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EDITED BY
Simone Marini,
National Research Council (CNR), Italy

REVIEWED BY
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Peter Leslie Croot,
University of Galway, Ireland

*CORRESPONDENCE
Abed El Rahman Hassoun
ahassoun@geomar.de

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A first scoring approach for evaluating the European Ocean Observing Community

Abed El Rahman Hassoun[1*], Toste Tanhua[1], Emma Heslop[2], Inga Lips[3], Marta Álvarez[4], George Petihakis[5], Maribel I. García-Ibáñez[6], Dimitris Velaoras[7], Michele Giani[8], Hermann W. Bange[1], Christian Lønborg[9] and Johannes Karstensen[1]

[1]GEOMAR Helmholtz Centre for Ocean Research Kiel, Kiel, Germany, [2]Intergovernmental Oceanographic Commission of UNESCO, Paris, France, [3]European Global Ocean Observing System (EuroGOOS) AISBL, Brussels, Belgium, [4]Centro Oceanográfico de A Coruña, Instituto Español de Oceanografía (IEO, CSIC), A Coruña, Spain, [5]Institute of Oceanography, Hellenic Centre for Marine Research, Crete, Greece, [6]Centre Oceanogràfic de les Balears, Instituto Español de Oceanografía (IEO, CSIC), Palma, Spain, [7]Institute of Oceanography, Hellenic Centre for Marine Research, Anavyssos, Greece, [8]National Institute of Oceanography and Applied Geophysics, Trieste, Italy, [9]Section for Marine Diversity and Experimental Ecology, Department of Ecoscience, Aarhus University, Roskilde, Denmark

The European Ocean Observing Community (EOOC) integrates inputs from diverse entities dedicated to comprehensively monitoring and forecasting oceanic phenomena in European Seas. With increasing climate and anthropogenic pressures, the urgency of ensuring the EOOC's preparedness to observe Essential Ocean Variables (EOVs) is evident. This paper advocates for the adoption of a scoring approach designed to evaluate the readiness of the EOOC in observing and forecasting key ocean phenomena. The proposed scoring methodology can be applied at both European and potentially regional and/or national levels, and emerges as a transformative tool for scrutinizing the EOOC's capability to predict and monitor key ocean phenomena. Our findings, based on the application of the scoring approach, suggest that while the community demonstrates commendable readiness levels for certain oceanic phenomena, 83% remain in developing stages, oscillating between "Idea" and "Trial" readiness levels. A closer examination exposes critical shortages predominantly in the coordination and observational facets (Process), and data management and information products (Output). The implications of these identified gaps reach far beyond academic realms, profoundly affecting diverse sectors and societal resilience (e.g., energy sector). The suggested scoring approach serves as a clear call for strategic investments and heightened support for the European observing community. By adopting a regular and systematic scoring methodology, we not only measure progress at present but also pave the way for a resilient and future-ready EOOC.

KEYWORDS

ocean observing, ocean forecasting, scoring, readiness level, European Seas

1 Introduction

The European Ocean Observing Community (EOOC; term recently introduced by Hassoun et al. (2024)), represents a collaborative network of observers and modelers from various European institutes, organizations, networks, and data portals. This network is dedicated to comprehensively monitor, analyze, and forecast any observable or measurable event, process, or pattern (ranging from localized events to global patterns) that occurs within the ocean's physical, chemical, biological, or geological systems, referred to here as ocean phenomena. Therefore, the EOOC covers a wide range of oceanic disciplines, from physical to biological, and operates across both coastal and open-ocean settings, extending beyond European Seas to the global ocean. The EOOC's initiatives play a crucial role in addressing key challenges such as climate change mitigation, marine resource management (Tanhua et al., 2024), and advancing scientific understanding of ocean dynamics. This is achieved not only by setting requirements for harmonizing the observation of key ocean variables and standardizing measurement practices but also by providing meaningful data and products that guide and inform EU's directives (e.g., the Maritime Strategy Framework Directive[1]) and ultimately EU legislation and environmental targets and strategies (e.g., The European Green Deal[2], and the 2050 climate neutral strategy[3]). However, the sustained effectiveness of the EOOC's initiatives hinges on the identification and rectification of its existing gaps, regularly and systematically, beyond the lifetime of generally short-term projects and observing efforts. The diversity of research topics, priorities, needs, and methodologies within the EOOC arises from disparate national and institutional objectives, leading to disjointed ocean observations, and thus services, across Europe (Hassoun et al., 2024). This variability extends to the types of observations conducted, variables monitored, methodologies employed, practices followed, temporal and geographical coverage, and the diversity of ocean components monitored (European Marine Board, 2019; Martín Míguez et al., 2019). This results in both temporal and spatial observation gaps hampering the readiness level (RL) of the EOOC's initiatives to meet emergent societal needs and challenges. Considering the substantial investments in ocean observing, the EOOC must work on improving the RLs of its components to observe Essential Ocean Variables (EOVs)[4] in real-time and with low uncertainties. EOVs are a set of key variables identified to monitor and assess the state of the ocean and its interactions with the Earth's climate system, and are defined by the Global Ocean Observing System (GOOS)[5]. Given the changing oceanic landscape due to anthropogenic pressures, the EOOC initiatives' preparedness (readiness or fit-for-purpose) is important to forecast short- and long-term patterns and provide timely warnings. Collaborative efforts among stakeholders, researchers, and policymakers are indispensable to ensure that the efforts of the EOOC remain reliable and scientifically relevant, and are able to guide Europe toward a more informed society and a resilient European Seas.

To systematically evaluate the RL of the EOOC's initiatives in its observing and forecasting ability, we propose here a scoring approach for the technological readiness level (TRL) of monitoring and forecasting key ocean phenomena following the Framework of Ocean Observing (FOO) (Lindstrom et al., 2012). Our scoring approach uses a previously established methodology (Hassoun et al., 2023) and expands it to a broader community of ocean observers through a comprehensive survey. The collected data were aggregated and averaged, and the results presented here demonstrate the validity and applicability of the proposed scoring framework. This scoring approach serves (i) to pinpoint gaps obstructing the comprehensive monitoring and forecasting of ocean phenomena and (ii) to provide straightforward metrics that could help guide stakeholders (funders, supporters, etc.) and users within the EOOC. The proposed scoring approach is suggested to be applied in other parts of the world's ocean where an evaluation of the observing and forecasting capabilities is needed.

2 Methodology

To develop the proposed scoring approach, we relied on the European Union (EU)-funded action EuroSea deliverable D1.9[6] elaborated in Hassoun et al. (2024). Briefly, an exhaustive examination of key EU projects and peer-reviewed publications was conducted to identify gaps in observing and forecasting key ocean phenomena and threats at the EU level. These phenomena, such as marine biodiversity and non-indigenous species, food webs, ocean warming, ocean acidification, eutrophication, deoxygenation, and plastic pollution, among others, align with the Good Environmental Status (GES) of the EU Marine Strategy Framework Directive (MSFD)[7] and phenomena and threats covered by Copernicus Marine Environment Monitoring Service (CMEMS)[8]. While the original scoring approach was developed by a smaller team (Hassoun et al., 2023), this paper extends its application by incorporating feedback from a broader community of observers through a survey. This survey aimed to assess the feasibility of the scoring approach and obtain more reliable scores from experts in specific fields, which helped to better highlight the strengths and weaknesses of the proposed scoring approach.

The FOO table, which contains the items used to conduct the scoring, was developed by IOC-UNESCO[9] experts, who are mainly oceanographers. As a result, the existing criteria can only be applied

1 EU Marine Strategy Framework Directive - European Commission (europa.eu).

2 The European Green Deal - European Commission (europa.eu).

3 2050 long-term strategy - European Commission (europa.eu).

4 Essential Ocean Variables – Global Ocean Observing System (goosocean.org).

5 Global Ocean Observing System – GOOS is a permanent global system for observations, modeling, and analysis of marine and ocean data (goosocean.org).

6 D1.9_Gaps_of_the_European_Ocean_Observing_and_Forecasting_System.pdf (geomar.de).

to typical ocean dynamics, such as the ocean phenomena identified through the GES of the MSFD and threats by CMEMS. In this paper, we did not further develop new items or criteria to score other aspects of the EOOC initiatives that cannot be evaluated using the existing FOO criteria, such as the interdisciplinarity of observations, the efficiency of observational networks, the accuracy of modeling, policies and legislations, coordination and management, awareness and literacy, etc. Therefore, the scoring was exclusively applied to the following 18 phenomena: Biodiversity and Non-Indigenous Species (NIS), Food Webs, Eutrophication, Ocean Warming, Ocean Acidification, Ocean Carbon Storage, Ocean Deoxygenation, Non-Carbon Greenhouse Gases (GHGs), Contaminants, Plastic Pollution, Sea Level Rise (SLR), Sea Ice, River Inputs, Oil Leakage, Sea Floor Integrity/Bathymetry, Underwater Noise, Geological geohazards, and Human Activities.

2.1 The scoring approach

To evaluate the performance and readiness of the EOOC initiatives in observing and forecasting key ocean phenomena, we relied on the FOO concept, initially developed as TRLs by NASA (National Aeronautics and Space Administration) (Sadin et al., 1989), and later adopted and edited by Lindstrom et al. (2012) to develop the concept of the 9 ocean observing Readiness Levels (RLs). While both TRLs and RLs assess readiness and maturity, TRLs specifically focus on the technological aspect. TRLs are not a measure of the design validity; instead, they indicate the maturity level of specific critical technology elements at the time it is evaluated (DoD, U.S, 2023). In contrast, RLs refer to the readiness of various systems of observing and forecasting, processes, or organizations to accomplish specific tasks or objectives. The RLs can encompass technological readiness but may also include other factors such as organizational readiness, stakeholder readiness, and regulatory readiness. Moreover, RLs are often used to assess the preparedness of an entity to undertake a particular action or initiative.

Therefore, our scoring approach uses the concept of RLs and evaluates three pillars of the ocean observing value chain: "Requirements = inputs", "Observations = processes", and "Data and Information = outputs" (Pearlman et al., 2019). This evaluation addresses the requirement setting process on: - Why to observe a specific phenomenon? What should be observed to cover this phenomenon? How should this phenomenon be observed? It also examines the outputs related to data management, products, and services used to understand trends and impacts. The 9 RLs are grouped into three categories based on their advancement: "Concept", "Pilot," and "Mature" (Lindstrom et al., 2012).

Although the criteria for these advancement levels are rather general, we applied them to assess the RLs of the EOOC's past and current initiatives in observing and forecasting various ocean phenomena. Scores were assigned to items/criteria at each level on a level-by-level basis. Full compliance with the criteria yields a score of 100% for a given level, while a score of 80% is defined as a "pass" to the next level. We established this threshold to harmonize our scoring approach with a similar approach recently used by Lange et al. (2023) for "Data Management and Information Products" linked to high-quality biogeochemical EOVs data synthesis products, demonstrating its usefulness in evaluating various components of the ocean observing value chain.

In our scoring approach, the RLs for each of the three FOO pillars were evaluated to identify gaps in the inputs, processes, and outputs (Table 1). It is noteworthy to highlight that the EOOC might meet some requirements at higher levels while not fulfilling the criteria for the 80% threshold at lower levels. For example, "*Ocean Warming*" received an RL of 7 for the Input pillar despite achieving a score of 86% at Level 9, because its score at Level 8 was below 80%, preventing it from exceeding Level 7 (Table 1). Detailed scoring documents are available in Hassoun et al. (2023).

2.2 Community feedback

To ensure an inclusive scoring process and gather feedback from experts within the EOOC, we widely circulated the developed scoring approach (Hassoun et al., 2023). Despite distributing the survey through numerous private and institutional mailing lists and social media channels, we received feedback from a limited number (n = 9) of experts on specific ocean phenomena based on their respective expertise. The respondents were affiliated to research institutes across five different EU countries (Table 2). Most of them are involved in ocean observation and monitoring planning, highlighting the importance of their feedback in accurately scoring the RL of the EOOC initiatives.

In this paper, the scores resulting from our own assessment (Hassoun et al., 2023) were averaged together with the ones from the EOOC experts, refined through direct consultations with them to clarify ambiguities in the scoring and discuss recommendations. The final scores (RLs featured in this paper) represent the arithmetic average (mean) of the aggregated scores. The average was chosen because it provides a clear and interpretable measure of central tendency, allowing us to combine diverse expert opinions into a single representative score. While this method assumes that the scoring levels are numerically equidistant (i.e., the difference between any two consecutive scores is consistent), this assumption was deemed acceptable based on the design of the scoring approach, which uses ordinal scales reflecting relative differences in capacity.

3 Results and discussion

In this section, we discuss the gaps in observing and forecasting each of the 18 included phenomena in a consistent manner. The scores provided by each respondent for every pillar are presented in

7 Descriptors under the Marine Strategy Framework Directive - European Commission (europa.eu).

8 Phenomena & Threats | CMEMS (copernicus.eu).

9 Intergovernmental Oceanographic Commission | Intergovernmental Oceanographic Commission (unesco.org).

TABLE 1 An example of a scoring case for "Ocean Warming" based on FOO RLs concept.

FOO Readiness Levels	Requirements Processes (Input)		% per level	RL	Coordination of Observational Elements (Process)		% per level	RL	Data Management & Information Products (Output)		% per level	RL
Mature												
Level 9 "Sustained"	Essential Ocean Variable: • Adequate sampling specifications	3	100%		System in Place: • EU	3	78%		Information Products Routinely Available: • Product generation standardized	3	83%	
					• Sustained indefinitely	2						
	• Quality specifications	3			• Periodic review	2			• User groups routinely consulted	2		
Level 8 "Mission qualified"	Requirements "Mission Qualified:" • Longevity/stability	2	67%		System "Mission Qualified:" • Regional implementation	3	89%		Data Availability: • EU available	2	67%	
					• Fully scalable	2						
	• Fully scalable	2			• Available specifications and documentation	3			• Evaluation of utility	2		
Level 7 "Fitness for purpose"	Validation of Requirements: • Consensus on observation impact	3	89%	7	Fitness-for-Purpose of Observation: • Full-range of operational environments	3	100%	8	Validation of Data Policy: • Management	3	83%	7
	• Satisfaction of multiple user needs	2			• Meet quality specifications	3			• Distribution	2		
	• Ongoing EU/international community support	3			• Peer review certified	3						
Pilot												
Level 6 "Operational"	Requirement Refined: • Operational environment	3	100%		Implementation Plans Developed: • Maintenance schedule	3	100%		Demonstrate: • System-wide availability	3	89%	
									• System-wide use	3		
	• Platform and sensor constraints	3			• Servicing logistics	3			• Interoperability	2		
Level 5 "Verification"	Sampling Strategy Verified: • Spatial	3	83%		Establish: • EU/International commitments and governance	3	100%		Verify and Validate Management Practices: • Draft data policy	3	83%	
	• Temporal	2			• Define standardized components	3			• Archival plan	2		
Level 4 "Trial"	Measurement Strategy Verified at Sea	3	100%		Pilot project in an operational environment	3	100%		Agree to Management Practices: • Quality control	3	100%	
									• Quality assurance	3		
									• Calibration	3		
									• Provenance	3		

(Continued)

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TABLE 1 Continued

FOO Readiness Levels	Requirements Processes (Input)		% per level	RL	Coordination of Observational Elements (Process)		% per level	RL	Data Management & Information Products (Output)		% per level	RL
	Concept											
Level 3 "Proof of concept"	Proof of Concept via Feasibility Study: • Measurement strategy	3	100%		Proof of Concept Validated: • Technical review	3	100%		Verification of Data Model with Actual Observational Unit	3	100%	
					• Concept of operations	3						
	• Technology	3			• Scalability (EU seas/ocean basin)	3						
Level 2 "Documentation"	Measurement Strategy Described: • Sensors/Automatic tools	3	100%		Proof of Concept: • Technical capability	3	100%		Socialization of Data Model: • Interoperability strategy	3	100%	
					• Feasibility testing	3						
					• Documentation	3						
	• Sensitivity/Dependencies	3			• Preliminary design	3			• Expert review	3		
Level 1 "Idea"	Environment Information Need and Characteristics Identified: • Physical • Chemical • Biological	3	100%		System Formulation: • Sensors/Automatic tools	3	100%		Specify Data Model: • Entities, Standards	3	100%	
					• Platforms	3			• Delivery latency	3		
					• Candidate technologies	3			• Processing flow	3		
					• Innovative approaches	3						

Table colors align with those used in the Framework for Ocean Observing (FOO) table as described by Lindstrom et al. (2012), ensuring consistency and comparability.

TABLE 2 Background of the survey respondents.

Respondent	Country	Number of phenomena scored	Role in EOOC
1	Germany	1	Ocean observation/monitoring planning
2	Greece	1	Ocean observation/monitoring operations and data collection
3	Spain	2	Ocean observation/monitoring planning
4	Spain	3	Ocean observation/monitoring operations and data collection
5	Denmark	3	Ocean data analysis
6	Greece	8	Ocean observation/monitoring planning
7	Italy	5	Ocean observation/monitoring operations and data collection
8	Germany	5	Ocean observation/monitoring planning
9	Germany	18	Ocean observation/monitoring planning

Table 3. More in-depth information related to gaps beyond the observation of key ocean phenomena (e.g., Data FAIRness, marine policies and legislation, coordination and management, and ocean literacy) have been recently published by Hassoun et al. (2024) and Tanhua et al. (2024). We begin each section with a summary of the scores across the three pillars: "Requirements Processes = Inputs", "Coordination of Observational Elements = Processes", and "Data Management & Information Products = Outputs". Following this, we provide detailed explanations of the scores in each pillar, along with clear recommendations for improvement for each phenomenon as shown in Table 4. By presenting the information in this consistent format, we aim to help readers easily compare the different phenomena's RLs and replicate this exercise to evaluate other regional and/or national observing communities.

3.1 General results of the scoring

Several phenomena exhibit varying RLs across the three pillars of "Requirements Processes = Inputs", "Coordination of Observational Elements = Processes", and "Data Management & Information Products = Outputs" (Table 3). This variation indicates the degree to which different oceanic phenomena are understood, monitored, and managed within European Seas. For instance, phenomena such as "Sea Level Rise" and "Eutrophication" show a nearly balanced score distribution across the three pillars, suggesting a relatively even focus on Inputs, Processes, and Outputs in these phenomena (Table 3). Conversely, the focus of "Oil Leakage" and "Geological Geohazards" is primarily concentrated in the Inputs and Processes pillars, with minimal attention to the Outputs pillar, which highlights the need for improvement in the development of data management and information products for these phenomena. In contrast, "Plastic Pollution" has a large focus on Inputs, suggesting that more resources or attention are being directed towards requirements and processes rather than observational coordination or output products.

Additionally, the concept of the "Valley of Death" is highly relevant to the scores presented in Table 3, where several ocean phenomena, such as Eutrophication, Ocean Carbon Storage, Ocean Acidification, Ocean Warming, Seafloor Integrity/Bathymetry, Food Webs, and Sea Ice, are rated 4-6 for "Data Management & Information Products = Outputs". This reflects a critical bottleneck in moving from RLs 4 to 6, often referred to as the "Valley of Death", where many technologies struggle to transition from prototype to reliable operational systems in real-world environments (Ford et al., 2007; Bauer et al., 2015; Hensen et al., 2015). For these ocean phenomena, the main limiting factors appear to be related to data validation, quality assurance/quality control (QA/QC), and archiving, rather than sensor development. This underscores the urgent need for a greater focus on enhancing data management infrastructure and support services to ensure that ocean monitoring systems can progress beyond this critical development stage and achieve full operational readiness. Given the various ongoing European initiatives, such as the Digital Twin of the Ocean[23] projects (e.g., EDITO[24], DTO-BIOFLOW[25], and DIGI4ECO[26]), which may enhance these scores—particularly in the third pillar, "Data Management & Information Products = Outputs", where data harmonization is urgently required—the following results can provide valuable guidance on the most pressing areas for action.

3.2 Scores for each phenomenon

In this section, the approach and its scores are concisely interpreted to showcase their relevance. A summary of the scores' interpretation can be found in Table 3. A detailed analysis of gaps and

23 European Digital Twin of the Ocean (European DTO) - European Commission (europa.eu).

24 European Digital Twin Ocean - EDITO.

25 Biodiversity Data for Digital Twins of the Ocean | DTO-BIOFLOW.

26 The Project | Digi4Eco.

TABLE 3 Detailed scores provided by the respondents for each ocean phenomenon across each pillar.

Phenomenon	Requirements Processes (Input)									
	1	2	3	4	5	6	7	8	9	Av.
Biodiversity & NIS						6	4		5	5
Food Webs						6			5	6
Eutrophication					9	6			6	7
Ocean Warming		4				9		7	7	7
Ocean Acidification			9	1	9		2	5	9	6
Ocean Carbon Storage			9	1	9		4	6	9	6
Ocean Deoxygenation				3			4	6	5	5
Non-Carbon GHGs	4								3	4
Contaminants						6	1		4	4
Plastic pollution						4		3	5	4
SLR						9			4	7
Sea ice									4	4
River inputs									5	5
Oil leakage									1	1
Sea floor integrity/Bathymetry									5	5
Underwater noise						7			4	6
Geological geohazards									3	3
Human activities									6	6

Phenomenon	Coordination of Observational Elements (Process)									
	1	2	3	4	5	6	7	8	9	Av.
Biodiversity & NIS						5	1		3	3
Food Webs						4			4	4
Eutrophication					9	6			6	7
Ocean Warming		1				5		6	8	5
Ocean Acidification			5	1	9		5	4	7	5
Ocean Carbon Storage			5	1	9		1	5	7	5
Ocean Deoxygenation				3			2	4	5	4
Non-Carbon GHGs	1								2	2
Contaminants						6	1		3	3
Plastic pollution						2		4	2	3
SLR						8			5	7
Sea ice									4	4
River inputs									4	4
Oil leakage									2	2
Sea floor integrity/Bathymetry									5	5
Underwater noise						7			4	6
Geological geohazards									4	4
Human activities									4	4

Phenomenon	Data Management & Information Products (Output)									
	1	2	3	4	5	6	7	8	9	Av.
Biodiversity & NIS						3	1		2	2
Food Webs						3			4	4
Eutrophication					9	5			3	6
Ocean Warming		2				1		5	7	4
Ocean Acidification			5	1	9		1	3	7	4
Ocean Carbon Storage			5	1	9		1	5	7	5
Ocean Deoxygenation				1			1	1	5	2
Non-Carbon GHGs	1								2	2
Contaminants						5	1		4	3
Plastic pollution						1		2	1	1
SLR						9			5	7
Sea ice									4	4
River inputs									3	3
Oil leakage									1	1
Sea floor integrity/Bathymetry									4	4
Underwater noise						3			1	2
Geological geohazards									4	4
Human activities									3	3

Numbers from 1 to 9 refer to the individual respondents, and 'Av.' refers to the average RL calculated based on all the scores.
Table colors align with those used in the Framework for Ocean Observing (FOO) table as described by Lindstrom et al. (2012), ensuring consistency and comparability.

TABLE 4 Summary of the scores' interpretation in each pillar for each of the 18 ocean phenomena covered in this assessment.

Phenomenon	Requirements Processes (Inputs)	Coordination of Observational Elements (Processes)	Data Management & Information Products (Outputs)
Sea Level Rise	**7:** This relatively high score reflects the comprehensive deployment of satellite altimetry, tide gauges, and GPS stations providing precise measurements of sea level changes. Continued advancements in sensor technology and the expansion of observational networks are essential to capture the spatial variability of sea level rise and its drivers. Innovations such as satellite missions (e.g., Sentinel-6 Michael Freilich, Jason-CS) offer enhanced capabilities for monitoring sea level globally, providing crucial data for climate models and predictions.	**7:** This score indicates a strong integration of data from various sources, supported by international collaborations such as GLOSS and partnerships within the framework of the IOC. These efforts facilitate a comprehensive understanding of sea level dynamics. Enhancing data exchange and standardization protocols further strengthens predictive modeling and regional analyses, enabling tailored adaptation strategies for vulnerable coastal zones.	**7:** This score demonstrates the successful synthesis of sea level data into accessible formats for scientists, policymakers, and the general public. Initiatives like the Copernicus Marine Service and the Integrated Climate Data Center offer user-friendly platforms for accessing sea level data and projections. Ongoing development of data visualization tools and decision-support systems is vital to translate scientific findings into actionable knowledge, aiding in coastal planning, ecosystem conservation, and community resilience building.
Eutrophication	**7:** The community's robust data collection capabilities for dissolved inorganic nutrients and chlorophyll concentrations are crucial for identifying and assessing eutrophication and are continuously refined which explains the score. Enhancing spatiotemporal coverage, particularly in areas susceptible to nutrient runoff, is still needed.	**7:** The high level of coordination among different monitoring programs and regional conventions across Europe (i.e., HELCOM[10], OSPAR[11]) underscores a concerted effort to tackle eutrophication. Better collaborative efforts, to integrate biogeochemical data with physical observations, are needed to provide deeper insights into eutrophication processes and their ecological impacts.	**6:** While good progress has been made in managing eutrophication data, further advancements are necessary to improve accessibility and utility. Developing user-friendly data portals and advanced modeling tools can aid in the prediction of eutrophication trends and the evaluation of mitigation strategies.

(Continued)

TABLE 4 Continued

Phenomenon	Requirements Processes (Inputs)	Coordination of Observational Elements (Processes)	Data Management & Information Products (Outputs)
Ocean Carbon Storage	**6:** The score denotes a good capability to monitor carbon fluxes and storage in European Seas using various techniques (i.e., discrete measurements, use of satellite data to estimate biological carbon sequestration, etc.). Yet, the score indicates that advancing the spatiotemporal coverage remains a priority, particularly for capturing the short- and long-term variability of carbon storage in different oceanic regions and depths.	**5:** Collaborative efforts, through initiatives like the Ocean Carbon and Biogeochemistry (OCB)[12] Program and the International Ocean Carbon Coordination Project (IOCCP)[13], are effectively consolidating carbon storage data from various sources. The score highlights the success of these efforts but also the potential for further integration across multidisciplinary studies to create a more detailed global picture of ocean carbon storage dynamics. Capacity building in terms of equipment, training and support would also help improve the RLs.	**5:** This score reflects the effective management of data related to ocean carbon storage and the production of information products that are likely informing climate models and carbon budget assessments. Improving this score further would involve enhancing the real-time availability of data and ensuring that data products are readily interpretable for decision-making in carbon management and climate policy.
Ocean Warming	**7:** The community's strength in data collection for ocean warming is indicative of a comprehensive network of temperature sensors and remote sensing capabilities. Expanding the spatial coverage of these observations, particularly in under-monitored regions and the deep ocean, is critical for a complete understanding of ocean warming dynamics, particularly that there is a large reliance on sea surface temperature data and incomplete vertical coverage especially in continental shelves and near-shore areas where Argo coverage is limited.	**5:** While notable progress has been made in aggregating temperature data, the coordination among different data sources requires improvement. The establishment of a centralized data integration framework could enhance the consistency and utility of temperature data, supporting more accurate climate models and forecasts.	**4:** The score suggests advancements in managing data but also underscores the need for further refinement in data accessibility and usability. Developing standardized data formats and improving the interoperability of databases will enable more efficient analysis and dissemination of information pertinent to ocean warming effects.
Ocean Acidification	**6:** The score indicates an established community for monitoring pH levels and other complementary variables. This suggests the utilization of advanced techniques, coupled with standardized and simple[14] methodologies to measure ocean chemistry. Room for improvements may lie in expanding sensor networks to undersampled regions and refining the precision and accuracy accomplished through consensus and metrologically-traced best practices and reference materials of existing measurement technologies.	**5:** Effective coordination is evidenced by the sharing of data and methodologies among international monitoring programs and scientific consortia focused on ocean acidification. The score implies good integration yet points to potential benefits from enhancing real-time data exchange and further aligning European and global research efforts to predict and mitigate the effects of ocean acidification.	**4:** While data is being managed to inform stakeholders, the score suggests that the usability of these data should be enhanced. Developing more comprehensive and accessible databases, improving predictive models of ocean acidification impacts, and delivering this information in an understandable format to policymakers and the general public would increase the score in this category.
Food Webs	**6:** The EOOC's approach to monitoring marine food webs encompasses a variety of techniques (e.g., biological sampling, analysis using stable isotopes, remote sensing). Enhancing the resolution and coverage of these methods is essential for capturing the dynamics of marine food webs, particularly in response to environmental stressors such as ocean warming and acidification. Efforts to integrate novel technologies, like environmental DNA (eDNA) sequencing, can provide new insights into biodiversity and trophic interactions, which could enable more accurate food web models.	**4:** Achieving effective coordination among various monitoring programs and research initiatives is still challenging due to the complexity of food web interactions and the diversity of habitats. Strengthening collaborative networks and standardizing data collection protocols across disciplines are critical steps toward a cohesive understanding of marine food web structures. Initiatives such as the Marine Biodiversity Observation Network (MBON)[15] and the Australian Integrated Marine Observing System (IMOS)[16] exemplify how coordinated efforts can enhance food web research and conservation.	**4:** The integration of multidisciplinary data into comprehensive information products for translating food web dynamics into actionable knowledge needs further improvements. Developing centralized databases and analytical tools that can accommodate complex trophic data, including species interactions and energy flow, is necessary for informing ecosystem-based management strategies and conservation planning. Advancements in data visualization techniques will further aid in communicating food web changes to a broad audience.
Underwater Noise	**6:** This score reflects a robust framework for monitoring underwater noise, with effective use of technologies such as passive acoustic monitoring systems and hydrophones. The score shows a strong capability for capturing noise data[17] from sources like shipping, industrial activities, marine construction as well as biological sounds. There may still be potential for further advancements, including expanding acoustic monitoring networks and improving detection sensitivity to cover a wider frequency range and quieter soundscapes.	**6:** This score indicates successful coordination and standardization among various initiatives and organizations that monitor underwater noise, contributing to a comprehensive understanding of noise levels across different marine regions. Continued efforts could focus on enhancing real-time data sharing and expanding collaborative research to understand the cumulative impacts of noise on marine organisms and ecosystems.	**2:** This score highlights challenges in the management of underwater noise data and its translation into useful products. To improve this, there is a need for developing more sophisticated databases that can handle the complexity of acoustic data and create user-friendly tools that allow stakeholders to interpret and utilize these data effectively. Advancements may include better analytical models to predict the propagation of underwater noise and assess its biological impacts, as well as improved visualization

(Continued)

TABLE 4 Continued

Phenomenon	Requirements Processes (Inputs)	Coordination of Observational Elements (Processes)	Data Management & Information Products (Outputs)
			tools to communicate these effects to policymakers and the general public.
Sea Floor Integrity/ Bathymetry	**5:** This score suggests that there are verified techniques in place for monitoring the integrity of the seafloor and collecting bathymetric data (e.g., multibeam sonar mapping and sub-bottom profiling). This score also indicates room for further refinement, especially in improving high-resolution mapping in deep-sea environments and more remote areas.	**5:** This score reflects a good level of coordination among various programs and institutions involved in seafloor monitoring, indicating effective sharing of bathymetric data and methodological approaches. Strengthening international collaborations, such as through the International Hydrographic Organization (IHO), could further enhance the collection and sharing of bathymetric data and enhance the score.	**4:** This score suggests that there are systems in place to store, process, and make the data available to users. To improve further, there is a need to focus on integrating bathymetric data with other marine datasets and enhancing the accessibility of these integrated data products for stakeholders and decision-makers.
Human Activities	**6:** This score indicates operational capabilities in the initial data collection regarding the monitoring of human activities (e.g., shipping traffic, fishing operations, pollution, marine infrastructure development). The score demonstrates the existence of well-established methods and technologies in place (e.g., AIS (Automatic Identification System) tracking for vessels, regular surveillance for various marine uses). However, even with this strong foundation, the score implies there is a need to expand and refine these methods to ensure comprehensive and adaptive monitoring as new forms of marine use emerge (e.g., massive expansion of offshore wind farms).	**4:** This score reflects an insufficient level of coordination between different entities and programs monitoring human activities in the marine environment. While data sharing and joint efforts may be occurring, the result also points to potential fragmentation and the need for more integrated, multidisciplinary approaches to manage the cumulative impacts of human activities. Strengthening European collaborations and regulatory frameworks can enhance the effectiveness of monitoring and management strategies.	**3:** This score suggests that while data are collected and to some degree accessible, there are improvements to be made in how these data are managed and transformed into information products. Enhancing the capacity to analyze, visualize, and disseminate data through user-friendly platforms can improve the decision-making process. Further development of predictive models and impact assessments can also provide a clearer picture of the future state of marine environments under different human activity scenarios.
Biodiversity & Non-Indigenous Species	**5:** The score reflects a structured approach to understanding marine life diversity and the spread of new species. More enhancements are needed in observational tools such as the use of ocean sound and its inclusion in biological EOV and the adoption of innovative eDNA techniques. This is particularly needed in remote and less-studied regions, like the Arctic, for expanding our understanding of biodiversity patterns across European Seas.	**3:** The score indicates ongoing efforts to harmonize observational methodologies across European Seas. The variability in data collection methods across national and regional monitoring programs presents a large barrier to creating a unified understanding of biodiversity and non-indigenous species distribution. Increasing the interoperability of data and fostering collaborative research initiatives are essential steps toward addressing coordination challenges.	**2:** The score highlights the complexity of integrating diverse datasets into accessible and useful information products. There is a critical need for developing standardized protocols for biodiversity data collection and analysis. Enhancing data sharing platforms and utilizing advanced data analytics can facilitate the effective use of biodiversity and non-indigenous species data in conservation planning and policy-making.
River Inputs	**5:** This score suggests a strong capability for collecting data on river inputs, with effective methodologies to measure volume, nutrient content, sediment loads, and pollutant levels. But, there is still a need to enhance *in-situ* monitoring networks and remote sensing capabilities to ensure comprehensive spatial and temporal coverage.	**4:** The score indicates relatively weak coordination between different monitoring programs and initiatives that collect data on river inputs. It suggests the existence of collaborative efforts in sharing data and methodologies, but reflects the need to further improve coordination. Initiatives like integrated watershed management programs could be further developed to synchronize efforts across borders, ecosystems, and research institutions.	**3:** This score reflects ineffectiveness in managing the data collected on river inputs and translating it into products and services. While data may be collected and available to some extent, improving this score would involve enhancing their integration into more sophisticated databases, developing better predictive models, and creating decision-support tools to assist in managing the impacts of river inputs on marine ecosystems.
Sea Ice	**4:** The score reflects a foundation in the methodologies and technologies deployed to monitor sea ice (e.g., satellite imagery, *in-situ* measurements, remote sensing). However, it also suggests that while the existing infrastructure is competent, there remains room for improvement in coverage, resolution, and the integration of new technologies. Advancements in satellite capabilities (e.g., higher resolution, new wavelengths) and the increased deployment of autonomous systems (e.g., underwater vehicles, ice-tethered	**4:** There is a level of collaboration among the various international programs, research institutions, and observational networks focused on sea ice monitoring, such as the Arctic Observing Network (AON) and the Antarctic Sea Ice Processes and Climate (ASPeCt) program. However, the score implies that further efforts are necessary to fully harmonize data collection efforts, standardize methodologies, and improve data exchange, for instance among Arctic and Antarctic research initiatives. Strengthening	**4:** The score suggests that while sea ice data are being effectively collected and managed, there are opportunities to enhance the synthesis of these data into meaningful services and products. The development of advanced modeling tools and predictive analytics can offer more accurate forecasts of sea ice trends and support decision-making for navigation, resource management, and climate adaptation strategies. Also, improving the integration of sea ice data with ecological and socio-economic data can help assess the

(Continued)

TABLE 4 Continued

Phenomenon	Requirements Processes (Inputs)	Coordination of Observational Elements (Processes)	Data Management & Information Products (Outputs)
	instruments) will provide more detailed insights into sea ice thickness, extent, and melting processes. Enhancing observational capabilities to better monitor polar night conditions and summer melt ponds would also be valuable for understanding sea ice dynamics.	international cooperation and interdisciplinary approaches are essential to address the complex challenges posed by changing sea ice conditions and their global implications.	broader impacts of sea ice changes on marine ecosystems, indigenous communities, and global climate feedback mechanisms.
Ocean Deoxygenation	**5:** The capacity to monitor dissolved oxygen across various marine environments forms the backbone of deoxygenation research. Augmenting the deployment coverage of oxygen sensors, particularly in areas experiencing rapid changes, is critical for capturing the dynamics of deoxygenation. The wide use of AUVs and advanced robotics should close this gap and improve the score.	**4:** Although coordination exists among observational networks, enhancing data sharing and standardization across platforms will facilitate a more comprehensive understanding of deoxygenation patterns and drivers. The Global Ocean Oxygen Network[18] is a promising initiative to close this gap.	**2:** The large gap in converting oxygen data into synthesis products highlights a need for advanced data analytics and modeling approaches. A remarkable effort has already started to close this gap, as a coordinated international effort toward building an open-access Global Ocean Oxygen Database and ATlas (GO2DAT) is envisaged to combine data from the coastal and open ocean (Grégoire et al., 2021). Also, improving the integration of deoxygenation data with other environmental parameters will aid in the development of ecosystem-based management strategies.
Contaminants	**4:** The score highlights the complexity of identifying and quantifying a vast array of contaminants. Prioritizing the monitoring of emerging contaminants and enhancing analytical capabilities are key steps towards a more effective monitoring strategy.	**3:** Achieving coherence in contaminant monitoring efforts requires improved collaboration among national and regional programs. This can be facilitated by adopting unified manuals and protocols (such as the ones developed by HELCOM[19] for instance) and leveraging technological advancements for more efficient data collection and analysis.	**3:** While data on contaminants is being collected, there is a need for more sophisticated data management systems that can handle the complexity and volume of information. Implementing best practices for data sharing and utilization will support risk assessment and policy formulation.
Plastic Pollution	**4:** This score indicates a developing but still inadequate infrastructure for systematically monitoring marine plastic pollution. The current methodologies, such as surface water trawls and aerial surveys, are foundational yet insufficient to comprehensively map the distribution, types, and sources of plastics, especially when considering the vast scale of microplastic and nanoplastic pollution. The score reflects the need for large advancements in detection technologies, including remote sensing capabilities and *in-situ* sensors, to enhance the granularity and scope of plastic pollution monitoring efforts. It also underscores the necessity for a broader application of innovative techniques like eDNA analysis to trace the ecological impacts of plastic pollution on marine life.	**3:** This score reveals a weak level of collaboration among the various entities involved in monitoring plastic pollution, including governmental agencies, non-governmental organizations, research institutions, and international bodies. While certain initiatives demonstrate successful partnerships, the score points to fragmented efforts and a lack of adopting a unified European strategy, although this might improve with the efforts of MSFD Technical Group on Marine Litter[20]. Enhancing coordination entails establishing more robust frameworks for data sharing, method standardization, and joint monitoring programs. It also implies a critical need for engaging a wider array of stakeholders, to foster a more cohesive and effective European and global response.	**1:** This low score highlights a large gap in producing services that might generate practical solutions for mitigating plastic pollution. Challenges include standardizing data collection protocols, the absence of comprehensive databases, and a lack of analytical tools capable of synthesizing diverse data streams into coherent, policy-relevant outputs. Improving this score requires the development of integrated data management systems that facilitate the accessibility and usability of data for scientists, policymakers, and the general public. It also calls for a concerted effort to apply machine learning and predictive modeling to forecast trends, assess the effectiveness of mitigation strategies, and inform sustainable material development and waste management practices.
Non-Carbon Dioxide Greenhouse Gases	**4:** The score reflects the existence of foundational efforts to monitor non-carbon dioxide Greenhouse Gases in marine settings. Expanding monitoring capabilities to cover more areas and depths, especially in regions with high biological activity and human influence, is critical to improve the score.	**2:** This score points to a fragmented approach in the monitoring. Establishing a more integrated observational network, involving both *in-situ* measurements and remote sensing, will enhance the coverage and consistency of data collection.	**2:** The score highlights limited accessibility and utility of collected data. Developing standardized methodologies for data collection, processing, and sharing, along with advanced analytical tools, is essential for improving the understanding and management of the potent Greenhouse Gases.
Geological Geohazards	**3:** This score indicates a moderate level of capability in monitoring geological geohazards, such as seismic activities, submarine landslides, and volcanic eruptions. It suggests that while some instrumental and methodological infrastructure is in place, there is considerable scope for improvement. Enhancing detection	**4:** The score highlights the existence of coordination among organizations and countries in the sharing of data and resources related to geological geohazards. But, there is still a need for better international cooperation, standardized protocols, and a unified response strategy to ensure effective monitoring and risk mitigation.	**4:** This score shows a need to improve the way geological hazard data is managed and used to create information products and also give more visibility to the current efforts and data produced. Developing centralized databases for hazard data, integrating different types of hazard information, and providing

(Continued)

TABLE 4 Continued

Phenomenon	Requirements Processes (Inputs)	Coordination of Observational Elements (Processes)	Data Management & Information Products (Outputs)
	and monitoring capabilities, such as expanding the use of seafloor observatories and improving seismic networks, can provide more comprehensive coverage and allow for earlier hazard detection.	Strengthening partnerships through programs like the Intergovernmental Coordination Group for Tsunami[21] can improve the ability of Member States to respond to and mitigate the risks associated with geological geohazards.	real-time access to data are essential steps. Creating predictive models and risk assessment tools will support hazard preparedness and emergency response efforts.
Oil Leakage	**1:** This low score indicates that the current capacity to monitor and respond to oil leakage is minimal. There is a critical need for improved detection methods, such as remote sensing technologies, *in-situ* chemical sensors, and regular surveillance activities, to identify and quantify oil presence in marine environments rapidly. Enhancing the technological infrastructure and developing rigorous protocols are necessary to elevate the readiness level for tackling oil spill incidents. Challenges also include the update of the current EOVs used to track this phenomenon and make them more inclusive, covering for example radar-based detection techniques.	**2:** This score suggests some existing coordination among agencies and organizations in sharing information and resources in the event of oil spill incidents. It also points to a fragmented approach and the need for a more integrated, rapid-response framework that brings together regional and international stakeholders. Strengthening cooperative agreements and emergency response protocols can improve collective efforts in oil leakage monitoring and mitigation. A good example to be followed would be the HELCOM regional cooperation[22].	**1:** This score reflects a large gap in the management and utilization of data related to oil spills. There is an urgent need for the development of centralized databases to document incidents, outcomes, and remediation efforts. Additionally, creating predictive models to assess the potential spread and impact of oil leaks and developing information products to guide response and recovery efforts are necessary to manage the environmental risks associated with oil leakage effectively.

Table colors align with those used in the Framework for Ocean Observing (FOO) table as described by Lindstrom et al. (2012), ensuring consistency and comparability.

recommendations has been published previously (Hassoun et al., 2024).

Sea Level Rise [Scored 7 for Requirements Processes, 7 for Coordination of Observational Elements, 7 for Data Management & Information Products]: The EOOC demonstrates 'fit-for-purpose' readiness in all pillars for observing and forecasting sea level rise. This suggests that a robust community is in place for tracking changes, likely due to the critical nature of this phenomenon for coastal management and marine infrastructures, as well as the feasibility of measuring it compared to other, more complex phenomena. The integration of networks like tide gauges and satellite altimetry ensures precise data collection, enhancing early warning systems and informing adaptation strategies. Continuous advancements and maintenance of these high scores are essential to address the escalating impacts of climate change-induced sea level rise. To sustain and further develop these RLs, the EOOC needs to focus on refining data collection methodologies, enhancing the accuracy of predictive models, and strengthening international collaborations, especially in data exchange and technological innovation (Jevrejeva et al., 2014; Bonaduce et al., 2016; Pérez-Gómez et al., 2021; Karstensen et al., 2020).

Eutrophication [Scored 7 for Requirements Processes, 7 for Coordination of Observational Elements, 6 for Data Management & Information Products]: Eutrophication is relatively well-monitored, with strong processes in place for data collection and coordination. However, there is slightly lower capability in transforming data into comprehensive information products. The Outputs RL indicates that while data is being managed effectively, further enhancement in accessibility and integration with other environmental data could be beneficial (EuroStat, 2020). Emphasizing the monitoring of nutrient dynamics and algal blooms will help manage the impacts of coastal eutrophication more effectively.

Ocean Carbon Storage [Scored 6 for Requirements Processes, 5 for Coordination of Observational Elements, 5 for Data Management & Information Products]: The evaluation of ocean carbon storage within the EOOC initiatives reveals a robust community capable of assessing how the ocean captures and stores carbon. High scores across all pillars indicate a well-established approach to observing, with good coordination among

10 HELCOM.

11 Convention | OSPAR Commission.

12 Ocean Carbon & Biogeochemistry (us-ocb.org).

13 HOME (ioccp.org).

14 Practical Best Practices for Ocean Acidification Monitoring (pubpub.org).

15 MBON – Marine Biodiversity Observation Network (marinebon.org).

16 Introducing IMOS (IMOS.org.au).

17 Home | International Quiet Ocean Experiment (IQOE).

18 global-ocean-oxygen-network (unesco.org).

19 Manuals and guidelines – HELCOM.

20 MSFD Technical Group on Marine Litter (europa.eu).

21 https://tsunami.ioc.unesco.org/en/coordination-and-information

22 Aerial surveillance and regional cooperation remain key in detecting oil spills in the Baltic Sea – HELCOM.

different initiatives and effective data management practices. The community is well-suited to provide essential data for carbon budgeting and climate modeling. Yet, as with any complex community, there is room for continuous improvement, especially in enhancing the practical application of data to support climate change mitigation strategies.

Ocean Warming [Scored 7 for Requirements Processes, 5 for Coordination of Observational Elements, 4 for Data Management & Information Products]: The 'fit-for-purpose' score in the Inputs pillar indicates strong infrastructure for collecting temperature data across European Seas. However, challenges remain in several areas, such as 1) in the reliance on sea surface temperature data, with the vertical aspect, particularly in continental shelf and nearshore regions, often overlooked due to limited coverage (e.g., of Argo floats) in these areas, 2) in coordinating these diverse data streams into consistent and actionable insights, and 3) in improving data integration and application toward mitigative strategies, as reflected in the lower Processes and Outputs scores. Addressing these gaps requires improving the integration of observations with ecological models and enhancing data quality and accessibility. A specific focus is needed to understand the long-term trends in temperature changes, especially in the high-latitude regions affected by sea ice melting and in the deep ocean (Kwok and Maksym, 2014; Buch et al., 2017).

Ocean Acidification [Scored 6 for Requirements Processes, 5 for Coordination of Observational Elements, 4 for Data Management & Information Products]: Monitoring ocean acidification is progressing, with a 'fit-for-purpose' Inputs score and a 'verification' score for process readiness. Challenges in data management and availability of information products highlight the need for advanced analytical techniques and improved data sharing (Hassoun et al., 2022; Álvarez et al., 2023). Wider deployment of sensors and autonomous observing platforms for pH and other carbonate system variables, especially in the deep ocean, can further these efforts. Current RLs suggest a strong operational foundation within the EOOC initiatives for monitoring ocean acidification. While the fundamental scientific infrastructure is in place to observe and forecast ocean acidification, translating this into a coordinated European action with accessible information remains an area for development.

Food Webs [Scored 6 for Requirements Processes, 4 for Coordination of Observational Elements, 4 for Data Management & Information Products]: Observing and forecasting the components of food webs is complex compared to physical ocean phenomena (e.g., sea level rise, and ocean warming). Nonetheless, the assessment shows good readiness in Inputs but indicates room for improvement in observational coordination and information product development (Ratnarajah et al., 2022). Enhanced communication and harmonized research practices are essential for managing data on phytoplankton, zooplankton, and fish abundance, which are crucial for ecosystem management and the sustainability of marine resources.

Underwater Noise [Scored 6 for Requirements Processes, 6 for Coordination of Observational Elements, 2 for Data Management & Information Products]: The high scores in the first two pillars reflect a recognition of underwater noise as an important environmental concern, leading to concerted efforts to observe it. However, the low score in the Outputs pillar highlights a gap in translating these data into actionable information and useful products that can inform policy and stakeholders. Strategies to address this gap include developing comprehensive databases, harmonizing noise measurement standards, and incorporating noise management into marine spatial planning (Dekeling et al., 2016). Ongoing initiatives, such as the establishment of databases for underwater biological sounds (Parsons et al., 2022) through projects like GLUBS[27] and international efforts such as IQOE[28], are actively contributing to the development of the ocean sound EOV. While there is a strong framework for capturing underwater noise, large improvements are needed in managing and utilizing this data (Hawkins et al., 2015). Enhancing data management, increasing the availability of information products, adopting innovative acoustic technologies, and improving databases for noise monitoring will support the mitigation of impacts on marine life (Harris et al., 2018).

Sea Floor Integrity/Bathymetry [Scored 5 for Requirements Processes, 5 for Coordination of Observational Elements, 4 for Data Management & Information Products]: Observing sea floor integrity and bathymetry indicates a moderate RL. Future efforts should prioritize deploying modern mapping technologies, coordinating European data sharing, and integrating these data into maritime safety and environmental protection frameworks (Ardhuin, 2018; EMODnet, 2018a; EMODnet, 2018b; EMODnet, 2018c). The scores indicate that the EOOC has made considerable progress in collecting and coordinating bathymetric data. However, to further enhance the monitoring of sea floor integrity, there is a need for increased deployment of high-resolution multibeam echosounders, the establishment of standardized data collection protocols across Europe, and improved data accessibility. Continuous improvements are essential to address unmapped areas, keep pace with technological advancements, and ensure that the growing volume of data continues to be effectively managed and integrated into decision-making processes for ocean governance and conservation.

Human Activities [Scored 6 for Requirements Processes, 4 for Coordination of Observational Elements, 3 for Data Management & Information Products]: Human activities, such as fisheries, are reasonably well-monitored, reflecting an operational input community. However, there are noticeable gaps in coordination and output that can be addressed by bolstering integration of socioeconomic data into environmental monitoring and enhancing stakeholder engagement (EMODnet, 2017; EMODnet, 2018a; EMODnet, 2018b; EMODnet, 2018c). The monitoring of human activities indicates a solid foundation for data collection, including vessel monitoring, fisheries management, and pollution control. Nevertheless, further efforts are needed to improve the sharing and utilization of data among regulatory bodies and the scientific community. Additionally, better interpretation of these data is

27 GLUBS | Global library of underwater biological sounds.

28 International Quiet Ocean Experiment (IQOE).

crucial for distinguishing between human and natural effects, ultimately leading to a more comprehensive understanding of both direct and indirect human impacts on marine environments.

Biodiversity & Non-Indigenous Species [Scored 5 for Requirements Processes, 3 for Coordination of Observational Elements, 2 for Data Management & Information Products]: Biodiversity and non-indigenous species observing have moderate scores indicating progress in data collection and some level of coordination among European institutes and researchers. However, improvements are necessary to address the identified gaps in data products and services, especially in producing meaningful knowledge from the collected data, analyzing long-term patterns, and integrating these data into marine management frameworks (Tintoré et al., 2019; SWD, 2020). Challenges in observational coordination and data management hinder a holistic understanding and managing biodiversity and non-indigenous species impacts on marine ecosystems. To enhance these efforts, the EOOC needs to organize systematic monitoring programs and adopt innovative tools for efficient observations, focusing on the less-understood European Seas to facilitate the development of biosecurity programs in regions lacking baseline data (Carvalho et al., 2023).

River Inputs [Scored 5 for Requirements Processes, 4 for Coordination of Observational Elements, 3 for Data Management & Information Products]: The EOOC approach to observing river inputs reflects a solid foundation with notable room for growth. The community demonstrates a good capability to capture the quantity and quality of materials from rivers entering marine environments, such as nutrients, sediments, and pollutants. While these efforts are well-coordinated among various stakeholders, the scores suggest that further alignment could streamline the efficiency of these initiatives. The lower score (RL in 'proof of concept') in data management highlights the need for enhanced processing and synthesis of data into actionable insights, which is crucial for addressing the impacts of river inputs on coastal ecosystems and for managing the land-sea interface more effectively (EMODnet, 2018a; EMODnet, 2018b; EMODnet, 2018c; Ratnarajah, 2021).

Sea Ice [Scored 4 for Requirements Processes, 4 for Coordination of Observational Elements, 4 for Data Management & Information Products]: The EOOC initiative has demonstrated a balanced approach to sea ice observing, with consistent RLs at the 'trial' level across all pillars. This reflects the critical importance of continued investment in observational infrastructure, collaboration, and data management innovation. While strides have been made in observing sea ice, continued investment in remote sensing and *in-situ* measurements is crucial for improving the understanding and forecasting of sea ice. Enhancing the integration of diverse data sources and standardizing methodologies will support better climate change response strategies in polar regions, for instance. Specific focus is needed to address the challenges of observing sea ice extent, thickness, and overall health in the context of climate change (Kwok and Maksym, 2014; Leppäranta, 2023).

Ocean Deoxygenation [Scored 5 for Requirements Processes, 4 for Coordination of Observational Elements, 2 for Data Management & Information Products]: The EOOC monitoring efforts in this area highlight a well-established data collection system, but there remains considerable scope for improvement in the synthesis and application of these data. Despite advances in sensor technology, persistent gaps in comprehensive dissolved oxygen coverage remain, particularly in offshore regions and deep waters (Grégoire et al., 2021; 2023). Increasing temporal resolution and sampling frequency, as suggested by Pereiro et al. (2022), is critical for capturing the dynamic variability of ocean oxygen levels, especially in areas prone to deoxygenation. Moreover, the current reliance on static monitoring systems in coastal areas and the absence of robust, long-term autonomous platforms in the open ocean hinder the ability to effectively observe large-scale deoxygenation trends. Addressing these gaps requires investment in Automatic Underwater Vehicles (AUVs) and advanced observational platforms, which could greatly enhance our understanding of ocean oxygen dynamics, particularly in Oxygen Minimum Zones (OMZs) and other critical regions where observations remain sparse. Additionally, integrating these improved observational capabilities into global databases and networks would largely improve our ability to manage the ecological impacts of oxygen loss on marine ecosystems and services.

Contaminants [Scored 4 for Requirements Processes, 3 for Coordination of Observational Elements, 3 for Data Management & Information Products]: Observing and monitoring contaminants, such as heavy metals and pesticides, is moderately developed but requires harmonization across EU efforts. Addressing the variety of emerging contaminants, ensuring interoperability of data, and aligning strategies with international organizations are critical for enhancing monitoring, predictability and management. Also, there are various challenges in achieving comprehensive coverage and integrating data into actionable insights (SWD, 2020; EuroStat, 2020).

Plastic Pollution [Scored 4 for Requirements Processes, 3 for Coordination of Observational Elements, 1 for Data Management & Information Products]: Obtained RLs for plastic pollution highlight the developing status of monitoring efforts. A moderate score, categorized as 'trial', for requirements processes indicates that foundational methods and tools are being employed to detect and quantify plastic contaminants in marine ecosystems. The score points to established but improvable capabilities, hinting at the need for broader coverage and more refined detection methodologies, particularly for microplastics. The lower scores for coordination of observational elements and data management & information products suggest that, while collaborative efforts exist, large enhancements are necessary (Lebreton et al., 2017; Koelmans et al., 2019; Borrelle et al., 2020; Ajith et al., 2020). The challenges include insufficient spatial and temporal coverage, difficulties in integrating diverse data sources, and a lack of standardization in data collection and analysis, or at least in adopting the newly released best practices and policies. These gaps indicate that the EOOC's efforts in observing plastic pollution are still in the developmental stages, with substantial room for enhancement in data collection, coordination, and information synthesis.

Non-Carbon Dioxide Greenhouse Gases [Scored 4 for Requirements Processes, 2 for Coordination of Observational Elements, 2 for Data Management & Information Products]: The scores clearly reflect the need for large improvement across all pillars for non-carbon dioxide GHGs monitoring, such as methane (CH_4) and nitrous oxide (N_2O), in European Seas. The EOOC has made initial efforts to observe these gases; however, challenges remain, particularly in coordination and data management, indicating substantial room for improvement. Expanding spatial and temporal monitoring coverage, strengthening atmospheric monitoring capabilities, and standardizing measurement protocols as well as providing sustainable long-term data archive infrastructure are key to understanding the global dynamics of these gases (Bange et al., 2019; Bange, 2022; Kock and Bange, 2015; Rees et al., 2022).

Geological geohazards [Scored 3 for Requirements Processes, 4 for Coordination of Observational Elements, 4 for Data Management & Information Products]: The scores reflect the early-stage development of observational and data management systems for marine geological geohazards. The low scores across all three pillars highlight key gaps in the capacity to monitor and respond to such events. A major contributing factor to these low scores is the limited integration of real-time seismic data into the ocean observing framework. While global seismic networks provide near real-time alerts for terrestrial events, they have not yet been formally incorporated into EOVs for marine hazard monitoring. For instance, earthquakes with magnitudes greater than 7 at sea, which can trigger tsunami warnings, are detected by terrestrial seismic arrays. However, these data are not fully integrated into marine observation systems, limiting the effectiveness of early-warning mechanisms. The gap in recognizing advancements in real-time ocean-based seismic data, such as those noted by Roset et al. (2018), further underscores the need to update the criteria for this EOV. Moreover, while tsunami early warning systems, such as those developed under the IOC-UNESCO Tsunami Programme[29], play a vital role, they are predominantly linked to terrestrial networks rather than ocean-based real-time seismic monitoring. Given the existence of these real-time seismic networks, it is essential to integrate them more effectively into marine geohazard monitoring frameworks to enhance coordination and improve data products. A successful example is 'WARN', the Web-enabled Awareness Research Network, part of Ocean Networks Canada's "Oceans 2.0" data management system, which performs early detection of tsunami and earthquakes in Canada (Heesemann et al., 2014). While some mechanisms for detecting geological events are in place, substantial improvements are still needed to strengthen observational networks and develop specialized data management systems. Ongoing efforts must focus not only on sensor development but also on ensuring robust data management and real-time operational frameworks (Ramirez-Llodra et al., 2011; McQuaid et al., 2020).

Oil Leakage [Scored 1 for Requirements Processes, 2 for Coordination of Observational Elements, 1 for Data Management & Information Products]: Monitoring oil leakage is evidently underdeveloped in most European Seas, although it is relatively advanced in the Baltic Sea[30]. Enhancing oil spill detection technology, implementing more stringent monitoring protocols, and developing robust data management frameworks are vital for protecting European Seas in the event of oil spill incidents. Our scores highlight an area of concern within the EOOC's current initiatives that requires immediate and comprehensive improvements (EMODnet, 2016; 2020). One factor contributing to the low scores is the gap in current EOVs. For instance, the Ocean Colour EOV focuses on visible and infrared reflectance, while oil spill detection relies on radar wavelengths. Synthetic Aperture Radar (SAR) data, such as those from Sentinel-1, are commonly used for oil spill detection (Topouzelis, 2008; Misra and Balaji, 2017; Wang et al., 2019), but these data are not currently integrated into any existing EOV. Incorporating a specific EOV related to contaminants, with sub-variables for petroleum hydrocarbons and other pollutants from oil spills, would largely improve monitoring capabilities. This gap underscores the need to update certain EOVs to address threats like oil spills. Developing more advanced monitoring and detection systems, strengthening coordination mechanisms, and establishing efficient data management frameworks are critical steps toward safeguarding marine environments from potentially detrimental impacts of oil spills.

4 Strengths and limitations of the scoring approach

Our assessment is grounded on an extensive literature review of key EU documents that address various ocean phenomena at European level, complemented by direct communication with researchers from the EOOC. The pan-EU scoring approach that we propose here offers a holistic perspective on the status of the EOOC's capacity to observe and predict various ocean phenomena. The scores presented for each phenomenon are not solely based on our personal assessment but also incorporate input from the EOOC members who tested our proposed scoring approach and provided both scores and suggestions for improvement. This collaborative process ensures that, while the scoring system may carry some degree of subjectivity, it remains inclusive and reflects the perspectives and feedback of the EOOC.

However, it is important to note that European regions and nations have varying capacities and specific needs, which might to some degree affect the scores derived in our assessment, in case the scoring approach will be applied for a specific European sea (e.g., Baltic Sea, Mediterranean Sea, etc.) or at the national level. Implementing our scoring approach at the national scale would help to build a more detailed European picture by relying on a nation by nation independent assessment. In this case, the scoring approach would not only offer a more precise and useful evaluation of national gaps, since observations are mainly nationally-funded, but it would also help identify regional gaps as challenges, services, and products often have a strong regional dimension. This approach

29 Intergovernmental Coordination Group for the Tsunami Early Warning and Mitigation System in the North-Eastern Atlantic, the Mediterranean and Connected Seas (ICG/NEAMTWS) | Tsunami Programme UNESCO-IOC.

30 Aerial surveillance and regional cooperation remain key in detecting oil spills in the Baltic Sea – HELCOM.

could ultimately provide more targeted recommendations that might be addressed nationally and/or regionally. Further, we also acknowledge that the number of feedbacks (n=9) might be considered small, and some few ocean phenomena would benefit from additional experts' inputs (e.g., Oil spills, etc.). This should be considered in future applications of this scoring approach. Moreover, averaging the scores of respondents may not hold in all cases, and alternative measures, such as the median or a consensus score, could provide different insights. For example, the median is less sensitive to extreme values and could be useful when scores are highly variable. In this study, we chose to use the mean to capture the full range of opinions and allow for more detailed comparisons of capacities across various criteria, particularly given the small number of participants. However, future iterations of this scoring approach should consider other aggregation methods to further refine the assessment approach. This highlights the challenge of generalizing our findings across the broader EOOC. Future efforts could additionally benefit from larger datasets, which would enable the use of more rigorous statistical analysis and thus provide greater confidence in quantifying the RLs of the various ocean phenomena. Additionally, our scoring approach is based on the 10-year-old FOO requirements table, hindering us from applying it to evaluate other aspects of the ocean value chain, such as coordination, management, modeling, policies and legislations, and governance. Therefore, our exercise proves that this table needs to be updated to evaluate the EOOC initiative's RLs in observing and forecasting not only ocean phenomena but also in fulfilling the objectives of the various ocean value chain components (e.g., coordination and management, data FAIRness, marine policies and legislations, and ocean literacy) in a regular and systematic way. Acknowledging the inherent complexity of responding to the survey is also essential. Consequently, given its efficacy as a useful tool, an improvement could involve providing explicit, user-friendly instructions to assist respondents in future assessments.

5 Conclusions

In this paper, we propose the adoption of a scoring approach within the European Ocean Observing Community (EOOC). By systematically evaluating Requirements Processes, Coordination of Observational Elements, and Data Management & Information Products, this approach not only highlights the strengths and capabilities in crucial ocean topics but it also clearly identifies specific areas where improvements are essential. Scores reflecting moderate to strong capabilities in data collection and coordination underscore the EOOC's commitment to understanding complex ocean phenomena. Meanwhile, lower scores in data management point to critical opportunities for enhancing the usability of the collected data. By emphasizing the importance of comprehensive observing, collaborative efforts, and strategic data synthesis, the scoring approach might foster a culture of continuous improvement and innovation. It enables relevant stakeholders (e.g., researchers, institute directors, the EU commission, and funders) to remain agile and responsive to the dynamic challenges posed by ocean health and climate change, ultimately leading to more informed policies, sustainable resource management, and oriented calls for projects.

Data availability statement

The original contributions presented in the study are included in the article/supplementary material. Further inquiries can be directed to the corresponding author.

Author contributions

AH: Writing – review & editing, Writing – original draft, Visualization, Validation, Methodology, Investigation, Formal analysis, Data curation, Conceptualization. TT: Writing – review & editing, Validation, Supervision, Project administration, Methodology, Funding acquisition. EH: Writing – review & editing, Validation, Methodology. IL: Writing – review & editing, Project administration, Methodology. MÁ: Writing – review & editing, Methodology. GP: Writing – review & editing, Methodology. MG: Writing – review & editing, Methodology. DV: Writing – review & editing, Methodology. MG: Writing – review & editing, Methodology. HB: Writing – review & editing, Methodology. CL: Writing – review & editing, Methodology. JK: Writing – review & editing, Methodology.

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Conflict of interest

The authors declare that the research was conducted in the absence of any commercial or financial relationships that could be construed as a potential conflict of interest.

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