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EDITED BY
Laurent Coppola,
UMR7093 Laboratoire d'océanographie de Villefranche (LOV), France

REVIEWED BY
Tim Moltmann,
University of Tasmania, Australia
Adèle Révelard,
Balearic Islands Coastal Ocean Observing and Forecasting System (SOCIB), Spain

*CORRESPONDENCE
Juan José Dañobeitia
juanjo.danobeitia@emso-eu.org

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The role of the marine research infrastructures in the European marine observation landscape: present and future perspectives

Juan José Dañobeitia[1,2]*, Sylvie Pouliquen[3,4], Nicolas Pade[5], Christos Arvanitidis[6], Richard Sanders[7,8], Adrian Stanica[9,10], Claire Gourcuff[3], George Petihakis[1,11,12], Valentina Tegas[1] and Paolo Favali[1,13]

[1]European Multidisciplinary Seafloor and Water-column Observatory (EMSO ERIC), Rome, Italy, [2]Consejo Superior de Investigaciones Científicas (CSIC-UTM), Barcelona, Spain, [3]European Contribution to the International Argo Programme (Euro-Argo ERIC), Brest, France, [4]Institut Français de Recherche pour l'Exploitation de la MER (IFREMER), Plouzané-Brest, France, [5]European Marine Biological Resource Centre (EMBRC ERIC), Paris, France, [6]e-Infrastructure for Biodiversity and Ecosystem Research (LifeWatch ERIC), Seville, Spain, [7]Integrated Carbon Observation System (ICOS ERIC), Ocean Thematic Centre, Bergen, Norway, [8]NORCE - Norwegian Research Centre, Bergen, Norway, [9]International Centre of Advanced Studies on River-Sea Systems (DANUBIUS-RI), Bucharest, Romania, [10]Romanian National Institute of Marine Geology and Geoecology (GeoEcoMar), Bucharest, Romania, [11]European Global Ocean Observing System (EuroGOOS), Brussels, Belgium, [12]Hellenic Centre for Marine Research (HCMR), Athens, Greece, [13]Istituto Nazionale di Geofisica e Vulcanologia (INGV), Rome, Italy

The ocean regulates the exchange, storage of carbon dioxide, plays a key role in global control of Earth climate and life, absorbs most of the heat excess from greenhouse gas emissions and provides a remarkable number of resources for the human being. Most of the geo-hazards occur in oceanic areas. Thus, high-quality systematic observations are necessary tools for improving our understanding, and subsequent assimilation to provide early warning systems. A holistic scientific approach for the understanding of the ocean's interrelated processes requires coordinated and complementary monitoring and observation programmes. Research Infrastructures (RIs) are large-scale facilities that provide resources and services for the scientific communities to conduct high-level research and foster innovation. RIs benefit from strong governance and multi-annual funding from their member states with operational life spans in decades. RIs promote knowledge, outreach and education to public, private, and policy stakeholders, and they play a key role in enabling and developing research in all scientific domains and currently represent a growing share of coordinated investment in research, and also in providing essential observations to operational services such as Copernicus. They are strategically important for Europe to lead a global movement towards a data-driven, interconnected, open digital twin that brings together different disciplines, clean technologies, public and private sectors and a broad scientific/technological community, as well as education and training. In Europe several marine RIs have been established, which are maintained by national and European Union (EU) resources. The aims of these infrastructures are aligned with the key priorities of the UN Decade of Ocean Science for Sustainable Development; and with the new European Research Area (ERA) Policy Agenda annexed to the Council conclusions on the

ERA governance[1], which set out 20 concrete actions for 2022-2024 to contribute to the priority areas defined in the EU Pact for R&I[2]. The purpose of this paper is to demonstrate that the combined expertise and assets of Europe's marine RIs can form a comprehensive and holistic framework for long-term, sustainable integrated marine observation. Through this integration process the marine RIs can become better and better a significant pillar of the European Ocean Observing System (EOOS). Such a framework must be built as part of interfaces of interaction and promote not only scientific excellence but also innovation at all levels.

KEYWORDS

European Marine Research Infrastructures (ERICs), European Strategy Forum on Research Infrastructures (ESFRI), United Nations Decade of Ocean Science for Sustainable Development, European Ocean Observing System (EOOS), European Open Science Cloud (EOSC)

1 Introduction

The ocean regulates the exchange, storage and release of carbon dioxide, controls the climate, absorbs most of the heat excess from greenhouse gas emissions (Zanna et al., 2019) in the atmosphere and the life within it produces about half of the oxygen that we breathe. The ocean has played a key role in the dynamics of our planet, in the origin and evolution of life, and today it continues to be a critical environment for life and climate control, by redistributing and absorbing heat: as much as 93% of the excess energy resulting from the increased greenhouse gas emissions has been stored by the Earth in the oceans, over the past 50 years (EMB, 2019a). The ocean is changing due to global warming, natural variations and anthropogenic pressures. Therefore, it is essential to understand these changes by monitoring and measure then to understand what the impact on our society might be in the short, medium, and long term.

The First and the Second World Ocean Assessment (WOA I, 2016; WOA II, 2021) report a gradual deterioration in the health of the oceans, along with changes and losses in structure, function, and societal benefits derived from marine systems. Rapid climatic variation and multiple interacting environmental stressors are forecasted to have significant negative impacts in the coming years (IPCC, 2021; von Schuckmann et al., 2021; IPCC, 2022). As outlined in the UN Decade of Ocean Science for Sustainable Development (2021-2030), science-based knowledge on global change mitigation and adaptation policies are urgently needed (IOC, 2021). These policies must rely on a good knowledge of the system and its state, and sustained by systematic ocean observation that allows scientists and decision-makers to build different scenarios on possible consequences.

The European Commission, confirming its commitment towards an improved ocean governance in the recent Joint communication on the EU's International Ocean Governance agenda (2022)[3], sets four key objectives including building up international ocean knowledge for evidence-based decision-making in order to pledge the protection and sustainable management of the ocean. Ocean science, observation, environmental monitoring and modelling are considered vital for evidence- based action to protect and sustainably manage the ocean; too many gaps in the knowledge of the ocean are still detected. Actions and solutions to the ocean health crisis and development of a sustainable blue economy are linked to the level of knowledge, understanding and capacity to innovate.

Today more and more countries around the world regard research and innovation as a top priority for economic growth. Large-scale research facilities are crucial to the development of science, offering unique opportunities for innovation with a wide range of interactions between individual research infrastructure (RIs) and the surrounding economic and industrial environment. By their nature, RIs are a long-term national strategic investment with a broader socio-economic impact depending on the nature of a RI, the specific character of its broader innovation ecosystem, and the strategic objectives that it is pursuing (OECD, 2017).

Many marine observation programmes are being implemented worldwide, such as ONC (Ocean Networks Canada)[4] in Canada, OOI (Ocean Observatories Initiative)[5] and IOOS (Integrated Ocean

1 14308/21 Future governance of the European Research Area (ERA) - Council conclusions (adopted on 26/11/2021)

2 Council Recommendation (EU) 2021/2022 of 26 November 2021 on a Pact for Research and Innovation in Europe European Commission (2022). The EU Blue Economy Report. 2022

3 https://oceans-and-fisheries.ec.europa.eu/publications/setting-course-sustainable-blue-planet-joint-communication-eus-international-ocean-governance-agenda_en

4 https://www.oceannetworks.ca/

5 https://oceanobservatories.org/

Box 1 - ERIC-European Research Infrastructure Consortium
The European Research Infrastructure Consortium (ERIC) is a specific legal form that facilitates the establishment and operation of Research Infrastructures with European interest. The ERIC allows the establishment and operation of new or existing Research Infrastructures on a non-economic basis.

Observing System)[6] in USA, ECSSOS (East China Sea Seafloor Observation System; Yu et al., 2019) in China, DONET (Dense Ocean floor Network System for Earthquakes and Tsunamis)[7] in Japan, IMOS (Integrated Marine Observing System)[8] in Australia, and SAEON (South African Environmental Observation Network)[9] in South Africa, In Europe, several marine European RIs Consortia (ERICs; see Box 1[10]) have been established to underpin and support European research and observation efforts (ESFRI, 2021). They aim to structure research communities and implement guidelines and best practices laid out in international frameworks of the Intergovernmental Oceanographic Commission (IOC), such as the Global Ocean Observing System (GOOS), Genomics Standards Consortium (GSC), and the European Ocean Biodiversity Information System (EurOBIS), and seek to actively contribute to the United Nations Decade of Ocean Science.

The purpose of this paper is to validate that the combined expertise and assets of Europe's marine RIs can contribute with an important part of a comprehensive and holistic framework for long-term, sustainable integrated marine observation. It also underlies the need and, consequently, the importance to implement the coordination, cooperation and integration among them to better play the role of essential pillar for the European Ocean Observing System (EOOS) (EOOS, 2018b). After an introduction, the contribution of the RIs for conducting research, fostering innovation, and promoting education is highlighted (§ 2), the European landscape of marine RIs is presented (§ 3) and their added value is discussed (§ 4). Finally, the challenges (§ 5) and present and future perspectives of the marine RIs (§ 6) are introduced.

2 The contribution of the RIs

RIs provide advanced scientific equipment or instrument suites; resources and services to research communities to conduct high-level research, foster innovation in their fields, and enable cutting-edge research. RIs benefit from strong governance, direct links and multi-year funding from their member states with operational life spans measured in decades. These infrastructures promote knowledge, dissemination and education for a diversity of stakeholders and services, both in the public and industrial sectors and can be single-site, distributed, or virtual infrastructures. RIs are at the core of knowledge, and thus play a vital role in the advancement of knowledge and technology, industry and their exploitation (Figure 1).

An effective and efficient construction and operation of RIs is a key priority in realising the current European Research Area (ERA)[11] and in promoting open science and innovation. The ERA Policy Agenda sets out voluntary actions for the period 2022-2024 to contribute to the priority areas defined in the Council Recommendation on a Pact for Research and Innovation in Europe (Pact for R&I 2022)[2], where RIs were recognized as crucial to establish one specific dedicated priority area for joint action: the Council of the EU explicitly recommends mobilising a broader range of funding sources for world-leading research infrastructures and exploring novel ways of funding transnational and virtual access. The RIs are playing an integrating and structuring role at all levels, including e-infrastructures, in the European knowledge and innovation ecosystem as recognised by the EU Council in the conclusions on the future governance of the ERA. The recent EU Blue Economy Report 2022[12] aims at providing support to policymakers and stakeholders in the quest for a sustainable development of oceans, coastal resources and, most notably, to the development and implementation of policies and initiatives under the European Green Deal in line with the new approach for a sustainable Blue Economy. The marine EU RIs play a key role significantly contributing to most of the established and emerging and innovative sectors discussed in this report. The European Commission also places the marine RIs together with specialised research institutes and developers, capable of maintaining a competitive EU position in ocean research and observation. Although the monitoring and observation of the oceans in Europe is quite developed, the landscape remains somewhat fragmented. To properly address this fragmentation, the sustainability and efficiency of information provision must be addressed, while strong leadership and governance is required. It is essential to establish a coordination structure of marine observation in Europe to support the joint development of services, which will contribute to regional, national, European and global development (EC, 2016).

3 The European landscape of the marine RIs

The EU has provided leadership since 2002, when the EU council established the new *European Strategy Forum on Research Infrastructures* (ESFRI). The Forum was given the mandate to develop a coherent strategy on RIs in Europe and to support

6 https://ioos.noaa.gov/

7 https://www.jamstec.go.jp/donet/e

8 https://imos.org.au/

9 https://www.saeon.ac.za/

10 http://data.europa.eu/eli/reg/2009/723/oj

11 14308/21Future governance of the European Research Area (ERA) - Council conclusions (adopted on 26/11/2021)

12 European Commission (2022). The EU Blue Economy Report. 2022

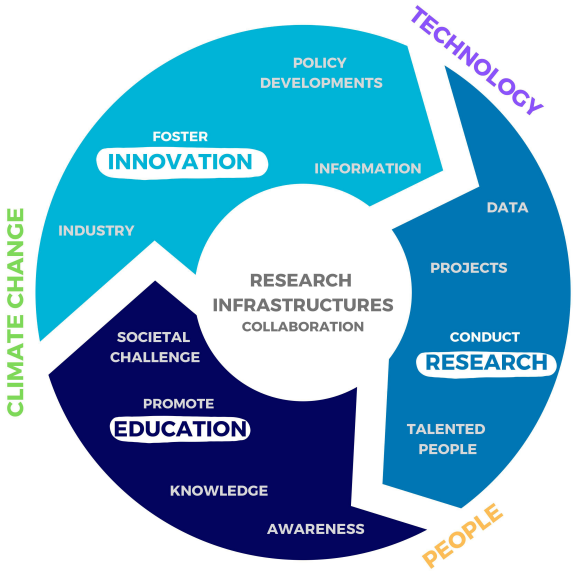

FIGURE 1
The central role of the RIs for conducting research, fostering innovation and promoting education, that are the key drivers of a knowledge-based society.

multilateral cooperation for the better use. In 2006, the first ESFRI roadmap was published (ESFRI, 2006), outlining for the first time Europe's determination to supports its strong research communities with the advanced equipment, facilities, and resources, necessary to push the frontiers of science; nowadays the roadmap - its last 6th edition was released in 2021 - is acknowledged as the main orientation tool for the European RI landscape (ESFRI, 2021).

Multi-platform marine RIs have been revealed as an effective and promising strategy for developing an observation system to face the global challenges that affect the Ocean and therefore the entire Planet. The UN Decade of the Ocean Science for Sustainable Development (2021-2030) (IOC, 2021), approved and supported by the General Assembly of the United Nations, offers welcome opportunities to the entire marine community and to society at large to deepen our understanding of marine systems, adjust to sustainable development and preserve the health of the oceans for future generations (Ryabinin et al., 2019). A joint priority identified is to increase our understanding of how the oceans function, by monitoring anthropogenic impact, modelling and predicting consequences of climate change, ocean acidification, marine pollution, ecosystem resilience and the ocean-climate connections through long-term ocean observations. Furthermore, for the different scientific communities, major issues are the collaboration/integration on common topics, such as the major societal challenges (Ruhl et al., 2011), the alignment of best practices and tools, and the change of current mindset in doing research, by taking into account multidisciplinarity.

In situ observations provide relevant information on the ocean environment, on its physical, geological, biogeochemical, and ecological characteristics, which are essential to understand critical aspects of the state of the ocean, changes in processes and consequences from these changes (EMB, 2021). Europe has 89,000 km of coastline, with the blue economy's traditional sectors contributing up to 1.5% of the EU-27 GDPs (Eurostat, 2015). All marine activities depend on the good knowledge of the physical, chemical, geological and biological characteristics of the sea and their variability. The Blue Economy sectors, such as natural resources, shipping and tourism, all require in-depth knowledge of the marine environment as well as reliable forecasting capabilities to provide mitigation procedures and their adaptation to changing conditions. Marine RIs are distributed large-scale facilities for long-term sustained ocean observations necessary to support climate and environmental policies, sustainable blue economy, preserve nature, and reverse ecosystem degradation and biodiversity decline (EMB, 2021). In Europe, the global ocean observations capability is represented by the following established marine RIs:

- EMSO ERIC[13] for fixed-point seafloor and water column observatories (Eulerian);
- Euro-Argo ERIC[14] for global network of profiling floats (Lagrangian);
- LifeWatch ERIC[15] for biodiversity and ecosystem research;
- EMBRC ERIC[16] for studying marine biological resources;
- ICOS ERIC[17] for carbon dioxide and greenhouse gas observations in the ocean, atmosphere and land;
- DANUBIUS-RI[18] for river-sea systems with focus on river-sea interactions.

These RIs are distributed (ESFRI, 2021) and included as landmarks by ESFRI because they reached an advanced implementation stage and represent major elements of competitiveness of the ERA (with the exception of DANUBIUS-RI, accepted on the ESFRI Roadmap in 2016). All are subject to periodic monitoring procedures.

In particular, each of the marine RIs contributes to specific aspects of the ocean and its scientific fields: EMSO main activity is dedicated to observations of the biogeochemical and environmental characteristics from the seafloor and through the water column to the surface with an Eulerian approach; Euro-Argo observes the physical and biogeochemical characteristics along the water-column with a Lagrangian approach; LifeWatch supports research on biodiversity, marine habitats and ecosystems; EMBRC is focused on the biological component at fixed observation sites, and understanding the behaviour, genetic, and physiological responses of marine organism to environmental stressors; ICOS measures the carbon dioxide and the greenhouse gases on land, atmosphere and ocean and their interfaces; DANUBIUS-RI focuses on the

13 https://emso.eu/

14 https://www.euro-argo.eu/

15 https://www.lifewatch.eu/

16 https://www.embrc.eu/

17 https://www.icos-cp.eu/

18 https://www.danubius-ri.eu/

characteristics of the interactions of river-sea systems and the rivers` impact on the ecology, the ecosystem, and health of the seas under their influence. These considerations support how the marine RIs can become the cornerstones of observation frameworks in Europe. Table 1 summarises the structure, vision, mission and purpose of the marine RIs.

Figure 2 shows the geographical distribution of the Countries involved in the ERICs and in the Research Infrastructure.

Each of these infrastructures has its own specific field activity, from marine biology and ecosystems, geo-hazards, greenhouse effects, physical and operational oceanography to river-ocean interactions, and combined, cover a significant part of the marine

TABLE 1 Structure, vision, mission and purpose of the marine Research Infrastructures.

RIs, website, references	Structure	Vision	Mission	Purpose
EMSO ERIC European Multidisciplinary Seafloor and water column Observatory www.emso.eu Favali et al., 2015	Fixed-point observatories in 14 key sites around European seas (Arctic, Atlantic, Mediterranean and Black Sea) for high-quality time series data on climate change, marine ecosystems and marine hazards	To become a world leader in Marine Environmental Sciences and Technology, from seafloor up to the surface	To establish a comprehensive and intelligent sensor system in water column, seafloor, and sub-seafloor environments as part of an integrated, sustainable and distributed organisation that provides high quality data, information, and knowledge	To illuminate major environmental processes to understand the complex interactions among the geosphere, biosphere, hydrosphere and atmosphere.
EURO-ARGO ERIC European contribution to the International Argo programme www.euro-argo.eu Roemmich et al., 2019	Maintain a quarter of the 4,700 profiling floats of the Argo international program	To revolutionised the European capacity of observing the interior of the ocean from the surface to the abyss inspiring the science we need for a sustainable ocean and contributing to society's wellbeing and resilience	Develop a long-term, sustainable European contribution to the OneArgo global ocean monitoring system to better understand and predict the ocean, its role in the climate system and its health	To provide high-quality data, services and product covering the global ocean and European seas in support to the research (climate and oceanography) and operational oceanography (e.g., CMEMS) communities with extensions towards biogeochemistry, greater depths and high latitudes
LifeWatch ERIC e-Science and Technology European Infrastructure for Biodiversity and Ecosystem Research www.lifewatch.eu Arvanitidis et al., 2016	e-Science research facilities to increase knowledge and deepen understanding of Biodiversity organisation and Ecosystem functions and services	The vision behind LifeWatch ERIC is to become the Research Infrastructure providing access to the world's biodiversity content, services and communities in one click	LifeWatch ERIC aims to accelerate the research effort of the scientific community by delivering a European state-of-the-art e-Infrastructure on biodiversity and ecosystem research: a Digital Twin which (a) provides access to, and support for, key scientific services by applying cutting-edge ICT technology, (b) enables reproducible analytics, (c) is co-designed and co-created with the user communities and (d) is tuned with the needs for research that provides key insights for society, in particular science-based policy	To offer new opportunities for large-scale scientific development; to enable accelerated data capture with innovative new technologies; to support knowledge-based decision-making for biodiversity and ecosystem management; to provide training, dissemination and awareness programmes
EMBRC ERIC European Marine Biological Resource Centre www.embrc.eu	Biological resources, services, facilities, and technology platforms in its 70 marine research organisations in 10 European countries. An 'omics based observatory is in operation since 2021 across 19 EMBRC sites	To advance the understanding of life in the oceans and to sustainably harness its potential for the benefit of humankind valuing quality and reproducibility in science, and holds itself to the highest ethical standards for working with living organisms	To provide access to marine biological organisms and their habitats for experimental purposes and applied research; to promote the sustainable use of marine resources, to deepen fundamental knowledge on marine organisms and their role in the environment, pushing the frontiers of science, to explore marine biodiversity for new products, inspiration, and innovation; to promote the use of marine experimental models in mainstream science	To advance fundamental and applied marine biology and ecology research promoting the development of blue biotechnologies
ICOS ERIC Integrated Carbon Observation System https://www.icos-cp.eu Macovei et al.,	Standardised and open data from more than 140 measurement stations across 13 European countries to observe greenhouse gas concentrations in the atmosphere as well as carbon fluxes between the atmosphere, the land surface and the oceans. OTC currently coordinates 22 ocean	ICOS is a state-of-the-art infrastructure providing high-quality and relevant data for a broad spectrum of users who transform it for scientific breakthroughs, and for	To produce standardised, high-precision and long-term observations and facilitate research to understand the carbon cycle and to provide necessary information on greenhouse gases. We promote technological developments and demonstrations related to greenhouse gases by linking research, education and innovation	The ICOS Ocean Network provides long-term oceanic observations required to understand the present state and better predict future behaviour of the global carbon cycle and

(Continued)

TABLE 1 Continued

RIs, website, references	Structure	Vision	Mission	Purpose
2020 Ocean Thematic Centre (OTC) https://otc.icos-cp.eu/	stations in seven countries, monitoring carbon uptake and fluxes in the North Atlantic and the Nordic, Baltic and Mediterranean Seas	knowledge for climate action		climate-relevant gas emissions
DANUBIUS-RI International Centre of Advanced Studies on River-Sea Systems www.danubius-ri.eu Friedrich et al., 2019	European river-sea systems, facilities and expertise; a 'one-stop shop' for knowledge exchange in managing river-sea systems; access to harmonised data; and a platform for interdisciplinary research, education and training	To achieve healthy River-Sea Systems and to advance their sustainable use, in order to live within the Planet's ecological limits by 2050	To facilitate and contribute excellent science on the continuum from river source to sea; to offer state-of-the art research infrastructure; and to provide the integrated knowledge required to sustainably manage and protect River-Sea Systems	To overcome the fragmentation of science, knowledge, data and management approaches in rivers and seas by integrating spatial, temporal, disciplinary and sectoral thinking providing science-based solutions to societal risks arising from global and climate change as well as coincident extreme events

environment. When reaching an operational level, RIs have all included in their strategy the need to be more effective through enhanced coordination and fostered cooperation. Moreover, this will significantly favour advancements towards the EOOS framework (EOOS, 2018a; EOOS, 2018b).

Ocean challenges are of multiple geographical scales, from local to regional or basin scale, to European and global. Europe's marine RIs cover different domains, from seafloor to sea surface, and estuarine (Figure 3). There is a natural overlap among the marine RIs, which cover from physics to biology, with a different interrelated angle of approach contributing to a deeper knowledge. Moreover, all together they cover different portions of the ocean from seafloor to surface and from open ocean to estuary, presenting a wide geographical and technical coverage.

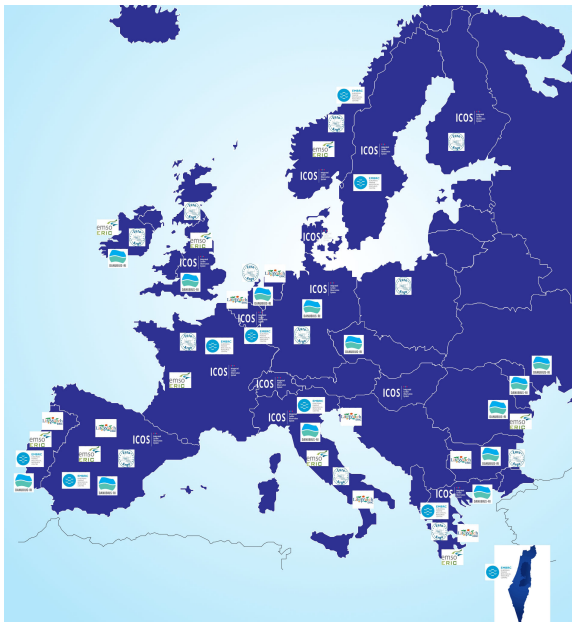

FIGURE 2
The geographical distribution of the Countries involved in the ERICs and in the Research Infrastructure.

The promotion of inter- and multi-disciplinary and cross-domain scientific research, which supports thematic hubs as examples of innovation in scientific and technological applications, offers a practical way to take advantage of the synergies of these RIs (Figure 3) to understand the complexity and challenges of global change. The launch of such thematic hubs constitutes a significant leap in enabling scientific and technological discoveries and producing innovation at the same time.

As a direct response to the 2014 EurOcean Rome Declaration where it was proposed the further development of EOOS (EC, 2015). The main objective of EOOS, which is a coordinated action co-designed with users, funding decision makers and observation implementers is to ensure long-term sustainability to integrate European ocean observation capabilities (EOOS, 2018a; Lara-Lopez et al., 2021). EOOS is a system based primarily on significant investment made by European countries in ocean observation complemented by EU funds to generate pan-European added value, and with the RIs as an essential component (EOOS, 2018b).

Some of the European marine RIs (EMBRC, EMSO, DANUBIUS-RI, LifeWatch, Euro-Argo) in the framework of this initiative, are ready to develop an active long-term participation of their Member States in the development of EOOS as part of an integrated observation system. They have clearly expressed their aim to strengthen collaboration by joining forces and favouring their synergies towards integrated multidisciplinary and cross-domain research on ocean observing systems (Dañobeitia et al., 2020). These RIs deliver relevant scientific results, support and contribute to address global societal challenges, and foster innovation. Their data support new operational services within global and European observing systems (GOOS and EuroGOOS), and EU data aggregators (e.g., Copernicus, CMEMS, EMODnet), or other European entities like Joint Programming Initiatives (JPIs, 2022). By bringing together the marine RIs under a joint strategy, it

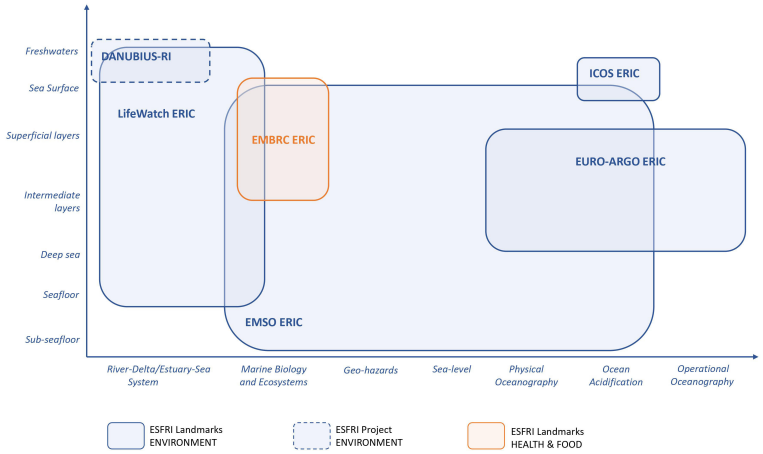

FIGURE 3
The different domains covered by the European marine RIs versus depth from seafloor to sea surface and fresh water (modified from ESFRI, 2018a).

favours alignment to the EOOS objective, leading to defragmentation of the observing landscape and thus act as essential pillars of a coordinated European ocean observation effort.

RIs promote the dissemination and updating of harmonised data standards, ontologies and data and other resources catalogues following FAIR (Findable, Accessible, Interoperable, Reusable) principles (Wilkinson et al., 2016), facilitating "online" exchange of data, as well as development of integrated services. These principles are applied to ocean data services (Tanhua et al., 2019) following best practices and standards (Pearlman et al., 2019). The RIs pursue a co-design and co-development approach based on commonalities that guarantee access to resources by multiple research communities, and offer common sustained funding models to promote long-term sustainability and interoperability (ESFRI, 2017).

Marine RIs support the development of advanced technologies, promoting best practices for the design and operation of ocean monitoring systems to foster the implementation of interoperable solutions between different RIs. At the global level, the system of Essential Ocean and Biodiversity Variables (EOVs and EBVs; Muller-Karger et al., 2018) offers a shared framework for monitoring the oceans and life within it, using the same metrics and variables. The marine RIs are well positioned to work with their research communities to implement workflows and standards that enable delivering essential variables across their partner organisations, creating the first monitoring programme based on these globally agreed indices (Benedetti-Cecchi et al., 2018; Levin et al., 2019). Another example of common interest is the need for lower cost sensor solutions with low-power consumption, miniaturisation, modularity, interoperability, and cost-efficiency of a whole swarm of physical and biogeochemical sensors and equipment. This contributes to a better understanding, protection and safety of the marine environment and ecosystems, to the assessment and mitigation of the risks connected with the climate change (e.g., loss of biodiversity, sea level rise), to a better support of operations through better coverage in space, time and quality of the observations, and to the assessment and mitigation of the geo-hazards (e.g., earthquakes and tsunamis, volcanic eruptions, seabed instabilities).

Thematic collaboration on specific scientific and technological topics between different marine RIs, clearly stimulates the progress in ocean observation capabilities with a smart agenda of trans-disciplinary and strategic marine research for societal benefit, in a kind of assortment of topics which are well described in "Navigating the Future V" (EMB, 2019b).

The principles around of which RIs operate are:

- Addressing societal challenges - among the challenges that we face today, such as climate change, pollution, loss of biodiversity, and sustainable harvest of protein from the sea, are considered of utmost importance. Although the degree of demonstration of these may differ between regions and countries, the problems are of a greater scale: European and even Global. RIs are the primary key instrument for providing high-quality data and information to a wide variety of stakeholders for looking for solutions to most of those problems.
- Means to build European critical mass - Big science and complex research questions are quite often beyond the capacity of a single nation or a single infrastructure. Despite its long-standing tradition of excellence in research and innovation, existing centres of excellence often fail to reach the critical mass necessary to tackle major societal challenges in the absence of adequate networking and cooperation.
- Scientific excellence - by bringing together state-of-the-art research infrastructures operating in the different member states, Europe promotes scientific excellence, harmonisation, and reproducibility. Researchers across Europe can now access sophisticated and complex equipment, know-how, long-term time series of quality data and a variety of products. As activities at the RIs are at the frontiers of science, they encourage new ideas, experimentation and research. They attract talent and offer career building opportunities to young researchers and engineers.

- Enriched research environments - RIs are at the core of the knowledge triangle, acting as natural crossroads between research, innovation and industry, the results of which can be glimpsed in the form of industrial applications, technology patents and spin-offs. They bring together highly qualified scientists, engineers, technicians and managers, funding agencies, public authorities, policy decision-makers and industry, including SMEs. Due to their scientific and technical multi- and cross-disciplinarity, RIs promote beneficial interactions with positive socio-economic impacts. Spin-off companies and technology parks are just a few examples. Then it is worth to underline the importance of the RIs for the European operational services and their support for monitoring the European policies.
- Connection to Global Science - RIs can have a direct contribution to global efforts in terms of challenges with projects and initiatives supporting international collaborative activities, contributing to the International global networks (e.g., GOOS, GCOS), promoting harmonisation and standardisation of processes and ensuring an open channel for dialogue. They offer an environment that generates a high flux of proposals and experiments stimulating international collaborations in many different disciplines and sectors.

4 The added value and challenges of the marine RIs

The marine RIs in the Environmental Domain have successfully implemented a system of standardised ocean observations over the last few years, based on long experiences of the marine organisations involved, in addition to supporting national and European policy and a solid basis for decision-making, science-based decisions, guiding adaptive responses within the framework of sustainable development.

Ocean knowledge and data are essential elements recognized by the European Commission to promote a new approach for a sustainable Blue Economy. Marine RIs must take a step forward in technology sharing, interoperability and data exchange to achieve a mature and competitive system with near real time observing capabilities. Better knowledge of the ocean and its ecosystems, together with free access to data, will enable to properly support industry, public authorities and civil society in their decisions (EC, 2021a)[19].

For example, the marine RI's coverage will allow them to produce data on carbon uptake from a broad range of habitats, form deep ocean to coastal areas. Combined, this data can support improved climate models and predictions, understand the state of the ocean, changes in marine ecosystems, and monitor environmental hazards and their potential socio-economic impact. Supporting this level of data products and results will constitute a significant contribution to sound decision making on marine matters and exploitation. Also, RI's contribution to operational marine and climate services and the Blue Economy, will account for a significant part of our national economies by 2030.

RIs face challenges in the short-, medium-, and long-term, including sustainability, wide participation of countries, interacting with diverse scientific communities, increasing links with the global landscape, while staying up-to-date with technical and operational developments. These challenges can be better addressed through an integrative process, avoiding duplication, unnecessary investment and enhancing complementarities as argued hereafter.

The RIs represent long-term strategic investments by Member States whose first challenge is to secure funding to guarantee operational, effective and competitive capacity during their lifetime. Therefore, the success of RIs is intrinsically related to their duration and long-term financing, well beyond the average life-time of a project. The cost of investing in marine RIs that underpins a broad range of research and innovation activities is substantial. According to a preliminary assessment carried out by the JPI "Healthy and Productive Seas and Oceans" (JPIs, 2022), the annual research budget dedicated to marine and maritime research in Europe is close to €1.9 billion, 40% of which are spent in RIs of many types, including those described in the paper, but also on research vessels, buoys, robotics etc. In the case of the European RIs, there are two components that play a crucial role in overall sustainability: the national facilities that are the backbone of any RI and the European framework under which the RI operates. Nationally, the demand for RIs is high throughout all fields of science, but funds available for capital investment and running costs are generally limited and fall short of meeting demand. While for the established RIs there is a national commitment to support during the design phase, in reality funding needs to be revised over the life-time of the RI to keep up with the state-of-the-art progress in terms of scientific and technological enhancements.

Seeking new funding and collaboration opportunities (in addition to membership contributions) is a demanding but necessary process with the challenge of developing and/or contributing to project proposals in line with the RI strategy and implementation plans. Specific EU RI calls have proven very successful (and efficient); enhancing the innovation part of the RIs, contributing thus to their competitiveness and sustainability. Moreover, according to *Science Europe Policy Brief on Research Infrastructures in EU Framework Programming*[20], the direct funding of running costs of RIs recognised as "of European relevance" should be eligible in order to limit RI's reliance on institutional funding. Distributed RIs could receive more support as they would benefit less from institutional funding for running costs and rely more on project grants. Furthermore, it could be argued that in the case of RIs with a direct contribution to global networks

19 COM (2021) 240 final https://eur-lex.europa.eu/legal-content/EN/TXT/?uri=COM%3A2021%3A240%3AFIN

20 https://www.scienceeurope.org/our-resources/policy-brief-on-research-infrastructures-in-eu-framework-programming/

and challenges, their contribution could be seen as a European contribution with a subsequent central support.

Recently, the European Commission launched calls to promote the integration of the RIs in local, regional and global innovation systems, to improve their scientific competitiveness and technological synergy with industries through co-design and co-development. The alignment of national, regional and EU R&I systems already led to positive effects for some RIs - especially some large RIs supporting structured research communities. As highlighted by EGERIC, the Expert Group on the ERICs, in the recent *Report on assessment on the implementation of the ERIC regulation*[21],the capability of the ERICs in promoting the synergies between national and structural funding, as well as in being aligned with the smart specialisation strategies could be further stimulated and included in the governance of the 'ERIC-system' within the ERA, contributing to the overall sustainability.

Stakeholders play a critical role in the creation, evolution and maintenance of ocean observing systems, therefore effective stakeholder communication and involvement is crucial to developing and prioritising RIs in an integrated ocean observing system (Mackenzie et al., 2019). Stakeholders and users - scientific and technological communities, SMEs and industries, general public and policy-makers - are at the core of every RI. The gathering of requirements to design and implement user specific services is of paramount importance, and thus an efficient and long-term communication channel with them is an essential requirement. This process is not straightforward as it is often hard to connect with the users and establish strong relationships, while in the case of industry, significant barriers often stand in the way of progress. The cooperation of the RIs with industry is based on scientific excellence, and the quality of services while academic users must also engage in this collaborative process (Figure 1). Collaborating companies (SMEs, large and multinational companies) can be users or providers of RIs with specific R&D, innovation and/or sales objectives (ESFRI, 2018b).

Each European marine RIs has developed clear drivers through a multi-year strategic plan, but due to the complexity of environmental science and the needs of specific research communities, this has led to these drivers being highly diverse which is also reflected in the activities of the RIs. Identifying common drivers amongst the marine RIs and defining joint strategies is an essential step towards a more integrated observation and monitoring of the environment Within the cluster of the environmental research infrastructures, ENVRI[22], a drive for coordination between the environmental RIs was launched encouraging the exchange of experiences and best practices. ENVRI is a community of RIs, projects, and networks working in the environmental domain, promoting coordination, especially around data, the European Open Science Cloud, and driving FAIR data generation for RIs. The forum is also important for coordinating environmental research and joint discussions with the Commission.

5 Present and future perspectives

During the RI consolidation process, it is very important to establish synergies and strong links with other RIs. In addition to the activities in ENVRI, this link is done through funded European projects, enabling RIs to build an integrated multi-platform observing system, reducing overlaps, filling gaps, increasing efficiency, enabling interoperability, agreeing on data and metadata standards, and adopting new available technologies. Fostering an integrated approach to marine observations is an essential requirement and would be a significant added value for each RI.

There are three elements that are essential to achieve amongst RIs to move towards a highly coordinated marine observatory in Europe: cooperation, coordination, and integration.

Cooperation (*The action or process of working together towards a shared aim*). Marine research observations require significant investments in infrastructures and sophisticated equipment. Such investments are challenging for a single entity, so active cooperation is key to facilitate its development, long-term maintenance and efficiency especially when it comes to open ocean systems both at regional and global scale.

Thematic collaboration on specific scientific and technological topics stimulates the progress in ocean observation capabilities with a smart agenda of trans-disciplinary and strategic marine research for societal benefit, in a kind of assortment of topics as described in "Navigating the Future V" (EMB, 2019b). In particular, each of the marine RIs contribute to specific aspects of the ocean and its scientific fields: EMSO main activity is dedicated to observations of the biogeochemical and environmental characteristics from the seafloor and through the water column to the surface with an Eulerian approach; Euro-Argo observes the physical and biogeochemical characteristics along the water-column with a Lagrangian approach; LifeWatch supports research on biodiversity, marine habitats and ecosystems; EMBRC is focused on the biological component at fixed observation sites, and understanding the behaviour, genetic, and physiological responses of marine organism to environmental stressors; ICOS measures the carbon dioxide and the greenhouse gases on land, atmosphere and ocean and their interfaces; DANUBIUS-RI is focused on the characteristics of the freshwater - marine continuum with a focus on the river-sea interactions in deltas and estuaries and their impact on the ecology, the ecosystem, and health of the seas under the influence of the rivers. All together these RIs can contribute to develop a 4D image of the ocean, stressing the advantages to promote even more an interdisciplinary cross-domain approach.

The marine RIs are in the position to work with its research communities to implement workflows and standards that would enable the production of essential variables across their partner organisations, creating the first monitoring programme based on these globally agreed indices (Benedetti-Cecchi et al., 2018; Levin et al., 2019). Furthermore,

21 European Commission, Directorate-General for Research and Innovation, Assessment on the implementation of the Eric Regulation, Publications Office of the European Union, 2021, https://data.europa.eu/doi/10.2777/747211

22 https://envri.eu/

as the RIs are investing in maintaining long-term observations and technological developments, they are also well placed to advance lower cost sensor solutions with low-power consumption, miniaturisation, modularity, interoperability, and cost-efficiency. The operational cost of marine observation is a considerable barrier to long-term sustainability. Progress on this field will contribute considerably to better operations through increased coverage in space and time making possible for instance a more efficient assessment and mitigation of geo-hazards.

Coordination *(The act of making parts of something, groups of people, etc. work together in an efficient and organised way)*, Firstly, coordination would facilitate the efficient use of resources both internal to individual/distributed infrastructures and external environment. In this context, the ENVRI Science Cluster has been developed through a set of successive collaborative projects where environmental RIs work together and develop common solutions at all stages of their planning, design and operation guaranteeing their complementarity and interoperability, increasing efficiency and avoiding duplication of effort. The current project, ENVRI-FAIR (2019) is focussing on data interoperability, while the EOSC Future Science Project[23] perform new cross-disciplinary scientific analysis based on research collaboration, demonstrating how EOSC can be used to create knowledge and services from inter-working research communities.

The coordination also allows joint events to highlight the potential of the marine RIs and propose joint actions to answer collectively to societal needs. The first example of RIs' coordination is the *EMSO Conference: preparing for UN Decade of Ocean Science* which took place in Athens in February 2020 in which, the participant RIs Consortia (EMSO, EMBRC, Euro-Argo, ICOS Marine, LifeWatch and EPOS[24]), together with the ESFRI project DANUBIUS-RI, discussed innovative ways by which the science community can coordinate activities to address the United Nations ambitious Sustainable Development Goals and support the Horizon Europe mission on "Healthy Oceans, Seas, Coastal and Inland Waters". Furthermore, as highlighted in the conference statement[25], the participating RIs approach challenges with a single voice in a synergistic and coherent way. The second example, is the *Cooperation Framework between Marine Research Infrastructures* at the 9th EuroGOOS Conference, where the future strategy was discussed under a collaboration plan co-designed within the framework of the UN Decade of Ocean Science and the EOOS, identifying collaborative actions in the design, monitoring and implementation of integrated networks, joint educational activities, and the exchange of project results (Gourcuff et al., 2021).

Integration (*The action or process of combining two or more things so that they work together*). The trend in the marine domain is towards an integrated "fit-for-purpose" be it regional, European or global system in line with the approach outlined in the Framework for Ocean Observing[26] by GOOS. For processes and phenomena that demand distributed multiple-large-scale observations, national systems are insufficient as they rarely exceed country boundaries. On the other hand, regional efforts such as the Sea Conventions and the GOOS Regional Alliances (GRAs) focus mostly on coordination aspects. Considering the current grand challenges, such as climate change and the continuing loss of biodiversity, in which appropriate integrated activities are necessary, marine ERICs are useful facilities both at regional and European level, and can play a relevant role at the global level. It is thus very important that there are links with Global networks, maintaining an active dialogue which will ensure exchange of information and knowledge and, more importantly, alignment of strategy and priorities. This important link between national, regional and international level, is provided very efficiently by the RIs in benefit of the wider community, much exceeding the RI partnership.

Data harmonisation activities can be a starting point towards RI integration but actions must also go further. Today, the marine RIs collect data which will significantly increase in the very near future with the development of systems able to collect more variables. Much effort has already been invested in implementing reliable and effective data management infrastructures following the FAIR principles and in compliance with the EU data repositories (e.g., EMODnet, EurOBIS). To face the increase in complexity, RIs are following the recommendations expressed by the European Marine Board (EMB) in the report on Big Data in Marine Science (Guidi et al., 2020). Data acquisition through "smart sensors", adoption of community standards for data handling and management, improvements in data interoperability for easier sharing between scientists, industry and governments, the use of big data analytics and ways to facilitate collaborations between scientists (marine, computer and data) and data managers are some of the recommendations to move towards better data and services integration. In addition, upgrading the European marine RIs metadata and data services is now possible through the development of Virtual Research Environments (VREs). Moreover, in order to align with the EOSC requirements (EC, 2021b) and further developments are needed in the future to develop the integrated data services from the RI data systems.

The development of the Digital Twin of the Ocean (DTO)[27] is expected to increase the development of integrated multi-platform services for a wider variety of users. The DTO is considered as a key element by the European Commission: it is part of the Digital Ocean Knowledge System - funded under the EU Mission Restore our Ocean and Waters[28] - and, it is recognized also as a fundamental component of the Destination Earth (DestinE)

23 https://eoscfuture.eu/

24 https://www.epos-eu.org/

25 https://emso.eu/wp-content/uploads/2020/02/EMSO-ERIC-Conference- Statement_FINAL-1.pdf

26 https://www.goosocean.org/index.php?option=com_content&view=article&id=282&Itemid=420

27 https://digitaltwinocean.mercator-ocean.eu/

initiative, embedded in the new European Digital Programme[29]. Destination Earth (DestinE) aims indeed to develop - on a global scale - a highly accurate digital model of the Earth to monitor and predict the interaction between natural phenomena and human activities. DestinE is expected to contribute fundamentally to the objectives of the twin transition, green and digital, as key objectives of the EU Green Deal[30] and Digital Strategy[31]. In this context the marine RIs provide key data for the DTO goals.

Consolidating on the progress made so far and moving forward in strengthening the main three aspects we believe that future priorities include:

Cooperation Work on a compatible and interconnected strategy and implementation plans strengthening communities and smoothing out differences;

a) Identify common metrology standards and data inter-comparison procedures;
b) Design and implement interoperable services towards different categories of stakeholders;
c) Strengthen relationships with stakeholders in a synergistic way, paying particular attention to policy makers, funding institutions at national and European levels, industry and academia.

Coordination

a) Develop technology, augment relationship with industries for innovative developments of common interest, fostering miniaturisation and low cost friendly sensors;
b) Plan common activities at sea and in labs of reciprocal interest – planning interdisciplinary activities;
c) Design and develop training programmes for researchers, technologists and technicians to increase comprehension, common languages and homogenised best practices;
d) Create joint education and training programmes for researchers, technologists and technicians to increase comprehension, common languages and homogenised best practices;
e) Create common communications messages;
f) Improve mobility of all staff that will benefit cohesion.

Integration

a) Work together on the development of integrated monitoring strategies to answer scientific and respond to societal needs;
b) Continue with the integration and harmonisation of data, its management and processing with an open access approach following the FAIR principles;
c) Connect existing data infrastructures operating at each RI, enhancing the already strong links with EU data aggregators (such as CMEMS, EMODnet) in a consistent and uniform way.

6 Conclusions

European marine RIs constitute a dynamic infrastructure framework, sustained primarily by Member States through long-term financial commitments and by competitive national and European Commission funding calls. European integration is politically and strategically supported by the EC through project calls, supporting activities to develop the European RIs as well as their services facilitating research, innovation and developing socio-economic impacts.

Marine RIs are key large-scale tools for understanding marine environment complexities, heterogeneities and interrelationships through multi-interdisciplinary approaches. Addressing environmental challenges is crucial for humanity, its resources, and for life on Earth. Assessment and monitoring of the state of the environment is highly dependent on accurate information about fundamental processes in the geosphere, hydrosphere, biosphere and atmosphere, and their interactions. They have a significant role in strengthening safety and protection at sea and mitigate the multiple risks related to severe changes due to climate change, sea-level rise, geo-hazards, anthropogenic pollution, and loss of biodiversity among other stressors for the benefit of future generations. Marine RIs provide high-quality, sensitive environmental sustained services that can equally contribute to support thematic actions of regional and/or global impact (e.g., global changes, loss of biodiversity, environmental risks) for a wide variety of operational, public, societal and industrial stakeholders. They are an essential element of the earth's observing system, complementary to satellites and models and fundamental in the development of the Digital Twins of the Oceans (DTO).

Furthermore, the interdisciplinary multi-domain science of the marine RIs applied to complex processes ranging from very small to broad observation scales and from very short to long time scales, may determine new scientific discoveries in an almost unknown realm, the ocean.

Although RIs and in particular ERICs are fully integrated structures with the appropriate capacity to fulfil their mission, the complexity of the marine system highlighted above, demands a synergistic approach. Cooperation, coordination and integration activities within the RI ecosystem are very important in order to maximise benefits for the society by reducing fragmentation and avoiding duplication of effort.

The recently launched UN Decade of the Oceans is a suitable context to strengthen RI collaboration by emphasising multi-platform capabilities, through the development of multi-sensor technologies and the adoption of multi-parameter and interoperable methodologies for multinational marine co-

29 Regulation (EU) 2021/694 of the European Parliament and of the Council of 29 April 2021 establishing the Digital Europe Programme and repealing Decision (EU) 2015/2240

30 COM(2019) 640 final

31 COM(2020) 67 final and COM(2021) 118 final

designed, integrated and sustained marine observing systems. This will increase the ocean observing capacity, facilitating sharing of infrastructure, promoting best practices, and developing innovative technologies and approaches.

Considering the ocean observing value chain from requirements to societal benefits, end-user engagement is crucial towards a sustained and integrated ocean observing system. In this, RIs have a significant role, as they are developing detailed methods to ensure that data products, information, services and knowledge are provided to stakeholders in a way directly relevant to their requirements.

European marine RIs have great potential in fulfilling Europe's goal of being a major player with regards to the implementation of healthy and productive oceans, seas, coastal and inland waters at a global level, to alleviate with knowledge and information, the increasing socio-economic impacts. Furthermore, global challenges demand global approaches by joining forces and combining skills and data around the globe. The European Union's contribution is to effectively utilise its well established intergovernmental RIs and ERICs. Here its capabilities, that cover all types of scientific services, are requisite if there is to be a fuller understanding of the Global Ocean, from its coast line to its deepest depths. European marine RIs are an important part of the jigsaw and will help establish the vectors that can be used to determine and resolve the critical environmental challenges on a global scale. The current ERIC framework is important, in that it can support and facilitate RIs to be structured and organised in a way that ensures they operate within the same rules and regulations in all EU countries. National commitment by ERIC partners enables the sustainability of the RI, allowing for long-term planning, but strong and long-term political support both at national and EU level is also a key component for the longevity of the ERICs.

Author contributions

JD provided the overall guidance and contributed to writing most of the sections together with PF and GP, who additionally made a global revision of the manuscript. SP, NP, CA, RS, AS, CG contributed to implement their specific section and all gave contributions to all the text. VT significantly contributed to European Policy matters. GP provided the original figures. All authors contributed to the article and approved the submitted version.

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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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References

Arvanitidis, C., Chatzinikolaou, E., Gerovasileiou, V., Panteri, E., Bailly, N., Minadakis, N., et al. (2016). LifeWatchGreece: construction and operation of the national research infrastructure (ESFRI). *Biodiversity Data J.* 4, e10791. doi: 10.3897/BDJ.4.e10791

Benedetti-Cecchi, L., Crowe, T., Boehme, L., Boero, F., Christensen, A., Grémare, A., et al. (2018). "*Strengthening europe's capability in biological ocean observations*," Eds. Á. Muñiz Piniella, P. Kellett, K. Larkin and J. J. Heymans (Ostend, Belgium: Future Science Brief 3 of the European Marine Board), 76.

Berry, A., Kassis, D., Gourcuff, C., and Pouliquen, S.. (2021). *Cooperation framework between marine research infrastructures* (Zenodo). doi: 10.5281/zenodo.6810214

CMEMS. Available at: https://marine.copernicus.eu/.

Copernicus. *European Programme for the establishment of a European capacity for earth observation*. Available at: www.copernicus.eu.

Dañobeitia, J. J., Pouliquen, S., Johannessen, T., Basset, A., Cannat, M., Pfeil, B. G., et al. (2020). Towards a comprehensive and integrated strategy of the European marine research infrastructures for ocean observations. *Front. Mar. Sci.* 7. doi: 10.3389/fmars.2020.00180

EC (2015). "EurOCEAN 2014: connecting science, policy and people," in *Conference report and Rome declaration*. Eds. K. Larkin, N. McDonough, N. Wouters and A. Caetano (Rome, Italy: Publications Office). Available at: https://data.europa.eu/doi/10.2777/71034.

EC (2016). *European Charter for access to research infrastructures*. doi: 10.2777/524573

EC (2021a). *The EU blue economy report 2021* (Publications Office). doi: 10.2771/8217

EC (2021b) *Strategic research and innovation agenda (SRIA) of the European open science cloud (EOSC)*. Available at: https://data.europa.eu/doi/10.2777/935288.

EMB (2019a). "Navigating the future V: marine science for a sustainable future," in *Position paper 24* (Ostend, Belgium). doi: 10.5281/zenodo.2809392

EMB (2019b). "Navigating the future V: recommendations for the ocean decade," in *EMB policy brief n.6*. doi: 10.5281/zenodo.3465570

EMB (2021). "Sustaining in situ ocean observations in the age of the digital ocean," in *EMB policy brief n,9*, ISBN: . doi: 10.5281/zenodo.4836060

EMODnet. Available at: http://www.emodnet.eu/.

ENVRI-FAIR (2019). "ENVironmental research infrastructures building fair services accessible for society," in *Innovation and research*. Available at: http://envri.eu/envri-fair/.

EOOS (2018a) *EOOS strategy 2018-2022*. Available at: www.eoos-ocean.eu.

EOOS (2018b) *EOOS implementation plan 2018-2022*. Available at: www.eoos-ocean.eu.

ESFRI (2006). "Strategy report on research infrastructures in Europe," in *Roadmap 2006*, 84 pp.

ESFRI (2017). "Long-term sustainability of research infrastructures," in *ESFRI scripta*, vol. 2. (Milan), 85 pp.

ESFRI (2018a). "Strategy report on research infrastructures in Europe," in *Roadmap 2018*. Available at: http://roadmap2018.esfri.eu.

ESFRI (2018b). "Long-term sustainability of research infrastructures," in *ESFRI scripta*, vol. 3. (Milan), 145 pp.

ESFRI (2021). "Strategy report on research infrastructures in Europe," in *Roadmap 2021*. Available at: http://roadmap2021.esfri.eu.

EuroGOOS. Available at: http://eurogoos.eu.

Eurostat (2015). *Eurostat regional yearbook 2015* (Luxembourg: Publications Office of the European Union), 312 pp.

Favali, P., Beranzoli, L., and De Santis, A. (Eds.) (2015). "Seafloor observatories: a new vision of the earth from the abyss," in *Springer-praxis books in geophysical sciences* (Berlin Heidelberg: Springer-Verlag), 676 pp. doi: 10.1007/978-3-642-11374-1

Friedrich, J., Bold, S., Heininger, P., Bradley, C., Tyler, A., Stanica, A.the DANUBIUS-PP Consortium (2019). DANUBIUS-RI Science and Innovation Agenda. DANUBIUS-RI - The International Centre for Advanced Studies on River Sea Systems. *H2020 DANUBIUS-PP deliverable* doi: 10.5281/zenodo.3712902

GCOS. Available at: https://gcos.wmo.int.

GOOS. Available at: www.goosocean.org.

Guidi, L., Fernandez Guerra, A., Canchaya, C., Curry, E., Foglini, F., Irisson, J.-O., et al. (2020). "*Big data in marine science*," Eds. B. Alexander, J. J. Heymans, A. Muñiz Piniella, P. Kellett and J. Coopman (Ostend, Belgium: Future science brief 6 of the European marine board), 52. doi: 10.5281/zenodo.3755793

IOC (2021). *UN Decade of ocean science for sustainable development* (ECO Magazine Special Issue in partnership with UNESCO), 288.

IPCC (2021). *Climate change 2021: the physical science basis. contribution of working group I to the sixth assessment report of the intergovernmental panel on climate change*. Eds. V. ,. P. Masson-Delmotte, A. Zhai, S. L. Pirani, C. Connors, S. Péan, N. Berger, Y. Caud, L. Chen, M. I. Goldfarb, M. Gomis, K. Huang, E. Leitzell, J. B. R. Lonnoy, T. K. Matthews, T. Maycock, O. Waterfield, R. Y. Yelekçi and B. Zhou (Cambridge, United Kingdom and New York, NY, USA: Cambridge University Press). doi: 10.1017/9781009157896

IPCC (2022). *Climate change 2022: impacts, adaptation, and vulnerability. contribution of working group II to the sixth assessment report of the intergovernmental panel on climate change*. Eds. H.-O. Pörtner, D. C. Roberts, M. Tignor, E. S. Poloczanska, K. Mintenbeck, A. Alegría, et al Eds. (Cambridge University Press).

JPIs (2022). Available at: https://ec.europa.eu/programmes/horizon2020/en/h2020-section/joint-programming-initiatives.

Lara-Lopez, A., Heslop, E., and Lips, I. (2021). "European GOOS national focal points survey: funding and coordination across ocean observing and marine monitoring in Europe," in *A European ocean observing system (EOOS) report*, 25 pp.

Levin, L. A., Bett, B. J., Gates, A. R., Heimbach, P., Howe, B. M., Janssen, F., et al. (2019). Global observing needs in the deep ocean. *Front. Mar. Sci.* 6. doi: 10.3389/fmars.2019.00241

Mackenzie, B., Celliers, L., L.P.d.F., A., Heymans, J. J., Rome, N., Thomas, J., et al. (2019). The role of stakeholders in creating societal value from coastal and ocean observations. *Front. Mar. Sci.* 6. doi: 10.3389/fmars.2019.00137

Macovei, V. A., Hartman, S. E., Schuster, U., Torres-Valdés, S., Moore, C. M., and Sanders, R. J. (2020). Impact of physical and biological processes on temporal variations of the ocean carbon sink in the mid-latitude north atlantic, (2002-2016). *Prog. Oceanography* 180, 102223. doi: 10.1016/j.pocean.2019.102223

Muller-Karger, F. E., Miloslavich, P., Bax, N. J., Simmons, S., Costello, M. J., Sousa-Pinto, I., et al. (2018). Advancing marine biological observations and data requirements of the complementary essential ocean variables (EOVs) and essential biodiversity variables (EBVs) frameworks. *Front. Mar. Sci.* 5. doi: 10.3389/fmars.2018.002

OECD (2017). "Strengthening the effectiveness and sustainability of international research infrastructures," in *Science, technology and industry policy*, vol. 48. (OECD Publishing), 66 pp.

Pearlman, J., Bushnell, M., Coppola, L., Karstensen, J., Buttigieg, P. L., Pearlman, F., et al. (2019). Evolving and sustaining ocean best practices and standards for the next decade. *Front. Mar. Sci.* 6. doi: 10.3389/fmars.2019.00277

Roemmich, D., Alford, M. H., Claustre, H., Johnson, K., King, B., Moum, J., et al. (2019). On the future of argo: a global, full-depth, multi-disciplinary array. *Front. Mar. Sci* 6. doi: 10.3389/fmars.2019.00439

Ruhl, H. A., André, M., Beranzoli, L., Çağatay, M. N., Colaço, A., Cannat, M., et al. (2011). Societal need for improved understanding of climate change, anthropogenic impacts, and geo-hazard warning drive development of ocean observatories in European seas. *Prog. Oceanography* 91, 1–33. doi: 10.1016/j.pocean.2011.05.001

Ryabinin, V., Barbière, J., Haugan, P., Kullenberg, G., Smith, N., McLean, C., et al. (2019). The UN decade of ocean science for sustainable development. *Front. Mar. Sci.* 31. doi: 10.3389/fmars.2019.00470

Tanhua, T., Pouliquen, S., Hausman, J., O'Brien, K., Bricher, P., de Bruin, T., et al. (2019). Ocean FAIR data services. *Front. Mar. Sci*. 6. doi: 10.3389/fmars.2019.00440

von Schuckmann, K., Le Traon, P.-Y., Smith, N., Pascual, A., Djavidnia, S., Gattuso, J.-P., et al (Eds.) (2021). Copernicus Marine service ocean state report. *J. Oper. Oceanogr.* 14 (Suppl_1), 185. doi: 10.1080/1755876X.2021.1946240

Wilkinson, M. D., Dumontier, M., Aalbersberg, I. J., Appleton, G., Axton, M., Baak, A., et al. (2016). The FAIR guiding principles for scientific data management and stewardship. *Sci. Data* 3, 160018. doi: 10.1038/sdata.2016.18

WOA I (2016) *First world ocean assessment*. Available at: www.un.org/Depts/los/woa.

WOA II (2021) *Second world ocean assessment*. Available at: www.un.org/regularprocess/woa2launch.

Yu, Y., Xu, H., and Xu, C. (2019). A sensor web prototype for cabled seafloor observatories in the East China Sea. *J. Mar. Sci. Eng.* 7, 414. doi: 10.3390/jmse7110414

Zanna, L., Khatiwala, S., Gregory, J. M., Ison, J., and Heimbach, P. (2019). Global reconstruction of historical ocean heat storage and transport. *Proc. Natl. Acad. Sci.* 116, 1126. doi: 10.1073/pnas.1808838115