical transport and transformation into dissolved organic material.

Remineralization occurs via oxic and anoxic processes, as well as denitrification, and is modulated by oxygen availability, which is explicitly modeled as a state variable. Oxygen dynamics are linked to carbon fixation and respiratory processes, governed by fixed stoichiometric ratios. Additionally, the model includes air-sea gas exchange mechanisms for CO_2 and O_2 based on the parameterizations proposed by Wanninkhof (2014). The CO_2 flux enters a DIC pool and interacts with total alkalinity (TA) to determine acid-base chemistry, with pH computed as a derived variable.

D. VLab 4: “Marine Environmental Indicators”

The Marine Environmental Indicators (MEI) VLab enables users to monitor and evaluate the environmental conditions of marine areas, providing essential support for decision-making in ocean management. By integrating multiple data sources, the platform offers a unified data analysis service, facilitating online computation of indicators through Jupyter Notebooks or a dedicated web application. This application leverages the VRE Analytics Engine services to generate indicator outputs. This VLab is divided into three sections representing three indicators: Marine Heatwaves (MHW), Ocean Heat Content (OHC) and Trophic Index (TRIX).

The MHW Indicator aims to assess the environmental status of marine areas based on prolonged periods of anomalously high sea surface temperatures (SSTs).

Over recent decades, global ocean warming, particularly in the Mediterranean Sea, has led to increased intensity, frequency, and duration of these events. MHWs are defined as periods when SSTs exceed the 90th percentile of a baseline period for at least five consecutive days. This threshold-based approach considers both the duration and intensity of warming, making it a widely accepted standard for identifying MHWs [8]. The Mediterranean Sea is a hotspot for MHWs due to its semi-enclosed nature, high regional SST variability, and sensitivity to atmospheric and oceanic changes.

The Mediterranean Sea has shown an accelerated warming trend, with SST increases ranging from 0.034 to 0.048 °C/year, surpassing the global average [9]. MHWs have been reported across various Mediterranean sub-basins, with notable events in 2003, 2012, 2017, and 2022. These events were characterized by SST anomalies exceeding 4°C and durations extending up to several months. For instance, the 2003 event affected 46-70% of the Mediterranean, with SST anomalies reaching up to 7°C, extensively studied for its ecological and economic impacts [9]. In contrast, the 2022 MHW set records for its duration and geographic spread, covering up to 70% of the basin [10].

The occurrence of MHWs results from complex interactions between atmospheric and oceanic processes. Key drivers include atmospheric forcing such as increased solar radiation, reduced cloud cover, and persistent anticyclonic conditions. Ocean dynamics also play a critical role, with reduced vertical mixing, strong stratification, and advection of warm water masses amplifying their effects. Additionally, large-scale climate modes such as the East Atlantic Pattern and North Atlantic Oscillation significantly modulate the characteristics of these events [9].

MHWs have profound impacts on both ecological and socio-economic systems. Ecologically, they cause mass mortality of marine species, disrupt ecosystems, and drive shifts in species distributions [9]. Economically, they result in substantial losses for fisheries and aquaculture, while also affecting industries reliant on marine biodiversity. These impacts underscore the need for robust monitoring and forecasting systems. Recent advancements, such as the Copernicus Marine Service, have significantly enhanced our ability to detect and predict MHWs. Short-term forecasting systems, including the Mediterranean Forecasting System (MedFS), have demonstrated reliability in predicting the onset, intensity, and duration of these events, aiding in mitigation efforts [10].

Despite significant progress, several challenges remain. Variations in MHW definitions and detection methodologies hinder cross-regional comparisons. Additionally, the limited understanding of subsurface MHWs and their vertical extent presents a research gap. Uncertainty in predicting long-term trends under various emission scenarios and inadequate data on socio-economic impacts also complicate adaptive measures.

To bridge current knowledge and response gaps, future research should focus on strengthening monitoring capabilities by integrating satellite observations with in situ measurements. Equally important is the quantification of socio-economic impacts and the identification of the most

vulnerable regions, which will enable the development of targeted and effective mitigation strategies. Translating scientific understanding into actionable climate adaptation policies will be crucial to enhancing societal and ecological resilience to these extreme events.

In summary, MHWs are key indicators of ocean health and the broader effects of climate change. Advancing their detection, monitoring, and forecasting is vital for reducing their impacts and supporting the sustainable management of marine ecosystems. As a well-recognized hotspot, the Mediterranean Sea provides critical insights into the changing dynamics of MHWs and their far-reaching implications

The OHC is considered an important Ocean Monitoring Indicator of ocean warming due to climate change. With about 90% of the excess heat accumulated in the Earth system deposited in the world's ocean, the Earth Energy Imbalance causes rising ocean temperatures and increasing ocean heat content (OHC). [11,12,13] provide every year an updated estimate of OHC for the global ocean and its regional basins starting from the World Ocean Database data. The Copernicus Marine Service also provides in its Ocean Monitoring Indicators catalogue the Mediterranean OHC Anomaly (0-700m) time series and trend from Reanalysis & Multi-Observations Reprocessing, but without a systematic yearly update. The Mediterranean Sea is the ocean region that shows the highest warming, thus it is extremely important to have a rapid and efficient OHC assessment. The aim of this OHC indicator is to provide to the users an operational workflow to rapidly estimate the OHC indicator in the Mediterranean Sea from multiple historical datasets using the DIVAnd mapping tool for gridding temperature in situ data.

The evaluation of OHC indicator in the Mediterranean Sea domain is linked to several input data sources. The in-situ temperature data spanning the time period after 1950 comes from CMEMS CORA, EuroArgo, World Ocean Database and SeaDataNet is gathered querying the beacon monolithic instances available to the Blue-Cloud VLabs. The data is then an input to the DIVAnd tool for the generation of sliding decadal gridded fields to be used for the computation of the OHC from various data sources. The present implementation of the OHC indicator uses temperature gridded fields computed [14,15], but new temperature gridded fields from the above-mentioned sources are in development. The OHC notebook will be updated accordingly. Moreover, once the Blue Cloud EOV dataset will be produced, the relative OHC estimation will be integrated in the workflow.

The users can compute the OHC in sub-regions of the Mediterranean Sea, in different layers of the water column between the sea surface and 2000 m depth and for selected time periods

The assessment of the risks and impacts of eutrophication in estuarine and coastal waters is one of the key issues in marine environmental management [16]. The Trophic index (TRIX), introduced by [17] to characterise the trophic conditions of seawater, is a linear combination of the logarithms of four state variables (Chl-a, DIN, TP and the absolute percentage deviation from oxygen saturation, aD %O). Therefore, this composite index aggregates pressure (nutrients), biological response (Chl-a, a proxy for biomass) and environmental disturbance in the water quality (oxygen) [18].

The trophic state depends on the availability of nitrogen and phosphorus for primary production, which in terms determines the phytoplankton biomass and oxygen saturation. In TRIX the nutrients are represented ideally by total nitrogen and total phosphorus; chlorophyll-a is a substitute parameter for phytoplankton biomass, as production is not routinely measured; and the deviation of oxygen saturation from 100% (aD%O) in the productive layer indicates the production intensity of the system [18]. This simple index permits one to synthesise key eutrophication variables into a simple numeric expression to make information comparable over a wide range of trophic situations, while avoiding the subjectivity in the usage of traditional trophic terminology.

E. VLab 5: “Global Fisheries Atlas”

The Global Fisheries Atlas VLab acts as a comprehensive platform built on top of authoritative data or knowledge sources describing fisheries activities [19].

This VLab aims to better describe fisheries activities at a global scale by disseminating standardized knowledge and data [20]. More than ten sources have been harmonized and are accessible from the Global Fisheries Atlas. The VLab content is made accessible by various entry points either through graphical user interface (GUI) or programmatic access (e.g. API, SPARQL endpoint) to fit different needs and users profiles. Web mapping applications are made available to browse and explore Global Record of Stocks and Fisheries (GRSF) knowledge base and Global Tuna Atlas, both describing fisheries activities at a global scale [21]. Beyond data sources already integrated, this VLab provides methods and tools to reproduce, update or customize this work to deal with other use cases.

High-resolution data in the fisheries domain (meaning at the fishing operation level) are often confidential, primarily due to economic and strategic interests. However, there is an increasing demand from both scientists and citizens for fisheries data, information, and knowledge to be made accessible in order to address emerging scientific questions and support informed decision-making. Despite this, there is currently no global policy or EU directive enforcing the compliance with FAIR principles for fisheries data, nor is there a standardized fisheries data management framework comparable to the e.g. INSPIRE or Water framework directives, which mandate the FAIRness of spatial data by implementing OGC standards.

As a result, we demonstrate that there is a way forward in this direction by using pre-harmonized public domain datasets that are reported by countries to the tuna Regional fisheries management organizations (RFMOs) at a lower spatio-temporal resolution (e.g. using grids at a 1° or 5° per month). Though these datasets are made freely available on tuna RFMOs Websites, they have not been assigned DOIs to ensure proper preservation and citation, and they don't share the same structure. Indeed, unlike other domains, the fisheries sector lacks widely adopted *de facto* or international standards for both data formats and access protocols. This is the reason why VLab 5 provides a FAIR data generation workflow which harmonizes these heterogeneous tuna fisheries datasets by complying with the CWP standardized data structure promoted by FAO for fisheries domain data. The VLab currently focuses on the key use cases of tuna fisheries as all fisheries datasets worldwide can't all be

harmonized in the framework of a single project. Both FAIR data and code generated by the Global Fisheries Atlas are made available out of the VLab in widely used repositories (e.g. Zenodo or Software Heritage) and reproducibility is fostered by using containerization and continuous integration [22,23].

III. DISCUSSION

The five V Labs introduced within the context of the Blue-Cloud 2026 project, and accessible to the public through registration on the Blue-Cloud platform, serve as a powerful demonstration of the capabilities that can be achieved when combining FAIR data principles with cross-disciplinary collaboration. These V Labs are not only a key component of the Blue-Cloud 2026 initiative but also act as a model for how data-driven scientific platforms can foster new insights across a range of marine and environmental sciences.

Currently available in their beta versions, these V Labs are undergoing continuous development, with the final releases expected by the end of the year. During this phase, the team is actively gathering feedback from users to refine the services, ensuring that they meet the diverse needs of researchers, policymakers, and other stakeholders in the field. This iterative approach is essential for enhancing the accessibility, functionality, and overall user experience of the platform.

As the Blue-Cloud 2026 project continues to unfold, the V Labs are poised to make a significant contribution to advancing marine and environmental research. By integrating data from various sources and facilitating advanced analytical tools, they support the development of actionable knowledge on critical issues such as climate change, biodiversity, and ocean health.

Furthermore, the Blue-Cloud 2026 initiative is aligned with and will contribute to larger-scale projects such as the European Open Science Cloud (EOSC) and the European Digital Twin of the Ocean (EDITO). These projects, built upon the principles of open, accurate, and interoperable data, are crucial in empowering the scientific community and ensuring that the findings and innovations developed within these platforms are accessible to policymakers. The integration of these V Labs into the broader digital infrastructure landscape will help bridge the gap between scientific research and policy decision-making, promoting evidence-based approaches to environmental management and sustainability.

Ultimately, the Blue-Cloud 2026 project's Virtual Labs are a key stepping stone towards realizing the vision of an interconnected, data-driven research ecosystem. By continuing to refine these platforms, we hope to contribute to the long-term advancement of marine and environmental sciences, facilitating collaborations that will address some of the most pressing global challenges.

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