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The Italian effort toward a coordinated observation of Essential Variables (EOV, ECV, EBV) in European Marine Environments. Long-term observation in the central Mediterranean seas and Italian coasts

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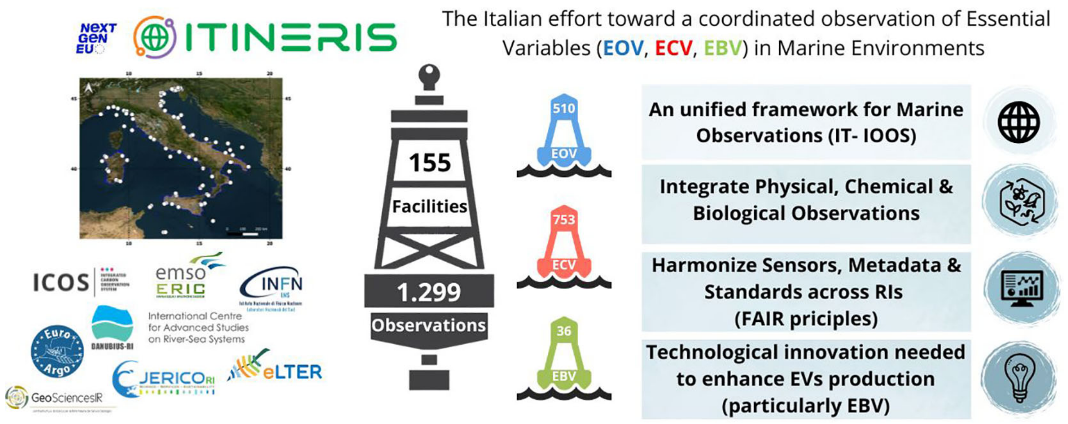
Monitoring Essential Ocean, Climate, and Biodiversity Variables (EOVs, ECVs and EBVs) collected through the marine Research Infrastructures (RIs) is critical for assessing environmental status, improving scientific knowledge and defining environmental policies. This study evaluates the capacity of the Italian marine monitoring system, including facilities such as fixed stations, buoys, autonomous platforms, and mobile systems across the Mediterranean Sea, to produce those variables. Conducted in 2023 within the framework of the ITINERIS project (https://itineris.cnr.it/), which aims to strengthen coordination among national and ESFRI RIs (European Strategy Forum on Research Infrastructures), the analysis systematically examines the spatial, thematic, and technological coverage of EOVs, ECVs, EBVs observations and their alignment with international standards for environmental monitoring of 155 facilities from eight Italian and pan-European marine RIs. Of the 107 EVs recognized, 50% were actively produced by the RIs considered, with over 90% meeting the established requirements for EVs. These numbers will be updated to reflect the new equipment acquired during the project's implementation up to early 2026, which is expected to boost EVs production by approximately 38-40%. The national monitoring network demonstrates a high degree of maturity for oceanic and climate variables, while biodiversity observations remain less represented, indicating the need for further technological innovation and automation. These findings emphasize the importance of enhancing coordination and harmonization among RIs to ensure balanced and interoperable monitoring. The study provides key recommendations to strengthen Italy's capacity to contribute to the global characterization of EOVs, ECVs, and EBVs and to support evidence-based environmental assessments and the development of robust environmental management strategies at European level.

KEYWORDS

environmental observation, ESFRI, Essential Variables, Mediterranean Sea, research infrastructures



GRAPHICAL ABSTRACT

Highlights

- A comprehensive assessment of marine Essential Variables (EVs) across Italian RIs was conducted.
- A survey on 155 monitoring facilities belonging to eight national and pan-European RIs was carried out.
- More than 1000 Essential Variables (EOVs, ECVs, EBVs) data streams were identified and validated.
- Over 90% of the observations met core standards of GOOS, GCOS, and GEO BON.

1 Introduction

1.1 The Essential Variables frameworks

Systematic monitoring of marine environments is a challenge for improving scientific knowledge, climate change predictions, managing marine resources, mitigating extreme events, and promoting the sustainability of life in coastal areas and oceans. Assessing the status and trends of ocean and marine life indicators is fundamental to supporting policy and management decisions, especially considering the increasing anthropogenic impact on marine resources, coastal development and restoration, and the impacts of climate change (Halpern et al., 2017; Gattuso et al., 2018; Ryabinin et al., 2019; Upadhyay, 2020; Livore et al., 2021; Satterthwaite et al., 2021; Silveira et al., 2022; Sun et al., 2024).

To address these challenges, since the 90s the Intergovernmental Oceanographic Commission (IOC) of UNESCO and World Meteorological Organization (WMO) have promoted the Global Ocean Observing System (GOOS website, https://goosocean.org) and Global Climate Observing System (GCOS website, https://gcos.wmo.int/site/global-climate-observing-system-gcos), aiming to develop a sustained, internationally coordinated framework for a comprehensive ocean observing system that integrates physical, biogeochemical, and biological observations (Tanhua et al., 2019). GOOS and GCOS, together with its expert panels, teams and networks — including the European Global Ocean Observing System (EuroGOOS website, https://eurogoos.eu), the European Ocean Observing System (EOOS website, https://www.eoos-ocean.eu), and the Group on Earth Observations Biodiversity Observation Network (GEO BON website EBVs, https://geobon.org) — has promoted the quantification of Essential Variables (EVs). These variables constitute a globally accepted and scientifically robust set of parameters that support sustained, standardized, and policy-relevant Earth and Ocean system observations (Bax et al., 2019; Centurioni et al., 2019; Zeng et al., 2019). A complete list of acronyms used throughout this work is provided in Annex 1.

Many international scientific communities have contributed to identifying and operationalizing EVs across domains, including oceanography, climatology, biogeochemistry, and biodiversity, promoting harmonization of observational approaches and data sharing standards across platforms and institutions.

EVs are categorized into three main categories: EOVs, ECVs, and EBVs. They were developed by international communities to provide standardized, policy-relevant variables for marine, climate, and biodiversity monitoring. Their selection is mainly based on criteria such as scientific relevance, feasibility, and cost-effectiveness (Constable et al., 2016; Levin et al., 2019).

The GCOS defined ECVs to provide a consistent set of variables necessary for detecting climate variability and changes across atmospheric, terrestrial, and oceanic domains. ECVs support climate modelling, long-term observations, and the development of effective mitigation and adaptation strategies.

GOOS developed the EOVs to monitor fundamental components of ocean dynamics, including physical processes, biogeochemical cycles, and biological and ecological systems. EOVs support cost-effective, integrated monitoring to improve ocean forecasting, climate projections, and marine policy (Constable et al., 2016; Levin et al., 2019). GOOS regularly reviews and expands the list of EOVs, which also includes a category of BioEco EOVs, biogeochemical and biological variables capturing the ecological dimension.

Finally, GEO BON website EBVs introduced the EBVs to capture the biodiversity dimensions at the genetic, species, and ecosystem levels, allowing for consistent monitoring and assessment of biodiversity (Pereira et al., 2013). Their implementation requires standardized data collection and curation to support biodiversity assessment for scientific, policy, and sustainable development applications.

EOVs, ECVs, and EBVs are complementary and interdependent rather than isolated concepts (Lehmann et al., 2020; Masò et al., 2020; Kim et al., 2023; Le Boyer et al., 2023). Their interoperability is increasingly recognized; for instance, the inclusion of EBVs as "complementary variables" in BioEco EOVs highlights their integration and reinforces connections between marine and bio-ecological monitoring efforts (Pereira et al., 2013; Satterthwaite et al., 2021; Balvanera et al., 2022; Navarro et al., 2022; Manea et al., 2022).

1.2 The environmental RIs within the European framework and the NRRP-ITINERIS project

At the European level, European Strategy Forum on Research Infrastructures plays a strategic role in identifying and supporting the development of key research infrastructures (RIs) of pan-European interest, of which, in this study, EMSO, ICOS, and Euro-Argo as environmental landmarks and DANUBIUS and eLTER as RI Projects, contribute in providing essential variables, fostering their integration and long-term sustainability (Bojinski et al., 2014; Balvanera et al., 2022; Silveira et al., 2022; von Jackowski, 2025). RIs are crucial at the EU level as they enable cutting-edge research, support innovation, and address grand societal challenges through shared access to high-quality data, services, and technologies. Italy actively participates in all the major pan-European environmental RIs and hosts several nationally relevant RIs (Dañobeitia et al., 2020; De Santis et al., 2022). However, the independent development, diverse histories, and heterogeneity of these infrastructures have led to overlaps in variable monitoring for different scientific and policy purposes. Coordinated action and harmonization are therefore essential.

Italy has adopted the National Research Infrastructure Plan (PNIR, 2021-2027) as a key component of its National Research Program (PNR) for the 2021–2027 period. The PNIR plays a strategic role in coordinating national research infrastructures with European counterparts, particularly those identified by the ESFRI website. The PNIR outlines the technical and strategic priorities for RIs, promoting innovation and high-level expertise that aligns with national strategic directions by enabling targeted projects.

To achieve an integrated approach to environmental observation, 22 RIs have joined forces to launch the ITINERIS website (Italian Integrated Environmental Research Infrastructures System, https://itineris.cnr.it/) project under the National Recovery and Resilience Plan (NRRP) as a part of the Next Generation EU program. The project is coordinated by the National Research Council of Italy (CNR) and involves the National Institute of Oceanography and Applied Geophysics (OGS), Ca' Foscari University of Venice, University of Florence, the National Institute for Nuclear Physics (INFN), the Italian Institute for Environmental Protection and Research (ISPRA), and the National Institute of Geophysics and Volcanology (INGV) as partners. The ITINERIS project aims to establish an Italian integrated system of RIs for the observation and study of the atmosphere, marine domain, terrestrial biosphere, and geosphere.

The marine component of the project ITINERIS focuses on integrating all the relevant marine RIs to ensure access to Italian facilities, services, and marine data, facilitating long-term monitoring of EVs. A key objective is the development of the Italian Integrated Ocean Observing System (IT-IOOS), designed to strengthen Italy's contribution to European and International Ocean observation initiatives (i.e., EuroGOOS website,; EOOS website; GOOS website) and to address the challenges of the Ocean Decade and the Mediterranean Sea observations (Ryabinin et al., 2019; Heymans et al., 2020; UNESCO UNESCO IOC, 2021). The project also aims at enhancing the digital automation of Italian research vessels, expand, homogenize and improve the quality and interoperability of ocean sensors, infrastructures, data flows, and data storage and availability, following the FAIR (Findability, Accessibility, Interoperability and Reusability) principles (Wilkinson et al., 2016).

Among the 22 RIs participating in ITINERIS, eleven are relevant for the observation of the European marine environment, and eight contributed to this study: EMSO ERIC, Euro-Argo ERIC, and ICOS ERIC are pan-European RIs currently being operative and providing high-quality scientific services. They are recognized by the ESFRI and are legally constituted as European Research Infrastructure Consortium (ERICs). DANUBIUS-ERIC and eLTER RI are also recognized by the ESFRI and are in their implementation phase as projects. JERICO is currently a European initiative that has recently applied to enter the 2026 ESFRI Roadmap. Respect to the two Italian facilities, Geosciences IR is a project, although LNS is a National Research Infrastructure.

This work provides an in-depth assessment of marine EV observations in Italy at several European ERICs and RIs with different level of implementation, addressing monitoring intensity across variables, their spatial distribution, and the contributions of facilities and RIs. It also examines compliance with proposed standards and identifies gaps, overlaps, and bottlenecks. The results presented here reflect the initial phase of the project; however, by 2026, the overall improvement in EV data production driven by project activities and the acquisition of new instrumentation for facilities and monitoring networks is expected to reach approximately +38–40% compared to the baseline conditions.

2 Methodology

2.1 Study areas and facilities

Italy is surrounded by the Mediterranean Sea, which is subdivided into several sub-regional basins: the Ligurian Sea, Tyrrhenian Sea, Sardinian Sea, Adriatic Sea, and Ionian Sea, each with distinct oceanographic and ecological characteristics. A comprehensive map (Figure 1) displays the distribution of the 108 fixed facilities among the 155 facilities of the eight RIs included in this study. Each facility corresponds to a sampling station or an observing platform equipped with one or more sensors designed to measure one or more parameters (Satterthwaite et al., 2025). Mobile platforms are excluded from the map as their locations vary over time. Facilities serve as operational units through which RIs generate observations underpinning their services. The variables observed do not always correspond directly to an EV unless accuracy, continuity, and methodological requirements are met (Pearlman et al., 2019; Waldmann et al., 2022; Yang et al., 2022; Rolle et al., 2023).

The work covers coastal, offshore, and deep-sea environments, revealing areas with high observational density— such as the

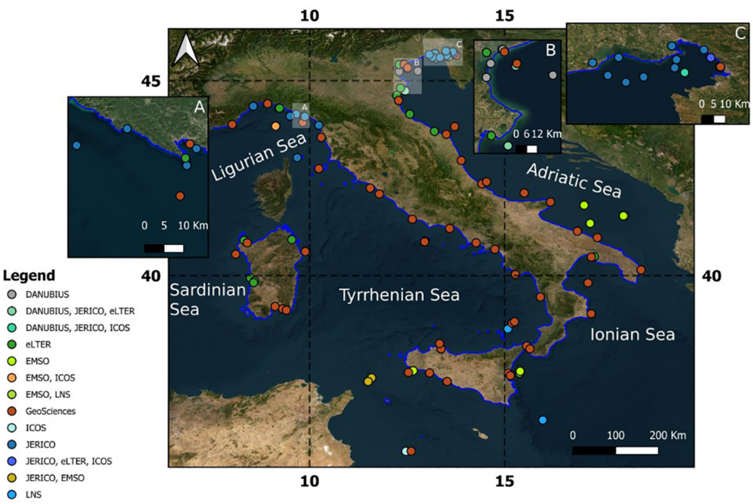


FIGURE 1
Geographic distribution of Italian marine facilities (fixed stations, platforms, moorings, etc.) with the RIs involved in ITINERIS.

northern Adriatic and Ligurian Seas—where multiple RIs are co-located and share facilities equipped with different instrumentation. In contrast, other regions, such as the central Tyrrhenian and Ionian Seas remain underrepresented. This uneven coverage is primarily linked to the limited number of fixed long–term stations in deep–water settings, where installation, operation, and maintenance are technically demanding and economically costly. These logistical constraints reduce the persistence and spatial continuity of observations in offshore basins. Strengthening the synergy between fixed and mobile observing systems would help compensate for these gaps and ensure more consistent data coverage across the entire Italian marine area (i.e., latitudes and longitudes).

Annex 2 lists all the facilities included in the survey along with their coordinates. It also includes mobile platforms that are only partially represented in the static map. For instance, Argo floats contribute significantly to open-sea data acquisition (42 floats), representing a mobile, dynamic complement to fixed-point infrastructures. Their inclusion in quantitative analyses increases the total count of facilities to 155.

Measured parameters can contribute simultaneously to multiple EV frameworks, depending on the context and specific characteristics emphasized in each framework. For instance, chlorophyll-a concentration is a key parameter either for EOV, ECV and EBV frameworks. It is relevant as an EOV for ocean productivity, an ECV for climate-related carbon cycle and Ocean Color, and an EBV for assessing primary producers in biodiversity studies (McMahon et al., 2021). This cross-framework relevance highlights the need for interoperable monitoring approaches and standardization across domains (Miloslavich et al., 2017; Pereira et al., 2013; Bojinski et al., 2014). Such synergy ensures cross-validation of measurements and enhances the robustness of long-term data acquisition.

JERICO facilities are concentrated mainly in the northern Adriatic and Ligurian Seas, including HF Radars along the Ligurian coast and in the Gulf of Trieste, providing comprehensive data on coastal dynamics. The Italian branch of eLTER (LTER-Italy network), contributing to the ITINERIS project, operates 16 facilities in marine and transitional environments, with a higher density in the northern Adriatic (Capotondi et al., 2021). This region also hosts key sites such as the Po River Delta and Venice Lagoon, where DANUBIUS and other RIs jointly operate through consolidated facilities (De Pascalis et al., 2025).

Offshore platforms in the Ligurian, Adriatic and Ionian Seas extend observations into deeper waters (from –200), enabling the study of ocean-atmosphere interactions and biogeochemical cycles. EMSO has three regional facilities in the western Ionian Sea, southern Adriatic, and Ligurian Sea. Some of these sites are shared and co-managed with ICOS for surface and shallow measurements, which are complemented by ICOS coastal stations in the northern Adriatic. The LNS (Capo Passero and Catania), together with EMSO, hosts deep-sea laboratories involving submarine fiber optic cables for advanced acoustic and optical research. GeoSciences includes the national tide gauge and wave monitoring network managed by ISPRA, providing widespread and consistent coastal monitoring along the Italian coasts. Euro-Argo, in contrast, relies on autonomous mobile vehicles, such as Argo floats, which simultaneously collect several EOVs, ECVs and EBVs in the upper 2-to-4 km of the water column. These instruments are deployed at predetermined sites and times and then drift with deep ocean currents, providing dynamic spatial coverage.

In some areas, multiple RIs are co-located, creating synergies that broaden the range of EVs observed. In certain cases, the same EOV/ECV/EBV is made available by more than one RI, ensuring long-term data availability, cross-validation, and strengthening collaborative monitoring.

2.2 Identification of Essential Variables for ocean, climate, and biodiversity monitoring

EOVs, ECVs, and EBVs represent complementary sets of variables, each with distinct purposes and characteristics (Table 1). For this study, a total of 54 EVs were considered: 24 EOVs, 23 ECVs and 7 EBVs, selected based on their relevance to the

TABLE 1 **Conceptual overview of EVs, detailing the focus, purpose, primary frameworks, applications, cross-domain interactions, and classes.**

Attribute	EOVs	ECVs	EBVs
Focus	Physical, biogeochemical, and biological aspects of the ocean.	Climate system processes across the atmosphere, land, and oceans.	Biodiversity changes at genetics, species, and ecosystem levels.
Purpose	To assess ocean health, marine resource sustainability, and climate-ocean interactions.	To monitor and understand climate change and variability for science and policy.	To track biodiversity trends for conservation and sustainable management.
Primary Framework	GOOS	GCOS	GEO BON
Applications	Marine ecosystem management, fisheries sustainability, understanding ocean-climate feedback.	Climate modeling, adaptation strategies, policy frameworks like the Paris Agreement.	Biodiversity conservation policies like the Convention on Biological Diversity (CBD).
Interactions	Strong interconnection with EBVs for marine biodiversity data (BioEco EOVs); overlaps with ECVs in physical ocean variables.	Overlaps with EOVs in ocean-related climate variables (e.g., sea level; plankton) and with EBVs in terrestrial ecosystem monitoring.	Relies on ECVs for climate-driven biodiversity impacts and EOVs for marine biodiversity metrics.
Classes	Physics; Biochemistry; Biology and Ecosystems; Cross-Disciplinary	Atmosphere Surface; Upper Atmosphere; Atmospheric Composition; Ocean Physical; Ocean Biogeochemical; Ocean Biological/ Ecosystems	Ecosystem function; Ecosystem structure; Genetic composition; Species traits; Species population; Community composition

Blu is for EOVs, red for ECVs and green for EBVs.

marine domain and their measurability. Variables outside this scope, such as those pertaining to the terrestrial domain or cryosphere (e.g., snow cover, permafrost), or those not monitored by any Italian facility, were excluded.

The selected variables, grouped into thematic groups/classes, are listed in Annex 3. To enhance graphical representation and to ensure consistent interpretation, the official EVs categorization was slightly refined. In particular, underrepresented categories were merged into broader thematic groups. This reorganization, detailed in Annex 3, was designed to provide a more coherent and accessible overview of EVs.

2.3 Metadata collection and analytical approach

To evaluate Italy's capacity to produce marine EVs, a structured survey was conducted in 2023 among facility and RI managers involved in the ITINERIS project. Based on the expertise of the managers involved in each RI, a standardized form was designed to collect detailed information on all facilities under their responsibility. The form was conceived as a reusable and scalable tool, adaptable to different contexts and potentially applicable across multiple RIs and future initiatives. Respondents provided detailed information on the variables measured, instrumentation used (including accuracy, time resolution, and depth), and associated metadata. This collaborative effort yielded a comprehensive overview of the extent and maturity of EVs monitoring across the Italian marine domain. While the initial configuration of facilities and the governance structures of each RI are specific (Table 2), the harmonized workflow developed within the RRNP ITINERIS project provides a coordinated approach that can be applied across infrastructures.

In total, 155 facilities were reported in the survey. Of these, about 70% are fixed platforms, while 30% are mobile oceanographic platforms (Annex 2). To ensure scientific consistency, a validation process was applied to assess whether each reported parameter met the operational criteria to be considered an EV. In detail, reported parameters were checked against the official definitions and methodological guidelines established by (GOOS website; GCOS website, ECVs; GEO BON website EBVs; Levin et al., 2019; Lantéri et al., 2022). Variables meeting all criteria from the official EVs sheets—including sensor specifications, continuity over time, and adequate resolution—were classified as "CORE", indicating full compliance. Variables measured but not fully meeting these requirements due to sporadic sampling, insufficient accuracy, or limited temporal resolution, were classified as "SUPPORTING". Accordingly, the CORE/SUPPORTING classification was based on the operational information consistently reported across facilities—sensor type and specifications, brand and model, declared accuracy, depth range, temporal continuity, and effective resolution—rather

TABLE 2 Overview of the RIs involved in the ITINERIS project, including scope, facility types, and contributions to marine monitoring.

Research infrastructure (RI)	Type of RI	Scope	Number of facilities	Type of facilities involved in this study	Contribution
DANUBIUS-ERIC	ESFRI Project	River-Sea Systems of major European rivers	10	Multidisciplinary observatories on rivers, deltas and coasts	Understanding of River-Sea interactions and processes
EMSO ERIC	ESFRI Landmark	Deep sea and water column	15	Multidisciplinary seafloor cabled observatories, moorings and buoys	Bio-geophysical, oceanographic and chemical data to monitor climate change on the ocean system
Euro-Argo ERIC	ESFRI Landmark	Open Ocean profiling	44	Autonomous Argo floats	Profiles for climate and oceanographic research
ICOS ERIC	ESFRI Landmark	Greenhouse gases and carbon cycle	5	Atmospheric, ecosystemic, and oceanic stations	High-quality carbon and greenhouse gases data for climate change
eLTER RI	ESFRI Project	Ecosystem and Socio- Ecological Long-Term Research	16	Coastal and transitional research sites	Long-term ecological monitoring of transitional and coastal ecosystems
JERICO	Applied to the 2026 ESFRI Roadmap	Costal Marine Systems	25	Fixed platforms, Lagrangian buoys and drifters, HF radars, gliders, multiparametric buoys, tide gauges, ferry boxes, coastal benthic observations, calibration facilities for coastal observations	Multiplatform approach for high-resolution coastal oceanography
GeoSciences Project	National Research Infrastructure	Earth systems and coastal dynamics	51	Tide gauges, wave buoys, meteorological sensors, research vessels	Observational networks for oceanographic, atmospheric, and seismic data
LNS Italian National Facility	National Research Infrastructure	Deep-sea physics, acoustic and astrophysics	6	Cabled observatories, acoustic and optical sensors	Provide accesses to advanced research laboratories and seafloor observatories

than on a formal audit of compliance with GOOS website, GCOS website, ECVs, GEO BON website EBVs, or other best –practice standards.

While SUPPORTING variables do not achieve the full EV status, they remain valuable, especially in areas where CORE observations are absent or incomplete. This process led to the creation of a validated EVs list, used as the basis for subsequent analyses (Annex 4), adopting two complementary quantitative approaches:

1. EVs per facility – quantifies, for each facility, the number of produced EVs, reflecting the diversity of variables being observed.
2. EVs per sensor – includes repeated measurements of the same EV across different depths, instruments, or sampling conditions within a facility, providing a more detailed assessment of observational intensity and redundancy.

Finally, the CORE/SUPPORTING classification was incorporated into both analyses to evaluate the proportion of fully compliant observations versus those requiring improvement. This distinction offers insights into the overall maturity of monitoring practices across Italian facilities.

It should be noted that this survey does not encompass all RIs and facilities operating in the Italian Mediterranean. Other infrastructures such as EMBRC-ERIC, not covered in this study, may also influence the broader observational landscape.

3 Results and discussion

3.1 Survey results: overview of EVs, facilities, and RIs

Within the ITINERIS project, metadata was collected and validated from 155 facilities distributed across 8 RIs, including 108 fixed platforms and 47 mobile oceanographic platforms (Annex 2).

The analysis considered a total of 54 EVs (Annex 3), comprising 24 EOVs, 23 ECVs, and 7 EBVs. A detailed numerical breakdown by variable type is provided in Annex 4.

At the first level of analysis—*EVs per facility*—each EV was counted once per facility, regardless of depth, sampling frequency, or sensor characteristics. Using this approach, the 155 facilities reported 1.299 EVs: 510 EOVs, 753 ECVs, and 36 EBVs (Annex 4).

A second perspective—*EVs per sensor*—accounts for multiple observations of the same EV within a facility when measured at different depths or under distinct instrumental conditions. This method captures vertical resolution and observation density, which are especially relevant for variables such as temperature, salinity, and oxygen. Such multiple data points along the water column or repeated measurements at the same location often reflects specific scientific objectives, including profiling stratification, detecting gradients, or monitoring dynamic processes, thereby reflecting the intensity and purpose-driven character of the observational effort. When these repetitions are included, the number of observations increases to 1.707 EVs, distributed as 687 EOVs, 967 ECVs, and 53 EBVs (Annex 4).

Furthermore, each EV was categorized as either CORE or SUPPORTING. Overall, more than 90% of entries (1.550 out of 1.707) were qualified as CORE, corresponding to 619 EOV, 878 ECV, and 53 EBV.

3.2 Quantification of observational efforts

This section provides a quantitative overview of the observational effort across the ITINERIS network, focusing on thematic distribution (e.g. Physics, Ocean). The analysis considers both EVs per facility and EVs per sensor, thereby capturing diversity and density of observations (Figure 2).

At the facility level, a total of 1.299 EVs were reported, with a marked dominance of EOVs and Ocean ECVs (75%). Specifically, facilities recorded 510 EOVs, 753 ECVs, and 36 EBVs. A similar pattern is observed at the sensor level (Figure 2, bottom). EOVs are primarily physical, with smaller contributions from biological and biogeochemical domains. Within the ECVs, ocean variables prevail over atmospheric ones, consistently with the marine focus of the survey. EBVs account for the smallest fraction and are primarily linked to ecosystem function and structure.

The limited presence of EBVs can be explained by their methodological complexity and lower degree of operational standardization compared to EOVs and ECVs. Unlike physical and chemical variables, which are supported by mature sensor technologies, automated platforms, real-time data flows, and international standards (e.g., Euro-Argo, Copernicus), EBVs often rely on manual sampling, laboratory analyses (taxonomy, microscopy, eDNA), and specific expertise (Miloslavich et al., 2018; Balvanera et al., 2022).

Their operationalization is still under scientific debate (Kissling et al., 2015; 2024), and definitions, metrics, and standards remain under development. As a result, only 36 unique EBVs were reported across all facilities, despite growing policy and scientific demand. Indeed, at the European level, EBVs are increasingly recognized within EU biodiversity policy frameworks—such as the EU Biodiversity Strategy for 2030 and related research infrastructures—as key tools for harmonizing biodiversity monitoring and supporting evidence-based decision-making.

The distribution of EVs also reflects the overlap of parameters across frameworks (e.g., sea surface temperature and salinity, as both EOVs and ECVs), which highlights their complementarity and interdependent nature. It also mirrors a historical emphasis on physical and climate-related parameters, which are technically easier to monitor using established automated methods.

Finally, these patterns are shaped by long-term investment strategies, institutional priorities, and national research agendas across the eight RIs. Climate and oceanographic monitoring have benefited from long-standing funding and strong international coordination, resulting in widespread automation and standardization. In contrast, biodiversity monitoring has evolved through fragmented and localized efforts and still faces significant

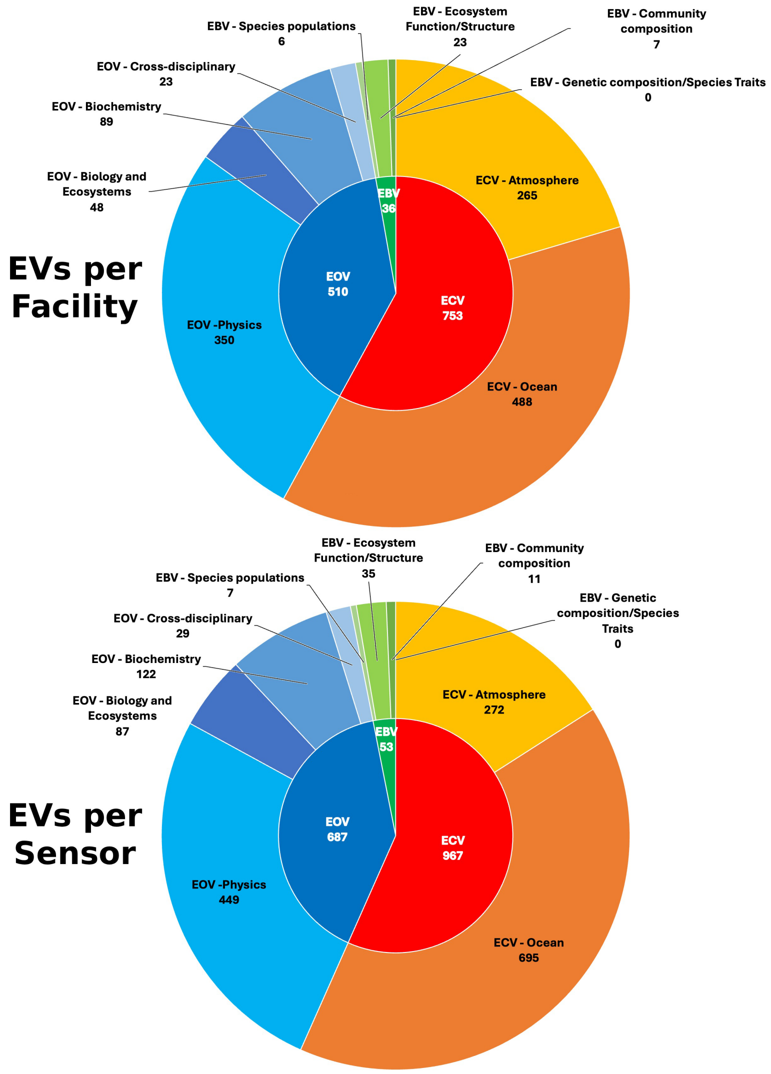


FIGURE 2
Distribution of EVs by type EOVs, ECVs, EBVs, and relative subgroups/classes (Annex 3) based on counts per facility (top) and per sensor (bottom).

barriers to operational standardization and technological automation. The ongoing work of initiatives such as EuropaBON, particularly its proposal for an EU Biodiversity Observation Coordination Centre (EBOCC; Liquete et al., 2024), underscores both the urgency and the opportunity to bridge this gap through enhanced coordination and harmonization at the European scale.

3.3 Marine EVs across Italian RIs

A more detailed analysis was conducted by comparing the contributions of individual RIs to marine EVs. Thematic specializations, complementarities, and gaps are summarized in Table 3 and Figure 3. Beyond the numerical overview, Table 3 reveals clear patterns: Euro-Argo, eLTER, and JERICO dominate EOV production, GeoSciences stands out in atmospheric ECVs, while EMSO, DANUBIUS and ICOS contribute significantly to biogeochemical EOVs, underscoring both complementarities and distinctive focuses across infrastructures.

Specifically, Euro-Argo, eLTER, and JERICO report 186, 97, and 70 EOVs, respectively. This reflects the deployment of dedicated oceanographic and coastal facilities. Euro-Argo's extensive network of profiling floats primarily delivers high-resolution physical data, particularly temperature and salinity, through its autonomous fleet (Roemmich et al., 2019). eLTER integrates atmospheric and marine monitoring, with a strong emphasis on ecosystem and biodiversity indicators. JERICO, focused on coastal dynamics, shows a pronounced contribution to physical EOVs through its network of fixed and mobile platforms and HF radars. GeoSciences contributes moderately (50 EOVs), but with a strategically distributed geographic coverage through national wave and tide gauge networks. Meanwhile, EMSO, DANUBIUS, ICOS, and LNS concentrate on specialized domains. EMSO and DANUBIUS, for example, provide biogeochemical EOVs such as dissolved oxygen, pH, nutrient concentrations, and carbon fluxes, especially in deep-sea and transitional systems (Table 3) (Miloslavich et al., 2017; Bax et al., 2019). LNS, as a producer of cross-disciplinary EOVs, demonstrates

TABLE 3 Detailed numerical count of EVs per facility subgroups per RI.

EVs	DANUBIUS (10)	EMSO (15)	Euro-Argo (44)	ICOS (5)	eLTER (16)	JERICO (25)	GeoSciences (51)	LNS (6)	Total
EOV - Physics	15	32	145	12	44	52	50	0	350
EOV - Biology and Ecosystems	6	2	11	2	22	5	0	0	48
EOV - Biochemistry/ Biogeochemistry	7	9	26	6	28	13	0	0	89
EOV - Cross-disciplinary	3	6	4	1	3	0	0	6	23
ECV - Atmosphere	14	10	0	12	26	34	169	0	265
ECV - Ocean	26	36	166	20	73	72	86	0	479
ECV - Cross-disciplinary	2	0	4	1	2	0	0	0	9
EBV - Species populations	1	0	0	0	5	0	0	0	6
EBV - Ecosystem Function/ Structure	5	1	2	1	9	5	0	0	23
EBV - Community composition	2	0	1	0	3	1	0	0	7
EOV	31	49	186	21	97	70	50	6	510
ECV	42	46	170	33	101	106	255	0	753
EBV	8	1	3	1	17	6	0	0	36
Total	81	96	359	55	215	182	305	6	1.299

Blu is for EOVs, red for ECVs and green for EBVs. Grey is for DANUBIUS, Light green is for EMSO, Dark yellow is for Euro-Argo, Light blue is for ICOS, Dark green is for eLTER, Mid blu is for JERICO, Brown is for GeoSciences, Dark blu is for LNS.

the growing role of multi-thematic RIs in supporting integrated and holistic ocean observations strategies.

Regarding ECVs (Table 3), multiple RIs broadly contribute. GeoSciences supplies extensive atmospheric and surface ocean variables via national networks. Euro-Argo provides oceanic observations through its autonomous profiling floats, while JERICO and eLTER add atmospheric and interdisciplinary components from transitional and coastal ecosystems. ICOS, though covering fewer variables, ensures the production of standardized greenhouse gas time series (Rebmann et al., 2018; Steinhoff et al., 2019; Santaren et al., 2025).

EBV contributions are more asymmetrically distributed across RIs compared to EOVs and ECVs (Table 3). Over 70% of EBV contributions are attributed to eLTER, reflecting its ecological mission. DANUBIUS, JERICO, EMSO, and Euro-Argo provide more limited, targeted biodiversity data, often through BioEco EOVs such as chlorophyll or plankton productivity (Table 3). eLTER's strength lies in ecological monitoring sites, particularly in lagoons and transitional waters, where biodiversity indicators such as plankton functional groups, species richness, and ecosystem productivity are recorded. Most of these measurements remain manual or campaign-based, lacking full automation (Turak et al., 2017; GEO BON website EBVs, 2022). Nevertheless, several RIs are advancing automation for biological and ecological variables; for example, Euro-Argo's BGC-Argo floats are increasingly equipped with optical and particle sensors to capture biodiversity proxies (Claustre et al., 2020; Organelli et al., 2021; Picheral et al., 2022).

Figure 3 illustrates the thematic distribution of EVs within each RI, highlighting scientific focus, technical capacity, and the relative weight of different observation domains. The analysis demonstrates varying levels of specialization and multidisciplinarity across the Italian RIs.

The patterns in the pie charts indicate that some RIs focus predominantly on specific domains, while others exhibit more diverse profiles/topics/themes and can also be grouped based on similarities. Euro-Argo and EMSO show strong specialization in EOVs and ocean-related ECVs, which together account for nearly all their monitored variables. This aligns with their missions originally centered on ocean physics and broadened since 2012 on biogeochemistry (Claustre et al., 2016; Henson et al., 2016), supported respectively by autonomous floats and fixed moorings (Table 2). In Euro-Argo, the high number of observations is closely linked to the number of deployed floats (i.e., 42, Annex 2). Recent technological advancements in biogeochemical Argo floats, equipped with optical and biogeochemical sensors, are gradually extending Euro-Argo's coverage into biological domains (e.g. Organelli et al., 2021).

ICOS shows a distribution similar to Euro-Argo and EMSO (Figure 3) (Rintala et al., 2025), but with a stronger specialization in atmospheric ECVs (orange in the chart), reflecting its mandate for greenhouse gas monitoring and air-sea carbon dioxide fluxes, which also requires the measurement of atmospheric variables.

Other RIs present a more varied internal EV distribution. eLTER spans all three EV categories and is the principal contributor to EBVs (17), while also contributing significantly to ECVs (101). Its representation of EOVs is more limited compared to ocean-focused infrastructures, yet its ecological and environmental monitoring in multi-domain ecosystems makes it the most thematically diverse RI.

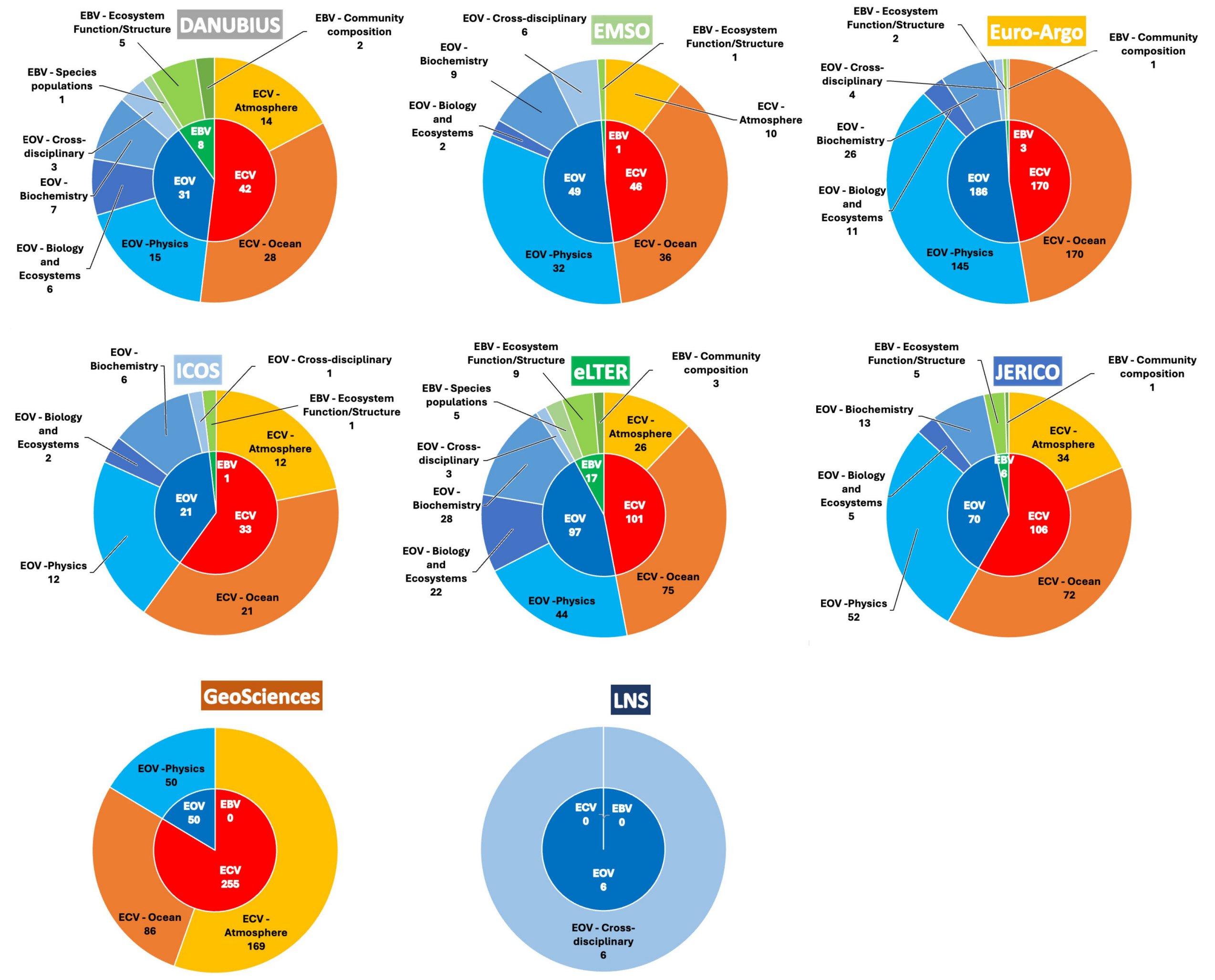


FIGURE 3
Distribution of EOVs, ECVs, and EBVs, and relative subgroups/classes, within each of the eight Italian RIs.

JERICO shows a similar pattern, with contributions to physical EOVs, oceanic ECVs, and a consistent EBVs output (6). Its focus on coastal and marine observing systems is reflected in the prominence of physical ocean variables and a notable contribution from atmospheric measurements, relevant for air–sea fluxes in coastal processes. DANUBIUS also contributes across categories, particularly biogeochemical EOVs, emphasizing multidisciplinary studies in transitional water bodies and bridging riverine, coastal, and marine environments, and reinforces its role in modelling those environments.

GeoSciences, as a national RI, is a major contributor of ECVs (255), primarily through atmospheric (169) and oceanic (86) parameters, ensuring broad coverage of key EVs across Italian seas. LNS, though contributing fewer EVs overall (6), provides focused and unique cross-disciplinary observations, such as underwater sound.

The results show in the pie charts confirm that some RIs, including Euro-Argo, EMSO, ICOS, Geosciences, and LNS, are strategically specialized, delivering depth in selected domains or topics, while others, such as eLTER, JERICO, and DANUBIUS, act as multidisciplinary platforms, supporting broader scientific agendas. The similarities in pie chart compositions among eLTER, JERICO, and DANUBIUS highlight their potential synergies, enabling enhanced temporal and spatial coverage as well as a wider variety of EVs, further supported by co-located facilities. Multidisciplinary RIs naturally span a wide array of EVs, enhancing ecosystem-level assessments and integrated monitoring, whereas specialized RIs provide focused observations within specific domains. This complementarity between breadth and depth ensures that RIs collectively support both integrated and targeted scientific applications.

3.4 Gaps and core/supporting categories in EVs production

The acquisition of a wide variety of relevant EVs is only one dimension of achieving comprehensive coverage of marine observations. Equally important is a quality assessment that highlights both areas of maturity and structural gaps.

The analysis, summarized in Figure 4, examines the three major EV categories using the EVs per sensor approach, capturing detailed information and depth coverage. Each histogram distinguishes

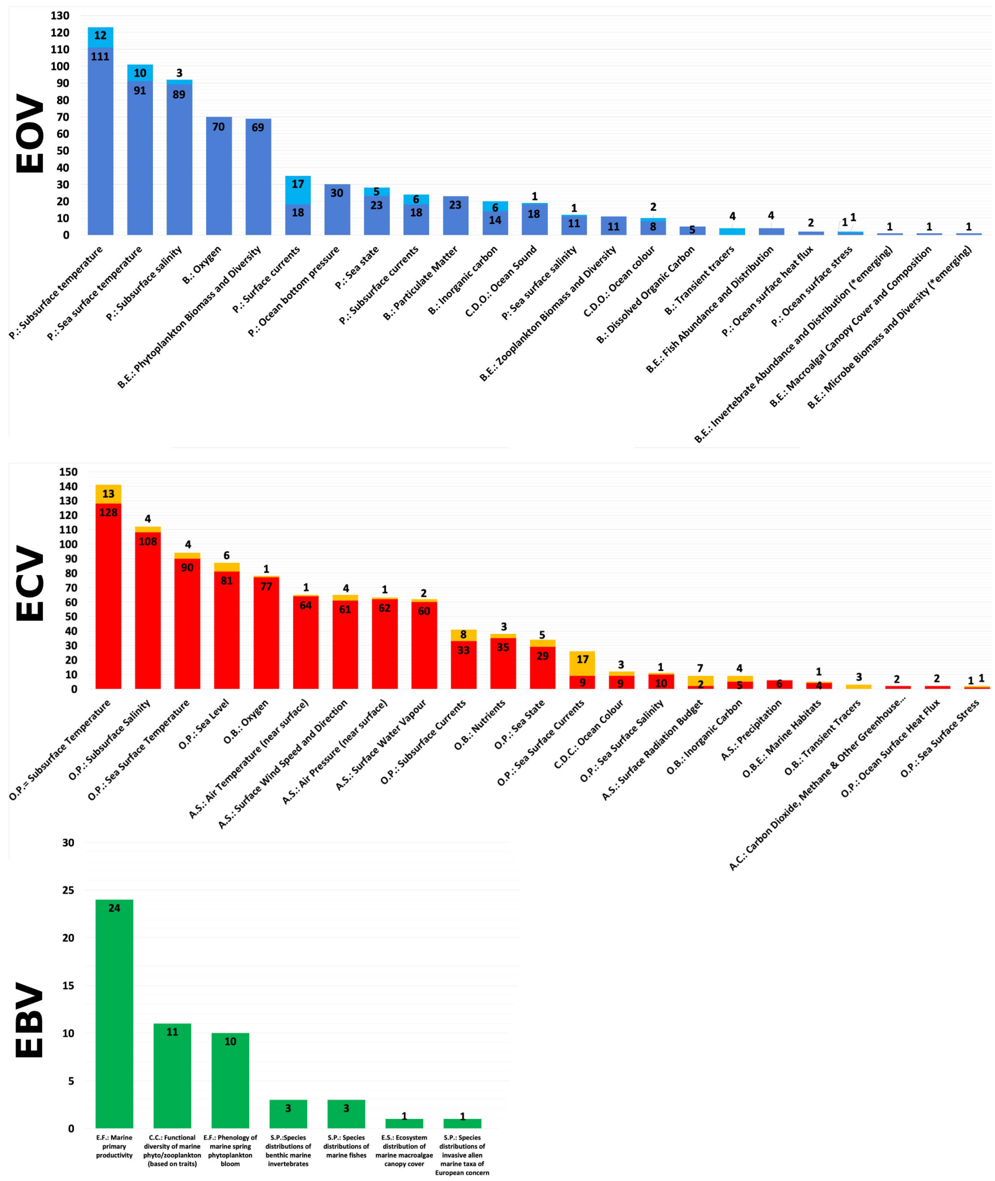


FIGURE 4
Distribution of CORE (blue, red, green) and SUPPORTING (light blue, orange) EVs per facility across RIs for EOVs and ECVs, while only CORE EBVs are present (no SUPPORTING EBVs). Core EVs meet international standards, while Supporting EVs complement them where coverage is limited.

between CORE EVs, which fully comply with the formal requirements of international observation frameworks (e.g., GCOS website, ECVs, GOOS website, GEO BON website EBVs), and SUPPORTING EVs. When comparing sensor characteristics and sampling methods against formal requirements, we found that most variables classified as SUPPORTING failed to comply primarily due to limitations in sensor accuracy and insufficient time resolution. Accuracy issues often are due to the lack of information provided by manufacturers or sensor obsolescence hindering technological upgrades. Temporal–resolution limitations arise also from manual sampling strategy, which may not consistently achieve the frequency required by international best–practice guidelines. These analyses are consistent with European–scale assessments, which similarly highlight sensor accuracy, temporal resolution, and methodological fragmentation as major drivers of non–compliance within observing systems (Hassoun et al., 2024). SUPPORTING EVs often act as ancillary parameters that enrich CORE EVs and contribute critical insights in context where CORE coverage is lacking or incomplete.

The EOVs (illustrated in dark blue for CORE EOVs and light blue for SUPPORTING EOVs) reveal a broad and heterogeneous distribution, indicative of the complexity and multidimensionality of ocean monitoring. Among the most frequently recorded CORE variables are Subsurface Temperature (111), Sea Surface Temperature (91), Surface Salinity (89), and Oxygen (70), confirming the strong technological foundation and long-standing emphasis on physical oceanography within the national observation landscape. These variables also correspond closely to the most frequently produced parallel ECVs, reinforcing their relevance for both ocean and climate science. The EOV category also includes variables more specific to oceanographic research, such as Sea state, Currents, and EVs that describe ocean conditions (color, sound, surface stress, etc.).

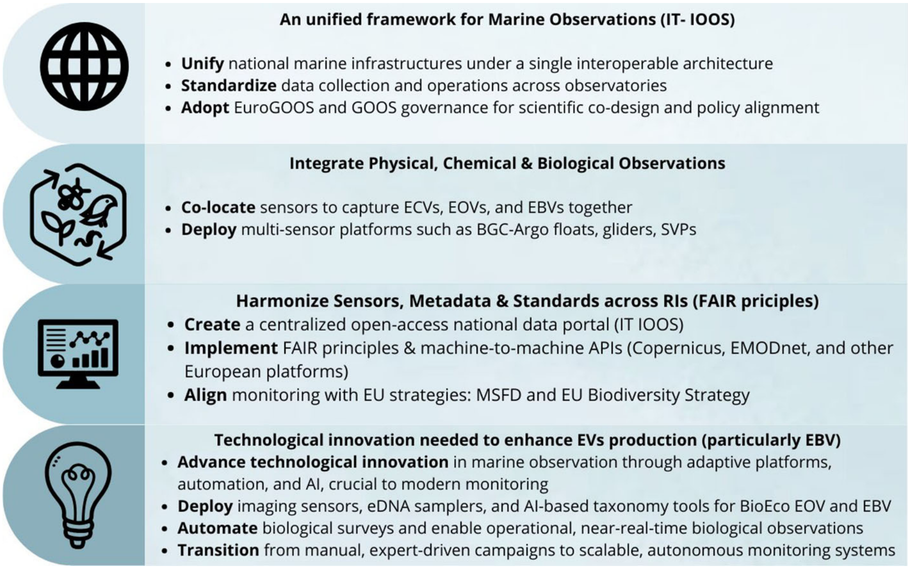


FIGURE 5
Strategic roadmap for enhancing Italy's marine EVs observation system.

Interestingly, about 10% of the recorded temperature values (subsurface or surface) fall into the SUPPORTING category, as they do not meet GOOS/GCOS standards for accuracy (required measurement uncertainty (2-sigma) of 0.1 and 0.3 K respectively)—a remarkably high fraction for a variable traditionally considered robust. Currents also show limitations, with roughly half of the values classified as SUPPORTING, reflecting persistent validation challenges. Beyond these well-established parameters, the histograms reveal a sharp decline in frequency for more specialized or emerging variables such as Invertebrate abundances, Macroalgal canopy cover, Microbe biomass and diversity, many of which are reported only once.

The ECV histogram (in red-orange Figure 4) reveals a similar consolidated and standardized monitoring effort compared to EOVs, with a prevalence of CORE values (91% CORE for EOVs; 90% CORE for ECVs). The most frequently and reliably monitored ECVs are Subsurface Temperature (128), Subsurface Salinity (108), Sea Surface Temperature (90), Sea level (81), and Oxygen (77). These benefit from mature technologies and harmonized methodologies, underscoring the robustness of the climate observation segment. Where SUPPORTING values do appear, they generally reflect methodological gaps—such as discontinuous time series or non-standardized sensors—rather than a lack of monitoring per se.

The EBV histogram (in green, Figure 4) highlights a markedly different situation: all reported EBVs are classified as CORE values. Marine Primary Productivity is the most frequently produced (24 cases), followed by six additional EBV classes, each represented at least once. The fact that all reported EBVs are classified as CORE reflects the characteristics of the limited subset currently implemented, rather than an intrinsic simplicity of EBV validation. The narrow scope and diversity of EBVs produced point to broader methodological, technical, and operational challenges. The dominance of pelagic biodiversity indicators reflects the historical focus of biological observation programs on ecosystem productivity, as well as their direct relevance to European environmental frameworks, such as the Marine Strategy Framework Directive (MSFD), the Water Framework Directive (WFD), and the Habitat Directive. Despite their quality, however, EBVs remain underrepresented in number and diversity.

When comparing the three histograms (Figure 4), several trends emerge. A strong overlap is visible between ECVs and EOVs, especially for oceanic variables like temperature and salinity, which are often derived from the same instruments and serve both climate and oceanographic monitoring needs. In contrast, only EOVs and ECVs show both CORE and SUPPORTING values, whereas EBVs are represented exclusively by CORE values. This asymmetry underscores a broader structural issue: not all environmental measurements meet the strict criteria for EV classification. The issue is not limited to a single variable or site, as shown in Figure 4. Where SUPPORTING values occur (i.e., in EOVs and ECVs), their wide distribution across variables highlights the selective and rigorous nature of EV frameworks, which prioritize parameters offering scientifically robust and policy–relevant insights.

In this context, the long-term viability of CORE EVs depends not only on observational availability, but also on adherence to internationally agreed standards, best practices, and interoperable data workflows that ensure consistency and comparability across observing systems and scales. Overall, the analysis highlights the need to go beyond observational coverage. Strengthening data quality, methodological standardization, and long-term continuity is essential to ensure that national data streams contribute to global assessments and decision-making. Recent European community-level syntheses developed under the UN Ocean Decade (UNESCO IOC, 2021), including coordinated assessments of observing-system gaps and alignment efforts within GOOS website and EuroGOOS website frameworks, further contextualize the Italian case as part of a broader continental push toward integrated, interoperable, and sustained ocean observing systems (Pearlman et al., 2019; Ryabinin et al., 2019; Heymans et al., 2020; Hassoun et al., 2024).

4 Conclusions

The results presented in this study highlight the significant effort already undertaken by the Italian marine observation system until 2023, just before the ITINERIS project, while also revealing key challenges that require coordinated, long-term solutions. Moving forward, Italy must consolidate these efforts by implementing a comprehensive and integrated strategy for EVs production across the oceanographic, climatic, and biodiversity domains. Persistent gaps remain in several basins, particularly offshore deep waters and sections of the coastline, where long–term observations are fragmented, or biogeochemical and biological variables remain undersampled. Addressing these gaps is crucial to improve the detection of environmental trends, support climate services, and respond to emerging ecosystem pressures.

As summarized in the infographic (Figure 5), several strategic and operational priorities emerge as essential to support this transformation.

The establishment of the IT-IOOS represents the cornerstone of national coordination. As envisioned within the ITINERIS framework, IT-IOOS should unify multiple RI-based observing systems. Inspired by models such as EuroGOOS website and GOOS, this national system is promoting scientific co-design and cross-institutional collaboration, ensuring that Italy's marine data actively support both domestic policy and European international commitments (Constable et al., 2016; Levin et al., 2019; UNESCO IOC, 2021; Dañobeitia et al., 2023).

The advancement of cross-domain and cross-RI integration is necessary to fully characterize the several spatio-temporal scales that represent marine ecosystems and meet the growing demand for transdisciplinary data. Experience shows that stronger communication between RIs fosters integration and reduces redundancies (Dañobeitia et al., 2023). Co-locating sensors to monitor physical, chemical, and biological variables (e.g., at fixed stations, on Argo floats, gliders, and buoys) will enhance environmental monitoring capacity (Muller-Karger et al., 2018; Bittig et al., 2019). Integration starts with harmonization and interoperability of observing systems, enabling more advanced approaches such as data integration and assimilation. These efforts should initially focus on ecologically strategic areas already identified by the individual RIs and later be expanded to fill geographic gaps, particularly in the west Sardinia, Tyrrhenian and Ionian seas, where monitoring remains insufficient. However, it is important to note that spatial coverage strongly depends on the type of observing facility, for instance, while fixed stations and moorings are few in the Ionian Sea, mobile platforms, such as Argo floats, provide comparatively better coverage in that area. In line with recent recommendations for regional coordination in the Mediterranean (e.g., Hassoun et al., 2024), our assessment also highlights the complementarity of existing Italian facilities within the broader Mediterranean observing landscape. Fixed stations, gliders, Argo floats, and research vessels each contribute unique spatio–temporal strengths, and their combined use helps mitigate persistent geographic and thematic data gaps. Strengthening cross–facility integration, particularly in under–represented areas such as the western Sardinia, Tyrrhenian, and Ionian basins, will be essential to enhance basin–wide observation capacity and to converge toward more coherent, sustainable monitoring strategies.

A critical enabler of integration is the harmonization of sensor calibration protocols, data formats, and quality control procedures across RIs (Pearlman et al., 2019). The adoption of FAIR data principles (Wilkinson et al., 2016) is essential to achieve semantic and technical interoperability, and to facilitate data sharing with European platforms like Copernicus Marine Service and EMODnet. To maximize the usability of EV data for both research and policy, Italy should establish a Single Access Point (SAP) to host, visualize, and distribute high-quality, machine-readable marine datasets.

Despite progress, a significant gap persists in monitoring biodiversity and ecosystem variables. EBVs and BioEco EOVs are underrepresented in the current system, primarily due to the time, and labor-intensive nature of observations and analyses. Dedicated investment is needed in sensor innovation and development, particularly in bio-optical devices (Organelli et al., 2021; Picheral et al., 2022), eDNA samplers, and AI-assisted taxonomic tools (Balvanera et al., 2022; Lumbierres et al., 2025; Miloslavich et al., 2017). Such advances will expand coverage, reduce reliance on campaign-based observations, and enable a transition towards automated, continuous monitoring, in line with international standards and scientific demand (Danovaro et al., 2020; Gattuso et al., 2018).

Alongside technological advancements, investment in human capital is essential. Training the next generation of marine scientist, data stewards, and technicians requires programs developed in close cooperation with RIs, fostering interdisciplinary skills in sensor operation, marine informatics, and data governance (Halpern et al., 2017; Miloslavich et al., 2018; Ballari et al., 2023).

Through shared protocols and coordinated cross–network operations, Italy aims to enhance its national capacity for sustained and expanded long–term ocean observations, while offering a replicable operational architecture for European efforts to harmonize and optimize marine observing infrastructures.

In conclusion, Figure 5 shows key areas of action: harmonized methods and metadata, targeted biodiversity technology development, and alignment with global standards. These pillars form the basis for a modern, responsive, and science-driven Italian marine observing system offering a replicable framework that other countries can apply through the establishment of defined points of contact and the use of a clear survey form for consistent information gathering.

Thanks to the ITINERIS project, the production of EVs across the Italian seas has increased substantially. The results presented in this paper reflect the early stages of the project, while by 2026 the overall improvement in EV production, driven by the project's efforts and the acquisition of new instrumentation for facilities and monitoring purposes, can be estimated at approximately +38-40% compared to the initial baseline. In particular, the preliminary calculations suggest an increase of around 30% for EOVs, 50% for ECVs, and 40% for EBVs data streams although these results should be considered provisional and not yet fully validated as the presented survey. Once these implementations are consolidated, they can be examined and evaluated in a future study.

These findings provide a comprehensive snapshot of the EV monitoring landscape in Italian seas, emphasizing not only the richness of observations but also the need for harmonization and standardization across facilities and RIs to maximize coherence and long-term value.

Data availability statement

The data analyzed in this study is subject to the following licenses/restrictions: Datasets are available upon request. Requests to access these datasets should be directed to emilio.urbinati@cnr.it.

Author contributions

ST: Conceptualization, Data curation, Formal analysis, Investigation, Methodology, Project administration, Resources, Supervision, Validation, Visualization, Writing – original draft, Writing – review & editing. EU: Conceptualization, Data curation, Formal analysis, Investigation, Methodology, Project administration, Resources, Supervision, Validation, Visualization, Writing – original draft, Writing – review & editing. DB: Conceptualization, Methodology, Supervision, Writing – review & editing, Visualization. CB: Conceptualization, Methodology, Supervision, Writing – review & editing, Visualization. FD: Conceptualization, Methodology, Supervision, Writing – review & editing, Visualization. MM: Conceptualization, Methodology, Supervision, Writing – review & editing, Visualization. MBel: Writing – review & editing. FBe: Writing – review & editing. MBer: Writing – review & editing. AB: Writing – review & editing. RB: Writing – review & editing. FBr: Writing – review & editing. GB: Writing – review & editing. CCan: Writing – review & editing. VC: Writing – review & editing. CCar: Writing – review & editing. LC: Writing – review & editing. AC: Writing – review & editing. SD: Writing – review & editing. GD: Writing – review & editing. AD: Writing – review & editing. DE: Writing – review & editing. MG: Writing – review & editing. SG: Writing – review & editing. GG: Writing – review & editing. ZK: Writing – review & editing. GL: Writing – review & editing. DL-O: Writing – review & editing. CM: Writing – review & editing. SM: Writing – review & editing. EM: Writing – review & editing. EO: Writing – review & editing. FP: Writing – review & editing. EP: Writing – review & editing. SP: Writing – review & editing. APe: Writing – review & editing. JP: Writing – review & editing. APo: Writing – review & editing. GR: Writing – review & editing. FRi: Writing – review & editing. FRu: Writing – review & editing. GS: Writing – review & editing. KS: Writing – review & editing. RSc: Writing – review & editing. RT: Writing – review & editing. RSa: Writing – review & editing, Funding Acquisition.

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Conflict of interest

The author(s) declared that this work 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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Supplementary material

The Supplementary Material for this article can be found online at: https://www.frontiersin.org/articles/10.3389/fmars.2026.1771479/full#supplementary-material

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