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The discovery of the unknown planet: The ocean

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The discovery of the unknown planet: The ocean

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Editorial: The discovery of the unknown planet: the ocean

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Editorial on the Research Topic
The discovery of the unknown planet: the ocean

The ocean is the engine of the Earth's ecosystem; it regulates the climate and absorbs more than 90% of the excess heat from greenhouse gas emissions. A consequence of this is that temperature, acidity, and stratification of the oceans affects biodiversity and the functioning of marine ecosystems. The impacts of anthropogenic pollution and eutrophication, intensive coastal development and extensive farming and agriculture, are increasing stressors on marine and coastal ecosystems; this has been accompanied by an overexploitation of marine resources.

Seventy per cent of the Earth's volcanism occurs on the ocean floor, which together with large seismic events and submarine landslides, are the main sources of earthquakes and tsunamis causing catastrophic damage as well as having a high socio-economic impact. As a result, there is great interest to both explore and understand the biogeochemical processes within the ocean. This also involves research into what has been an unexplored area of the Earth, the 'deep ocean'. As part of this desire to understand all aspects of the ocean, the United Nations (UN) launched the '2021-2030 Decade of Ocean Science for Sustainable Development'. This initiative and associated challenges are expected to mobilize the global ocean community to provide answers and possible solutions that will ensure the sustainability and protection of the seas and coastlines of the world.

In this Research Topic we have papers that discuss:

- 'Science matters', how gas manifestations relate to ocean acidification. In particular research surrounding the Aegean Sea, where there are multiple challenges resulting in a marine ecological assessment for European Seas, including long-term monitoring of marine fauna at artificial reefs at the EMSO[1] test site off the Spanish coast; and also involves the discovery and chemical composition of deep-sea anoxic brine pools in the Eastern Mediterranean. This is accompanied by extremely valuable Japanese seismic observations, that use distributed acoustic sensing technology in a seafloor cable. See Daskalopoulou et al., Ramirez et al., Francescangeli et al., Herut et al., and Shinohara et al.

- 'Technological matters', related to the importance of using advanced observation equipment and image analysis, ultimately reducing the costs of ocean research with a smaller environmental footprint. Examples of this include: EGIM[2] standardized and interoperable instrumentation; tele-operated resident robots for deep applications; video-imaging systems together with multi-parametric sensors at a shallow cabled observatory such as that off Spain; low-cost deep-sea imaging and analysis tools for deep-sea exploration off western Canada; and a low-cost, modular imaging and sensor platform to increase deep observation capabilities, known as Maka Niu. See Lanteri et al. Chatzievangelou et al., Ottaviani et al., Bell et al., and Novy et al.
- Development and enhancement of observatory systems, such as the volcanic seafloor observatory at Santorini in the Aegean Sea and EMSO's[1] western Ionian facility through the infrastructural project InSEA[3] that includes a wet demonstration test of the innovative concept of SMART[4] telecommunication cables which house various oceanographic and seismic sensors to improve real-time knowledge of many natural phenomena, and are an improvement on the present tsunami early warning systems. See Nomikou et al., and De Santis et al.
- Data management aspects, such as the Oceans 2.0/3.0 data management and archival system for the internet-connected ocean implemented in Canada. See Owens et al. and Moran et al.
- Organizational Perspectives, discussing the collaborative efforts required from local/regional and global communities. An example is the role of marine infrastructures in the European marine observation landscape that stresses the importance of an integration process with co-design and co-development as central features. Mendes Silveira et al., and Dañobeitia et al.

The advantage of a modular type of platform, including diverse suites of underwater sensors, like EGIM[2] is clear; these can be further optimized using artificial intelligence. This scientific work stresses the importance of continuous monitoring from smaller observatories dedicated specifically to the monitoring of volcanoes and other earth or ocean features of interest. Some examples of this have already started at Santorini, and other areas of biodiversity observations, where it is seen as both feasible and complementary to the ocean observations that include regional, cabled observatories. These include, for example, ONC[5] in Canada, EMSO[1] in Europe, DONET[6] in Japan, and some variants of SMART[4] cables on a global scale.

Expanding deep-sea observations and broadening underwater installations that include dedicated infrastructures, special laboratories and multi-platform observatories is the way forward to a better understanding of our oceans. This has been a long-term European commitment effort led by EMSO ERIC[7] involving a number of European countries.

The research infrastructure for deep ocean fixed observations plays a key role in obtaining the requisite scientific understanding, because it is the infrastructure and platforms, with the associated operations and maintenance that drives the cost. There already exists the capability to collect long-term time series and spatial data from the surface, through the water column and down to the deep seafloor. This infrastructure with the sensing can make fundamental and unique contributions in the understanding and promotion of the necessity of a multidisciplinary approach that includes all parties that use, utilise, develop and depend on the oceans of the world.

There are many global scientific and technological infrastructure programmes that already monitor and study the ocean. providing a better understanding of how it plays its part in all aspects of life, whether in the sea or on land. The aims of many of these programmes are already perfectly aligned with the key priorities of the UN Agenda 2030, European Commission (EC) Horizon Europe framework programme (2021-2027), and strongly contribute to the strategic areas of other initiatives, such as the European Union (EU) JPI[8] Oceans.

Nonetheless, what has been outlined above requires an effective and efficient data management that will enable and ensure quality control on a massive scale as well as disseminating this underwater data through a transparent and known management, providing a clearer 4D view of the ocean. This will result in a better understanding of the complex natural and anthropogenic phenomena taking place in the deep ocean that ultimately affects climate, coastal and open sea habitats, natural resources, health and ocean sustainability.

The work and research already completed by the bodies mentioned, indicate that the science, the technology and a greater will from government bodies provide an excellent opportunity to more fully understand the waters that cover the globe, and where encouraged by SDGs[9] It will be possible to foster the 'blue economy' which is based on greater knowledge and understanding and a friendlier use of the oceans.

This Research Topic, within the sections 'Deep-Sea Environments and Ecology', and 'Ocean Observation', consequently highlights the benefits of having an integrated and interdisciplinary approach. The

1 European Multidisciplinary Seafloor and water-column Observatory

2 EMSO Generic Instrument Module

3 Initiatives in Supporting the consolidation and enhancement of the EMSO infrastructure and related Activities

4 Science Monitoring And Reliable Telecommunications

5 Ocean Networks Canada

6 Dense Ocean floor Network System for Earthquakes and Tsunamis

7 European Research Infrastructure Consortium

8 Joint Programming Initiative

9 Sustainable Development Goals

papers have in accordance with this included local and global observations from some of the main worldwide actors in the field of better understanding and protecting the oceans of the world. The results of this have produced themes that are all in agreement and need to be addressed. These are:

- Highlighting the application of international and European ocean observing strategies.
- Showcasing recent and on-going infrastructure program developments.
- Sharing scientific and technology development results that advance integrative assessment.
- Realising use of best practices, data quality control and FAIR[10] principles.
- Documenting data life cycles - origination to delivering analysed information to users.
- Synthesising perspectives on the present and future.

This Research Topic has brought together original research along with technological papers, perspectives, and reviews that focus on delivering integrated ocean observing information to allow for sustainability from the coast to the deep sea. It attracted 16 contributions and involved 178 authors, these can be found in the following link:

https://www.frontiersin.org/research-topics/18542/the-discovery-of-the-unknown-planet-the-ocean.

The response to '*The Discovery of the Unknown Planet: The Ocean*' from within the scientific world and those working in other areas has been extremely positive and it has had a very significant impact with the total number of views presently that of over 38,000.

Author contributions

All authors listed have made a substantial, direct, and intellectual contribution to the work and approved it for publication.

Conflict of interest

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The Ever-Changing and Challenging Role of Ocean Observation: From Local Initiatives to an Oceanwide Collaborative Effort

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Ocean observation has seen a rapid evolution and has become crucial in providing the much needed data and information toward a well-supported and accurate description of ocean processes which influence the environmental, economic, and societal systems. There has been a significant progress in technologies which have enabled the expansion of the sampling and observing systems both on temporal and spatial scales. Furthermore, online, free access, data portals have grown in number and quality, provided by data aggregators, which have promoted the creation of standardized methods for marine data acquisition and management. Ocean observation is now global, but it depends on the single institutions and laboratories' capability to guarantee the operation of instruments and longevity in data acquisition. International collaborative initiatives are crucial to support the ever-growing databases and feed the services and products that are fundamental to Blue Growth. Collaboration must be developed at local and regional levels and the monitoring system must ensure data consistency, integrity, and redundancy. The "Atlantic Observatory – Data and Monitoring Infrastructure" project, is an example of a Portuguese effort to bring together on-going initiatives working in the Atlantic area and provide access to high quality marine environmental data covering the Atlantic Ocean basin.

Keywords: ocean observatories, ocean data, data platforms, data collectors, data aggregators

INTRODUCTION

The ocean drives global, regional and local-scale Blue Economy, with impacts in the societal and environmental systems, and ocean-related issues have seen a constant growth in importance in the political agenda in the last 20 years (e.g., Campbell et al., 2016; Blythe et al., 2021). Importantly, there has been a growing awareness on the importance of understanding our seas and ocean in light of Blue Growth, which calls for an holistic and sustainable management of marine social-ecological systems in view of economic growth derived from marine and aquatic resources (Eikeset et al., 2018; Rayner et al., 2019). Also, a changing ocean, experiencing increased warming and acidification owing to climate change, may impact human activities and may also create hazardous situations for coastal communities, through increased storminess and sea levels for example, and therefore, the seeking for information and accurate description of ocean processes resorting to long-term time series is crucial and has been quickly growing (Ruhl et al., 2011; Dañobeitia et al., 2020).

Ocean monitoring relies on the establishment of an end-to-end solution aiming to describe some part of the ocean system. A suite of platforms and sensors measuring and collecting data with the aim of studying the ocean in a certain location, over a period of time, constitute an ocean Observatory. The overall infrastructure includes the land-based facility where data is collected, stored and made available to aggregators and users.

Ocean observation provides the data and information for a well-supported and accurate description of the physical, geological, chemical, and biological ocean processes, and there has been a significant progress in technologies which have enabled the expansion of the sampling and observing system. The ability to monitor the Ocean using autonomous vehicles was especially important in increasing the spatial and temporal monitoring resolution. Still, the vast dimension and depths of the oceans, along with the complex interaction between the physical and biogeochemical spheres, challenge our ability to rigorously describe and model ocean dynamics. Furthermore, the high cost of the equipment, and the fact of being largely a remote environment presents significant obstacles for sustained observations (Crise et al., 2018). Another important question derives from the need to ensure homogeneous long-term data sets able to detect small changes (interannual to decadal) from a background of natural variability (several decades to centuries), and also rapid changes associated with short term extreme phenomena. For example, the study by Henson et al. (2016) shows how spatial and temporal scales of ocean observation are important to understand and distinguish between natural long-term variability and the influence of anthropogenic forcing on the marine environment.

Ocean observatories are key components of ocean observation and have come to evolve from single, site-specific initiatives (e.g., *in situ* sensors), to global and interoperable ocean observing systems linked to data-sharing platforms/data repositories that interact to support ocean knowledge and management (Bax et al., 2018). Data collectors are now part of broader observation networks and observation data is centralized in national and regional facilities and data centers.

The "Atlantic Observatory – Data and Monitoring Infrastructure" project, is an effort led by the Portuguese Institute for Sea and Atmosphere, I.P., funded by the EEA Grants "Blue Growth" Program, to defragment on-going initiatives from the different national research groups working in the Atlantic area, toward the creation and operation of an integrated marine observation system. It is an example of national and regional endeavors focused on gaining from on-going global, regional and national initiatives, promoting networking between stakeholders. A data platform – *we are Atlantic* – will act as a single storage and access datapoint, for both data collectors and end-users seeking information and services associated to the ocean. To support this effort, an assessment of the level of general development of ocean observation was made and the present paper provides a perspective of ocean observatories progress and future challenges, in view of the evolving ocean data needs.

EVOLUTION OF OCEAN OBSERVATION

Beginning in the second half of the XX century, substantial advances were made regarding the methods and techniques used for sampling and measurement of water properties, physical processes, and sea bottom characteristics. Observation platforms evolved from ships to submersible human operated vehicles, and later to remotely operated and autonomous equipment, such as submersibles, moorings and seabed landers, drifters and floaters, and gliders. Modern research vessels remain essential as platforms for data collection, and for deployment and recover of other instruments, enabling the monitoring of the atmosphere, the ocean surface, the water column, the seabed, and subseafloor (Nieuwejaar et al., 2019). Likewise, sensors developed to be mounted on and operated from these platforms evolved to gradually include the measurement of more parameters and with higher accuracy. Remote observation techniques, land-based or airborne and spaceborne, have also evolved to include sensors suited for ocean applications and provided a spatial coverage inaccessible to the previous *in situ* ocean observation methods. Some recent and comprehensive reviews of ocean observation technologies can be found in Bean et al. (2017) and Lin and Yang (2020).

Ocean observation developments benefited greatly from advances in communication technology, through the use of underwater acoustics, radio or satellite beacons, and more recently, relying on Global Navigation Satellite System receivers for positioning and data transfer, which can now be done in real-time (e.g., Tomkiewicz et al., 2010; Paull et al., 2018; Howe et al., 2019). Also, development of power systems, such as fiber-optic cables, digital batteries, and new technologies that harvest renewable energy from the environment, has enhanced the capability to collect data for longer periods of time (e.g., Whitt et al., 2020; Matias et al., 2021; Wang et al., 2021).

According to Tanhua et al. (2019), new technology platforms collected more data on the oceans in 2018 than was gathered during the entire XX century. But, despite the significant evolution in marine observation systems, the ocean is vast and largely inaccessible to the current existing equipment and resources. However, it is also interconnected; in a way that processes are linked, and patterns spread globally, so that any available data is of extreme importance to all who study the ocean. Being a data science, oceanography often uses interpolation and extrapolation methods between and from local examples to fill in gaps and describe under-sampled locations. In this sense, ocean scientists quickly realized that data sharing was essential for a sustainable and efficient ocean observation and put forth the "collect once, use many times" principle, based on data sharing and interoperability.

The variety of platforms and sensors available, and the wide number of parameters (e.g., atmospheric, oceanographic, biogeochemical, opto-acoustic, bathymetric) that can be collected in different ways and with different resolutions, motivated the definition of standards and best practices regarding workflows of data collection and processing techniques. The Ocean Data Standards and Best Practices Project from International Oceanographic Data and Information Exchange (IODE) for example, aims to achieve broad agreement and commitment to adopt a number of standards and best practices related to ocean data management and exchange. The Global Ocean Observing System (GOOS) identified a set of Essential Ocean Variables and recommend common standards for data collection and dissemination to maximize the utility of data (Lindstrom et al., 2012; Miloslavich et al., 2018).

Laboratories and institutions dedicated to ocean data collection created data repositories and online data portals with free access, whilst promoting their own ocean observatories' efforts. Data aggregators were created to foster ocean databases and avoid duplication, complying with metadata standards, assuring data interoperability and, most importantly, providing data quality control and guidelines. The European Marine Observation and Data Network (EMODnet), Pan-European Infrastructure for Ocean and Marine Data Management (SeaDataNet) and the Ocean Biodiversity Information System (OBIS) are just a few examples of such marine data aggregators.

Ocean observation databases currently provide widespread, in time and space, information on several ocean parameters and thus have encouraged new data processing techniques, greatly improving the ocean modeling capabilities, supported also on the rapid development of computer simulation technology. Several global, regional, and coastal ocean models are now freely available and provide hindcast, real-time and forecast of major ocean variables, such as currents, waves, and temperature (e.g., Tonani et al., 2015).

The once science-oriented ocean observation efforts are now also focused on providing access to data, information, and products to intermediate- and end-users (Pinardi et al., 2019). Marine service providers rely on the data collectors and data aggregators to provide marine information in a suitable and fit-for-purpose way, whilst supporting Blue Growth. There is currently a fluid workflow between data collectors (*i.e.*, operators of instruments), data aggregators and service providers (*i.e.*, organizations that bring together data from several sources and further process it to provide services) in the marine data management landscape. On the other hand, the present magnitude of data sharing, and data harvesting is leading to data redundancy, and often, unfortunately, to data inconsistency, calling for mechanisms that allow users to track data back to the sources and assure that ownership is not lost, such as Digital Object Identifiers.

Ocean observatories, though local, have evolved to perform at wider scales, providing and utilizing data globally and fostering a comprehensive and integrated approach to marine sciences and ocean issues. Data processing and analysis now depends on global databases and relies on collaboration across countries, regions, and communities, encompassing multiple disciplines and technologies, and is now more focused on the applications and benefits for markets and end-users.

Many initiatives for integrated ocean monitoring exist worldwide and are a sign of how ocean observation is evolving to represent an interlinked effort between stakeholders from different areas and disciplines. Some examples are the Ocean Observatories Initiative (OOI), an ocean observing network providing real-time, freely available data from more than 800 instruments along the Pacific and Atlantic Oceans (Trowbridge et al., 2019) and the Australia's Integrated Marine Observing System (IMOS), a research infrastructure operated by a consortium of institutions, delivering open access to high quality marine and climate data (Hill et al., 2010). Overall, these kinds of initiatives are providing sustained observations over the long-term, collecting crucial data to understand patterns and trends of ocean processes.

In Europe, ocean observation is overseen by a number of organizations, commissions, directives and policies, and is put into practice by projects and programs, increasingly through international consortiums, such as the European Research Infrastructure Consortiums (ERICs). ERICs are long-term scientific facilities sustained by strategic investments, which through collaboration enhance the efficiency and effectiveness of ocean observation (European Strategy Forum on Research Infrastructures [ESFRI], 2018; Dañobeitia et al., 2020). The European Multidisciplinary Seafloor and Water Column Observatory (EMSO-ERIC), the Integrated Carbon Observation System (ICOS-ERIC) and the EuroArgo-ERIC are examples of the success of such infrastructures that rely on collaborations to provide an integrated observation of the ocean.

The European Global Ocean Observing System (EuroGOOS) created operational networks of specific platforms (tide gauges, ferryBox, gliders, HF-Radars, fixed stations (such as those from EMSO-ERIC), EuroARGO, Marine Mammals), promoting the collaboration among European observing infrastructures and jointly making data available to the European and global data portals (some examples are listed in **Table 1**). The list is extensive and reflects the effort put into ocean observation in the last decades.

A comprehensive and complex list and timeline of the existing marine science organizations, policies and ocean observation initiatives at regional and global scale can be found in reports from the European Marine Board, AtlantOS (Larkin and Heymans, 2018) and EuroSea (Muñiz Piniella and Heymans, 2020) projects. Importantly, globally, these organizations have identified a range of scientific, socioeconomic, resource management and conservation goals and drivers that require systematic ocean observations. The common goals are to foster data quality observation systems, in compliance with the best practices in collection and management, providing uniform information and services that will meet the societal needs, across research, industry, policy domains, and importantly the United Nations Sustainable Development Goals. The current ocean observation framework has allowed for the development of several open data platforms that provide global marine information through multi-data visualization tools that deliver maps or graphs, with a comprehensive and impressive spatial and temporal coverage. Some of these advanced data portals that, based on their intuitive and easy operation, are able to reach a wider public and users, include the OceanOPS, and at the European level, the EMODnet thematic Data Portals, the My Ocean portal and most recently the *in situ* OceanTAC of the Copernicus Marine Service.

Ocean observatories are, more than ever, challenged to provide quality and significant measurements, standardized and

TABLE 1 | List of selected data collectors, data aggregators and service providers in the ocean observation framework at the European level.

Data collectors
National observing and monitoring systems operated by national organizations and research institutions
Regional and global marine research infrastructures, networks and programs coordinated by intergovernmental, collaborative groups
ARGO programme
FerryBox network
OceanGliders programme
European HFR network
European multidisciplinary seafloor and water column observatory-ERIC | EMSO-ERIC
Animal-borne instruments | ABI European research vessel operators | ERVO
Global ocean ship-based hydrographic investigations programme | GO-SHIP
OceanSITES
Ship observations team | SOT
Global ocean acidification observing network | GOA-ON
Continuous plankton recorder | CPR Survey
Global sea level observing system | GLOSS
Ocean tracking network | OTN
Marine biodiversity observation network | MBON
Data buoy cooperation panel | DBCP
Data aggregators and service providers
The European marine observation and data network | EMODnet
Pan-European infrastructure for ocean & marine data management | SeaDataNet
Copernicus marine environment monitoring service | CMEMS
Ocean biodiversity information system | OBIS
Joint centre for oceanography and marine meteorology *in situ* observations programmes support | OceanOPS
World ocean database | WOD
World data center PANGAEA
International council for the exploration of the sea | ICES

open-access, and to guarantee longevity in data collection to support models and analysis, services and products that can sustain the global and ambitious ocean observing demands. To this end, the "Atlantic Observatory – Data and Monitoring Infrastructure" project will create a network consisting of the relevant marine authorities and research institutions from mainland and the archipelago Portuguese Atlantic regions, filling in an existing gap in the national landscape to provide a structured, coherent and effective gathering and sharing of information about the ocean system.

FUTURE OF OCEAN OBSERVATORIES

Ocean observation faces a number of challenges to ensure its efficiency and sustainability. There is a growing need for increased spatial and temporal resolutions to feed the fast-growing modeling capabilities and technology. Data-acquisition platforms must be cost-effective, and increasingly rely on autonomous systems, which in turn require long-term power supplies and permanent communication links that can transfer data to land-based infrastructures. Information storage and analysis is becoming a huge challenge because of the amount and complexity of the data that is expected to increase with the progress in ocean observation. The complex communication ecosystem that connects underwater objects in maritime and underwater environments, generating big marine data, has inspired the new scientific concept of the Internet of Underwater Things (IoUT), described thoroughly in Jahanbakht et al. (2021).

In order to respond to the rapid growth and needs of data sharing and visualization, ocean observatories must increasingly rely on the utilization of cloud platforms. These provide a number of services, such as application programming interfaces (API's) and facilitated streaming of data and models, coupled to high-performance mass storage, which is unmatched by the traditional data workflows (Vance et al., 2019). Still, challenges related to budget and data transformation may represent a slower shift to cloud-based data storage and sharing widespread usage.

Cost-control, efficiency, and longevity of ocean observatories call for optimization of the data collection and sharing strategies. No longer any data is good data, but instead, efforts must be made in assessing what kind of data is needed, as well as where and when it should be collected. In this sense, data interoperability and information exchange are crucial to decide where data gaps exist and where data is most needed. For example, the ARGO program has added great spatial coverage of water characteristics to all ocean basins. However, they work mainly at intermediate depths and still fall short of accurately describing both the deep ocean and the nearshore and coastal areas, where there is a great need for information, for example, for the aquaculture industry.

Future needs and strategies have been put forth by many organizations and it is generally agreed that ocean observation is essential for the knowledge base and promotion of Blue Growth, as well as the European Green Deal policy aiming to achieve a climate neutral continent by 2050. The principle is now that data is measured once and used not only many times, but especially for many purposes. GOOS put forth a Framework for Ocean Observing in the form of a guide to help decide what ocean variables to measure and why (FOO, 2012). Observation activities must continue to be planned jointly between institutions and countries under a framework for collaboration on national, regional and global scale.

To foster open collaboration and interoperability, data management must assure that information complies with the FAIR data principles (Wilkinson et al., 2019), guaranteeing that data are findable, accessible, interoperable, and reusable. Likewise, collaboration between scientists, technicians, industry and communities, can only be fostered through enhanced data sharing and communication, which constitutes a goal of the Decade of Ocean Science for Sustainable Development promoted by the United Nations[1].

More than ever, ocean observation is regarded as a network and global effort to promote advances in ocean science and deliver greater benefits for both the ocean ecosystem and for society. The European Marine Board policy brief on sustaining ocean observations (European Marine Board, 2021a), stresses the importance of promoting synergies and complementarities between the different *in situ* networks, satellite observations and their joint model-based analysis, optimizing the existing capabilities in terms of measured parameters and space/time coverage. The future must keep focus on the creation of integrated multi-platform observing systems, reducing overlaps, filling gaps, increasing efficiency, adopting new technologies, and increasing spatial and temporal resolution to unprecedented levels (Dañobeitia et al., 2020).

OCEAN OBSERVATORIES IN THE OCEAN OBSERVATION VALUE CHAIN

In the scope of the global Blue Growth, marine science and technology is growing in importance, by improving the sustainable economic development of our seas and ocean (OECD, 2019). The downstream use of science, focused on market demands and societal needs is naturally occurring and creating a value chain for ocean observation that was, until recently, disregarded. According to the Ocean Economy 2030 report (OECD, 2016), ocean-based industries' contribution to economic output and employment, is significant and expected to double by 2030.

Data collectors and data aggregators, analysts, and service providers, deliver added value to intermediate and end-users in sectors such as transport, tourism, fisheries, marine biotech, resource extraction and energy. However, it is not an easy task to assess the economic impact of the ocean observation value chain. The economic benefit relies on the added value along the overall chain and it must be assessed as a whole. It is very difficult to place an economic value on an individual instrument, but it is feasible to evaluate the worth of a model or other fit-for-purpose product (e.g., sea-state forecasts) by analyzing usage statistics, such as number of accesses and downloads. Especially in the present digital and open-access framework, data are retrieved from multiple sources and providers to feed models and end-products, meaning that every single ocean observation equipment and sensor contribute to multiple outlets and the overall ocean observation value chain.

Despite the relevance of ocean data focused in a particular area or environment, long-term changes in the ocean environment can only be detected by fixed observatories or by repeated observations over the same area or ecosystem. This approach is in the basis of EUROSITES[2] or EMSO[3] initiatives, but there is still a long way to go before the availability of homogeneous long-term data series.

Citizen participation is increasingly encouraged and is becoming a big part of the overall ocean observation value chain. The level of involvement is a measure of public awareness and drives new initiatives and investment. AtlantOS program, for example, supports the creation of a multiplatform, multidisciplinary and Atlantic-wide system, which requires that data collected by the observing platforms be used for many different observing objectives (deYoung et al., 2019).

There has been a massive evolution in ocean observation, technology-wise and in terms of approach on how to optimize resources to meet the real data needs. Ultimately, the goal is to describe ocean processes and evolution, and to that end we need to collect and make available the right information to allow models to mimic ocean processes and create virtual reality of ocean behavior. In the future, the ocean observation efforts should fill the need to integrate a wide range of data sources, transform data into knowledge and provide citizens, governments and industries with the capacity to inform their decisions, through a streamlined and accessible Digital Twin of the Ocean (European Commission, 2020; European Marine Board, 2021b). To reach this goal, big data, numerical models, digital technologies such as supercomputing, artificial intelligence and data analytics must come together to provide a consistent, high-resolution, multi-dimensional and (nearly) real-time description of the ocean. But we are not there yet. The greatest challenge is the integration of the different ocean processes. Satellite-based data, *in situ* data, and numerical modeling must be capable of representing all variables across

[1] https://sdgs.un.org/goals

[2] https://www.eurosite.org/

[3] http://emso.eu/

the blue (physical), white (sea ice) and green (biogeochemical) ocean (Copernicus Marine Service, 2021), guarantee their interoperability, and simulate past, present and future conditions. But, despite the great challenges that a Digital Twin of the Ocean represents, it is the goal that all ocean observation efforts should look toward when designing their objectives.

DISCUSSION

The role of ocean observation has changed over the last decades, fostered by growing needs of data and information, as well as by a public awareness of the importance of ocean-health. We have witnessed a rapid evolution in ocean observation, ranging from acquisition of data to delivery of marine-related services, which provide the information and foundations toward a well-supported and accurate description of ocean processes. Importantly, observatories evolved from local initiatives to an oceanwide collaborative effort. Ocean data acquisition, processing and analysis are now focused on providing standardized, quality-assured, and largely disseminated data through global databases, which rely on collaboration across communities, regions, and countries, scientists and citizens, encompassing a wide range of disciplines and technologies. A multitude of open data portals is now available and provide global marine information through multi-data and multi-dimensional visualization tools, with a comprehensive and impressive spatial and temporal coverage, targeting different end-users and blue markets. The competition between the different players in the field will also contribute for increasing availability of open data and more focused downstream applications.

In line with the current European directives, the Data and Monitoring Infrastructure of the Atlantic Observatory will be a user-driven initiative, facilitating the access of economic players and the citizens to information related with the Atlantic Basin relevant for Blue Growth at all scales. It will consider citizen participation in the monitoring systems, in identifying the relevant services and information, while fostering their commitment toward the preservation of the ocean environment.

Ocean observation is now global, but one cannot forget that it is grounded on the single institutions and laboratories. They are, more than ever, challenged to guarantee the operation of instruments and longevity in data acquisition to support ever-growing databases, models and analysis, and services and products that can sustain the global and ambitious ocean observing demands. In this sense, local and regional data and monitoring infrastructures must be robust enough to guarantee data consistency, integrity, and redundancy.

DATA AVAILABILITY STATEMENT

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

AUTHOR CONTRIBUTIONS

TS took the lead in writing the manuscript with input from all authors.

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Challenges for Marine Ecological Assessments: Completeness of Findable, Accessible, Interoperable, and Reusable Biodiversity Data in European Seas

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The ongoing contemporary biodiversity crisis may result in much of ocean's biodiversity to be lost or deeply modified without even being known. As the climate and anthropogenic-related impacts on marine systems accelerate, biodiversity knowledge integration is urgently required to evaluate and monitor marine ecosystems and to support suitable responses to underpin a sustainable future. The Census of Marine Life (CoML, 2000–2010) was the largest global research program on marine biodiversity. A decade after, and coinciding with the steep increase of digitalization of our society, we review existing findability, accessibility, interoperability, and reusability (FAIR) biodiversity data coming from one of the most reliable online information systems: the Global Biodiversity Information Facility (GBIF). We evaluate the completeness of available datasets with respect to the CoML benchmark, along with progresses in understanding spatial–temporal patterns of marine biodiversity in the European Seas in the last decades. Overall, we observe severe biases in available biodiversity data toward the north-western marine regions (particularly around the United Kingdom and the North Sea), the most recent years (with a peak in the number of reported occurrences in the 2010s) and the most conspicuous, abundant, and likely "appealing" taxa (e.g., crustaceans, echinoderms or fish). These biases may hamper research applications, but also global-scale data needs and integrative assessments required to support cost-effective progresses toward global biodiversity conservation. National to international joint efforts aimed at enhancing data acquisition and mobilization from poorly known regions, periods, and taxa are desirable if we aim to address these potential biases for the effective monitoring of marine ecosystems and the evaluation of ongoing impacts on biogeographic patterns and ecosystem functioning and services.

Keywords: biodiversity assessments, Census of Marine Life, completeness, European Seas, GBIF, open biodiversity data, FAIR principles

INTRODUCTION

There is increasing evidence that human activities over the last decades/centuries have grown to become significant driving forces of global processes. This has caused the Earth System to depart from the comparatively stable conditions that characterized the Holocene Epoch, when human societies have flourished (Steffen et al., 2011; Whitmee et al., 2015; Zalasiewicz et al., 2020). Accordingly, the term "Anthropocene" is being increasingly used to refer to this new *status quo*, when large-scale human effects are exerting impacts on the environment that result in the contemporary biodiversity crisis and in the collapse of many ecosystems (Rockström et al., 2009; Steffen et al., 2011; Whitmee et al., 2015).

Among natural habitats, oceanic systems are of particular concern since they are among the most important (in terms of nature contributions to people), complex, poorly understood, and likely most impacted of Earth's biomes (Hoegh-Guldberg and Bruno, 2010; IPCC, 2014; Halpern et al., 2015; Ramírez et al., 2017). Ocean warming and pollution, marine habitat degradation, and overexploitation of marine resources (among others) are posing serious threats to marine biodiversity, much of which could disappear without ever being known (Ramírez et al., 2017; Cuyvers et al., 2018; Pinsky et al., 2018; FAO, 2020; Landrigan et al., 2020). As the climate and anthropogenic-related impacts on marine systems accelerate (Burrows et al., 2011; Coll et al., 2012; Micheli et al., 2013; Ramírez et al., 2017; Boyce et al., 2020), biodiversity knowledge integration is urgently required to evaluate and monitor marine ecosystem health, and to support suitable responses to underpin a sustainable future.

Reliable and systematic biodiversity assessments are challenging in the vast and remote oceans. The first large-scale, multidisciplinary, and multinational assessments on marine biodiversity date back only to the 1990s, with the Census of Marine Life (CoML) likely being the most extensive of all of them (Costello et al., 2010). The CoML mobilized more than 2,700 scientists from more than 80 countries and ca. US$650 million, and spanned the 2000–2010 period (Costello et al., 2010). A decade after, and coinciding with the steep increase of digitalization of our society, digital data and online information systems may offer a means for marine biodiversity assessments at an unprecedented extent and spatial, temporal, and taxonomical resolutions (Jarić et al., 2020b); while contributing to our understanding of the processes, patterns, and mechanisms underlying the ongoing contemporary biodiversity crisis (Meyer et al., 2015; Ball-Damerow et al., 2019).

Recent efforts toward digitization of natural history collections (Beaman and Cellinese, 2012), along with the development of digital, open-access repositories (e.g., Global Biodiversity Information Facility – GBIF) and online platforms for citizen science (also known as citizen observatories; e.g., Sullivan et al., 2014), have driven a steady accumulation of species occurrence digitized records over the past decade. To date, online databases sum up more than one billion records; they have unlocked previously inaccessible data and expanded their availability to researchers around the world (Ball-Damerow et al., 2019).

However, the biggest challenge for digitized biodiversity data and for subsequent ecological/environmental applications is obtaining records of sufficient quantity and quality for specific region, period, and taxonomic group of interest (Ariño et al., 2013; Meyer et al., 2015). Digital biodiversity databases are still in the initial stages of development. For example, recent estimates suggest that only 10% of biological collections are available in digital form (Ariño, 2010; Page et al., 2015; Ball-Damerow et al., 2019), and it would take many decades to completely digitize estimated holdings at current rates (Ariño, 2018; Ball-Damerow et al., 2019). As such, completeness of biodiversity digitized data is likely biased; with remote regions, particular periods, and "less common" taxa being under-sampled or completely unrepresented (Boakes et al., 2010; Meyer et al., 2015, 2016b; Ruete, 2015). These biases directly influence opportunities for inference and application of biodiversity digitized data (Katsanevakis et al., 2015; Meyer et al., 2015, 2016b). While continued digitization of available biodiversity databases is desirable, efforts aimed at identifying and addressing these potential biases (e.g., through targeted data mobilization, Hobern et al., 2012) should be prioritized if we aim to use these data for the effective monitoring of marine ecosystem, and the evaluation of ongoing impacts on biogeographic patterns, and ecosystem functioning and services (Levin et al., 2014; Meyer et al., 2015).

With a long-standing natural, cultural and economic heritage, the European Seas has experienced a long history of anthropogenic perturbations, and encompass some of the most impacted marine systems on Earth (particularly in their northern parts, Halpern et al., 2008; Ramírez et al., 2017). They also contain some of the historically and presently best explored and known marine areas of the world (e.g., Narayanaswamy et al., 2010; Ojaveer et al., 2010; Costello and Wilson, 2011). This knowledge builds up at multiple levels of ecological complexity (from individuals to communities and ecosystems) and bridges among contrasting sampling methodologies and analytical techniques (Narayanaswamy et al., 2013). However, there is a need of synthetic and integrative marine biodiversity assessments, based on existing findable, accessible, interoperable, and reusable (FAIR) biodiversity data, that may contribute toward our comprehension of the "known, unknown and unknowable" biodiversity, the monitoring of marine ecosystem, and the sustainable management and conservation of marine biodiversity (Narayanaswamy et al., 2013; Levin et al., 2014; Katsanevakis et al., 2015).

In this work, we assessed existing FAIR biodiversity data for the European Seas available on GBIF, one of the biggest biodiversity information infrastructures. We evaluated the "completeness" of these datasets with respect to the CoML benchmark (Costello et al., 2010; Narayanaswamy et al., 2013), along with progresses in understanding spatial–temporal patterns of marine biodiversity in the region in the last decade. In particular, we aimed at assessing how the observational effort available in digitized datasets is currently distributed to maximize the completeness of the three main informational dimensions of species diversity: spatial, temporal, and taxonomical. We then discuss how potential biases may affect future analytical efforts toward building integrated marine assessments (e.g., species and

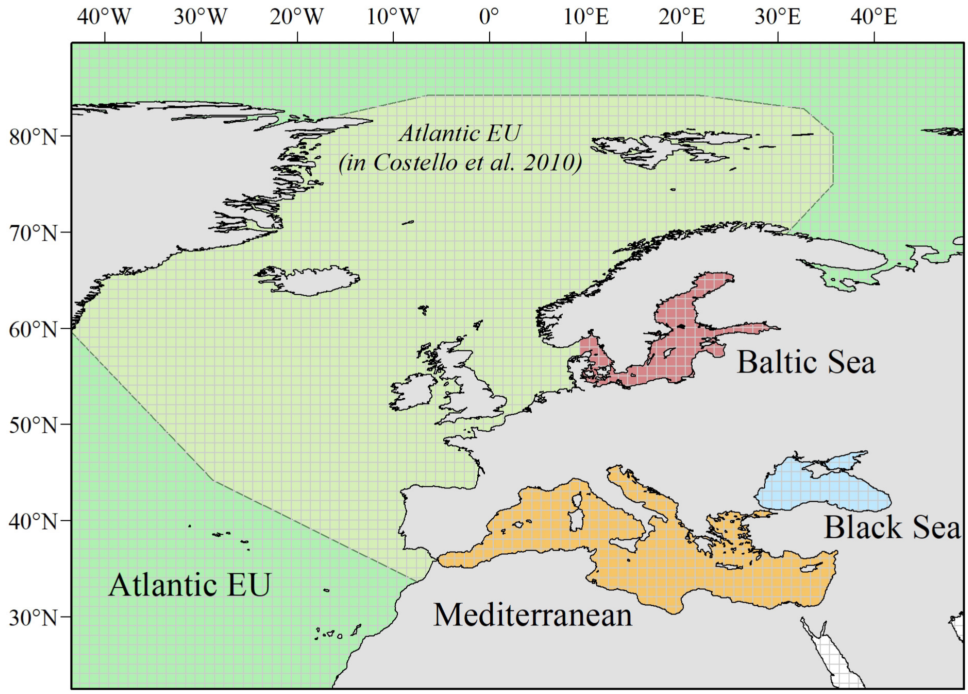

FIGURE 1 | Study area. We considered a wide enough polygon (longitude: ∼ –50.2° to 62°; latitude: ∼24.2° to 89.6°) to include all relevant European Seas. Following Costello et al. (2010) when analyzing biodiversity information from the Census of Marine Life, we distinguish among four basins: Atlantic EU, Baltic Sea, Black Sea, and Mediterranean Sea. The Atlantic EU considered in Costello et al. (2010) was smaller than what we consider as the whole Atlantic EU area. This is because we additionally include water masses around the Macaronesia (including Azores, Madeira, and Canary Islands), and the northernmost Atlantic waters. To evaluate spatial patterns in the total number of occurrences and individual species, we consider a 1° × 1° grid map covering the whole study area.

biodiversity distribution and trends) and hamper prospects for research and sustainable management applications.

MATERIALS AND METHODS

Data Mining

Based on data from GBIF, we evaluated spatial–temporal patterns in the number of occurrences and individual species within the European Seas, as proxies of "sampling effort" and species richness, respectively. Following Costello et al. (2010) when analyzing biodiversity information from CoML, we distinguished among four basins within the study area: Atlantic EU, Baltic Sea, Black Sea, and Mediterranean Sea (**Figure 1**). Occurrences and species were also grouped following the categorization provided by Costello et al. (2010): Protozoa, Crustacea, Pisces, Tunicata, Mollusca, Annelida, Cnidaria, Platyhelminthes, Echinodermata, Porifera, and Bryozoa. Because several groups in Costello et al. (2010) were paraphyletic (e.g., Pisces), we first mapped the correspondence between these groups and the appropriate taxa in GBIF. Due to a large number of occurrences (>20 millions) and for facilitating the analysis within R x64 4.1.0 software (R Core Team, 2021), data were downloaded from GBIF web portal[1] through different queries (see **Supplementary Table 1** for details on each query, and associated DOIs). Through each query, we downloaded the total number of occurrences for selected taxa within a wide enough polygon to include our study area (longitude: ∼ −50.2° to 62°; latitude: ∼24.2° to 89.6°). We considered "Present" as the occurrence status, as there is a wide consensus that, in general, online biodiversity datasets should be mainly regarded as "presence only" data (Graham et al., 2004). Obtained datasets were then masked to remove occurrences in the mainland.

Importantly, digitized biodiversity data are not exempt from errors, with species identity and locality being the most error-prone aspects of collection information (Graham et al., 2004; Ball-Damerow et al., 2019). Given the large number of occurrences we dealt with, and the broad and descriptive nature of our objectives (i.e., evaluating the completeness of FAIR biodiversity data available on GBIF), we did not check for specific data quality, errors, and accuracy. Overall, erroneous and inaccurate records primarily lead to overestimation of species richness out of biodiversity hot spots (Maldonado et al., 2015). However, the effects of inaccurate data are certainly diluted in studies that include a large number of records, as it is our case (Pyke and Ehrlich, 2010).

Spatial, Temporal, and Taxonomical Completeness of Open Biodiversity Data

As a proxy to the spatial distribution of sampling effort, we estimated the total number of occurrences per cell within a

[1] www.gbif.org, accessed in June 2021.

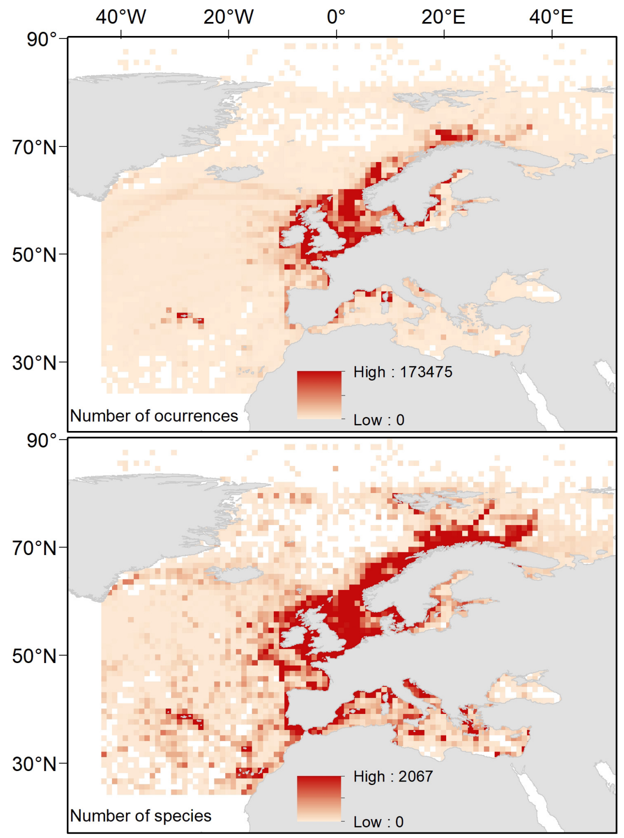

FIGURE 2 | Spatial distribution of total number of occurrences and total number of species per cell in a 1° × 1° grid map.

1° × 1° grid map covering the whole study area. This represents a "coarse"-enough resolution to be not excessively restrictive in our spatial completeness assessments, while ensuring the capture of relevant patterns of biodiversity distribution at the European Seas level (see Meyer et al., 2015). Cells were categorized according to the four-level basin category, i.e., Atlantic EU, Baltic Sea, Black Sea, and Mediterranean Sea. To evaluate patterns in species richness, we used a similar approach and estimated the total number of unique species per 1° × 1° cell. Per-cell information and non-linear least squares regressions were used to evaluate the relationship between our proxies to sampling effort and species richness. In particular, we used the Michaelis–Menten equation [y − ax/(b + x)], which is one of the most used functions to project species accumulation curves (Keating and Quinn, 1998; Longino et al., 2002, see also Meyer et al., 2015). We manually defined starting values for non-liner regression by visually exploring plots and allowing the model to efficiently converge.

The Michaelis–Menten equation considers a decay curve with a rapid initial increase in species richness as sampling effort rises, and a gradual decrease in the slope while approaching to a horizontal asymptote. This relationship can be interpreted as an indicator of the sampling effort necessary to achieve a good representation of the species richness for a given area (Costello et al., 2013). We therefore calculated basin-specific thresholds at which 75% of species were detected with respect to the asymptote value. The thresholds were determined by predicting the number of occurrences needed using the fitted functions of each basin. To evaluate the data spatial completeness, we therefore considered that those points over the threshold corresponded to areas (i.e., cells within the 1° × 1° grid map) showing an "adequate" sampling effort.

Data temporal coverage and completeness was evaluated by estimating the total number of occurrences per taxa, year, and basin. To evaluate potential biases in the relative contribution of particular taxa to the total number of occurrences reported for a given year and basin (p_i), we yearly estimated a basin-specific Shannon index ($H' = -\sum_{i=1}^{R} p_i ln p_i$). Assuming that there have been no major local extinction events or appearances of new species along the time-series, any deviation in the Shannon index could be therefore interpreted as incomplete taxonomic sampling.

Finally, we evaluated the data taxonomical completeness by comparing the total number of species per taxa and basin, with analogous results reported by Costello et al. (2010) and, hence, for the CoML. As the Atlantic EU basin, we considered here a wider area than the one used in Costello et al. (2010), in order to incorporate marine waters around the Macaronesia (including Azores, Madeira, and Canary Islands), and the northernmost Atlantic waters. However, and for comparison purposes, we also considered here what Costello et al. (2010) defined as Atlantic EU (**Figure 1**). It is also worth noting that the Black Sea constitutes an addition to the basins considered in Costello et al. (2010).

Data Contributors to Global Biodiversity Information Facility

Overall, GBIF datasets have been provided by more than 2,000 different publishers.[2] Here we wanted to identify the main contributors of biodiversity data for all considered marine basins. For that purpose, we estimated the total number of occurrences per contributor/publisher and basin. For representation purposes, we considered only the top 25 contributors on the list.

RESULTS

Data Completeness in the Spatial, Temporal, and Taxonomical Dimensions

Our spatially explicit proxy to sampling effort (i.e., total number of occurrences per cell) heterogeneously distributed spatially, with the highest sampling effort occurring in the North Sea and coastal areas around the Scandinavian Peninsula, the United Kingdom, the Azores Archipelago, and the North-western Mediterranean Sea. Analogously, our estimates of species richness were heterogeneously distributed, with the highest values largely occurring in those areas with the highest sampling effort. However, other "biodiversity hotspots" with relatively high values of species richness emerged in the northernmost areas of

[2] https://www.gbif.org/publisher/search

Scandinavian Peninsula (near the Arctic Sea), the Macaronesia (including Azores, Madeira, and Canary Islands), the coastal areas around the Iberian Peninsula, and the northernmost areas of the Western and the Central Mediterranean Sea (including Balearic, Tyrrhenian, and Adriatic Seas; **Figure 2**).

When evaluating the relationship between our proxies to sampling effort and species richness, we observed a highly significant, non-linear effect of sampling effort on species richness (**Table 1**). As expected for the Michaelis–Menten equation, our data followed a decay curve, with an increasing decay in the rate at which new species are reported for a particular area (1° × 1° cell) as sampling effort rose (**Figure 3**). These trends were consistent among basins, with the likely exception of the Black Sea, where a near-linear relationship was observed, suggesting that the relationship was far from saturation. Accordingly, results for the Black Sea should be taken with caution. Based on these relationships, and derived thresholds informing on their saturation levels, we identify some areas (1° × 1° cells) in the European Seas where sampling effort was apparently suitable for achieving a good representation of the species richness (**Figure 3**). Most of these areas (50 out of 65 cells) occurred in the Atlantic EU, and, particularly, around the United Kingdom and the North Sea. However, they represent only a small fraction of the Atlantic EU total area (ca. 1.2% of cells within the Atlantic EU basin). Despite the relatively large sampling effort in the Baltic Sea (**Figure 2**), only 2 out of 126 cells were categorized as suitable according to the considered threshold. Nine out of 359 Mediterranean cells were categorized as suitable and distributed along the North-western Mediterranean Sea.

Regarding the temporal coverage of open biodiversity data available on GBIF, we identified a common pattern among basins, with a rapid increase in the number of reported occurrences in the late 20th century, a peak around the 2010s, coinciding with the end of CoML, and a decrease afterward. In the case of the Mediterranean Sea, the pattern was similar but delayed in time, with the steep increase in the number of occurrences befalling in the mid/late 2010s, and peaking in the late 2020s. The Black Sea was likely the only exception to this pattern, as the number of reported occurrences was consistently low and largely oscillated along the time series (**Figure 4**).

No or minor biases in the taxonomic sampling were observed for Atlantic EU and the Baltic Sea since the 1990s, as revealed by the relatively constant values in the basin-specific Shannon index (H′). In the case of the Mediterranean Sea, the positive trend in the Shannon index suggested an incomplete taxonomic sampling likely due to the absence of Echinodermata, Porifera, and Bryozoa reported before the beginning of the 2000s. In the Black Sea, the unstable trend in the Shannon index suggested that the taxonomic completeness of reported data is far from complete (**Figure 4**).

The taxonomic completeness was also evaluated by comparing the taxonomic detail of GBIF data with analogous results reported by Costello et al. (2010) when analyzing biodiversity information from the CoML (**Figure 5** and **Table 2**). Overall, the total number of species reported in GBIF for the Atlantic EU and the Baltic Sea were higher than those previously reported in Costello et al. (2010), with the exception of the less conspicuous species; i.e., Protozoa and Annelida in the Atlantic EU, and Protozoa and Platyhelminthes in the Baltic Sea. In the case of Atlantic EU, this trend was consistent (except for Annelida) for both the area considered as Atlantic EU in Costello et al. (2010) and the area that we considered as the whole Atlantic EU, which additionally included Macaronesia and the Arctic Sea (**Figure 1**). The total number of species reported in GBIF increased when considering these additional areas. However, these differences varied among considered taxa, with Pisces and Mollusca showing the highest relative increases (38 and 30%, respectively), and Annelida and Platyhelminthes showing the lowest relative increases (6 and 3%, respectively; **Table 2**).

For the Mediterranean Sea, we found a deficit in the number of species reported in GBIF, except for Mollusca and Pisces (**Figure 5** and **Table 2**). The largest difference was found for the less conspicuous Protozoa. In the case of the Black Sea, no previous biodiversity information was reported in Costello et al. (2010), thus preventing from a comparative analysis. However, our results are still useful as an overview of the species richness and taxonomic completeness of open biodiversity data available on GBIF for this basin.

Top Contributors to Global Biodiversity Information Facility Datasets

The number of contributors to GBIF data differs among basins. However, the top 25 contributors represent ca. 90% of the total reported occurrences in the Atlantic EU and the Mediterranean Sea, and almost the 100% in the Baltic and the Black Seas (98 and 96%, respectively; **Supplementary Table 2**). The spectra for these relative contributions also differ among basins (**Figure 6**). For instance, the eight top contributors to reported occurrences in the Atlantic EU account for >60% of total occurrences. In contrast, the Swedish University of Agricultural Sciences (SLU) contributes alone to ca. 62% of reported occurrences in the Baltic Sea. In the Mediterranean Sea and the Black Sea, cumulative occurrences >60% are reached by the top three and four contributors, respectively (**Figure 6** and **Supplementary Table 2**).

DISCUSSION

Recent estimates suggest that ca. 48,000 marine species may exist in the European Seas, and that ca. 75% of them have been already described (Costello and Wilson, 2011). The proportion of species yet to be discovered here is, therefore, lower than elsewhere. Furthermore, most of these species' occurrences are already publicly available in digital platforms such as GBIF (as revealed by our comparison between CoML and GBIF outputs), which may facilitate potential uses of online biodiversity databases. However, while this statement may hold true when considering the European Seas as a whole, we provide here solid evidence highlighting that available FAIR biodiversity data for the European Seas are not homogeneously distributed spatially, temporally, and taxonomically. Our assessments on the magnitudes and biases in different metrics of completeness of digitized biodiversity data with regard to these three dimensions

TABLE 1 | Results of the non-liner regressions for all basins and for each individual basin.

Basin	*N*	Correlation	Estimate (a)	Estimate (b)
All	4,586	0.91	1,319 (1,283–1,350)***	9,617 (9,055–10,214)***
Mediterranean Sea	361	0.92	1,245 (1,158–1,335)***	5,005 (4,281–5,871)***
Black Sea	79	0.93	214 (142–457)***	449 (251–1,156)**
Atlantic EU	4,020	0.93	1,352 (1,322–1,382)***	9,404 (8,917–9,919)***
Baltic Sea	126	0.81	2,336 (1,637–3,680)***	85,949 (45,897–177,522)***

*Correlation between observed and predicted values is showed as estimation of goodness of fit. Estimates of equation parameters (a and b) are showed together with 95% confidence intervals between brackets. **p-value < 0.01; ***p-value < 0.001.*

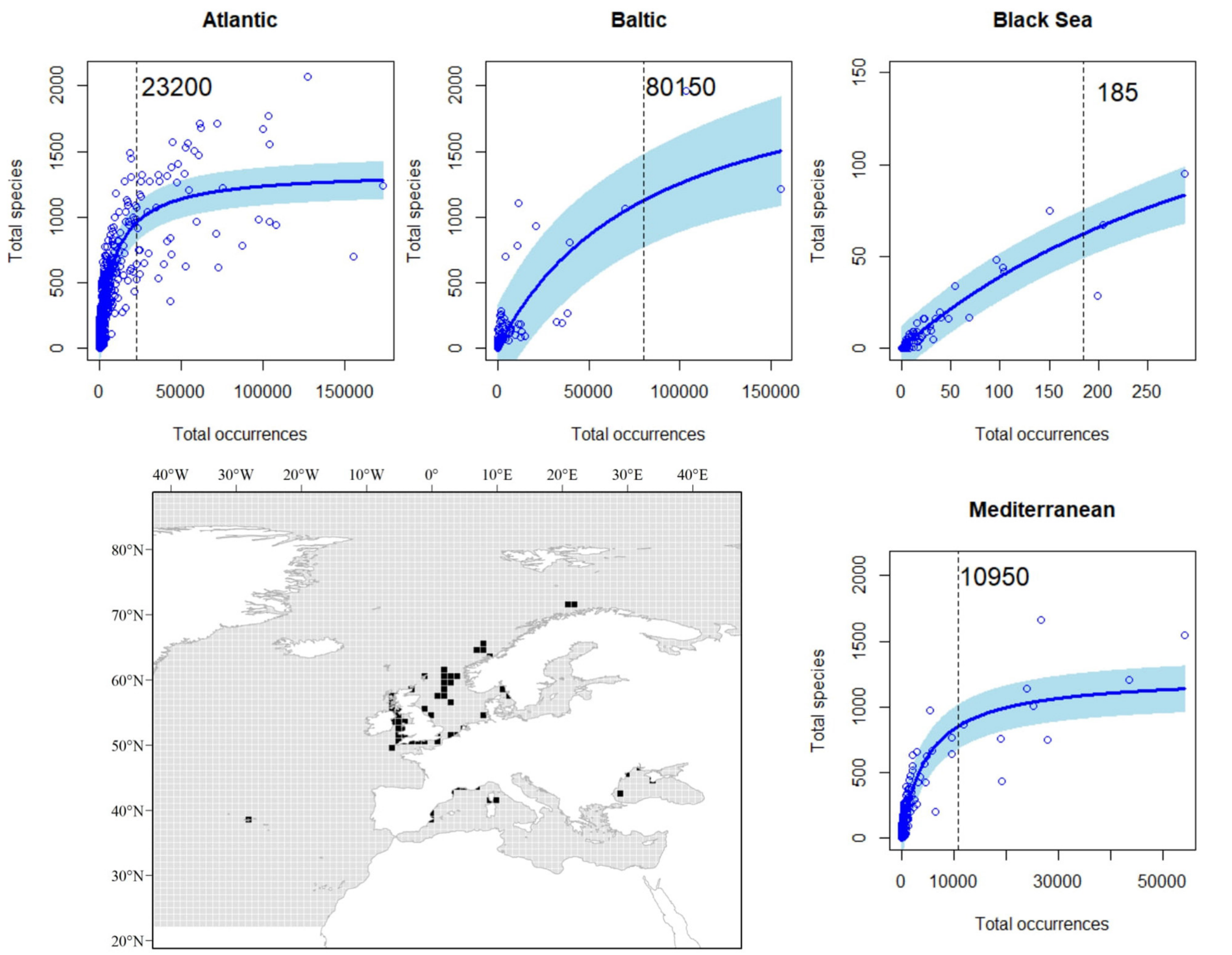

FIGURE 3 | Relationship between the total number of occurrences and the total number of species per cell in a 1° × 1° grid map; basin-specific thresholds (vertical dashed lines) and the spatial representations of those areas (black) with an adequate sampling effort to achieve a good representation of species richness.

are crucial for evaluating prospects for research and other applications and for prioritizing and monitoring activities to improve FAIR biodiversity datasets (Levin et al., 2014; Meyer et al., 2015, 2016b; Ball-Damerow et al., 2019).

Overall, our assessments on marine biodiversity showed a concentration of species in coastal waters, along with a northwestern-to-southeastern gradient of species richness, with most biodiversity hotspots occurring in the Atlantic basin and particularly in the North Sea, the coastal areas around the Scandinavian Peninsula and the United Kingdom. This general spatial trend widely concurs with those for previous biodiversity assessments (based on CoML) and may likely respond to analogous trends in marine productivity (Coll et al., 2010; Narayanaswamy et al., 2013). In agreement with previous assessments for the Mediterranean Sea, certain areas in the Alboran, Tyrrhenian, Adriatic, and Aegean Seas also emerged as

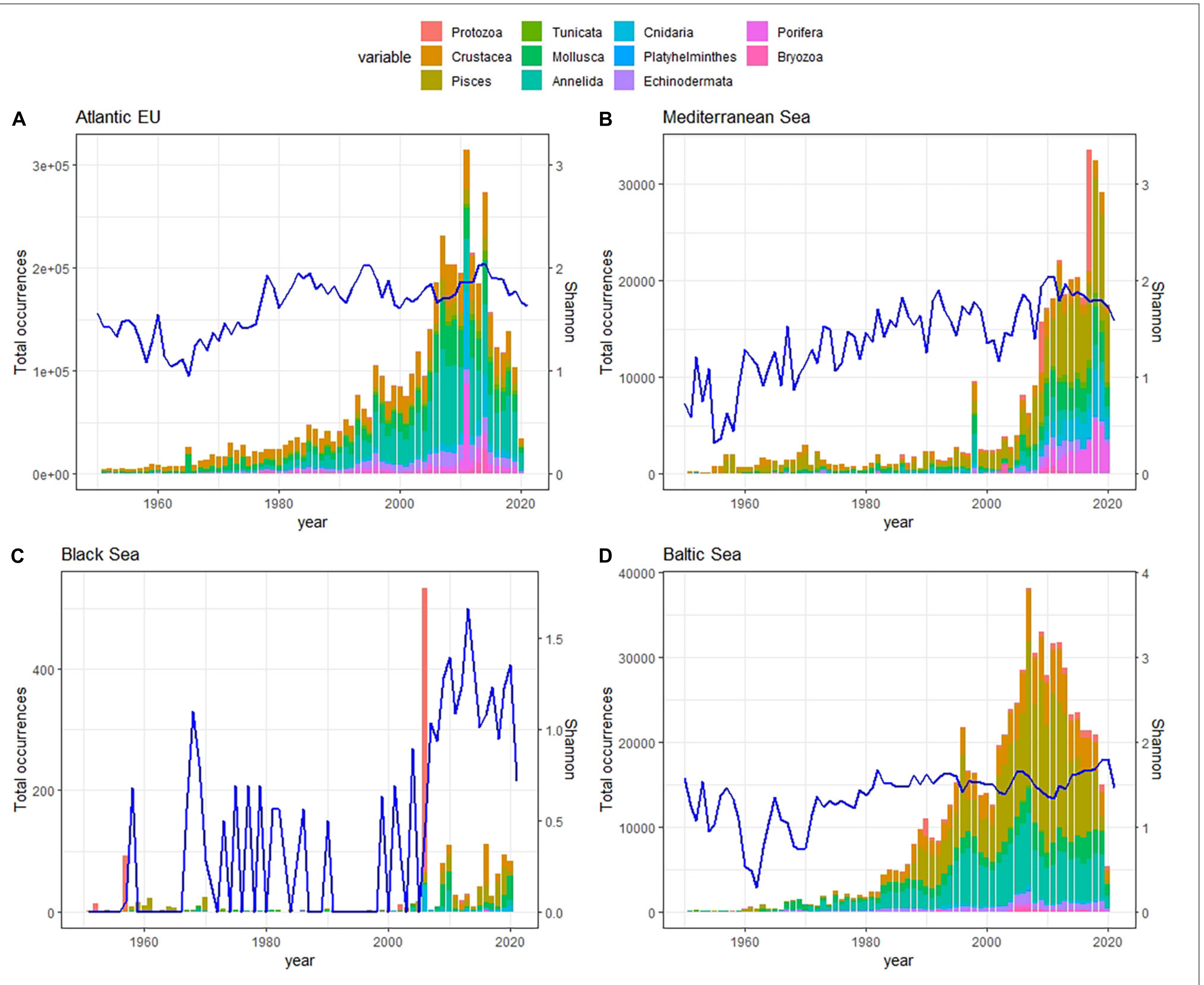

FIGURE 4 | Stacked bar plot showing basin-specific trends in the total number of occurrences per taxa along the last decades for the Atlantic EU **(A)**, Mediterranean Sea **(B)**, Black Sea **(C)**, and Baltic Sea **(D)**. Note that first occurrences date back to the XVII century, but here we just represent the 1950–2020 period. Different taxa are represented in colors, and the year-specific Shannon Index (blue line), which considered the relative contribution of particular taxa to the total number of occurrences reported for a given year and basin, was used as an indicator of the completeness in taxonomic sampling along the time-series.

important biodiversity hot spots likely due to the higher river and nutrient input, and the larger number of endemic species (Coll et al., 2010). Spatial patterns from GBIF biodiversity data also agree with previous assessments for the Atlantic Ocean showing that the northernmost and more productive Atlantic waters support also the higher species richness (Narayanaswamy et al., 2013). As an addition to these previous assessments, we also highlight certain inshore areas in the Macaronesia (including Azores, Madeira, and Canary Islands) as biodiversity hot spots.

Besides the ecological/environmental mechanisms underlying the spatial gradients in marine biodiversity, observed patterns may be also partially driven by the heterogeneous distribution of available data (driven by heterogeneous sampling effort and/or data mobilization) and the gaps in our knowledge of the biota (or the lack of information mobilization) along the southern and the eastern rims (Coll et al., 2010; Narayanaswamy et al., 2013; Levin et al., 2014). Indeed, our estimators on the sampling effort necessary to achieve a good representation of the species richness for a given area suggest that only a little proportion of the European Seas is well represented/studied, and that these well-studied areas concentrate in the North Sea, around United Kingdom and the North-westernmost areas of the Mediterranean Sea.

Socio-economic factors, such as proximity to research institutions, country participation in data-sharing networks, international cooperation, and financial resources (among others) may be driving detection, recording, or mobilization of biodiversity data into data-sharing networks (Meyer et al., 2015). Accordingly, most of the top contributors to marine biodiversity data for the European Seas are mainly based in high-income

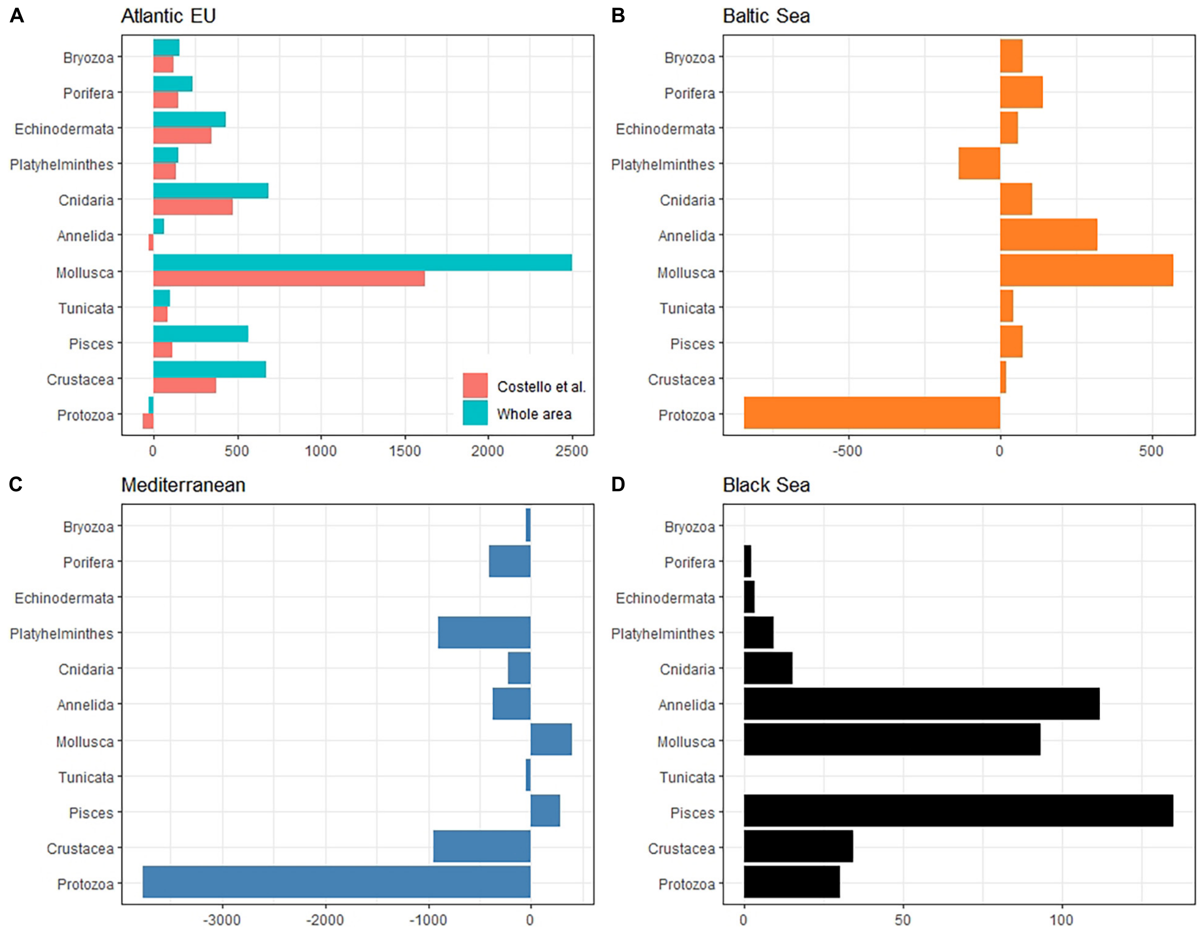

FIGURE 5 | Bar plot showing the difference between the total number of species per taxa reported in GBIF with respect to analogous results from Costello et al. (2010). Comparisons have been made for the Atlantic EU **(A)**, Mediterranean Sea **(B)**, Black Sea **(C)**, and Baltic Sea **(D)**. Positive values indicate a higher number of species reported in GBIF. What we consider here as Atlantic EU (whole area) differs from Costello et al. (2010) in that we also include marine waters around the Macaronesia (including Azores, Madeira, and Canary Islands), and the northernmost Atlantic waters (see **Figure 1**). For comparative purposes, we also consider the same Atlantic EU area as Costello et al. (2010). Note also that Costello et al. (2010) did not report biodiversity data for the Black Sea.

countries from North-western Europe. Hence, biodiversity data acquisition and mobilization are biased regionally, reflecting sparse efforts along the southern and easternmost marine areas.

Despite the spatial heterogeneity and the observed differences in the distribution of sampling effort and species richness, we observed a similar temporal trend in the reported number of occurrences among basins (with the exception of the Baltic Sea, for which the number of occurrences was consistently low throughout the last decades). In particular, we observed a steep increase in the number of reported occurrences from 1990s to 2000s coinciding with the digitalization of our society, the increase in Internet data traffic and the broad development of digital data-sharing platforms such as GBIF (note that GBIF was officially established in 2001[3]). Overall, these increasing trends peaked in the earlies 2010s matching with the end of the CoML, and thus pointing to a massive mobilization of biodiversity data acquired during this multinational biodiversity assessment project. In the case of the Mediterranean Sea, a second, even larger peak occurred a few years later. After these peaks, the number of reported occurrences has been decreasing to date, with current numbers being similar to those reported in the 2000s. This could potentially weaken prospects for GBIF-based research and applications to marine conservation and monitoring of marine ecosystems. Indeed, monitoring biodiversity trends requires more than a single snapshot of the status and distribution of species (Boakes et al., 2010). Accordingly, high temporal coverage, i.e., continuous recording of species through time, is essential for monitoring species' responses to environmental change, evaluating changes in biodiversity and to providing historical baselines (Whittaker et al., 2005; Boakes et al., 2010; Meyer et al., 2016b).

According to our proxy to the long-term taxonomical completeness (yearly and basin-specific Shannon index, H′), minor taxonomical biases should be expected for Atlantic EU and the Baltic Sea since the 1990s, matching with the steep increase in the number of recorded occurrences. However, while

[3]https://www.gbif.org/document/80661/gbif-memorandum-of-understanding

TABLE 2 | Number of species per basin and taxa reported in GBIG and Costello et al. (2010) when analyzing biodiversity information from the Census of Marine Life (CoML).

	Atlantic EU				**Baltic Sea**		**Mediterranean Sea**		**Black Sea**	
	GBIF			**CoML**	**GBIF**	**CoML**	**GBIF**	**CoML**	**GBIF**	**CoML**
	Whole area	**Costello et al. (2010)**								
Annelida	1,661	1,566	(6%)	1,595	732	411	804	1,179	112	
Bryozoa	524	486	(8%)	368	133	59	288	337	0	
Cnidaria	1,179	966	(22%)	491	221	117	447	674	15	
Crustacea	2,883	2,581	(12%)	2,209	607	587	1,246	2,190	34	
Echinodermata	679	590	(15%)	245	117	59	166	168	3	
Mollusca	3,853	2,975	(30%)	1,350	865	293	2,589	2,190	93	
Pisces	1,673	1,214	(38%)	1,104	249	176	961	674	135	
Platyhelminthes	391	380	(3%)	245	156	293	113	1,011	9	
Porifera	725	641	(13%)	491	142	0	271	674	2	
Protozoa	462	430	(7%)	491	329	1,173	280	4,044	30	
Tunicata	223	206	(8%)	123	44	0	112	168	0	

*For the Atlantic EU, we include the number of species reported for the area considered in Costello et al. (2010) as well as for the whole area that includes water masses around the Macaronesia and the Arctic Sea (see **Figure 1**). The relative differences between these two datasets are given within parentheses. Note that there is a lack of biodiversity data in the CoML for the Black Sea.*

this statement may hold true for the whole basins, reported geographical biases may imply taxonomical biases at those areas or marine regions where sampling effort was relatively low. In the case of the Mediterranean Sea, we observed a gradual increase in H′ as a likely result of the inclusion of several taxa in GBIF records since the 2000s (i.e., Echinodermata, Porifera, and Bryozoa). This suggests an early taxonomical bias that may prevent from putting the status of the present-day biota into a proper historical context (Willis et al., 2007; Boakes et al., 2010). In the case of the Baltic Sea, the chaotic trend in H′ values suggests an unbalanced taxonomic sampling.

Taxonomical biases can prevent from biodiversity comparisons among areas and periods, and imply that completeness pattern of a single-taxon is a poor predictor for un-assessed taxa and highlights the need to identify taxon-specific information gaps (Vale and Jenkins, 2012; Meyer et al., 2015). These biases may be caused by species traits that affect detection and collection probabilities. For instance, more records might be available for early-described species, those that are more conspicuous and show higher abundances, or those that attract more scientific or public interest (Meyer et al., 2016a, and the references therein). Accordingly, previous assessments (based on CoML) revealed that the most conspicuous, abundant, and likely more "appealing" or "charismatic" species of mollusks, crustaceans, bryozoans, echinoderms, fish, and other vertebrates were the most well known in the European Seas (Narayanaswamy et al., 2013). Overall, these groups were also better represented in GBIF with respect to the CoML benchmark and the less conspicuous protozoans, annelids, and platyhelminths. However, this pattern contrasted for the worse sampled Mediterranean basin, where the number of species reported in GBIF was lower than those reported in CoML for most clades (particularly for the less conspicuous protozoans), with the only exceptions of mollusks and fish.

If we are to achieve a complete representation of our current ecosystems, biodiversity information must be comprehensive and not just focus on the most conspicuous or charismatic species, or those of greatest conservation concern (Boakes et al., 2010). In this regard is worth noting that very few institutions account for most of the occurrences available in GBIF. This is particularly true in the case of the Baltic Sea, where a single institution (SLU) contributes to more than 60% of reported occurrences. Biases by these top-contributing institutions toward particular taxa (e.g., research or conservation interest for target groups or species) may result, therefore, in GBIF taxonomical biases. Enlarging the number of contributors to GBIF and balancing their contributions may help to prevent taxonomical biases and increase completeness.

Information on species distributions in space and time is a central aspect of biodiversity knowledge that is needed for the effective management of biodiversity and associated ecosystem services in a rapidly changing world (Whittaker et al., 2005; Butchart et al., 2010; Levin et al., 2014). FAIR biodiversity data available in GBIF provide vital information about where and when species occur and are widely used in ecology, evolution, and conservation research (Ball-Damerow et al., 2019). This information has the potential to contribute and inform actions toward multiple research questions and conservation targets at the global level. This can be the case for the Sustainable Developed Goals adopted by all United Nations Member States and the Convention on Biological Diversity (CBD[4]) that call for a reduction in the rate of biodiversity loss and claim for the development of an advanced and shared biodiversity knowledge base. At the European level, open biodiversity data may also contribute to achieving the objectives of the Marine Strategy Framework Directive, as biological diversity is the first of the

[4]https://www.cbd.int

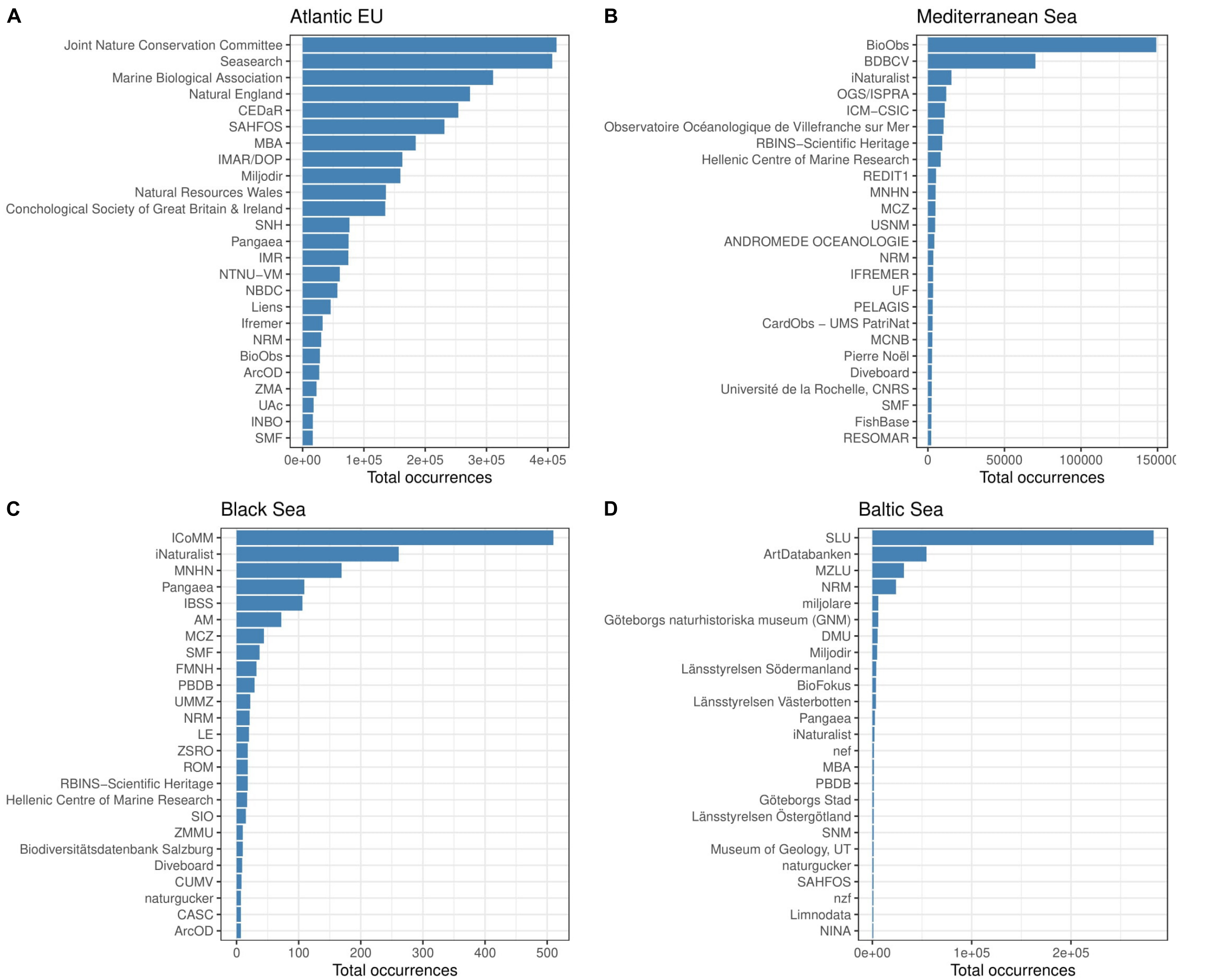

FIGURE 6 | Bar plot showing the total number of occurrences reported by single Institutions for the basins considered in the study. Information on main contributors is provided for the Atlantic EU **(A)**, Mediterranean Sea **(B)**, Black Sea **(C)**, and Baltic Sea **(D)**. We focused on the top 25 contributors for visualization purposes. However, these top contributors account for most of the reported occurrences (ca. 90% in the Atlantic EU and the Mediterranean Sea, and almost 100% in the Baltic and the Black Seas, see **Supplementary Table 2**).

11 descriptors of Good Environmental Status (GES) of the European marine waters. Examples of open biodiversity data uses toward these conservation targets may include marine spatial planning applications to minimize biodiversity loss through the improvement of networks of marine protected areas, safeguarding threatened species, and mapping and securing associated ecosystem services (Levin et al., 2014).

While acknowledging the potential of open biodiversity data, our assessments suggest that severe spatial, temporal, and taxonomical gaps and biases exist in FAIR biodiversity information, even for the comparatively well-known European Seas (see also Boakes et al., 2010; Jetz et al., 2012; Meyer et al., 2015); and these require careful consideration when developing conservation research and applications (Levin et al., 2014; Meyer et al., 2015; Ball-Damerow et al., 2019). For instance, the pervasive lack of biodiversity data for the south-easternmost marine areas (including the Black Sea) indicates that there are not sufficient occurrence (available) data to facilitate modeling approaches. Temporal biases in species occurrences toward the most recent decades may hamper our ability to monitor species' and biodiversity's responses to human impacts and environmental changes; whereas taxonomic biases toward the most conspicuous species may impede biodiversity comparisons across sites and periods. National to international join efforts aimed at generating and mobilizing biodiversity data should focus on data-deficient areas, periods, and taxa. These same recommendations could be extended to other, less studied marine regions in the world for which we should expect exacerbated spatial, temporal, and taxonomical biases in available FAIR biodiversity information. This will contribute to future modeling efforts toward building reliable and integrated marine assessments and digital twins of the oceans in general, and the European Seas, in particular.

Understanding the key driving factors of bias is important to prioritize activities in biodiversity data acquisition and mobilization. For instance, spatial distance to data-contributing institutions has been previously highlighted as one of the key drivers of spatial biases (Meyer et al., 2015). Together with the higher financial support to research in the northern, higher-income countries, this may contribute to explaining the northwestern-to-southeastern gradient in sampling effort and species richness in the European Seas. Overall, this may result in high levels of informational redundancy concentrated in a few northern places, often at the expenses of other, poorly known areas in the southern and eastern rims. While this extensive data availability may benefit local conservation efforts in the northern marine regions as well as many purely scientific endeavors, this can also trade off against global-scale data needs and integrative assessments required to support cost-effective progresses toward global biodiversity conservation (Meyer et al., 2015). An effective strategy for addressing these spatial gaps in FAIR biodiversity data may therefore lie in supporting international programs and cooperation, aimed at enhancing data acquisition and mobilization efforts in institutions nearby identified data gaps, and supporting participation in international data-sharing programs through direct partnerships or capacity building assistance (Meyer et al., 2015).

Further initiatives should also focus on preventing temporal biases by maintaining the necessary local and long-term logistics of field sampling, specimen processing (e.g., identification), and incorporation of data on global biodiversity information systems. Initiatives aimed at enhancing the identification and digitation of specimens in museum collections could also contribute to minimizing these biases in available FAIR biodiversity data (Ariño, 2010; Page et al., 2015; Ball-Damerow et al., 2019). In this regard, taxonomic work and support to taxonomists should remain also a priority, especially in the relatively poorly sampled non-vertebrates, because the utility of data-basing collections rests on the accuracy of the identifications and their taxonomical completeness (Graham et al., 2004). There is also much room for several large emerging economies including Russia or Turkey for addressing gaps in biodiversity data in poorly known areas for the eastern Mediterranean and the Black Sea. Success in building an adequate information basis for global biodiversity conservation and thus globally informed policies for environmental sustainability will depend on their support and may be determined by political rather than economic factors (Meyer et al., 2015).

In addition to these geographical, social, economic, and political factors limiting or biasing the availability and accessibility of biodiversity data, limitations inherent to ongoing research/academic systems may also add to the critical caveat of applying digitized data in research and conservation. Research funding usually leading to peer-reviewed publications is not improving the ability to address biodiversity information gaps and biases as greatly as direct support for data mobilization programs (Meyer et al., 2015). This suggests that most of the strongest limiting factors of completeness affect digitization and mobilization of existing data rather than the actual collection of new records in the field. In part, this is because current data-archiving policies and academic reward systems do not favor data-sharing activities (Whitlock, 2011; Enke et al., 2012; Meyer et al., 2015). The recent expansion of data journals (Chavan and Penev, 2011), online platforms for reporting species occurrence observations (Pimm et al., 2015), and efforts over the past decade to digitize specimen records (Page et al., 2015), have resulted in a steep increase in the number of data papers and papers describing a new database over time (Ball-Damerow et al., 2019). However, there is still a long way to go for this type of scientific activity to be recognized in a similar way to "classic" research work when it comes to obtaining the necessary merits and academics rewards to be competitive in scholarships, job positions, and calls for funding research. Improved reward systems, new data publishing mechanisms, and journal and public funding agencies' requirements aimed at making biodiversity data publicly available can incentivize both individual scientists and larger project teams to openly share biodiversity records (Whitlock, 2011; Enke et al., 2012; Meyer et al., 2015).

While biodiversity assessments led by trained field biologists will continue to play an important role in long-term monitoring of marine biodiversity as well as the creation of primary information for under-surveyed areas, novel approaches using digital data in active (e.g., citizen science; Chandler et al., 2017) or passive (iEcology and conservation culturomics; Ladle et al., 2016; Jarić et al., 2020a) ways are already providing increasingly valuable records for certain taxa at comparatively low cost (Hochachka et al., 2012; Jarić et al., 2020b).

DATA AVAILABILITY STATEMENT

The datasets analyzed for this study can be found in the GBIF (www.gbif.org, accessed in June 2021) through different queries. Details on each query and associated DOIs are included in the article/**Supplementary Table 1**. Further inquiries can be directed to the corresponding author.

AUTHOR CONTRIBUTIONS

All authors conceived the work and contributed substantially to the interpretation of results, and the writing, reviewing, and editing of the manuscript. JP, MC, and FR provided the funding. FR and VS extracted and analyzed the data. FR drafted the manuscript.

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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.2021.802235/full#supplementary-material

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Shallow Sea Gas Manifestations in the Aegean Sea (Greece) as Natural Analogs to Study Ocean Acidification: First Catalog and Geochemical Characterization

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The concepts of CO_2 emission, global warming, climate change, and their environmental impacts are of utmost importance for the understanding and protection of the ecosystems. Among the natural sources of gases into the atmosphere, the contribution of geogenic sources plays a crucial role. However, while subaerial emissions are widely studied, submarine outgassing is not yet well understood. In this study, we review and catalog 122 literature and unpublished data of submarine emissions distributed in ten coastal areas of the Aegean Sea. This catalog includes descriptions of the degassing vents through *in situ* observations, their chemical and isotopic compositions, and flux estimations. Temperatures and pH data of surface seawaters in four areas affected by submarine degassing are also presented. This overview provides useful information to researchers studying the impact of enhanced seawater CO_2 concentrations related either to increasing CO_2 levels in the atmosphere or leaking carbon capture and storage systems.

Keywords: CO_2 emissions, submarine gas vents, geogenic degassing, environmental impact, Greek Islands, gas flux

INTRODUCTION

The concentration of carbon dioxide (CO_2) in the atmosphere is increasing mainly due to fossil fuel combustion and industrial processes. Since the beginning of the industrial revolution at the end of the eighteenth century, its level increased from about 280 ppm and exceeded the average yearly value of 413 ppm during the year 2021 (NOAA, 2021). Being one of the major greenhouse gases, such rapid increase has severe consequences on earth's climate (IPCC, 2021). About one third of the anthropogenic CO_2 released into the atmosphere in the past two centuries has been taken up by the ocean (Sabine et al., 2004; Bindoff et al., 2019; Gruber et al., 2019). In aquatic systems CO_2

gas dissolves, hydrates and dissociates to form weak carbonic acid (Drever, 1997), and the pH is lowered according to the following reaction:

$$CO_{2(g)} + H_2O \Leftrightarrow H_2CO_{3(aq)} \Leftrightarrow H^+ + HCO_3^- \quad (1)$$

Current CO_2 emission rates exceed the buffering capacity of the oceans and cause a shift of marine carbonate chemistry and a decrease of pH that has been quantified in 0.1 units compared to the pre-industrial period (Haugan and Drange, 1996; Doney et al., 2009; Gattuso and Hansson, 2011; Jiang et al., 2019). Depending on different emission scenarios, models predicted that further CO_2 increase would cause an additional reduction of pH between 0.3 and 0.5 units by the end of the century (Caldeira and Wicket, 2005; Joos et al., 2011; Jiang et al., 2019). Business-as-usual CO_2 emission scenarios predict that atmospheric CO_2 will reach 750 ppm and pH levels will decrease to 7.8 by the year 2100 (Jiang et al., 2019). In addition to this, both surface temperature and heat content of the ocean have increased. Specifically at the ocean surface, temperature increased by 0.88°C on average from 1850–1900 to 2011–2020. Possible future scenarios anticipate that it will arrive at 0.86°C from 1995–2014 to 2081–2100 (IPCC, 2021). Similarly, ocean heat content increased by 0.28–0.55 YJ between 1971 and 2018 and will probably continue to increase until at least 2300 (IPCC, 2021). This projection applies also for low emission scenarios due to the slow circulation of the deep ocean.

Many studies evidenced that ocean acidification (OA) will exert significant and sometimes unexpected effects on marine ecosystems (Jiang et al., 2019). Because these changes decrease the saturation state of the carbonate ion ($CO_3{}^{2-}$) in seawater, organisms relying on calcification for growth or protection are assumed to be most severely affected (Doney et al., 2012). On the contrary, photosynthetic organisms, such as seagrass and algae, may benefit from the increasing pCO_2 which is an essential resource for their photosynthesis and survival (Fabricius et al., 2011; Koch et al., 2012; Russell et al., 2013). It should be mentioned that even though laboratory experiments documented the benefits of OA on seagrass growth, anthropogenic stressors might counterbalance positive effects of increased CO_2 and have likely blocked potential beneficial responses of OA (Koch et al., 2012; Doo et al., 2020). To face the problem of atmospheric CO_2 increase, apart from the most logical solution remaining the strong reduction of anthropogenic CO_2 emission, one remedy proposed is the geologic carbon sequestration. CO_2 capture and storage (CCS) systems concentrate and transfer liquid CO_2 into storage sites, including sub-seabed deep geological formations such as exhausted oil or gas reservoirs. This approach is considered promising, since technically feasible (IPCC, 2005), but as with all other human technologies, it is not exempt from drawbacks. One of these drawbacks is the possibility that the chosen reservoir is not perfectly sealed and undergoes CO_2 leakage (Monastersky, 2013). If these reservoirs are offshore, CO_2 leakages from CCS can drive strong local seawater acidification (Blackford et al., 2014), exceeding the values predicted by the worst scenario of climate change. Moreover, in the case of a CO_2 leak from a storage site, the gas will also acidify the pore water in the sediments surrounding the storage site (Millero et al., 2009). This may also increase the release of harmful elements from the sediments creating an additional negative impact on the marine environment (De Orte et al., 2014; Foo et al., 2018). Flohr et al. (2021) simulated CO_2 leakage from an offshore CO_2 storage site in the British sector of the central North Sea. The CO_2 release experiment (Flohr et al., 2021; Gros et al., 2021) lasted for 1 month and the authors illustrated that different approaches can detect, attribute and quantify the release.

Notwithstanding the increasing number of studies on the ecological consequences of OA and CCS leakage, many issues remain unexplored and, until now, the vast majority of them have been performed in laboratories mainly as short-term and univariate experiments (Cornwall and Hurd, 2016). To have a more realistic picture, experiments should be made on marine organisms in their natural ecosystems. In this sense, areas with natural CO_2 vents represent useful experimental locations to investigate the impact of OA on entire ecosystems (Hall-Spencer et al., 2008). Natural underwater vents of volcanic origin release gases composed mainly of CO_2 and may therefore represent a natural analog to study the impact of seawater acidification. The CO_2 vent areas are also perfect natural laboratories to study the impact of CO_2 leakage from CCS systems.

Few of these "natural laboratories" have already been used to study the effects of elevated CO_2 on ecosystems (Vizzini et al., 2010; Lauritano et al., 2015; Linares et al., 2015) sometimes evidencing the adaptation of complex ecosystems such as coral reefs (Golbuu et al., 2016; Teixidó et al., 2020).

These vent sites allow to study different habitats, including shallow coral reefs in Papua New Guinea, Japan, and Northern Mariana Islands (Enochs et al., 2016; Golbuu et al., 2016); seagrass meadows, macroalgae stands, and coralligenous in the Mediterranean Sea (Columbretes Islands, Spain—Linares et al., 2015; Ischia, Italy—Hall-Spencer et al., 2008; Vulcano, Italy—Boatta et al., 2013; Panarea, Italy—Rogelja et al., 2016; Methana, Greece—Baggini et al., 2014); as well as in the subtropical North East Atlantic reefs (La Palma, Canary Islands—Hernández et al., 2016). However, a larger representation of environments is needed to predict the biological and ecological consequences of OA.

Our study will give a first catalog of the gas vents within the Aegean Sea comprising a description of the areas. It will provide important information to researchers who study the impact of enhanced seawater CO_2 concentrations related to increasing CO_2 levels in the atmosphere or even to leaking CCS systems like (i) extension and morphology of the exhaling area; (ii) preliminary gas flux estimations and geochemical characterization of the gases; (iii) presence of possible confounding factors as for example emission of thermal waters and/or hydrogen sulfide, iron oxi-hydroxide flocculation. The geochemical characterization is based almost exclusively on literature data that are gathered together with some new results and are made available to the reader in **Supplementary Table 1**, while a description of the degassing sites and a rough estimation of the gas fluxes are available in **Table 1**. We also present unpublished data on pH and temperature measurements of surface seawaters in four areas affected by the submarine degassing (**Supplementary Table 2**).

TABLE 1 | List and general characteristics of the underwater degassing areas.

Sampling site	Place	Depth of the vents (m)	Seabed	Degassing areas features	Flux estimation
Therma port	*Samothraki island*	0–2	Sand	Isolated bubble trains	Low
Agia Paraskevi 1	*Chalkidiki peninsula*	0.5–1	Boulders	Diffuse bubbling	Low
Agia Paraskevi 2		5	Sand with white Stains	Aligned bubble trains and diffuse bubbling with hot waters	Medium
Xyna		0.5–1	Pebbles	Isolated bubble trains	Low
Ilion	*Euboea island*	0.5–2	Sand and boulders	Diffuse bubbling with hot waters	Low
Pausanias	*Methana peninsula*	0.5–2	Boulders	Diffuse bubbling	Low
Thiafi bay		1.5–5	Sand and boulders	Diffuse bubbling	Low
Mandrakia	*Milos island*	2.5	Sand, boulders and posidonia seagrass	Diffuse bubbling	Low
Voudia		2	Sand, boulders and posidonia seagrass	Diffuse bubbling	Low
Paleochori		4	Sand with yellow and white stains	Aligned bubble trains and diffuse bubbling with hot waters	High
Spathi bay		-	-	-	-
Agia Kyriaki		3	Sand	Diffuse bubbling	Low
DEH(Kanavas)		2	Sand	Diffuse bubbling	High
Skinopi		1.5	Sand and posidonia seagrass	Diffuse bubbling	Low
Agios Nikolaos(Palea Kameni)	*Santorini island*	0.5–1	Rocks, boulders	Bubble trains	Medium
Agios Giorgios(Nea Kameni)		0.5–1	Rocks, boulders	Bubble trains	-
Irinia(Nea Kameni)		0.5–1.5	Rocks, boulders	Isolated bubble trains	Low
Kolumbo	*Kolumbo submarine volcano*	about 500	-	Degassing chimneys, hot waters	-
Paradise beach	*Kos island*	1–1.5	Sand	Aligned bubble trains and diffuse bubbling	High
Kefalos		2	Sand	Aligned bubble trains and diffuse degassing	Medium-low
Therma		0.5–4	Rocks, boulders and Posidonia seagrass	Aligned bubble trains and diffuse bubbling with hot waters	Medium
Agia Irini 1		0.5–4	Boulders and sand	Diffuse bubbling	Low
Agia Irini 2		9	Sand	Isolated bubble trains	Low
Lies	*Nisyros island*	1.5	Rocks, boulders	Diffuse bubbling	Low
Katsouni		0.5–2	Rocks, boulders	Small isolated bubble trains	Low
Gyali West	*Gyali island*	11	Sand	Aligned bubble trains	High
Gyali South		1.5	Sand	Diffuse bubbling	Low
Gyali North		0.5–1.5	Boulders	Diffuse bubbling	Low

Estimated gas fluxes are divided into low (0.1 – 0.5 L/min), medium (0.5 – 1 L/min), and high fluxes (> 1 L/min).

STUDY AREA

The Aegean Sea (**Figure 1**) is located in the eastern Mediterranean and is a rift formed in a "backarc" setting. It is situated in the upper plate of the Hellenic subduction zone and west of Anatolia, where active tectonics is observed. In fact, the northern Aegean Sea is a part of the Eurasian plate and the boundary with the Aegean microplate is called the North Anatolian Trough (NAT). The latter is the continuation of the North Anatolian Fault Zone (NAFZ) and is a ∼300 km long system of tectonically active marine basins, up to 1,000 m deep (Le Pichon et al., 1987; Taymaz et al., 1991; Kreemer et al., 2004).

The thinning of various tectonic units mainly emplaced during the Upper Cretaceous– Paleocene convergence–collision processes has resulted in the creation of the basin (Boccaletti et al., 1974; Robertson et al., 1991). It should be noted that the Hellenic subduction system was active since at least the Late Cretaceous, while the "backarc" rift was developed during Eocene-Early Miocene (Agostini et al., 2010; Jolivet et al., 2013). Despite the long-lasting formation of the Aegean basin (∼40 Ma), the extension rate is relatively low, so that the oceanic crust was not generated (Agostini et al., 2010).

Nowadays, the extension is seemingly localized around the Corinth-Patras rift (southern Greece), however; it was widespread during the Miocene (Sébrier, 1977;

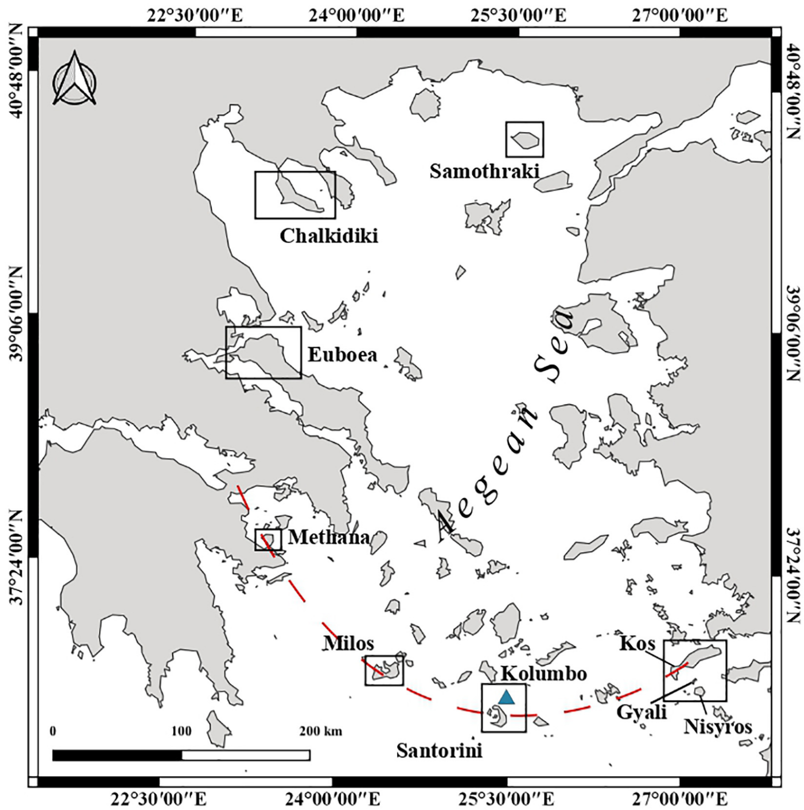

FIGURE 1 | Map of the Aegean sea where the south Aegean active volcanic arc (SAAVA) is drawn with a dashed red line. Study areas are delimited in black squares, while Kolumbo is marked with a light blue triangle. Details on the study areas are found in section "Geological and Geochemical Description of the Submarine Degassing Areas and *in situ* Observations".

Mercier et al., 1979). Oligo-Miocene extensional metamorphic complexes outcrop in the Cyclades archipelago and the northern Aegean Sea (Lister et al., 1984; Gautier et al., 1993). The extension has proceeded from north to south, while the subduction front was retreating southward (Lauritano et al., 2015).

This geodynamically active regime is also characterized by intense seismic activity (Taymaz et al., 2007), by the presence of the south Aegean active volcanic arc (SAAVA) (Fytikas et al., 1984) and anomalous geothermal gradients (Fytikas and Kolios, 1979). Similar to other regions of intense geodynamic activity, extensive geogenic degassing takes place (Daskalopoulou et al., 2018a, 2019a) with gas manifestations being widespread both on land and underwater.

GEOLOGICAL AND GEOCHEMICAL DESCRIPTION OF THE SUBMARINE DEGASSING AREAS AND *IN SITU* OBSERVATIONS

A total of 10 areas characterized by submarine degassing were documented and sampled along the Aegean Sea. **Table 1** summarizes the general characteristics of the underwater sampling sites. A brief description of the degassing sites and *in situ* observations documented during the field campaigns are presented in this paragraph. Where possible, underwater filming allowed us to document and describe the degassing areas, and estimate the gas fluxes (as described in **Supplementary Material**).

Samothraki Island

The island of Samothraki is located at the NE part of the Aegean Sea of Greece (**Figure 1**) and belongs to the Circum Rhodope Zone (Kauffmann et al., 1976). It comprises five lithological units, which include: (i) low-grade metamorphic rocks (basement unit), (ii) an ophiolitic complex, (iii) a granite intrusion with biotite and a contact metamorphic event, (iv) Cenozoic volcanic rocks, and (v) Quaternary clastic sedimentary rocks (Kotopouli et al., 1989; St. Seymour et al., 1996). The rough relief with steep slopes characterizing the SSE part of the island is the result of the tectonic uplift movements, whereas natural weathering and erosion are responsible for the geomorphology (Pavlidis et al., 2005).

Sparse emission points characterized by ambient temperatures are found within the fisherman port of Therma (**Figure 2A**). The manifestations are rich in CH_4 (72.7% on average-**Supplementary Table 1**), while CO_2 is also present (23.8% on average-**Supplementary Table 1**). The flux of the bubbles is low

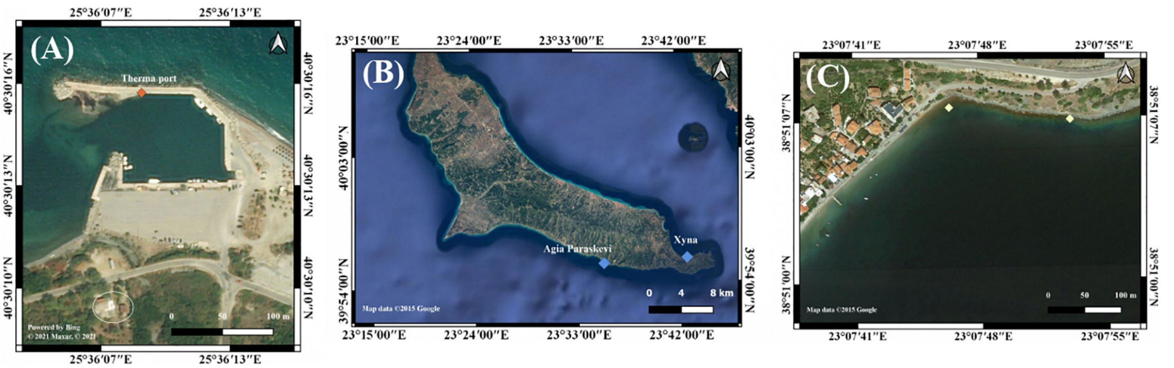

FIGURE 2 | (A) Map of the north section of Samothraki Island that shows the location and name of the emission point. The circled area corresponds to the degassing points of Pigi A and B, and Giotrisi at the hydrothermal system of Therma (Dotsika, 2012; Daskalopoulou et al., 2018a). **(B)** Map of the Kassandra Peninsula that shows the locations and names of the emission points. **(C)** Map of the Ilion area (Euboea) that shows the location of the sampling points.

(**Table 1**), and the gas manifestations, which are spread on an area of a few hundred m^2, are permanent.

This manifestation seems to have no relationship with the nearby (800 m south) on-land hydrothermal system of Therma (**Figure 2A**) that reaches emission temperatures up to 74°C (Dotsika, 2012) and whose bubbling gases have CO_2-rich composition (Daskalopoulou et al., 2018a). On the contrary, its CH_4-rich composition points toward a hydrocarbon reservoir like those that are widespread and exploited in the north Aegean Sea (Rigakis et al., 2001).

Chalkidiki Peninsula

Chalkidiki peninsula is located at NNW part of the Aegean Sea (**Figure 1**) and is a part of the Vardar-Axios Zone, and the Serbomacedonian and Rhodope Massif (from west to the east) (Kauffmann et al., 1976). The area of interest is situated at Kassandra peninsula in Vardas-Axios zone, with the latter being considered as a narrow fragment of the Serbomacedonian Massif (Kockel et al., 1977). Despite the various metamorphic facies, the zone mainly comprises granitic intrusions of Upper Jurassic age and carbonates of a similar age enclosing bauxite horizons (Mountrakis, 1985). The tectonic regime of the area is mainly influenced by Thermaikos gulf, which is the relic of an older larger elongated tectonic depression trending from NNW to SSE.

Underwater degassing takes place in two areas at the Kassandra Peninsula (**Figure 2B**). The first emission site is found in Agia Paraskevi in front of "Halkidiki Thermal Spa" hotel. The two neighboring main degassing points can be visually recognized from the hotel due to a lighter color with respect to the main sea body; they appear like large stains in the sea. One of the main degassing areas is next to the coast close to the thermal springs on land. The springs are at sea level within some small caves (Lazaridis et al., 2011). Bubbling gases sometimes occurred also inside the caves but are more widespread in the sea. In this area, the gases come up from a very shallow depth (<1 m) between the boulders that form the shore. Another degassing area is at some tens of meters from the coast. Here intense degassing occurs at about 5 m depth. Gas emission vents form some recognizable alignments and are probably accompanied by thermal water emission because most of the orifices are surrounded by white deposits. It is worth noting that H_2S is present both within the cave and in the two underwater degassing areas (**Supplementary Table 1**). The degassing is constant and the flux elevated (**Table 1**), especially at the area further from the coast. Here H_2S, although below the analytical detection limit (<10 ppm) in the sample collected close to the sea surface, could still be smelled in the atmosphere above the bubbling site. Considering that H_2S is highly soluble in water only where bubbling is very intense it may reach the surface after crossing 5 m of seawater.

The second degassing spot is found on the eastern coast of the Chalkidiki peninsula in Xyna. It is near the shoreline at the eastern end of a 3 km long sandy beach at the border with a private luxury resort. The gas flux is very low (**Table 1**). In correspondence to the bubbling site, on the beach (5 m from the shore) there is a small hypothermal spring (23°C) captured with a shallow well.

Euboea Island

The island of Euboea is found at the western part of the Aegean Sea (**Figure 1**) and is the second largest island of Greece. It consists of formations from the Sub-Pelagonian structural zone, while its southern part belongs to the Atticocycldic massif. Volcanism of Pliocene and Quaternary age took place in the area (Fytikas et al., 1976; Pe-Piper and Piper, 1989, 2002) contributing to the formation of geothermal fields. The major fault structures of the North Euboean Gulf, where the underwater vents are found (**Figure 2C**), comprise several segments of normal faults, trending about NW-SE and dipping NE with a total length of about 20–30 km (Pavlides et al., 2004).

Widespread underwater manifestations are found a few meters by the coast in the area of Ilion (**Figure 2C**). The widespread bubbling is constant and the flux, according to our estimation, is classified intense (**Table 1**). Hydrogen sulfide is present in minor concentrations (**Supplementary Table 1**), while the rusty color of the sediments suggests the existence of iron oxides deposition. It is worth noting that low pH values have been documented along the coast, with the lowest values being found in front of a high temperature and intensely degassing spring on land 10 m from the sea (**Supplementary Table 2**).

Methana Peninsula

Methana peninsula is located in Saronikos Gulf and represents the northwestern, still active part of the SAAVA (**Figure 1**). It belongs to the Atticocycladic zone and consists of Quaternary calc-alkaline volcanic rocks (andesites to dacites; Fytikas et al., 1986). Two different Pliocene-Quaternary tectonic domains within the Aegean plate are affecting the tectonic regime; a rapid N–S extension to the north and an E–W extension to the south (Jolivet et al., 2013).

Around the peninsula, two areas of submarine gas emissions have been recognized so far (**Figure 3A**). The first one is located in the northern part of the peninsula, where the "Pausanias baths" are found. These baths are associated with hydrothermal degassing emissions composed of almost pure CO_2 (D'Alessandro et al., 2008). They are found at about 3 m from the coast in a depth of 2 m. The seabed is formed of boulders and the flux is considered low (**Table 1**). Baggini et al. (2014) state that along the entire northern coast, the measured pH values of seawater are lower and highly variable with respect to their reference site. Local fishermen reported intermittent gas bubbling close to the coast about 3 km west of the Pausanias baths. This degassing site has not been confirmed and no gas sample has been collected. It may be related either to the historical eruption of 230 BCE, whose lava flow entered the sea in that area, or to the nearby active submarine volcanic edifice called Pausanias (Foutrakis and Anastasakis, 2018). In any case, the sea close to the Pausanias baths has been the site of many studies to investigate the effect of higher pCO_2 values on the local ecosystem (Baggini et al., 2014, 2015; Bray et al., 2014; Triantaphyllou et al., 2018; Patoucheas et al., 2021).

The second submarine vent is situated in the eastern part of the peninsula in a small bay called by the locals "Thiafi bay." This area is nearly 300 m long and is demonstrating on the beach widespread alteration from recent fumarolic activity. The alteration is particularly evident at its northern and southern ends, where it is expressed as native S and sulfates (alunite, gypsum, and alunogen) (Rahders et al., 1997). CO_2 fluxes on land are sometimes elevated and account for the whole area for about 500 t/a (D'Alessandro et al., 2008). The underwater gas vents show very low fluxes and are visible at shallow depths (<3 m) (**Table 1**) close to the coast (from the shoreline to distances of a few tens of meters). Few of these vents have a distinguishable orifice, and only some of them are associated with obvious deposits (possibly amorphous silica), whereas no thermal anomaly has been found at the gas vents (D'Alessandro et al., 2008).

In both degassing sites, CO_2 is the prevailing gas component (up to ∼98%), while H_2S was documented only in Thiafi (**Supplementary Table 1**).

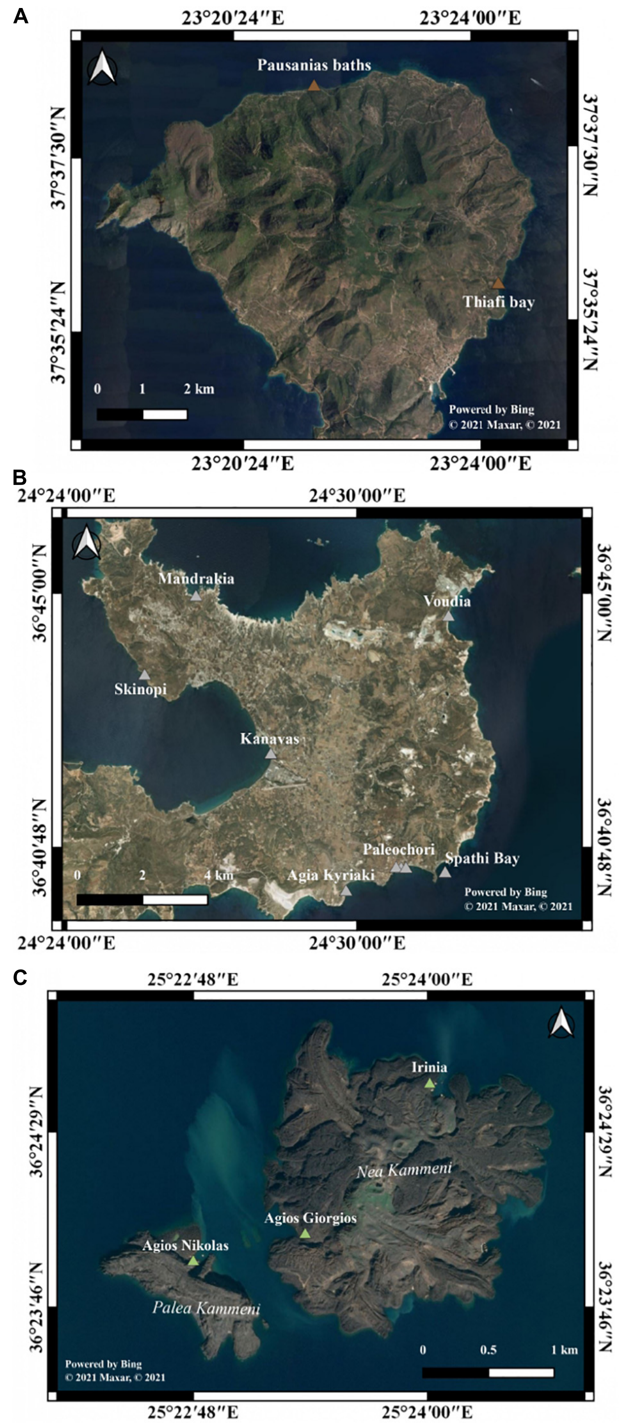

FIGURE 3 | (A) Map of the Methana Peninsula that shows the locations and names of the emission points. **(B)** Map of the western section of Milos Island that shows the locations and names of the emission points. **(C)** Map of the Kammeni Islands that shows the locations and names of the emission points.

Milos Island

Milos Island is found in the center of SAAVA (**Figure 1**) in the convergence zone between the African and the Aegean plates. It belongs in the Atticocycladic zone and comprises Upper Pliocene submarine and Upper Pleistocene to Holocene submarine-to-subaerial calc-alkaline volcanic domes, lavas, and pyroclastic deposits (andesites, dacites, and rhyolites; Fytikas et al., 1986; Stewart and McPhie, 2006). The youngest (Upper Pleistocene) volcanic activity is located in the volcanic centers of Fyriplaka in the south and Trachilas in the north, which are also present-day exhaling areas (Fytikas et al., 1986). However, the seabed around the island is hydrothermally very active. This is particularly noticeable in eight areas, located along the eastern part of the island (Dando et al., 1995; Cronan and Varnavas, 1999; Daskalopoulou et al., 2018b; Ivarsson et al., 2019). Gas emissions have been studied in the following sites (clockwise starting from the north): Mandrakia, Voudia, Paleochori, Spathi Bay, Agia Kyriaki, DEH (Kanavas), Skinopi (**Figure 3B**).

The little center of Mandrakia stands just on the prominent central part of a gulf oriented to the north. In the eastern part of the gulf, just close to some boulders, in a sandy seabed with a large Posidonia grassland, some sparse emissions are present tens of meters away from the shoreline, at a depth of about 3 m (**Table 1**). The vents stand exactly on the direction of the impluvium present on land and emit mainly CO_2 (about 98%).

Voudia bay has two submarine hydrothermal vents. One of them is situated few meters away from the shoreline aligned with altered rocks on the beach, while the other one is found in the southern part of the bay. According to Megalovasilis (2020), the temperatures of the vents range from 28 to 78°C. Daskalopoulou et al. (2019b) collected samples from the emanations spot and reported a CO_2-rich gas (96.6%), with minor contents of H_2S (3,100 μmol/mol; **Supplementary Table 1**). Evidence of sulfur yellow-concretions were noted on the walls of some degassing vents (**Supplementary Figure 2**). While sampling, the same authors have observed a relatively low flow (**Table 1**), which was afterwards confirmed by the documentation of Megalovasilis (2020).

Paleochori Bay is an 800 m long bay with apparent fumarolic activity at its eastern and western parts. Numerous intensively degassing seeps of elevated temperatures (up to 122°C; Dando et al., 1995; Khimasia et al., 2020) occur in the area. The emanating gases are rich in CO_2 (up to 93%; **Supplementary Table 1**) with minor enrichments in N_2 (up to 14%; **Supplementary Table 1**). H_2S is also present in concentrations up to 3.5% (**Supplementary Table 1**). The area is characterized by Fe- and S-alteration products (Cronan and Varnavas, 1999; Baltatzis et al., 2001; Voudouris et al., 2021). According to various authors (Dando et al., 1995; Yücel et al., 2013; Khimasia et al., 2020), the sea-bottom of the bay is dominated by areas of white and brown bacterial mat (**Supplementary Figures 2C,D**). Areas of gray/yellow sand with encrustations and of light brown sand with numerous burrows are also present. Godelitsas et al. (2015) suggested that the reddish or yellow-colored sediment patches in the center of the white mats might have been caused by elemental sulfur (**Supplementary Figure 2C**) and arsenic sulfides precipitation. It is worth noting that the gas ascends from rock fissures at a depth of about 2–3 m, resulting in bacteria-dominated outlets known as "White Smoker" (**Supplementary Figure 2E**). This degassing area is distinguished by the highest gas fluxes estimated in this study (about 1.8 L/min) (**Table 1**). It is important to note that the hydrothermal fluids release to the seawater huge quantities of potentially toxic elements. For example, several studies revealed concentrations of the order of thousands of μg/L of As, Ba, Fe, and Mn, and up to 1 μg/L of Hg (Price et al., 2013; Roberts et al., 2021) leading to the formation of hydrothermal precipitates rich in these and other (Sb, Tl) elements (Voudouris et al., 2021).

Spathi bay is located in the south-eastern sector of the island and extends for about 400 m. The coastline is characterized by

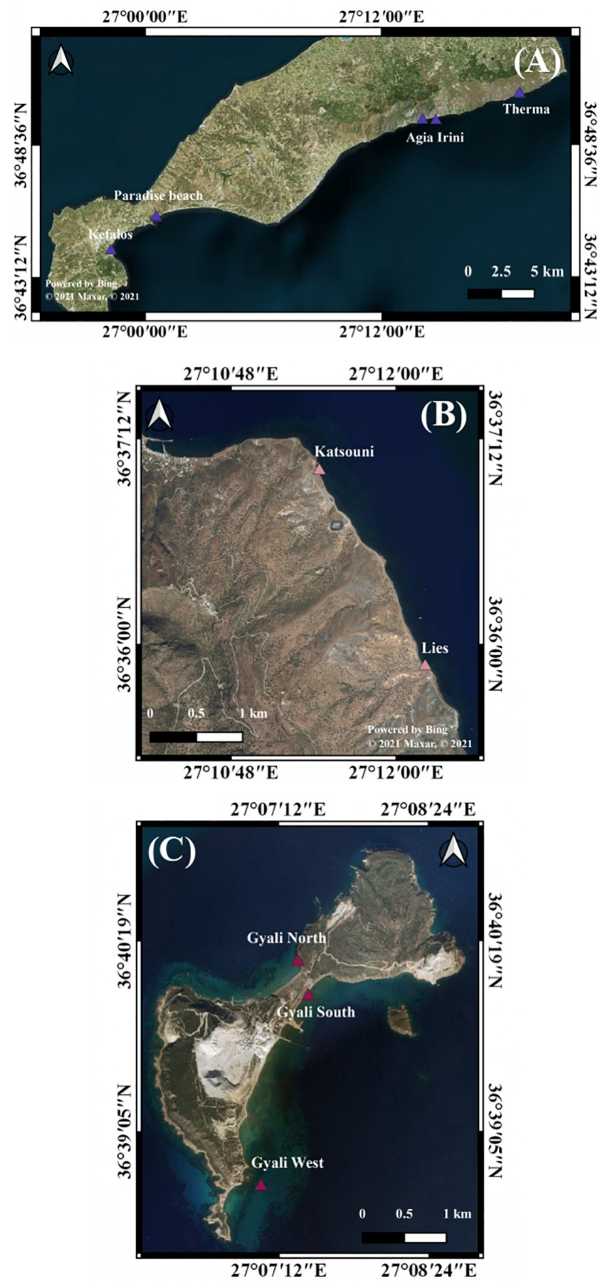

FIGURE 4 | (A) Map of the southern sector of Kos Island that shows the locations and names of the emission points. **(B)** Map of the NE sector of Nisyros Island that shows the locations and names of the emission points. **(C)** Map of Gyali Island that shows the locations and names of the emission points.

pebbles and is bordered to the west by an imposing promontory and to the east by striking stacks. We do not have detailed information on the underwater emissions as the gas sample was kindly taken by colleagues.

Agia Kyriaki is located in the southern sector of Milos, in a bay that stretches for about 500 m. The coast is predominantly sandy and the seabed is characterized by alternating sandy areas and reefs. The only underwater gas manifestation in this area is found at less than 10 m from the shoreline, where a few isolated bubble-trains with a low flux outcome from a substrate of rock blocks, at a depth of about 2–3 m (**Table 1**). H_2S was present in concentrations lower than 10 μmol/mol (**Supplementary Table 1**).

DEH is located in the sea along Kanavas coast close to the power plant of the Hellenic Public Power Corporation. The degassing area is about 400 m^2 with a CO_2 output estimated at 1.06 t/d (Daskalopoulou et al., 2018b). The numerous and widespread gas manifestations have low temperatures with H_2S being less than 16 μmol/mol (**Supplementary Table 1**). The sea bottom is sandy and very shallow (about 1–2 m) and clear alignments of high-flux degassing vents from fissures were noted (**Supplementary Figure 2A** and **Table 1**). The environment is disturbed by many human activities, i.e., a shipyard 500 m north, abandoned salt flats about 200 m south, and the power plant less than 100 m away which discharges its cooling water about 50 m from the bubbling area.

Skinopi is a small bay with a 100 m long pebble beach on which stand some characteristic houses and small jetties for fishermen's boats. It is located 1,500 m west of Adamas, the main port of the island. Close to the coast (tens on meters) there are many bubbling areas. The degassing area is shallow (<2 m) and not very active (low fluxes) (**Table 1**), while the sandy and boulders sea bottom is mostly covered by Posidonia grasslands. The gases are mainly composed of CO_2 (>82%), and H_2S is undetectable (**Supplementary Table 1**).

Santorini Island

Santorini volcanic complex is found in the center of the SAAVA (**Figure 1**). It comprises the islands of Thera, Thirasia, Palea Kammeni, Nea Kammeni, and Aspronisi, and belongs to the Atticocycladic zone. The complex consists of volcanic rocks (mainly pumice and glass) and metamorphic formations (mainly marbles and phyllites) (Druitt et al., 1989, 1999; Oikonomidis and Pavlides, 2017). The evolution of the volcanic centers is associated with two NE-SW faults; the Kammeni Line (Heiken and McCoy, 1984; Druitt et al., 1989, 1999; Parks et al., 2013) and the Columbo Fault Zone (Druitt et al., 1989, 1999; Mountrakis et al., 1998). In addition to this, Tzanis et al. (2020) demonstrated that both volcanism and the shape of the volcanic center are controlled by the tectonics.

Submarine gas vents are located in Palea and Nea Kammeni islets (**Figure 3C**). The emission point in Palea Kammeni is in the bay of Agios Nikolaos and is located close to the coast in the eastern part of the island. Two emissions have been documented in the Nea Kammeni island. One is called Agios Giorgios and is found on the western side of the island, while Irinia is on the eastern side where most of the island visitors are disembarked. Both Agios Nikolaos and Agios Giorgios are CO_2 dominated (Chiodini et al., 1998; Tassi et al., 2013; Daskalopoulou et al., 2018a) and present H_2S content up to 26 and 415 μmol/mol, respectively (**Supplementary Table 1**). The outlet temperatures of the two points are 36 (Agios Nikolaos) and 40°C (Agios Giorgios) (Böstrom and Widenfalk, 1984; Dotsika et al., 2009). On the other hand, Irinia shows a mixed CO_2-N_2 composition (Daskalopoulou et al., 2018b; Tarchini et al., 2019). All three sites are in protected coves where the seawater is heavily stained by iron oxides due to the input of the hydrothermal fluids. In the deepest parts of the coves, iron concentrations in seawater exceed 1 mg/L (up to 13.7 mg/L; Smith and Cronan, 1983). The iron, solubilized by the low pH CO_2-rich hydrothermal fluids, becomes oxidized on mixing with seawater and precipitates accumulating abundantly at the bottom of the exhaling areas (Smith and Cronan, 1983).

Kolumbo

Kolumbo is a submarine volcano found 7 km northeast off Santorini island (**Figure 1**). It is a high-temperature hydrothermal field (Sigurdsson et al., 2006) characterized by numerous vents of CO_2-rich gases (<97%) and fluids of ∼220°C (Carey et al., 2011). Despite its proximity to Santorini, volcanological and petrological evidence suggest the existence of two separate plumbing systems beneath the two volcanic edifices (Francalanci et al., 2005; Dimitriadis et al., 2009; Kilias et al., 2013). In addition to this, Rizzo et al. (2016) has documented a more than 85% mantle contribution for He (the highest across SAAVA). Gases collected in Kolumbo are CO_2 dominated (>98% on average; Carey et al., 2011; Rizzo et al., 2016, 2019; **Supplementary Table 1**).

Kos Island

Kos Island is located in the eastern part of the SAAVA (**Figure 1**). It comprises alluvial deposits with greenschists and flysch in the north, lacustrine and terrestrial deposits of the Pliocene age in the central part, while tuffs and ignimbrites of the Quaternary age are found in the south (La Ruffa et al., 1999). Faults of WNW-ESE and NE-SW orientation seem to control the tectonic evolution of the island and to be related to extensional processes and volcanic activity during the Pleistocene and Pliocene (Lagios et al., 1998). In the area, four submarine degassing centers have been recognized (Daskalopoulou et al., 2019b). Paradise beach and Kefalos are located in the western part of the island, while Therma and Agia Irini in the eastern (**Figure 4A**).

The submarine emissions of Paradise beach are rich in CO_2. H_2S is always below detection limit (**Supplementary Table 1**). The vents are found at approximately 20 m from the coast at 1–1.5 m depth. They are widespread and having elevated gas flows (**Table 1**).

The marine area of Kefalos at the SW of the island is interested by diffuse degassing, with a lot of bubble streams mainly concentered just to the east of the harbor area. Hundreds of little vents that emit trains of little bubbles are present in a sandy seabed at a depth of few meters.

Submarine gases of Therma present similar chemical characteristics to the gases of Paradise. However, they are found by the coast and are characterized by elevated temperatures (up to 45°C).

Two degassing vents have been recognized in the sea in front of the Agia Irini church. Despite the vicinity of the emission points, their prevailing gas components differ significantly. One (Agia Irini 1) is rich in CO_2 (>95%), while the other (Agia Irini 2) is rich in N_2 (34–99%). At both sites, H_2S is generally below detection limit (**Supplementary Table 1**).

Nisyros Island

Nisyros Island is found at the eastern end of the SAAVA (**Figure 1**) and is a quiescent active stratovolcano with intense fumarolic activity that is generated by the presence of a high enthalpy geothermal system (Marini et al., 1993). It belongs to the Atticocycladic unit and consists of Quaternary volcanic rocks and alternations of lava flows, pyroclastic deposits and lava domes. The island has an area of 47 km^2 and forms a truncated cone with a base diameter of 8 km and a 4 km wide central caldera (Hunziker and Marini, 2005), known as the Lakki Caldera. Numerous, mostly sub-vertical faults crosscut the island and the caldera. The vertical offsets for the majority of these faults decrease from the caldera rim toward the coast, where they practically disappear ("scissors-type" faults); something that evidences their association with volcano-tectonic effects (Stiros, 2000).

Two points of submarine vents have been recognized in Nisyros (**Figure 4B**). Lies and Katsouni are two gas manifestations rich in CO_2 (**Supplementary Table 1**). They are

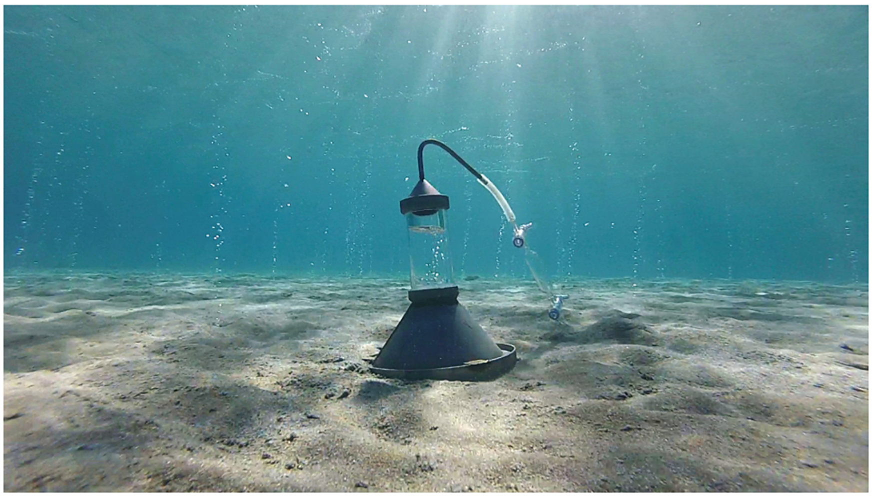

FIGURE 5 | Gas sampling with the use of the inverted funnel method at Kefalos (Kos Island). Note that the funnel was constructed at the mechanical laboratory of Istituto Nazionale di Geofisica e Vulcanologia, Sezione di Palermo (INGV-Palermo). Additional photos regarding the sampling technique are provided in **Supplementary Figure 1**. Photo courtesy of SC.

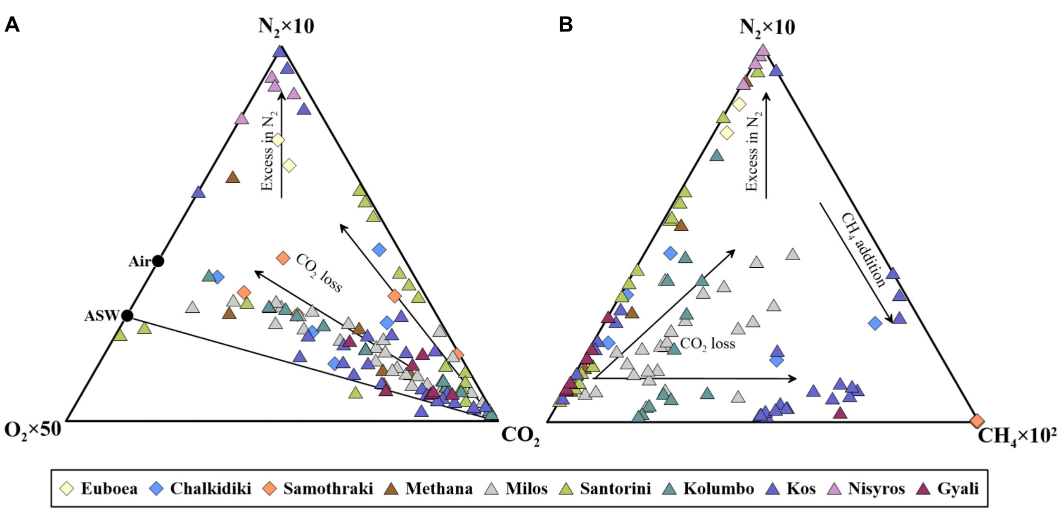

FIGURE 6 | Ternary plot of **(A)** CO_2-N_2-O_2 and **(B)** CH_4-N_2-CO_2. Processes impacting the gases are drawn with an arrow. The abbreviation "ASW" stands for air saturated water. Values of air and air saturated water (ASW) after Kipfer et al. (2002). Literature data from Chiodini et al. (1998), Shimizu et al. (2005), Kyriakopoulos (2010), Carey et al. (2013), Tassi et al. (2013), Rizzo et al. (2016, 2019), Daskalopoulou et al. (2018a,b, 2019b, 2021a), and Tarchini et al. (2019).

found few meters from the coast in < 2 m depth, where the sea bottom is mostly covered by boulders and pebbles. Both sites are characterized by low temperatures and medium to low gas fluxes.

Gyali Island

Gyali Island is located between the Islands of Kos and Nisyros (**Figure 1**). The small island is uninhabited except by workers for the extraction of pumice and occasional tourists visiting the picturesque bays. It consists of a thick rhyolitic pumice succession to the south (Gyali pumice breccia and overlying units) and rhyolitic lava to the north. These two formations are separated by an isthmus, which is found in the center of the island. According to Allen and McPhie (2000), the pumice breccia of Gyali is the result of a submarine phreatomagmatic eruption.

Three submarine vents have been recognized in the island (**Figure 4C**), in the area where the fault zones are located (Daskalopoulou et al., 2021a). The gas manifestations are rich in CO_2, with H_2S being found in minor content (**Supplementary Table 1**). Intense degassing activity is observed in both Gyali West and Gyali South, where the emissions are widespread at some tens of meters from the shore. In both areas the sea bottom is sandy, but while the former is at about 10 m depth the latter is shallower (1–3 m depth). The third site is less active in terms of degassing and is found very close to the shore. The bubbles rise at shallow depth (about 1 m) between large boulders.

GEOCHEMISTRY OF SUBMARINE GAS VENTS

In the current study, a total of 122 data from submarine gas manifestations are presented. This dataset comprises both literature (Chiodini et al., 1998; Shimizu et al., 2005; Kyriakopoulos, 2010; Carey et al., 2013; Tassi et al., 2013; Rizzo et al., 2016, 2019; Daskalopoulou et al., 2018a,b, 2019b, 2021a; Tarchini et al., 2019) and 7 unpublished results from submarine degassing areas distributed in ten areas of the Aegean Sea; seven of which belong to the SAAVA. Gases were collected using the inverted funnel method (**Figure 5**). Sample IDs, coordinates, references, gas flux estimations and their chemical and isotopic content are found in **Supplementary Table 1**. pH and temperature data of seawater affected by the submarine degassing are also presented in **Supplementary Table 2**. Details on the sampling techniques and the laboratory methods used are found in Methods section in **Supplementary Data Sheet 1**.

No samples plot close to the atmospheric point (Kipfer et al., 2002) in the CO_2-N_2-O_2 ternary diagram (air in **Figure 6A**), thus excluding important air contaminations. The vast majority of the samples present N_2/O_2 ratios higher than the ratios of air saturated waters (ASW; Kipfer et al., 2002), suggesting that the atmospheric component deriving from meteoric recharge has been modified by microbial or inorganic redox reactions that took place in the subterranean circuit. In their majority, gases are rich in CO_2, while few samples have N_2 or CH_4 as the prevailing gas species (**Figure 6B**). Geographically, gases rich in N_2 (Santorini, Nisyros, Kos, Methana) are distributed in the

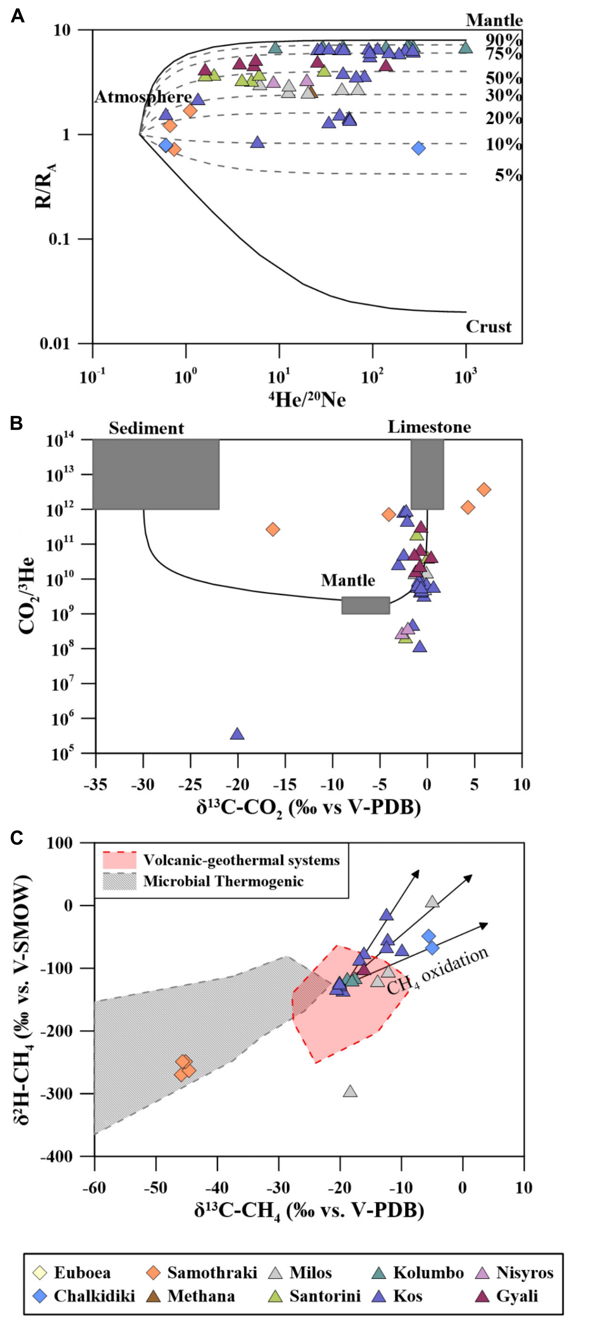

FIGURE 7 | Binary plot of **(A)** R/R_A vs. $^4He/^{20}Ne$ of the Hellenic gas emissions. The mixing lines between Atmosphere and Mantle and between Atmosphere and Crust are also plotted. Dashed lines represent mixing between atmosphere and end-members with different percentages of mantle contribution (after Sano and Wakita, 1985); **(B)** $CO_2/^3He$ vs. $\delta^{13}C$-CO_2. The composition for Sediments, MORB-like Mantle and Limestones end-members are, as follows: $\delta^{13}C$-CO_2 = −30‰, −5‰ and 0‰ and $CO_2/^3He = 1 \times 10^{13}$, 2×10^9 and 1×10^{13}, respectively (after Sano and Marty, 1995); and **(C)** modified Schoell binary diagram (Etiope and Schoell, 2014) between δ^2H-CH_4 and $\delta^{13}C$-CH_4 ratios for the Aegean submarine gas discharges. Slopes of biogenic and abiogenic oxidation of CH_4 are also plotted. Literature data from Chiodini et al. (1998), Shimizu et al. (2005), Kyriakopoulos (2010), Carey et al. (2013), Tassi et al. (2013), Rizzo et al. (2016, 2019), Daskalopoulou et al. (2018a,b, 2019b, 2021a), and Tarchini et al. (2019).

SAAVA and just after SAAVA to the north (Euboea), while CH_4 prevails in the gas vents of north eastern Aegean Sea (Samothraki) (Daskalopoulou et al., 2018a, 2019a). **Figures 6A,B** show the occurrence of dissolution processes, with the latter being likely responsible for the CO_2 loss and the enrichment of the less soluble gases (CH_4, O_2, and N_2).

An important atmospheric contribution for He is noticed for the gases of Samothraki Island as they plot close to the atmospheric point (**Figure 7A**, after Sano and Wakita, 1985). As expected, the vents located at the SAAVA present an enhanced MORB-type mantle contribution arriving up to ~90% (Kolumbo), while the gases of non-volcanic areas show a more crustal origin for He (up to ~95%). **Figure 7B** (Sano and Marty, 1995) reveals a mixed mantle-limestone origin for C for the great majority of the gases. The contribution of the organic sediment is relatively negligible. Some gases present $CO_2/^3He$ ratios that fall below the Mantle field, indicating CO_2 loss. This is likely due to the dissolution of CO_2 in water or to the precipitation of carbonates (Kanellopoulos, 2012; Winkel et al., 2013; Stefánsson et al., 2016, 2017; Kanellopoulos et al., 2017). A change in the flow as observed from Daskalopoulou et al. (2019b) for the sample of Kos presenting a strong decrease in $\delta^{13}C\text{-}CO_2$ may have also contributed to the dissolution processes. Methane for most submarine gases plots in the field ascribed to abiogenic hydrocarbons emitted from volcanic-geothermal systems (**Figure 7C**, after Etiope and Schoell, 2014). Contribution from biogenic sources cannot be excluded due to the wide range (from ~4 to 244) of $CH_4/(C_2H_6+C_3H_8)$ ratios (Bernard et al., 1978). Some gases exhibit high $\delta^{13}C\text{-}CH_4$ and $\delta^2H\text{-}CH_4$ values. This points to either organic or inorganic CH_4 oxidation processes. It is worth mentioning that isotope fractionation for organic and inorganic processes follow different fractionation paths (details in Daskalopoulou et al., 2018a, 2019b). Low $\delta^2H\text{-}CH_4$ values of Milos can be explained by non-equilibrium fractionation of CH_4-H with either H_2O or H_2 (Botz et al., 1996). Biogenic origin is attributed to CH_4 for the area of Samothraki. In particular, low $\delta^{13}C\text{-}CH_4$ and $\delta^2H\text{-}CH_4$ values as well as intermediate $CH_4/(C_2H_6+C_3H_8)$ ratio indicate mixing between thermogenic and microbially-derived gases. The latter has been attributed to CO_2-reduction by Daskalopoulou et al. (2018a) on the basis of carbon isotope fractionation factor between coexisting CO_2 and CH_4 (Whiticar et al., 1986).

The CO_2 loss is more evident in the binary plots of **Figure 8**. The positive correlation between He and N_2 indicates the impact of the CO_2 dissolution on the gases (**Figure 8A**). He and N_2, as well as CH_4 (**Figure 8B**), are less soluble respect to CO_2, hence the strong solubility difference between the gases in the marine environment may has resulted in CO_2 loss (Reid et al., 1987). In fact, D'Alessandro et al. (2014) showed that when a gas mixture ascends through non-saturated waters, solubility contrasts might enrich the less soluble gases. This is specifically applicable in reduced gas upflow conditions (Daskalopoulou et al., 2021b).

Figure 9 further evidences the impact of solubility-related processes on gas composition. The elevated CO_2/H_2S ratios of the gases in Kos, Gyali and Santorini demonstrate the interaction between magmatic gases and hydrothermal systems (**Supplementary Table 1**). This process, known as magmatic scrubbing (Symonds et al., 2001), occurs when ascending gases encounter any aquifer interposed between the source magma stored at depth and the surface (Di Napoli et al., 2016). The more water-soluble gas species dissolve due to the gas-water-rock interactions, thus modifying the composition of the primary magmatic gas phase. In their great majority, gases collected along SAAVA are poor in CH_4. This scarcity evidences the lack of underlying organic-rich source rocks in these areas. Few gases of Milos, Kos and Santorini are virtually enriched in CH_4 due to loss of CO_2 by dissolution as evidenced also in **Figure 8B**. Finally, some gases of Chalkidiki, Milos, and Euboea plot close to the atmospheric point, further demonstrating the CO_2 loss due

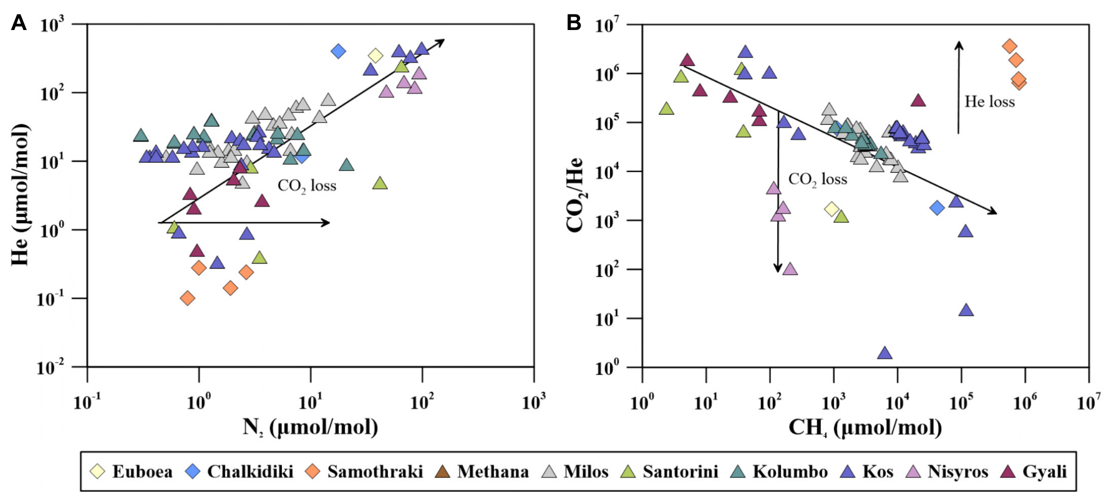

FIGURE 8 | Binary plot of **(A)** He-N_2 and **(B)** CO_2/He-CH_4. Processes impacting the gases are drawn with an arrow. Literature data from Chiodini et al. (1998), Shimizu et al. (2005), Kyriakopoulos (2010), Carey et al. (2013), Tassi et al. (2013), Rizzo et al. (2016, 2019), Daskalopoulou et al. (2018a,b, 2019b, 2021a), and Tarchini et al. (2019).

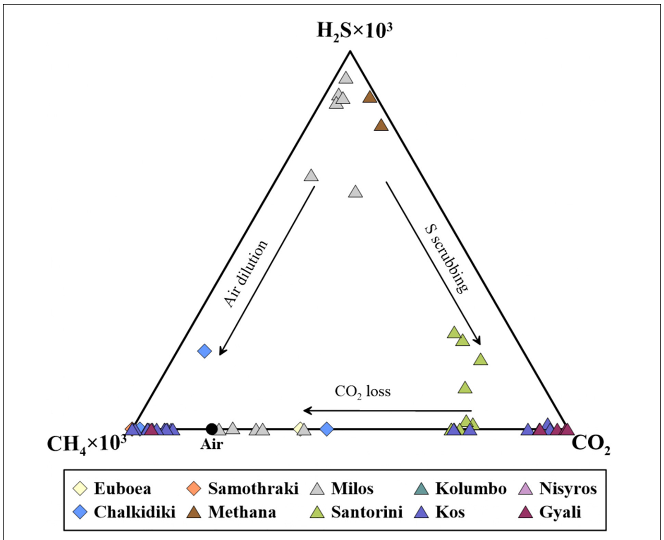

FIGURE 9 | Ternary plot of CO_2-H_2S-CH_4. Processes impacting the gases are drawn with arrows. Values of air after Kipfer et al. (2002). Literature data from Chiodini et al. (1998), Shimizu et al. (2005), Kyriakopoulos (2010), Carey et al. (2013), Tassi et al. (2013), Rizzo et al. (2016, 2019), Daskalopoulou et al. (2018a,b, 2019b, 2021a), and Tarchini et al. (2019).

to dissolution processes, but also indicating some contribution of the atmospheric component.

In order to further demonstrate the impact of water-gas interactions on the gas content, two samples for each site were collected at the degassing centers of Agia Paraskevi (Chalkidiki) and Agia Irini 2 (Kos). One of the two samples was taken in the usual manner from the emission site at sea bottom (for details see "Material and Methods" section in **Supplementary Data Sheet 1**), while the second at the sea surface after the gas bubbles have risen through the entire water column. Results evidence that sea bottom samples have CO_2 as the major component. In one case they show the presence of some H_2S. The superficial samples have much lower CO_2 concentrations, H_2S always below the detection limit, and become enriched in N_2, O_2, He, and CH_4 (**Figure 10** and **Supplementary Table 1**). These, sometimes very strong changes, can be explained by two processes that drive the gas exchanges between the rising bubbles and the seawater: mixing between two end-members and fractionation due to different solubility. The first process accounts for the virtual enrichment of the less soluble gases of hydrothermal origin (He and CH_4) with respect to CO_2 (**Figure 10A**). The second process is responsible for the decrease of CO_2 and H_2S (hydrothermal end-member) and the increase in O_2 and N_2 (Air-saturated seawater end-member) (**Figure 10B**). The extent of the changes suffered by the ascending gases depends on many conditions, which are mainly temperature, area of the interaction surface and interaction time (i.e. distance to be covered from the sea bottom to the surface). In the case of dry gases (no water vapor) the temperature is generally that of seawater because even if the emitted gases are hot they rapidly equilibrate with the seawater temperature due to the water/gas mass ratio and the thermal inertia of water. Both the interaction surface area and interaction time strongly depend on gas flux, bubble dimension, and depth of the water column. Higher gas fluxes, greater bubble dimensions, and lower emission depths all reduce gas exchange between bubbles and water, limiting the changes in gas composition. In the case of the above mentioned sites, the high gas flux and shallow depth of Agia Paraskevi prevents strong compositional changes like those registered in the site of Agia Irini 2. For example, while in the first case 78% of the initial CO_2 content arrives at the sea surface in the second case less than 1% does (**Supplementary Table 1**).

Changes on water characteristics were documented for the areas of Kanavas and Paleochori (Milos), Therma (Kos), and Ilion (Euboea) (**Figures 11A–D**). These areas comprise widespread degassing vents that are characterized by elevated CO_2 contents (>90%) and presence of H_2S

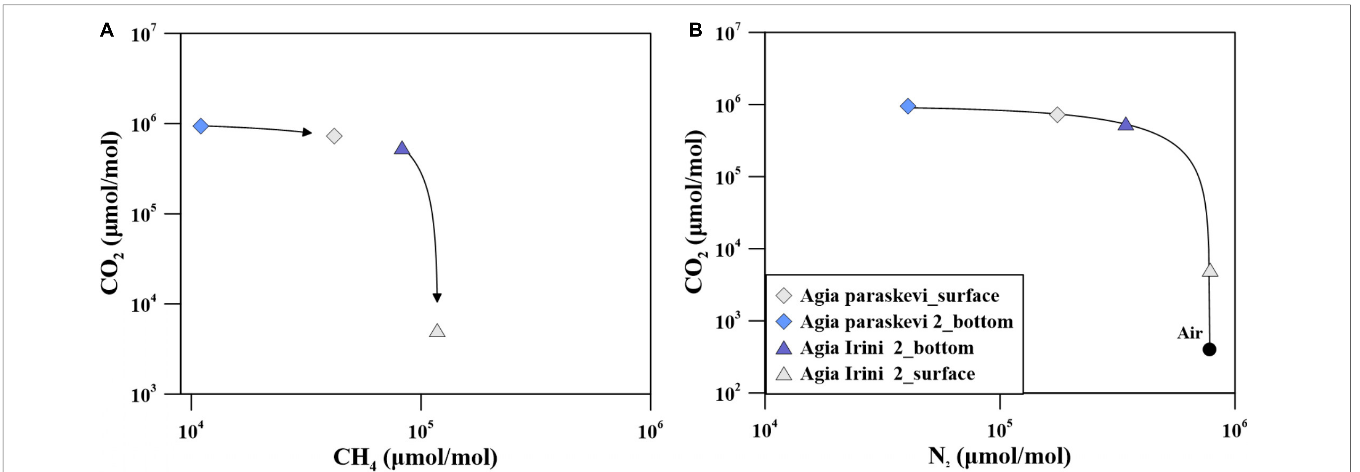

FIGURE 10 | Binary plot of **(A)** CO_2-CH_4 and **(B)** $CO_2 - -N_2$. Lines in **(A)** indicate the course toward less soluble gas species, while the line in **(B)** indicates mixing from the deeper to the shallower gas sample and then to the atmospheric end member. Values of air after Kipfer et al. (2002).

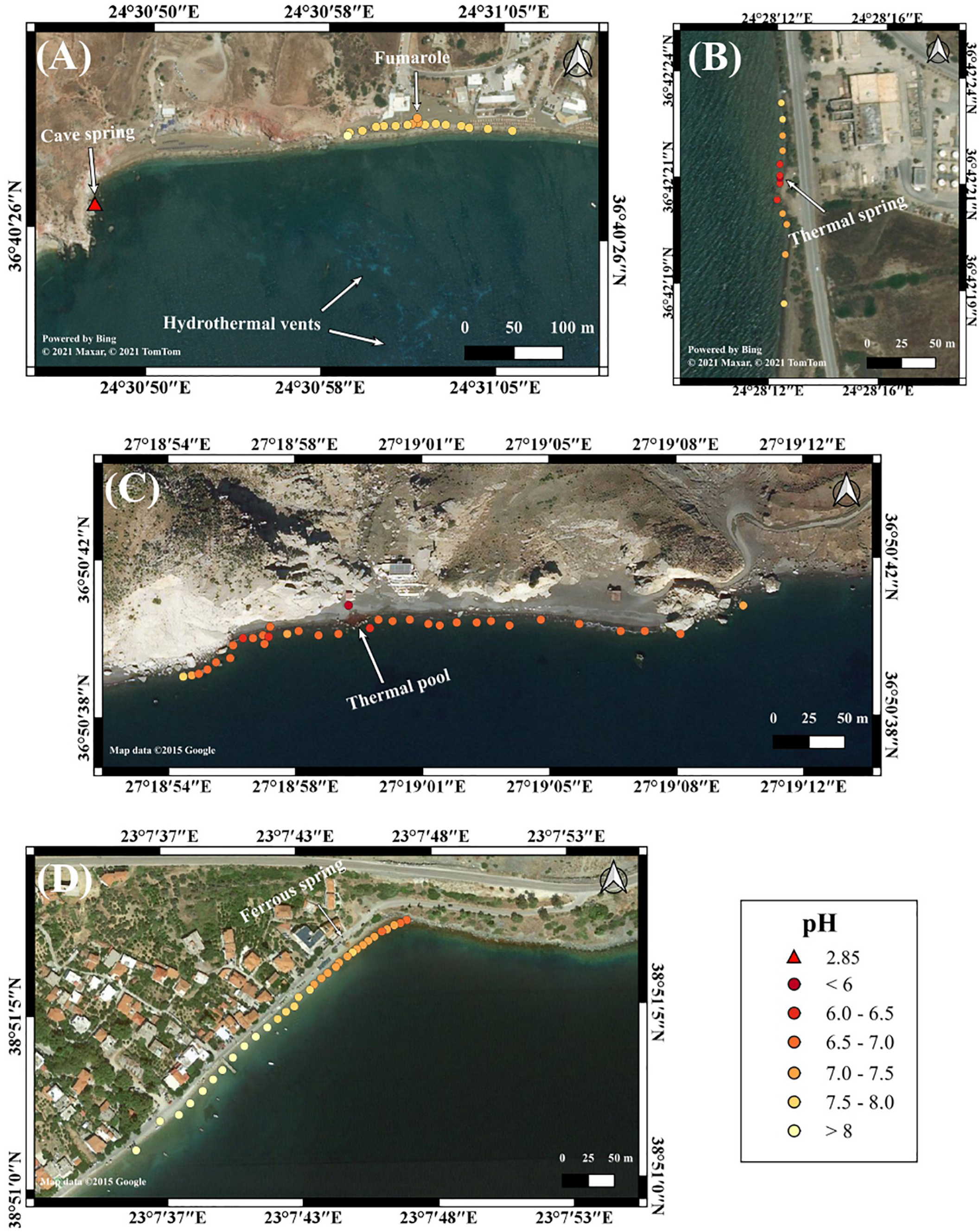

FIGURE 11 | pH transects for the areas of **(A)** Paleochori and **(B)** Kanavas at Milos, **(C)** Therma at Kos, and **(D)** Ilion at Euboea. Points of particular interest are marked with an arrow. The morphology of the seashore at Paleochori **(A)** was diverse when the measurements took place.

(**Supplementary Table 1**). pH transects that were performed along the coast revealed pH values lower than the value of average seawater (**Supplementary Table 2**). Such lowering of the pH is driven by the dissolution of CO_2 in seawater.

Daskalopoulou et al. (2018b) identified areas (on-land and in the sea) of intense degassing and anomalous CO_2 flux at both Kanavas and Paleochori that correspond to the sites where the lowest pH values are found (**Figures 11A,B**). These areas are connected to the main fault structures recognized in the island (Stewart and McPhie, 2006) that have likely taken part in the volcanic activity of Milos, acting as pathways for the ascending magma (Kokkalas and Aydin, 2013) and the uprising gases (Dando et al., 1995; Daskalopoulou et al., 2018b). Especially for Paleochori Bay, Aliani et al. (2004) and Khimasia et al. (2021) mapped minor fault structures in the bay with the latter using microbial mats and high temperatures (Khimasia et al., 2020) for

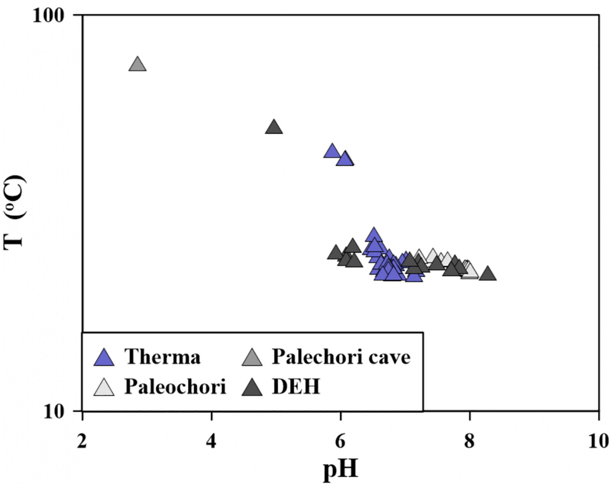

FIGURE 12 | Binary plot of pH-T for the areas where the transects took place.

fault identification. It is worth mentioning that the temperature profiles by Khimasia et al. (2021) took place at hydrothermal vents within the bacterial mats (**Figure 11A**). Intense on land and submarine degassing is also identified in the island of Kos at Therma with the CO_2 upflow being completely addressed to the hydrothermal component (Daskalopoulou et al., 2019b). Megalovasilis (2020) suggested that the low pH values (**Figure 11C**) are the result of either fluid mixing with seawater in the substrate or water-gas interactions. It is important to note that the lowest pH values in Milos and Kos are found in emission points characterized by high temperatures (**Figure 12**). This, combined with the waters' enriched SO_4-Cl content (Li Vigni et al., 2021), evidences the impact of hydrothermal activity on the systems.

In the area of Ilion, the low pH values are concentrated in front and east of a thermal (>62°C; D'Alessandro et al., 2014; Li Vigni et al., 2021) spring at the road (**Figure 11D**). The spring, as well as many of the thermal water emissions in Euboea, is connected to one of the tectonic structures in the border with the Sperchios Basin-Evoikos Gulf graben. The spring water ascents from the deep and hot geothermal system of the area (Li Vigni et al., 2021), and according to D'Alessandro et al. (2014) is affected by the Quaternary volcanic system. The volcanic impact though is also evident at the eastern side of the coast, where the degassing is diffuse. There, rocks present a rusty color, which is indicative of the emission of iron-rich (probably thermal) groundwater in the area. It is worth mentioning that the mobility of Fe and other trace metals (e.g., Cd, As, Pb) is enhanced by reducing conditions (Tarasov et al., 2005). The main driver is the dissolution of reactive gases (e.g., CO_2, H_2S, H_2) that results in intense rock leaching (Aiuppa et al., 2000).

OVERVIEW

Submarine degassing may have an impact on marine environments through ocean acidification. Hence, there is a necessity to study and better understand the ocean and its components. The current work reviews all known submarine gas manifestations of the Aegean Sea and summarizes the geochemical processes taking place in the individual areas.

All in all, degassing occurs in both volcanic and non-volcanic areas and is associated with the complex tectonics of the individual systems. Carbon dioxide is the dominant gas species for most vents and is often related to volcanism, geothermal energy, and elevated heat flow (Fytikas and Kolios, 1979). On the other hand, sites where CH_4 is the dominant gas species are likely related to hydrocarbon reservoirs (Rigakis et al., 2001).

The isotope signatures of He for gases found in SAAVA yield an important mantle contribution, while a dominant crustal origin characterizes gases in non-volcanic areas. Carbon dioxide derives from mixed mantle-limestone sources for most samples and in cases exhibits unimportant contributions from organic sediment sources. Methane is attributed to abiogenic hydrocarbons discharged from volcanic-geothermal systems. Inorganic and organic CH_4 oxidation processes resulting in isotope fractionation have also been identified (Daskalopoulou et al., 2018a). Only at Samothraki, where it is the main gas species, CH_4 is of biogenic origin.

The impact of water-gas-rock interactions on the initial gas phase is evident as soluble gas species dissolve in the water. This results in their depletion and the consequent enrichment of less soluble gas species. This phenomenon was also noticeable while comparing the composition of the gases at the emission point on the seafloor and the sea surface after its rising through the entire sea column. In addition to gas content variations, pH transects were performed in 4 sites. These are characterized by volcanic/geothermal activity, have CO_2 as the dominant gas species, and presented lower pH respect to the average marine value.

Even though the impact of gases on marine flora and fauna was not investigated in the current study, it shouldn't be disregarded. Various researchers (e.g., Boatta et al., 2013; Price and Giovannelli, 2017; Aiuppa et al., 2021; Caramanna et al., 2021) have already highlighted that shallow marine vents can provide us with an accessible and economic way to investigate the effects of CO_2 on the whole marine ecosystems. In addition to this, parameters like the presence of light, wave action, tides, the input of meteoric water, salinity variations, etc., can significantly influence the geochemistry of the vents and the microbial diversity and distribution (Giovannelli and Price, 2018).

It is important to note that this is a preliminary catalog of shallow submarine vents found in the Aegean Sea. Springs found in tectonic structures on-land close to the coast (Li Vigni et al., 2021) characterized by strong degassing (Daskalopoulou et al., 2019a) and soil alterations (D'Alessandro et al., 2020) can be good indications of nearby submarine degassing underscoring that the catalog has still to be completed. Nevertheless, we aim that this study will initiate further research on the OA in Greece and in other countries. Following the identification of new emission sites and the quantification of gas flow, research should move towards a bio-, hydro-, and geochemical monitoring direction. As a next step, the anthropogenic input has to be taken into consideration. Understanding and defining the impact of both geogenic and anthropogenic processes affecting the various spheres in systems such as the Mediterranean, will result in the improvement of not only the carbon cycle knowledge but also of the dynamics and vulnerability of individual systems. This research and our group invite researchers from related disciplines to use multiple approaches and investigate other aspects of this problem. Hence, we make results accessible as electronic supplements and we aim to publish them as stand-alone datasets with their own doi.

AUTHOR CONTRIBUTIONS

SC and KD contributed to the conception and design of this study. ML, GP, and SC collected the samples by diving. ML contributed to the laboratory analyses. KD and WD'A wrote the first draft while all authors contributed to manuscript revision, read and approved the submitted version. All authors were involved in the sampling campaigns.

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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.2021.775247/full#supplementary-material

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Canada's Internet-Connected Ocean

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Over fifteen years ago, Ocean Networks Canada (ONC) began with the world's first large-scale, interactive, real-time portal into the ocean, bringing continuous, real-time data to the surface for applications in scientific research, societal benefits, and supporting Canada's ocean industry. This marked the dawn of the Internet-connected ocean, enabling a more fulsome understanding of the ocean through ocean intelligence. These open data have improved our ability to monitor and understand our changing ocean offshore all three coasts of Canada, thanks to diversity of sensor systems to monitor earthquakes and tsunamis, deep sea biodiversity, whales, hydrothermal vents, neutrinos, ocean noise, ocean acidification, forensics experiments, and the impact of climate change, including sea ice thinning in the Arctic. This pioneering approach began in the late 1990s, when scientists began developing a new way of doing ocean science that was no longer limited by weather and ship-time. They imagined a permanent presence in the ocean of sensors to allow a continuous flow of ocean data *via* the Internet. This big science began to take shape early this century, when a partnership between United States and Canadian institutions was established. ONC evolved out of this international collaboration with seed funding from the Canada Foundation for Innovation, while in the United States, the Ocean Observatories Initiative (OOI) was funded. ONC works closely with OOI on that span the countries' west coast border. Recently similar observing initiatives in Europe have begun, led by EMSO, which now has a close collaboration with ONC as an Associate Member.

Keywords: ocean observing, marine life, climate change, marine geoscience, marine hazards, ocean data

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INTRODUCTION

Ocean Networks Canada's infrastructure includes large telecommunication cabled networks (NEPTUNE and VENUS; **Figure 1**), community-based networks along all three of Canada's ocean coasts, mobile systems on ferries, and land-based sensors that support coastal radar, weather stations, ship traffic, earthquake early warning, and tagged marine bird detection.

The cabled observatories are a node-based networks that follow the topology of the Internet protocol and supplies the power and communication capabilities required for data capture and real-time control of sensors, cameras, samplers, electro-mechanical profilers, and a seafloor crawler. Nodes connect power and Internet to sensors *via* junction box platforms that include step-down transformers at voltages suited to the instruments either located on the platform or connected *via* extension cables to sensors on the seafloor, beneath the seafloor (in boreholes and caissons), and in the water column (**Figure 2**). All sensors are part of a network topology that abides by the hierarchical structure of TCP/IP based communication. Communications can be any medium, from copper cable, fiber optics, point-to-point WiFi, the cellular network, micro-wave relays or satellite.

Ocean Networks Canada now operates over 9,000 deep sea, coastal and land-based sensors on all three of Canada's coasts, 24/7/365. Every day, 280 gigabytes of data are added to a rich and diverse petabyte-scale archive, most openly available on ONC's Oceans 3.0 data portal. These FAIR (findable, accessible, interoperable, reusable) open data enable over 20,000 users around the world to build and make use of ocean intelligence. "Findable" means that data are available through the data portal, searchable by instrument type, location or device ID. "Accessible" is implemented through the data portal user interfaces and APIs, ONC's user engagement group assists users with accessing data. "Interoperable" means that data are available using multiple format types, including open source format types. To ensure "Reusable" ONC assigns a DOI to evolving data sets for reuse and citations.

ONC conducts regular maintenance at all sites for its high service level. Data from instruments are monitored daily. When issues with data delivery or quality arise, remote troubleshooting starts. If remote troubleshooting is unsuccessful, a data gap is flagged and the instrument is scheduled for maintenance. In critical locations, to minimize data gaps, autonomous instruments are deployed to supplement the compromised cabled instruments.

Ocean Networks Canada's data are now a decade or more in length and represent a globally unique resource. These high-resolution time series permit researchers to investigate the dynamics of ocean processes across time-scales from hours, days, and seasons, to inter-annual and decadal scales. Researchers are able to undertake critical process studies that require well-characterized ocean environments. The research highlights described here would not have been possible without the cabled technology because it provides enough power for the use of camera lights and robots, temporal resolutions that resolve high frequency processes, long and continuous time series for discovery of trends, and high resolution monitoring over a wide area range to capture processes, e.g., from the shelf to the deep sea.

RESEARCH HIGHLIGHTS

Ocean Networks Canada's strategic plan (2017–2021) identified four major science themes: understanding ocean life; human and climate change impacts; seafloor/ocean/atmosphere links, and seafloor in motion. Research was enabled that advanced each of these themes and increased with the longevity of the time series. Here, some of the highlights that delivered on these themes are described.

Understanding Ocean Life

Barkley Canyon

The role of oxygen minimum zones in submarine canyon ecosystems was revealed for the first time by Domke et al. (2017), while Doya et al. (2017) showcased seasonal monitoring of deep-sea benthic life in the Barkley submarine canyon using data from a seafloor crawler controlled over the Internet using ONC's data system, Oceans 3.0.

Campanyà-Llovet et al. (2017) investigate a range of sedimentary and near bottom water biogeochemical proxies in a depth gradient along Barkley Canyon, and discussed the potential sources (i.e., macroalgae, phytoplankton, zooplankton; resuspended sediments) and degradation states of organic matter reaching the seafloor, and their role in structuring the macrobenthic infaunal communities.

De Leo et al. (2018) published a 20-month long time-series of seafloor video imagery, acoustic Doppler backscatter, and current profiling, witnessing for the first time the exact onset of the seasonal and deep overwintering migration of *Neocalanus* spp. copepods. Their work used ground-truth zooplankton net cast data in the Barkley Canyon area, and proposed a conceptual model of vertical current profile structure in the canyon axis acting to focus the deep zooplankton biomass near the core of its overwintering depth (∼1,000 m).

Chauvet et al. (2019) utilized ∼2.5 years of Barkley Canyon Axis seafloor video and environmental data to describe the seasonal and inter-annual variability of tanner crab abundances. The research confirmed a hypothesis that juvenile tanner crabs perform ontogenetic migration from deep to shallow depths and offers insights about the timing of these events immediately following sea surface phytoplankton blooms occurring in spring and summer.

Seabrook et al. (2019), for the first time, described the biogeochemical links between bacterial methanotrophic production and fishery biomass. Triggered by intriguing video observations of tanner crabs "farming" on methane bubbles at Clayoquot methane seep, adult tanner crabs were collected using ROV-deployed baited traps. Combined sulfur, carbon and nitrogen stable-isotope and RNA-based molecular analyses revealed that tanner crabs partially derive their nutrition from methanotrophic bacteria—an unprecedented link between a geochemical energy and a nutrition source for human consumption.

Coastal Sites

Gasbarro et al. (2019) discovered an anomalously severe hypoxic event in Saanich inlet, after a decade of oxygen decline at a rate of 0.07 mL L^{-1} y^{-1}. They used >10 years of Saanich time-series of dissolved oxygen data coupled with ROV video surveys from 2013 and 2016. Benthic megafauna was reported to follow a 56% overall decline in abundance during the extreme hypoxia events. The results also forecasted potential future scenarios under further and continuous oxygen loss in the Saanich fjor.

Leys et al. (2019) analyzed video imagery from Folger Pinnacle and showed a range of in-situ behaviors of a demosponge sponge *Suberites concinnus*, such as "twitches," "ripples," and "cringes." This last behavior is clearly associated with sudden changes in pressure caused by severe storms. A massive storm-driven pressure anomaly in 2013 preceded several contractions of the

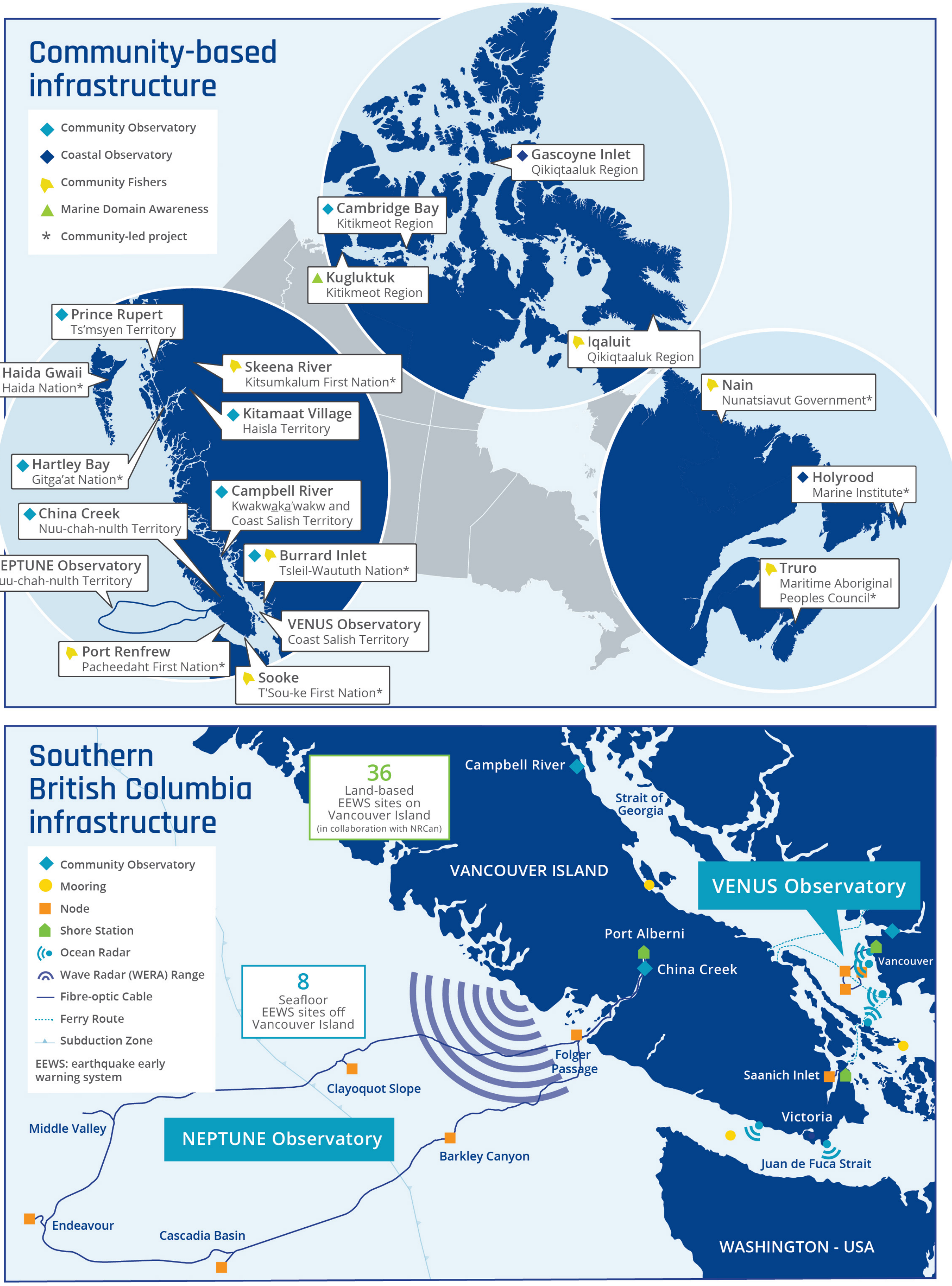

FIGURE 1 | ONC's infrastructure located on all three coasts.

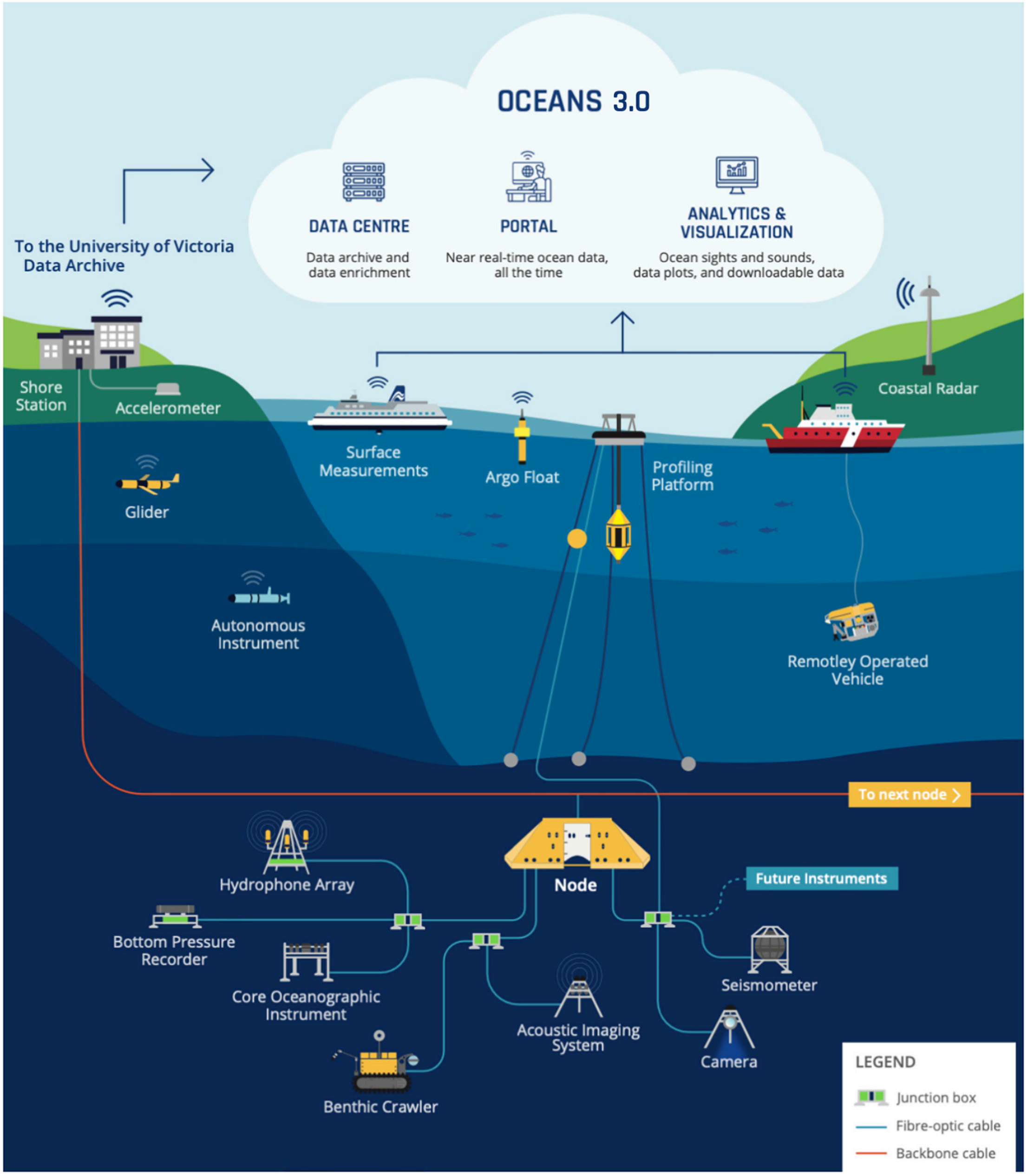

FIGURE 2 | Schematic diagram depicting a node connected to the backbone cable and extension cables connected to platforms and sensors.

sponge. These behavior changes due to environmental triggers set the stage for further research.

Human and Climate Change Impacts

Thomsen et al. (2017) demonstrated that carbon transfers to the deep ocean are surprisingly significant in winter months. Fjord research by Pawlowicz (2017) revealed the seasonally cyclic nature of low oxygen waters. Soontiens and Allen (2017) used ONC data to model constraints on ocean water mixing in fjords. Physical oceanographers determined that coastal currents can block the release of low-oxygen waters from fjords (Thomson et al., 2017). Ritts (2017) reported on the relationship between human-induced ocean noise and politics.

There is broad consensus that one of the oceanic consequences of climate change is an expansion and shallowing of low-oxygen zones and critical marine habitats (Breitburg et al., 2018). The work of Krogh et al. (2018) utilized time series to quantify the impacts of local sewage discharge on oxygen levels in the Salish Sea. Chu et al. (2018) used 14 months of video and oceanographic data from Saanich Inlet to describe the variability and environmental controls of benthic beta diversity. The data were used to demonstrate how sessile and mobile species respond and recover differently from seasonal hypoxia. Observations and time series from ONC's Cambridge Bay observatory are contributing (Hu et al., 2018) to assessments of Arctic amplification and changing sea-ice thermodynamics.

A study of CO_2 sequestration in the oceanic crust in the Cascadia Basin (Goldberg et al., 2018) was conducted. This included laboratory and modeling studies, potential source/transport scenarios including a carbon-negative scheme, and also economic, regulatory and project management risks analyses.

MacGillivray et al. (2019) reported on wide-scale co-operation among commercial vessel operators, Port Metro Vancouver, JASCO Applied Sciences, and ONC showed that slowing down deep sea vessels transiting through the Salish Sea reduces their underwater radiated noise. The results from this research are informing government decisions aimed at improving the habitat quality of the endangered southern resident killer whale population.

Seafloor, Ocean, and Atmospheric Links

In an astonishing study, Lelièvre et al. (2017) showed that tides and storms impacted deep-sea hydrothermal vent animals. In these same settings, Coogan et al. (2017) revealed insights about near-vent chemical processes in plume while Jackson et al. (2017) described diffuse hydrothermal flow using sound. Love et al. (2017) showed that there were variations in fluid chemistry that constrained hydrothermal vent phase separation. In 2017, Xu published three studies with co-authors that show the impact of tides on hydrothermal vents, further advancing the quantification of hydrothermal venting, and advanced the techniques in using acoustic imaging to study venting (Xu et al., 2017a,b,c). For cold methane seeps, Seabrook et al. (2018) reported on the large variation in the communities of flora and fauna they host.

Research spanning the entire water column, from beneath the sediment interface to the atmosphere, are contributing to a wide range of interdisciplinary results. Li et al. (2018) extensively used the coastal observatory data (ADCP, Echo-sounder, and CODAR) to assess the role of nonlinear internal waves in the Strait of Georgia. Wang et al. (2019) took advantage of in situ measurements of dissolved oxygen concentration from ONC sensors mounted aboard a ferry transiting the Strait of Georgia to estimate primary production and respiration rates. These are high resolution rate estimates which are otherwise difficult to resolve at scales necessary to understand biophysical regulation of atmosphere-ocean interactions and productivity at the base of the marine food web.

One of the most comprehensive studies to date of seafloor gas venting was carried out by Riedel et al. (2018) who estimated that about 1 gram of methane per square meter of seafloor—which totals about 100,000 tons of methane—is released along the Cascadia Margin off BC, Washington, and Oregon each year. They used all of ONC's water column sonar data from both single- and multi-beam systems and integrated the seafloor multi-beam sonar at Clayoquot Slope that continuously scans for bubbles escaping the seafloor. Furthermore, they used all of the publicly available ship-based data from the NOAA and OOI archives as well as a large non-published data set from Natural Resources Canada. This resulted in the first margin wide quantification of natural gas escaping the seafloor.

Zhang et al. (2019) used video footage of fluids escaping the Grotto vent at Endeavor ridge to study short-period variations in vertical fluxes of hydrothermal plumes. Quantitative analysis of digital video images of plumes using the particle image velocimetry method allowed the comparison of vents from mid-ocean ridges around the globe. Davis and Villinger (2019) used high resolution temperature data measured 1 m below the seafloor to study thermal properties of the sediments. They found that temperature variations are not only due to changes in bottom water temperature, but also observed adiabatic temperature changes due to tidal loading. The unique data set was acquired using a new instrument that was mainly developed to monitor acceleration, tilt, and pressure at the ocean floor.

Wang et al. (2019) analyzed ONC British Columbia Ferries time series of surface ocean measurements during transits across the Salish Sea. The analyses combines dissolved oxygen measurements with physical parameters to determine the relative role of physical transport, air-sea diffusion, and biological productivity for interpreting observed changes in the dissolved oxygen concentrations in near surface waters. The results of this work demonstrate the usefulness of the dataset for quantifying biological productivity at a daily timescale and the importance of measuring diurnal changes in dissolved oxygen for assessing the Net Ecosystem Productivity of the ecosystem—a key indicator for ecological assessment and environmental change.

Duke (2019) presented a study of the marine carbon cycle that utilizes the high resolution time series of biogeochemical properties to better understand the factors that affect inorganic carbon species distribution, seasonal dynamics in biological productivity, and ocean acidification in the Arctic. Both pH and pCO_2 were measured by in situ sensors on the regional community observatory operated by ONC. These results significantly contribute to the assessment of these sensors for operating in Arctic cold waters and for addressing seasonal changes in under-ice plankton productivity.

Seafloor in Motion

Gao et al. (2017) researched the thermal conditions on a segment of the Juan de Fuca Ridge that has implications for seismic and tsunami hazards. Rathnayaka and Gao (2017) presented the broad scale seismic structure of the Cascadia subduction zone. Davis et al. (2017) made a major discovery, using seismometer data—seafloor tilt is induced by ocean tides. A new real-time tsunami detection algorithm was developed and reported on by Chierici et al. (2017), while Grilli et al. (2017) used a tsunami algorithm for validation purposes. Tolkova et al. (2017) presented a new approach for rapid forecasting of tsunamis.

McGuire et al. (2018) studied the effect of dynamic stress transients on borehole seismic-geodetic observations at Clayoquot Slope. They found that the Alaska Earthquake did not trigger slow slip and tremor on the updip portion of the Cascadia megathrust. This is a significant since other subduction zones such as Hikurangi and Nankai are known to produce slow-slip events under similar circumstances. Lay et al. (2018) studied the complex rupture of the 2018 Mw 7.9 Gulf of Alaska Earthquake. Gao et al. (2018) investigated rupture scenarios of the Cascadia megathrust and their effect on tsunami generation. Gao (2018) examined the effect of along-strike and downdip variations in physical properties of the oceanic plate on seismicity of the Cascadia subduction zone. Rohr et al. (2018) used the Nootka fault zone as a case study to explore mechanisms for strike-slip fault initiation. Williamson and Newman (2018) assessed the suitability for a near-field tsunami early warning using open-ocean instrumentation.

Lintern D.G. et al. (2019) described ONC infrastructure from the Fraser Delta and ONC hydrophone records from turbidity currents, and emphasized the need for in-situ real-time observations for these types of hazards. Lintern G. et al. (2019) described ONC's Community Observatory in Kitimat Arm for its potential for live hazard warning system for underwater landslides and induced tsunamis.

The effectiveness of ocean observatories for gas hydrate research was published by Scherwath et al. (2019), with documentation of various studies that were realized with ONC data, and included spectacular three-dimensional images from the structural light imaging system, a laser camera, on the seafloor crawler Wally.

FORWARD TO 2030

Ocean Networks Canada recently completed its Strategic Plan 2030, titled "Advancing our Knowledge of the Ocean at a Critical Time." This ambitious plan sets out three major goals as well as strategies for delivering ocean intelligence for science, society, and industry.

Advance ocean observing. Ocean observation is a critical foundation for understanding our changing ocean and climate and the ocean's key role in buffering and moderating the Earth's climate. ONC's deep-sea, coastal, and land-based infrastructure provides real-time, long-duration, high-quality data of high spatial and time resolution. ONC plans to advance ocean observing by continuing and expanding the community-based ocean observing and international partnerships; equitably increasing workforce capacity; filling gaps in Canada's ocean observing networks to address high-priority national, provincial, and regional needs; and evolve the observing networks and data access. At the same time, ONC will build on existing time-series data; and enhance ocean knowledge sharing through learning, education, media communications, storytelling, and the arts.

Ocean Networks Canada's approach to ocean observing is a commitment to ensure that no data are stranded, measuring at the highest temporal resolution possible, and deliver data in real-time or near real-time. Unlike autonomous systems that mainly rely on preserving battery power, which limits temporal resolution, the ONC approach provides data at time resolutions from daily to seasonal to decadal. The advantage provided by ONC's NEPTUNE observatory is, for example, that dynamic changes associated with intermittent climate change impact events (e.g., heat extremes) can be studied in the detail needed to discern natural vs. climate-related variability. The real-time data can also be re-purposed to be used not only for science, but also for real-time valued added products needed for marine safety.

Develop and deliver ocean intelligence. Unlocking the immense potential of ocean intelligence requires increasingly innovative data interpretation tools to help us understand complex systems. ONC uses the International Council for Science World Data System as a world-leading standard. The global blue economy depends upon sustainable use of the ocean. Advanced data products are required to address and monitor the health of the ocean, inform safer shipping and ocean transportation, and provide vital ocean insights for communities. ONC plans to continue collaborations with local and Indigenous communities, public safety organizations, and governments to make ocean intelligence accessible to all stakeholders, from researchers, students, Indigenous partners, coastal communities and industry players, to policy-makers.

Ocean-based solutions for climate change mitigation and coastal resilience. As we face the growing impacts of climate change, coastal communities are disproportionately threatened by sea-level rise, storm surge, ocean warming and acidification, and declining seafood stocks. ONC will work with partners to enable solutions for coastal resilience and make major contributions to advance a sustainable ocean economy through the development of climate change mitigation and adaptation technologies that include carbon dioxide removal, forecasting coastal sea level rise and storm surges, monitoring ocean acidification in the vicinity of vulnerable ocean industries like shellfish farms, and transferring observing technologies to Indigenous coastal communities so that they expand upon their knowledge systems to grow their stewardship efforts.

AUTHOR CONTRIBUTIONS

All authors listed have made a substantial, direct, and intellectual contribution to the work, and approved it for publication.

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The Oceans 2.0/3.0 Data Management and Archival System

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The advent of large-scale cabled ocean observatories brought about the need to handle large amounts of ocean-based data, continuously recorded at a high sampling rate over many years and made accessible in near-real time to the ocean science community and the public. Ocean Networks Canada (ONC) commenced installing and operating two regional cabled observatories on Canada's Pacific Coast, VENUS inshore and NEPTUNE offshore in the 2000s, and later expanded to include observatories in the Atlantic and Arctic in the 2010s. The first data streams from the cabled instrument nodes started flowing in February 2006. This paper describes *Oceans 2.0* and *Oceans 3.0,* the comprehensive Data Management and Archival System that ONC developed to capture all data and associated metadata into an ever-expanding dynamic database. Oceans 2.0 was the name for this software system from 2006–2021; in 2022, ONC revised this name to Oceans 3.0, reflecting the system's many new and planned capabilities aligning with Web 3.0 concepts. Oceans 3.0 comprises both tools to manage the data acquisition and archival of all instrumental assets managed by ONC as well as end-user tools to discover, process, visualize and download the data. Oceans 3.0 rests upon ten foundational pillars: (1) A robust and stable system architecture to serve as the backbone within a context of constant technological progress and evolving needs of the operators and end users; (2) a data acquisition and archival framework for infrastructure management and data recording, including instrument drivers and parsers to capture all data and observatory actions, alongside task management options and support for data versioning; (3) a metadata system tracking all the details necessary to archive Findable, Accessible, Interoperable and Reproducible (FAIR) data from all scientific and non-scientific sensors; (4) a data Quality Assurance and Quality Control lifecycle with a consistent workflow and automated testing to detect instrument, data and network issues; (5) a data product pipeline ensuring the data are served in a wide variety of standard formats; (6) data discovery and access tools, both generalized and use-specific, allowing users to find and access data of interest; (7) an Application Programming Interface that enables scripted data discovery and access; (8) capabilities for customized and interactive data handling such as annotating videos or ingesting individual campaign-based data sets; (9) a system for generating persistent data identifiers and data citations, which supports interoperability with external data repositories; (10) capabilities to automatically detect and react to emergent events such

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as earthquakes. With a growing database and advancing technological capabilities, Oceans 3.0 is evolving toward a future in which the old paradigm of downloading packaged data files transitions to the new paradigm of cloud-based environments for data discovery, processing, analysis, and exchange.

Keywords: data management, data archival, quality assurance and quality control, data processing and analysis, metadata, persistent identifiers, data citation, data products

INTRODUCTION

About Ocean Networks Canada

Ocean Networks Canada (ONC), a University of Victoria initiative, operates world-class cabled ocean observatories in the northeast Pacific, Arctic and Atlantic Ocean basins for the advancement of science and the benefit of Canada. With an operational design life of more than 25 years, the Ocean Networks Canada infrastructure collects and provides essential data required to address pressing scientific and policy issues. The innovative cabled infrastructure supplies continuous power and Internet connectivity to a broad suite of subsea instruments from coastal to deep-ocean environments. These observatories are supplemented by sensors installed on ferries, autonomous gliders and moorings, coastal radars, and other instrument technologies. Data acquired through these systems are provided freely and in near real time, from thousands of instruments distributed across some of the most diverse ocean environments found anywhere on Earth.

As one of the original Major Science Initiatives (MSI) funded by the Canadian Foundation of Innovation (CFI), Ocean Networks Canada is a national research facility hosted and owned by the University of Victoria. The total investments to build and operate the ocean observatories exceed $350M to date.

Ocean Networks Canada is among the vanguard of organizations advancing *ocean intelligence*, as the data, data products, and services from ONC physical and digital infrastructure support research by a growing cohort of scientists across diverse sectors and disciplines (see **Supplementary Figure 43**), inform policy decisions, provide a platform for Canadian industry to test and develop instruments and respond to events, and transform ocean technology and infrastructure into new knowledge that positions Canada at the forefront of the field.

Purpose of This Paper

This paper serves several purposes. First, an end-to-end description of data acquisition, processing, storage and product generation systems is provided to help scientific users better understand how ONC manages and serves data. This knowledge will help the researcher gain confidence in reliability and reproducibility of ONC data, while supporting needs to describe data provenance for scientific applications. The goal is to provide a citable reference for the ocean scientist.

Secondly, this paper is intended as a general reference for the overall Oceans 2.0/3.0 software framework, which will be of interest to those working in the areas of scientific data management systems and oceanographic data repositories. This paper does not delve deeply into the specifics of code, but rather provides a broad overview of the many platforms and capabilities comprising Oceans 2.0/3.0.

Motivations for a Data Management System

Decades of experience with expensive scientific observatories (both space-based, e.g., the Hubble Space Telescope, and terrestrial, e.g., large seismic arrays in several countries) have demonstrated the value of maintaining well-curated data archives. An observing system that costs on the order of 10^8 to 10^{10} dollars to design, implement and operate for any number of years must ensure its legacy – typically the data it collects – remains available for the longest possible time; doing so enables verification and reproducibility of results, and can often lead to new, unexpected discoveries. The long-term scientific productivity of projects like the Voyager probes (still producing data 44 years after they were launched) and Hubble (18,000+ scientific papers with 900,000+ citations) is attributable in no small part to the efforts made from the early design phase to include an associated data management and archiving system (Pirenne et al., 1993).

The large, real-time, high time-resolution ocean observatories pioneered by Ocean Networks Canada's VENUS and NEPTUNE initiatives have similar long-term requirements for data management. From the early days, it became quickly apparent to the promoters of these initiatives that they could not be justified from either a science perspective (need for observations spanning decades) or a financial responsibility perspective (investment well into the $\$10^8$ range) without a robust companion data management system.

Genesis of the System

With the need for a data management system clearly established in the early stages, the promoters of VENUS and NEPTUNE commissioned studies to assess needs, including the expected data types that the ocean observing systems would produce, together with design considerations and indications of an overall architecture. One such study was performed by the National Research Council's Canadian Astronomy Data Centre (CADC) in 2004. CADC had, at the time, over 15 years of experience in dealing with research data from a variety of astronomical telescopes, both spatial and terrestrial, and with their curation, processing and visualization.

Toward the end of 2004, with the first staff in place, a prototype Data Management and Archiving System (DMAS) was developed to demonstrate the data acquisition, registration of new data and their archival. Simple but representative instruments were connected to the system, as shown in **Figure 1**.

The structure defined and tested through the prototype led to the development of an architecture that satisfied the eight requirements (**Supplementary Table 1**) of the nascent ocean data management system and which remain key structural elements in place today.

Following the prototype, an interim DMAS was developed to support the first of the VENUS arrays in Saanich Inlet on Vancouver Island, which went operational in February 2006. The key elements (including *data center* and *shore station*) were maintained, as developers focused on implementing code to interface with the various instruments deployed. Initially the Sybase relational data management system was chosen as a metadata database. A file management system called *AD*, in use at the CADC and at the European Southern Observatory, was implemented to host the data records from each instrument, split into 24-h data segments.

The interim DMAS rapidly evolved into a full-fledged system to support the second VENUS array (2008) and the NEPTUNE sensor network in 2010. Today, the system continues to grow and adapt, supporting an ever-expanding array of instruments and data types, and the significant combination of data products that can be derived from them. The flexibility and extensibility of the system has enabled expansion to support multiple communication technologies, and to collect data from many different locations, including the harshest deep ocean and arctic environments. The system also supports an increasingly diverse array of applications including an earthquake early warning system and a planned neutrino observatory. In 2012, DMAS was renamed and became known as *Oceans 2.0*, reflecting *Web 2.0* concepts of user contribution and participation, as described by Murugesan (2007) (see section "User-Contributed Content").

Features

The features of Oceans 2.0 were implemented to address the key top level requirements identified in **Supplementary Table 1**. Ocean Networks Canada designed a system structure and topology (illustrated in **Figure 2**) that would be able to support any number of sensors, instruments, sites and networks, modeled on the tree structure used by Internet Protocol (IP) networks (Rose and McCloghrie, 1990).

In ensuing years, the efforts of the Oceans 2.0 team consisted primarily in implementing:

- support for additional instrument types;
- new data products, i.e., packaging of data into containers that satisfy international or industry standards;
- improvements of visualization methods for the various data types (from time-series plots to hydrophone spectra to combined views of environmental sensors data next to video streams);
- dedicated tools to help users not only view data but describe or annotate these data streams (SeaTube, Digital Fishers);
- dedicated applications to allow the automated contribution of field data measured by trained individuals anywhere around the world (Community Fishers);

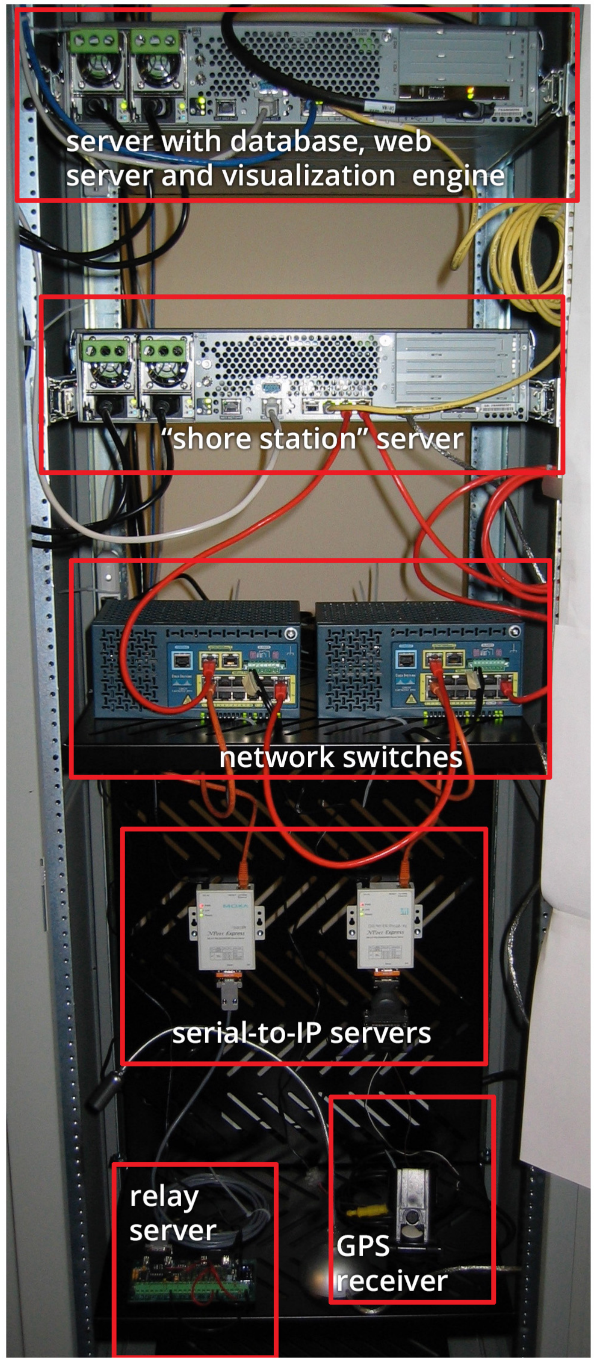

FIGURE 1 | View of Prototype DMAS, implemented in a single equipment rack. At top is the initial concept of the "data center," a server running the data repository, consisting of a database, web server and visualization software. Second from top is a server running the "shore station" with "drivers" that implement the communication protocols of each instrument, parsing and pre-processing. In the middle is network equipment that implements the tree topology of the infrastructure: switches representing connections within the network. Second from bottom are a pair of serial-to-IP terminal servers that interface to the "instruments" at the bottom of the image, in this example, including a relay server and a GPS receiver. This high-level architecture is still in place today, with multiple "shore stations" and hundreds of instruments supported.

- the ability to generate and associate Digital Object Identifiers to datasets, with tracking of their reprocessing history and versioning;
- an integrated observatory management system that includes full instrument preparation workflow, real-time monitoring and control of the infrastructure and full instrument metadata management, including the complete history of the instruments throughout their lifetime at ONC.

At the time of this writing, Oceans 3.0 supported:

- 9400 active sensors producing data;
- 930+ instruments producing data daily;
- 299 unique file-based data products;
- 8600 pre-generated plots produced daily;
- 2550 average daily data requests;
- 430 GB average volume of uncompressed data archived per day;
- 1.2 PB total uncompressed volume of archived data.

The rest of this review explores Oceans 2.0/3.0 features in depth.

ARCHITECTURE

Planning for Renewal

Ocean Networks Canada observatories are research infrastructures intended to last at least 25 years. This includes both the physical as well as the digital components. Given the pace of technology evolution, the design and operational plans must account for different time scales/lifetimes of various components so that they can be replaced as needed to retain currency with the state of the art, while providing continuity of service. Typical operational lifetimes for various technology elements are listed in **Supplementary Table 2**; these correspond to replacement cycles anticipated in the ongoing maintenance and renewal of the ONC's research infrastructures.

At its core, Oceans 3.0, the digital component of the Ocean Networks Canada research infrastructure, is a comprehensive management system for sensor networks. As a centrally managed infrastructure, its overall structure is hierarchical and tree-like, modeled after the Internet Protocol (IP) structure. As briefly presented in the introduction, it can be depicted in an entity-relationship diagram as illustrated by **Figure 3**.

Network

Ocean Networks Canada operates a collection of sensor networks, distributed across a vast geography, nearly extending from pole to pole, with systems in the Arctic as well as one being prepared for deployment in Antarctica as of this writing, and systems on both the Pacific and Atlantic coasts of Canada. The sensor networks and all the key elements of ONC data centers are integrated in a Class A private network (rooted at the non-routable IPv4 address 10.x.x.x). Interconnections between the distributed segments of the network are performed over virtual private networks (VPNs) that integrate a variety of Internet service provision methods ranging from cabled terrestrial, to wireless, and to satellite.

Ocean Networks Canada operates three data centers; the primary data center is located at the University of Victoria, in British Columbia, while secondary data centers (described in section "Business Continuity and Disaster Recovery") are housed in the interior region of British Columbia and Ontario. The backup data centers provide an important safeguard in the event of disruptions caused by a potential major seismic event on Canada's West Coast.

Ocean Networks Canada operates multiple *shore stations*, which provide a focal point and a *root* for their local subnet. The shore stations host equipment for communication with individual instruments, typically (but not always) located underwater. The overall configuration of shore stations, data centers and network connections is illustrated by **Figure 4**.

Since ONC's infrastructure is essentially an extension of the Internet underwater, Internet Protocol (IP) access is extended as far as possible toward the sensor endpoints. For legacy serial instruments, terminal servers located in junction boxes translate the serial protocol to make their data available over IP. The terminal servers are configured to act as *servers,* while software drivers interacting with instruments act as *clients* for the purpose of the socket connection.

Timing

An integral aspect of Ocean Networks Canada facility design, and a key enabler of multi- and trans-disciplinary research, is the ability to coordinate observations between completely different observing systems (such as satellites and *in situ* sensors). This is only possible if a single, very accurate clock signal is available to synchronize all the readings from all instruments.

Ocean Networks Canada's largest observing infrastructure (the NEPTUNE observatory) is equipped with three GPS clocks that follow the IEEE1588 Precision Time Protocol and can be inter-compared to ensure provision of the most accurate absolute time signal to all instruments underwater. All readings from all instruments are time-stamped at the shore station, and that time is used if the instrument cannot autonomously synchronize its internal clock with the shore station master clocks.

A single time reference allows the researcher to make direct comparisons between events seen in distinct data streams, for example, camera video and temperature readings, or the collation of data from seismic devices across the network to derive an earthquake epicenter. Additionally, the system enables secondary clocks to provide a higher accuracy time signal for specific local experiments, such as a planned neutrino observatory that will require nanosecond-level local timing.

Data Storage Formats

Resisting trends to build an archive in which datasets are stored in short-lived formats, or to choose one format among competing standards, ONC system architects decided to remain agnostic with respect to formats and select for internal storage those most appropriate for the given application. However, data downloads always respect users' choices. For example, Oceans 3.0 delivers the same data to users,

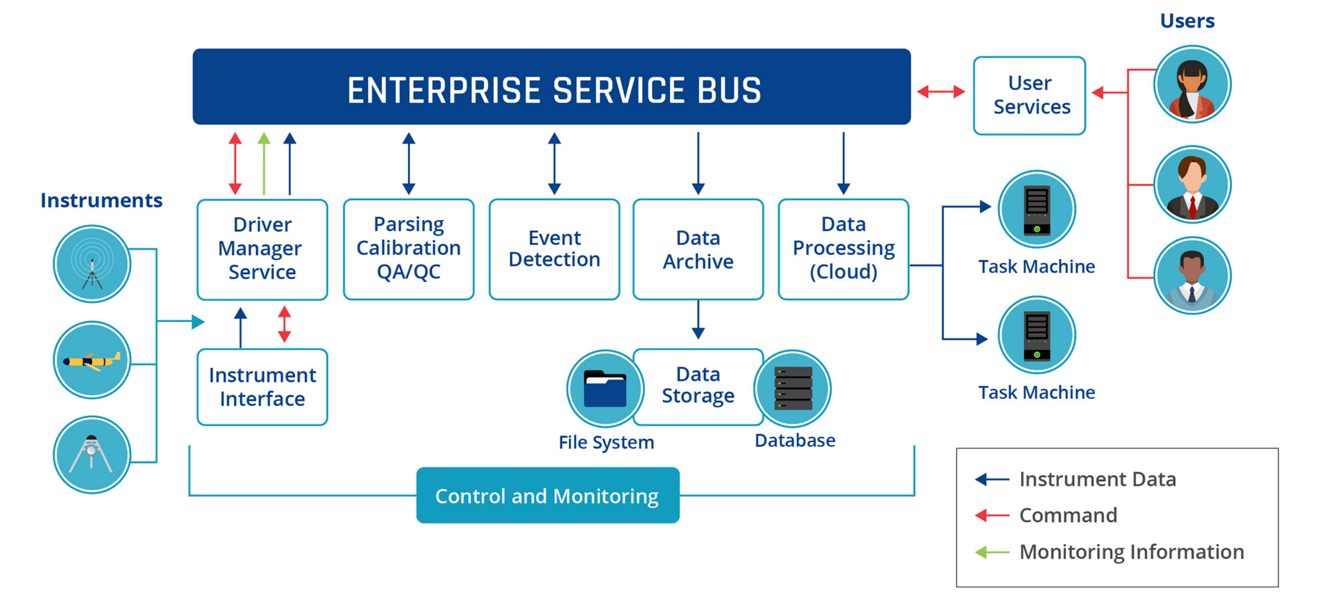

FIGURE 2 | Overview of the Oceans 2.0/3.0 Data Management and Archiving System (DMAS) structure, where a number of interconnected modules perform specific activities and pass their results to an Enterprise Service Bus for other subscribing modules to take on and process further.

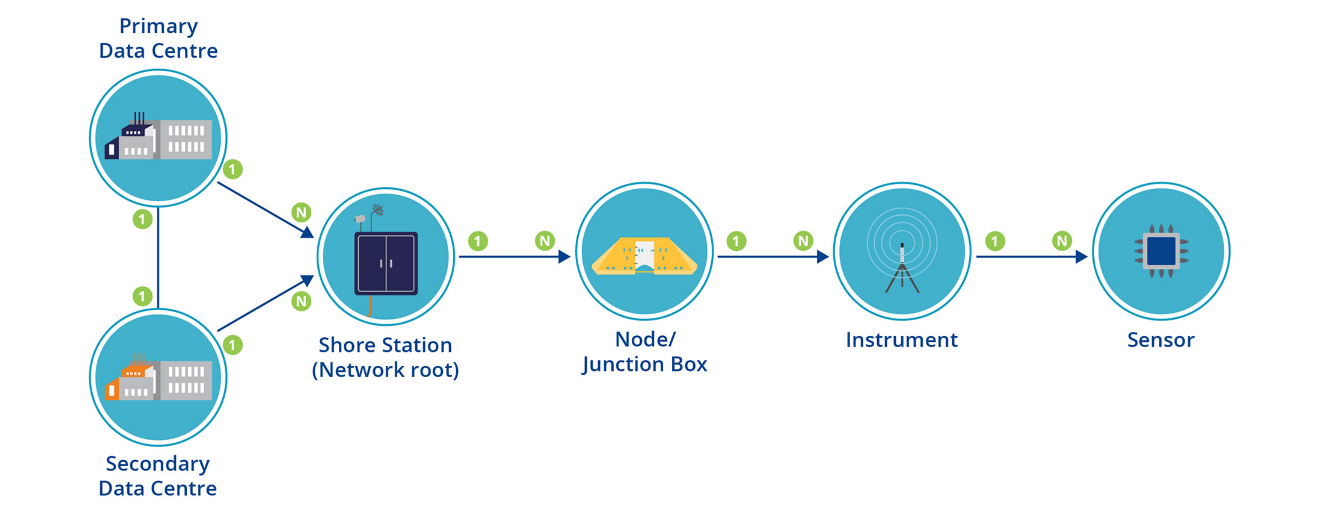

FIGURE 3 | ONC infrastructure represented by hierarchical entity-relationships extending from data center to sensor. The primary and secondary data centers support n shore stations, which in turn connect n nodes or junction boxes. Each junction box may have n connected instruments, with each instrument comprising n sensors.

whether formatted as Comma-Separated Values (CSV), in a MATLAB table or in NetCDF. To enable this, Oceans 3.0 performs format conversions on the fly when generating products from internally stored data. This averts the possibility of being locked into specific stored formats that could be deprecated after a few years, requiring costly internal conversions. ONC believes this approach has been a beneficial best practice, both for data managers and users, thanks to its flexibility.

Hardware and Software Technologies

A variety of hardware platforms, software systems and technologies are combined to host and operate Oceans 3.0, including storage and database systems, virtualization infrastructure, and physical machines for specialized applications.

Ocean Networks Canada's main storage system is a NetApp FAS8200 NAS (Network Attached Storage) with 1.5 PB of available storage as of July 2021. This system hosts the Oceans

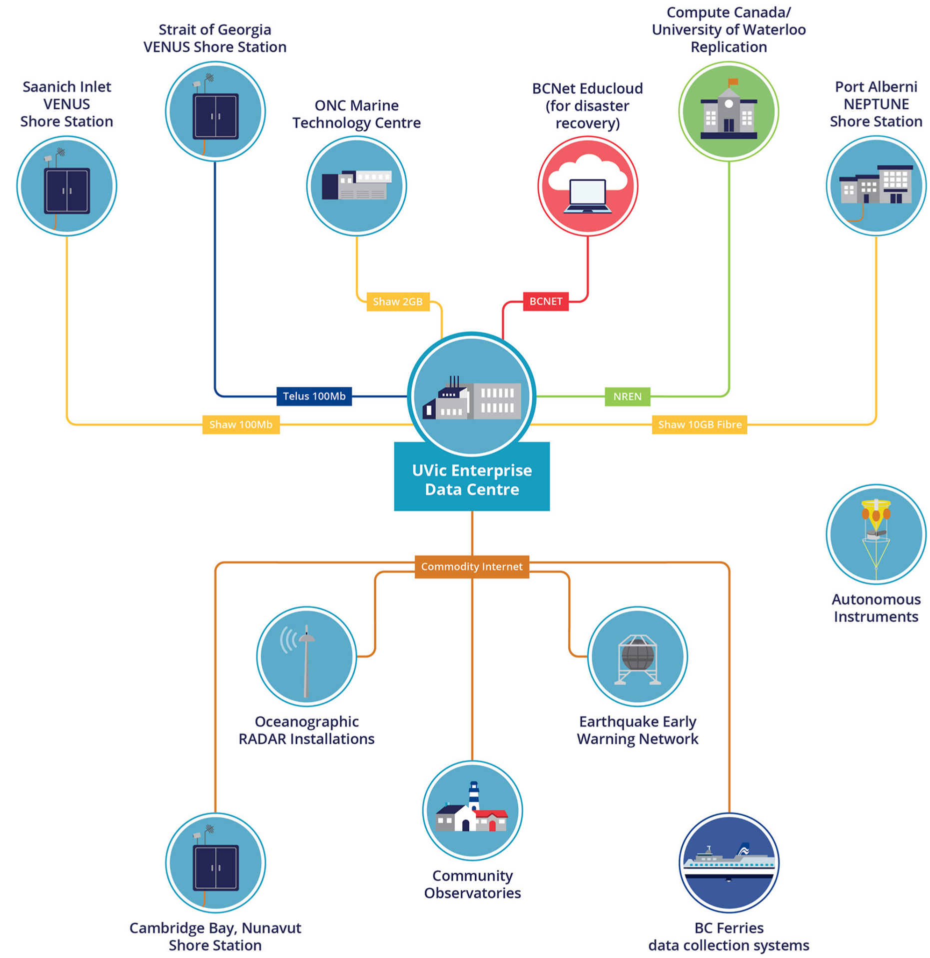

FIGURE 4 | ONC networks connecting shore-based network nodes to the University of Victoria Enterprise Data Centre.

3.0 Archive Data file server and archives. In addition, it hosts the Oceans 3.0 web server and all of ONC's virtual machines and associated file systems as well as ONC's supporting software systems used for system monitoring and graphing, issue tracking, documentation (including extensive details on data models, software requirements, design, etc.), and content management. These main data holdings are replicated in two back-up locations, as described in section Business Continuity and Disaster Recovery. At the time of writing, an additional layer of replication was in process of transitioning from Tivoli Storage Manager to Google Cloud.

Two main database systems support Oceans 3.0: Postgres and Cassandra. The Postgres database, which stores Oceans 3.0 metadata, is instantiated as a read/write master in the University of Victoria Enterprise Data Centre (UVic EDC), with read-only replicas at the UVic EDC and in the BCNet Educloud. The Cassandra no-SQL database, which stores Oceans 3.0 scalar data and other readings, is implemented as a 16-node cluster in the UVic EDC, with each datapoint replicated three times across the cluster. A backup Cassandra instance is implemented on BCNet Educloud across 12 nodes.

Ocean Networks Canada's virtualization infrastructure supporting all Oceans 3.0 software development and production platforms runs on 21 physical servers, supporting over 170 virtual machines.

Seven dedicated *task machines* are also in operation, performing all of the computation and rendering for Oceans 3.0 data product generation. At the time of writing, ONC was in process of shifting from CPU-based to GPU-based platforms for data product generation, with work underway to partially implement these within Compute Canada's cloud environment.

Instrument driver software runs on *driver machines* located in all ONC shore stations. These driver machines are operated as a redundant pair of machines, with the backup configured as a warm standby. The drivers running on these systems connect to oceanographic instruments, retrieve raw data and feed these data into the upstream components of the Oceans 3.0 data acquisition and archival system.

Oceans 3.0 runs on Gemini servers under the CentOS Linux operating system (Gemini is an open-source lightweight application-level server supporting the Open Service Gateway Initiative (OSGi) and encapsulating the ubiquitous open-source

Tomcat server). Some of the main software systems used to operate Oceans 3.0 include the ActiveMQ messaging service (for transferring data, scheduling jobs and handling communications among Oceans 3.0 computing components), Zenoss (for network monitoring), Prometheus, Graphite and Grafana (for metrics and monitoring), Graylog and Splunk (for log file aggregation) and Wowza (for video recording and streaming).

Business Continuity and Disaster Recovery

Because ONC shore stations and data center are all located in seismically active areas, ONC operates two disaster recovery locations, one in Educloud hosted in Kamloops, British Columbia (a location far removed from the coastal seismic hazard zone) and a second in Compute Canada hosted at the University of Waterloo, Ontario, Canada.

The disaster recovery location at the University of Waterloo maintains an exact copy of all archived instrument and sensor data. Data are copied daily and periodically checked for consistency. At the time of this writing, the replication and consistency verification processes were being revamped to accommodate the large volume of archived data, in excess of 10TB and 2 million files per month. A third replica of archived data was formerly maintained on tape backups. Due to rising costs of operating a tape library ONC decided to transition the third replica to Google Cloud in Montréal.

The Educloud disaster recovery location runs all the software required to start Oceans 3.0 in the event of a major disaster impacting the UVic data center. This includes database replicas (Cassandra and Postgres) and virtual machines. Aside from Oceans 3.0, this also includes development, documentation and monitoring systems required to maintain and operate Oceans 3.0.

User Management and Access Restrictions

Since Oceans 3.0 was designed not only for providing access to the data produced by instruments on the networks but also for managing and controlling those instruments, a user management scheme was integrated into the design of Oceans 3.0. Permission schemes for individuals and groups, as well as functions that require group authorization have been implemented and offer the full range of authentication/permissions features. The operation of a specific instrument, for example an underwater camera, assigns permissions to one implicit group and two explicit groups for managing the various operational aspects. The implicit group's permissions are restricted to merely viewing what the camera is seeing. One of the explicit groups allows its members to operate the camera (e.g., illuminate the lights, move the pan and tilt), whereas the third group members are allowed to change the observing program schedule.

Login is not required for simply browsing or accessing data; an anonymous use mode was implemented, which does not provide any access to specific features or assistance with data requests that may have gone awry. Login is required for users wanting to contribute content to the system, for instance to add annotations to data streams such as hydrophone audio or video recordings; this login requirement enables traceability, reporting by source, and helps prevent system abuse.

Specific cases where login is required also provide access to restricted data. Whereas the vast majority of the data are available immediately to users without any restrictions, in some specific cases restrictions are applied for sensitive data (more on this in section "Metadata"). This occurs when Oceans 3.0 is the repository of another organization's data, governed by data agreements that stipulate either limiting access restrictions to a specific group or for a proprietary period lasting from minutes to years. These restrictions are applied broadly by device, or specifically by data product and time for specific users and groups. Data restrictions are adhered to throughout Oceans 3.0, including programmatic access, interactive data access and all downloads. Data access restrictions are also configurable in the user management system of Oceans 3.0.

DATA ACQUISITION AND ARCHIVAL

The Oceans 3.0 data acquisition and archival system ingests readings from oceanographic instruments (referred to as *devices*), and stores them in database and file system archives. This highly automated pipeline is implemented by an interconnected set of software drivers, messaging queues, parsers, calibrators, Quality Assurance/Quality Control (QA/QC) tests, event detectors and archival routines.

Real Time Acquisition

Real time and near-real time data acquisition is handled by a series of systems and processes extending from instruments to database and file servers, as illustrated in **Figure 5**.

Step 1: Acquiring Data Readings

Programs that control and communicate directly with devices are called *drivers* within Oceans 3.0 nomenclature. The primary function of each driver is to acquire real time data from the device; they are designed to be as simple as possible for completion of this function. Drivers typically support a subset of the functions available on the target device, usually only commands related to configuring the device and retrieving data.

Data collected by drivers are published as Java Message Service (JMS) messages. Drivers are run on Java Virtual Machines (JVMs); there can be multiple drivers on one JVM. Typically, ONC spawns one JVM per physical machine and it is common practice to launch multiple JVM machines at a particular physical network location.

Within Oceans 3.0, network connections between drivers and devices are always handled through a Transmission Control Protocol (TCP) connection. Even serial data streams are converted into TCP format for network transmission. Different protocols are used for different devices, depending on configurations. Oceans 3.0 supports TCP, UDP, HTTP and SSH network connections.

Step 2: Publishing Onto the Parser Queue

Oceans 3.0 uses a *publish and subscribe* model for handling the JMS messages. These messages are published onto the

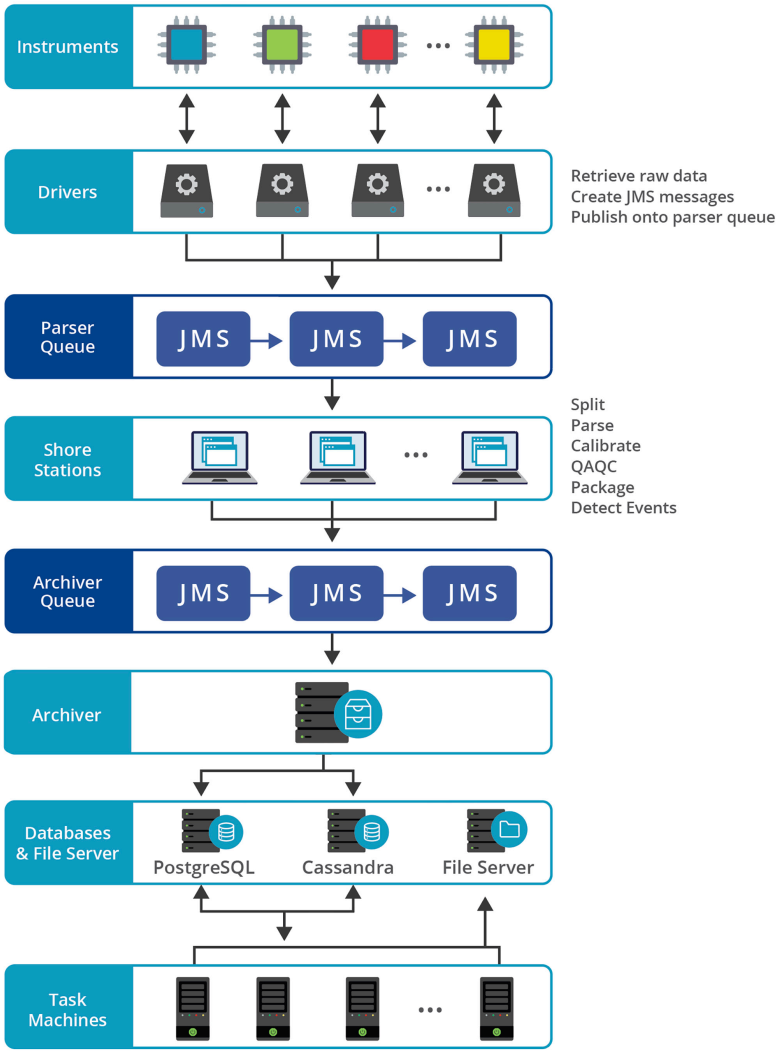

FIGURE 5 | Conceptual diagram illustrating the major ONC data acquisition steps and components.

parser queue. The JMS messaging standard is advantageous because of built-in failsafes, which ensure that any published message will reach its subscriber, even in the event of a lost connection or outage.

Oceans 3.0 employs the Active MQ implementation of JMS, which includes robust handshaking protocols and intermediary data backup. These messages are retrieved from the parser queue by the *shore station* for processing.

Step 3: Processing by the Shore Station

The Oceans 3.0 Shore Stations are not physical facilities, but rather JVMs running in the same physical location as the driver JVMs. These programs process JMSs sequentially, performing a number of operations along the way:

1. *Splitting* the raw data into components, such as device IDs or sub messages;
2. *Parsing* raw data and converting values into readings, configurations and complex data structures;
3. *Calibrating* parsed data, applying/converting units of measure, calculating derived quantities (e.g., salinity which is derived from other parameters);
4. *QA/QC* operations, such as checking for data out of bounds and flagging suspect data;
5. *Packaging* all of these elements into a new JMS containing the raw data along with parsed values, corrected values, derived values and QA/QC flags; and
6. *Event detection*, which can be any of a number of automated operations, depending on specific data values or ranges (e.g., sending an email).

Step 4: Publishing Onto the Archiver Queue

Finished JMS messages produced by the shore station are then published to the *archiver queue*, which is another instance of the Active MQ messaging service. This queue serves the same function as the parser queue, holding incoming messages, and allowing them to be picked up sequentially by the archiver, which subscribes to this queue.

Step 5: Archival

Although multiple shore stations are implemented within the Oceans 3.0 cyber infrastructure, there is currently only one *archiver* machine, which is another JVM running at the University of Victoria Enterprise Data Centre. The role of the archiver is to ensure all incoming data are stored in their proper storage systems. In the event that this system becomes overloaded or experiences malfunctions, the data remain in the MQ system until they can be safely archived. There is a manual process to re-ingest data failures and errors in the archiver (and the parsers on the shore stations). A new queue management and configuration system is being implemented in early 2022 which will allow for multiple archiver instances.

The incoming data, including raw data, sensor data and QA/QC flags, are stored in different systems, depending on the type of data. Currently, Oceans 3.0 supports the following storage systems:

- *Postgres* –an open-source SQL database, used for QA/QC flags in particular and all other metadata and data not stored in Cassandra;
- *Cassandra* – a no-SQL database, used to store parsed scalar sample values, complex readings, and as an accumulator for raw data prior to its writing into raw data files (Cassandra is used here instead of Postgres to more effectively handle and scale to the data throughput);
- *Archive Directory (AD)* – a file store, used to archive one concatenated file daily for each device.

Task Machine and Scheduled Jobs

The above steps comprise the end-to-end process of real time data acquisition, but some additional processing steps are handled by *task machines* at the end of this acquisition pipeline. Task machines incorporate a scheduler system, which runs thousands of jobs daily. One important scheduled job is the *daily job*, which runs every day after midnight UTC. This routine pulls all raw files recorded during the past day from the Cassandra database and writes them as one log file per device into the Archive Directory. These log files retain not only the data records, but also the commands and responses between the driver and the device. These log files are therefore an extremely valuable resource for troubleshooting and provenance. Another scheduled job pulls scalar data from Cassandra and generates 15-min averaged data values that are then stored back into Cassandra as *quarter (hour) scalar data*; the quarter scalar readings help improve performance when generating on-the-fly plots and other data products.

Other Acquisition Methods

Aside from the real time acquisition described above, Oceans 3.0 supports other types of acquisition for different data collection regimes.

3rd Party Data Push

For some systems, such as buoys operated by partner institutions, acquired data can be pushed directly to the Active MQ parser queue without passing through a driver. Additionally, some data are acquired via web services and sent directly to the archiver queue; this is the method for ship Automated Identification Services (AIS) data.

Store and Forward Acquisition

The *store and forward* model is used in situations where data are stored on an external device and forwarded to the Oceans 3.0 system periodically. Some examples of this are scheduled jobs that access external ftp or mail servers and upload the data. Some of these scheduled jobs also read the acquired files and push data directly onto the Active MQ parser queue, while all the files acquired this way are archived in the file system. Some independent drivers (not part of Oceans 3.0) also push files over the secure network to the file archiving scheduled jobs, where they can be tagged for post-processing by the data product pipeline.

Autonomous Systems

A variation on this model is used for data from autonomous systems, such as battery-powered moorings, which collect data over an extended period of time until the instruments are recovered and their raw data then ingested and processed. In these cases, the data are retrieved from the instrument at recovery or *in situ* following procedures outlined by the instrument manufacturers. These raw files are verified, renamed to ONC's file naming conventions, and uploaded to the archive. In cases where data parsing is intended, scripts are executed to convert the raw manufacturer files into daily log files that mimic those produced from the driver-operated instruments. Once these log files are archived, the files are added into a parser queue to follow steps 2–5 above, in similar fashion to real time data acquisition.

Device Control

Co-located Active Acoustic Devices

In some cases, multiple active acoustics devices, such as echosounders, Acoustic Doppler Current Profilers or sonars, are located in close enough proximity that signal interference could be problematic. For example, with two co-located sonars, the drivers for these sonars coordinate their timing by interlacing the acoustic pings from each sonar. This is done by using the ping of one of the sonars as a signal for the 2nd sonar to perform its ping following a predefined delay. **Supplementary Figure 1** illustrates this as a simplified timing diagram.

This solution is in use for several of ONC's co-located sonar devices. It can be used for pairings of co-located devices provided there is enough time between pings for each sonar to perform a ping and the secondary sonar can be operated in a poll mode.

Camera Control and Acquisition

Camera Systems

Camera systems consist of a camera, lights and in some cases a pan/tilt device and/or set of lasers. Oceans 3.0 supports multiple manufacturers and models of each of these components. Camera

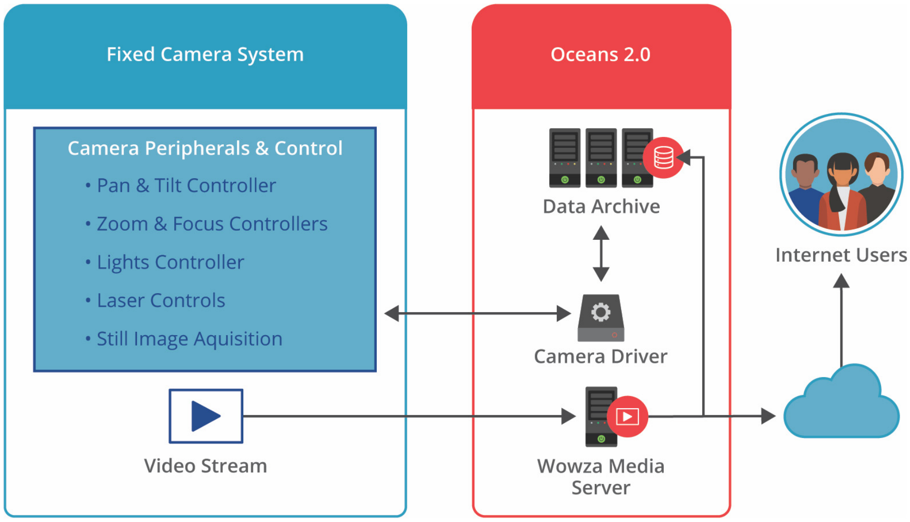

FIGURE 6 | Control, data acquisition and stream distribution system for a fixed-location camera on the ONC network.

operations include handling the video stream and controlling the various camera and peripheral settings. **Figure 6** illustrates the system for data acquisition, camera control and distribution of the video stream.

Video Streaming Server

A Wowza streaming video server is used to stream video from all cameras (Wowza Streaming Engine, 2022). Video is streamed in whatever format the camera supports and the video server maintains only one stream per camera. All Oceans 3.0 web pages that display streaming video from the cameras are connected to the Wowza streaming engine[1], which provides video streams in a standard format and resolution. This streaming server technology is compatible with the networks, cameras and servers used by ONC; at the time of adoption by ONC in 2008 it also had the advantage of being one of the only alternatives to the proprietary Adobe Flash format.

The video streaming server also writes each video stream to the AD file system. For deep sea camera systems, writing the stream is usually controlled by the status of the camera's lights; since there is almost no ambient light in the deep ocean, the stream is only written when the lights are illuminated.

Camera Driver

A camera driver is a type of driver as outlined in the above section Acquiring Data Readings. This driver contains additional capabilities to control various functions on the camera system such as zoom, focus, lights, pan/tilt, lasers, etc. Drivers transmit commands to the camera system and obtain telemetry and status information from the system. For some cameras, there is also a capability to record high-resolution still images, which are transmitted through the driver to the Oceans 3.0 data acquisition framework. Camera drivers implement a common set of camera commands that are the same for all camera systems regardless of the manufacturer or model (More on this in the Common Interfaces section "Common Interfaces" below).

[1]https://www.wowza.com/products/streaming-engine

Infrastructure Management Tools

Device Console

The Oceans 3.0 Device Console (**Supplementary Figure 2**) provides a real time display of instrument connectivity. This application serves as the command-and-control center for the observatory systems team, and is vital for the maintenance and troubleshooting of instruments. Using the Device Console, ONC system operators can start and stop instrument drivers. All users can obtain real-time summaries of any networked instrument's current status, uptime and last archived file; in addition, interactive quick plots of sensor readings and links to Device Details are provided.

Junction Box View

Junction boxes are an integral component of the subsea infrastructure, as they distribute power and communications to connected individual scientific instruments. Within the ONC infrastructure, many different types of junction boxes are deployed, each customized for its specific needs; some junction boxes are designed to serve very basic functions, while others are quite sophisticated, integrating many dozens of sensors and control systems. The Junction Box View tab in the Device Console (**Supplementary Figure 3**) allows observatory operators to monitor electrical conditions for each junction box port and connected device as well as activate and deactivate instruments via the port on/off buttons. This common interface provides a standardized means of monitoring and controlling a wide range of instruments connected to a wide variety of junction boxes.

SeaScript

SeaScript is a scripting language developed by Oceans Networks Canada that enables control of device behavior through a script. This tool serves as an engine for creating and executing scripts containing commands for sets of devices in order to accommodate complex experiments. Some use cases for SeaScript include remote execution of profiling system casts and operation of pre-defined recording routines for seafloor video cameras.

The SeaScript commands and comments in **Supplementary Figure 4** are part of a camera control sequence to control lights, pan/tilt, and camera settings then record an image. Such scripts can be scheduled to run periodically, for example every 4 h.

SeaScript allows scientific users to readily understand and easily customize the behavior of drivers. This is particularly useful in situations where the data acquisition routine is not clear from the outset and iterative refinements are required by the users to obtain the most meaningful results. Iterative software improvements include on-going support for new instrumentation and functions; for example, a new video camera was recently added that can be configured via SeaScript to record in 4K resolution.

Common Interfaces

Oceans 3.0 supports common interfaces for different devices of a given category, such as different camera models. By abstracting controls specific to individual makes and models to derive a generalized set of commands, the task of viewing and controlling different instruments is greatly simplified. At the time of this writing, 11 different camera model types were active on the ONC network, all supported by the same common control interface. Two contrasting examples are shown in **Supplementary Figure 5**.

Task Management

At any time, there may be hundreds of unscheduled and scheduled jobs running on Oceans 3.0 task machines. Unscheduled jobs typically process requests made by Oceans 3.0 users for specific data products, but also include reprocessing jobs initiated by ONC data stewards. Scheduled jobs are automated processes such as file generation and transfers that are part of ongoing operations. Jobs can also be batched and run as a consecutive set of tasks.

The Task Management interface (**Supplementary Figure 6**) allows specialists to see which jobs are queued, running, canceled, completed, or aborted with errors.

The Task Management interface also allows operators to define and edit specific tasks, such as an automated routine to illuminate a camera's lights and record video for a period of time before turning the lights off again. **Supplementary Figure 7** shows the Task Definition tab with task number 216, which runs a scheduled SeaScript job on the camera at the Folger Pinnacle location. The actual SeaScript is also shown in the lower part of this figure. Not all scheduled tasks are SeaScript routines; they also perform functions such as downloading files from an FTP site or generating 15-min averaged data and writing the values into the database.

Data Versioning

Data versioning is a necessary aspect of data management, which facilitates corrections or enhancements to datasets. Corrections may be required when fixes are made to calibration formulae, parsers, data processing algorithms, or other metadata that influence the resulting data products. Enhancement examples include adding more derived variables or improvements to data visualization parameters. On occasion, instruments send data in an unexpected format that breaks down-stream processes; once mitigating measures are identified and incorporated, it is sometimes possible to regain this segment of the time series through reprocessing.

The specific tools and procedures used vary depending on what part of the data product processing pipeline is affected. While there has always been some traceability of these events in the Oceans 3.0 database records and code versioning, there was limited ability to fully reconstruct and communicate the events pertaining to a particular dataset. Recognizing that dataset provenance is extremely important for reproducibility and to be able to apply versioning updates for dataset persistent identifiers, new infrastructure referred to as the *batch system* was developed in 2020.

In this revised system, batches are defined to encapsulate the triggers that initiate versioning of tasks, and the relevant DataCite DOI updates (see Persistent Identifiers and Data Citation section). A free-text field also allows data stewards to describe the reason and scope for the change. Triggers include items like calibration formula changes and parser updates. Versioning tasks include reprocessing the raw data (essentially redoing the Real Time Data Acquisition Steps 2 to 5 described above), re-generating derived data products, and file uploads (to fill gaps or replace faulty files). Once the tasks are complete, a new DOI is generated such that the new and previous DataCite DOIs are associated with one another using the "isPreviousVersionOf" and "isNewVersionOf" relationships.

This dataset versioning provenance information is communicated to end-users via the dataset landing page (as shown in **Supplementary Figure 8**).

This versioning approach is consistent with recommendations from the Research Data Alliance (RDA) Data Citation Working Group (Rauber et al., 2015) and the RDA Data Versioning Working Group (Principles 1, 5, and 6 of Klump et al., 2021). As new standards and best practices emerge from the research data community, ONC will continue to improve these frameworks. More information on this topic is also provided in section Persistent Identifiers and Data Citation.

METADATA

Ocean Networks Canada maintains a wealth of metadata and documentation to support the available datasets in Oceans 3.0. Metadata, often defined as *data about data*, provide users with the necessary information to discover, acquire and use data confidently and correctly. Metadata are also integral to the maintenance of ONC sensor networks.

Standardized metadata are provided to users in ISO 19115 (International Standards Organization, 2014) and DataCite metadata records, while more comprehensive content is available throughout the Oceans 3.0 data portal. An example snippet from an ISO 19115 XML metadata file is shown in **Supplementary Figure 9**; an example interface displaying metadata associated with a device is shown in **Supplementary Figure 10**. These metadata include details about the instrument life cycle events such as deployments, recoveries, maintenance, calibrations, configuration changes and more. All metadata records are maintained with the aid of the workflow tool described in the following section. In addition to instrument metadata, Oceans 3.0 maintains metadata describing a wide variety of entities, including non-instrument infrastructure, instrument platforms, expeditions, missions and remotely operated vehicle dives, etc.

Documentation for each instrument including manuals, calibration sheets and photos are curated in a content management system, and can be provided to data users upon request. For instrument deployments conducted through Remotely Operated Vehicle (ROV) operations, the annotated video is publicly accessible via Ocean 3.0's SeaTube interface (see section "Data Discovery and Access"). This feature allows users to visually contextualize the environment in which an instrument is placed. ONC also maintains a transaction history of changes to any metadata, including details of who made the change and at what time. In 2020–2021, ONC implemented a more robust system for tracking data versioning changes, such as reprocessing or file fixes. These data versioning metadata are now provided in the dataset landing page. Dataset versioning prior to the allocation of DOIs is mostly traceable in ONC's database, although not currently exposed to end-users. As of 2021, a maintenance history of changes was being implemented into the ISO 19115 metadata records.

Controlled Vocabularies

To efficiently serve Ocean Networks Canada's large, interdisciplinary user community it is important to follow widely accepted and consistent conventions when describing data. Controlled vocabularies, such as those maintained on the vocabulary server provided by the Natural Environment Research Council (NERC) define a common language for referencing variables and instruments. The NERC Vocabulary Server (National Oceanography Centre, 2021) provides access to lists of standardized terms that cover a broad spectrum of disciplines of relevance to the oceanographic and wider community. All of the vocabularies are fully versioned and a permanent record is kept of all changes. By referencing controlled vocabularies, ONC can be confident that its use of terms adheres to the current standards of active controlled vocabularies.

Vocabularies were selected from the NERC Vocabulary Server that paired with concepts used by the Oceans 3.0 data management system, including device type, device category, and units of measure. Once a controlled vocabulary was selected, terms from Oceans 3.0 were manually mapped to corresponding terms in the vocabulary. These mappings are stored in ONC's relational database, which simplifies management and maintenance of the controlled vocabularies. Implemented mappings include the SeaVoX Device Catalogue, SeaDataNet Device Categories, British Oceanographic Data Centre Data Storage Units, Climate and Forecasting Standard Names, IOOS categories, and Global Change Master Directory Keywords controlled vocabularies. Terms and the source-controlled vocabulary are returned to help users determine fitness for use of the data. Not every concept in Oceans 3.0 maps to a term in one of the selected vocabularies, in which case a null is returned with the search results. However, by adopting multiple vocabularies ONC minimizes gaps in the description of data.

Metadata Formats

Just as oceanographic data need to be provided in common and interoperable formats, so too do the metadata. Oceans 3.0 conforms to the ISO 19115-1:2014 Geographic Information Metadata schema to deliver metadata accompanying data search results.

There were several motivations to adopt ISO 19115. Developed by the International Standards Organization, the schema is well maintained with an active and engaged user community. The standard has been adopted by other organizations in the field of study, such as the National Oceanic and Atmospheric Administration, and is used by repositories that ONC contributes to, such as the Polar Data Catalogue. Additionally, the XML format of ISO 19115 ensures the metadata is machine readable, allowing users to easily parse documentation.

Extensive crosswalks have mapped concepts in Oceans 3.0 to relevant fields in the ISO-19115 schema. Mappings consider how metadata terms are defined in the main standard as well as how terms have been implemented by other organizations and the North American Profile of ISO 19115. The result is an ONC-tailored metadata profile that expands on the minimum mandatory requirements of ISO 19115. Doing so maximizes interoperability and provides users with the details they need to use the data obtained through Oceans 3.0.

Abiding by Principles and Standards

Ocean Networks Canada became a member of the International Science Council World Data System in 2014. This body, in partnership with the Data Seal of Approval (DSA) launched the CoreTrustSeal organization in 2017. CoreTrustSeal is an international community-based, non-governmental and non-profit organization promoting sustainable and trustworthy data infrastructures. CoreTrustSeal offers data repository certification based on conformance with an agreed set of requirements covering aspects such as data security, continuity of access, confidentiality, data integrity, discovery and identification. As of 2021, ONC was in process of preparing for recertification under CoreTrustSeal.

In developing ONC's data management policies, careful attention has been paid to Several seminal principles, including FAIR, TRUST, OCAPTM, and CARE.

FAIR Principles

In 2016, the 'FAIR Guiding Principles for scientific data management and stewardship' were published, offering guidelines to improve the *Findability, Accessibility, Interoperability*, and *Reuse* of digital assets (Wilkinson et al., 2016). The *Findable* principle implies that data and metadata should be easy to find for both humans and computers. The

Accessible principle ensures that once data are found, there are open processes for accessing them. *Interoperability* relates to the ability to integrate data from different sources as well as across different applications for analysis, storage and processing. *Reusability* is the ultimate goal, ensuring data are well-described so that they can be replicated or combined in different settings.

Ocean Networks Canada has strived to implement the FAIR principles within Oceans 3.0, although not all previous versions of data can always be accessed. In some situations when data are reprocessed, the older version becomes unavailable, but at minimum all associated metadata are preserved.

TRUST Principles

In 2020, Lin, et al. published the TRUST guiding principles for demonstrating the trustworthiness of a digital repository, including *Transparency, Responsibility, User Focus, Sustainability,* and *Technology*. The TRUST principles recognize that for a repository to provide "FAIR data whilst preserving them over time requires trustworthy digital repositories with sustainable governance and organizational frameworks, reliable infrastructure, and comprehensive policies supporting community-agreed practices." (Lin et al., 2020) *Transparency* calls for repositories to enable publicly accessible verification of specific repository services and data holdings. The *Responsibility* guideline requires repositories to ensure the authenticity and integrity of data holdings as well as the reliability and persistence of their services. *User Focus* ensures that data management norms and expectations of target user communities are met. *Sustainability* reminds that services should be sustained and data holdings preserved for the long-term. *Technology* refers to the infrastructure and capabilities implemented to support secure, persistent and reliable services. As part of ongoing efforts to maintain CoreTrustSeal certification, ONC strives to abide by TRUST principles as foundational for implementation of the Oceans 3.0 data repository.

OCAP™ Principles

In 2014, the OCAP™ principles, originally introduced in 2002, were refined and updated by The First Nations Information Governance Centre (2014). These principles and values are reflective of Indigenous Peoples' world view of jurisdiction and collective rights. They include *Ownership, Control, Access* and *Possession*. *Ownership* states that a community owns information collectively, and that ownership is distinct from stewardship. The *Control* principle asserts that Indigenous Peoples must have control over how their data are collected, used, disclosed and destroyed. The *Access* principle requires that Indigenous Peoples will have ongoing access to their data, while also having the right to make decisions regarding who can access these data. *Possession* describes the mechanism for Indigenous Peoples to assert and protect ownership of their data.

CARE Principles

In 2020, Carrol et al. published the CARE Principles for Indigenous Data Governance, in recognition that "ongoing processes of colonization of Indigenous Peoples and globalization of Western ideas, values, and lifestyles have resulted in epistemicide, the suppression and co-optation of Indigenous knowledges and data systems" (Carroll et al., 2020). The CARE principles seek to balance the FAIR principles for open data against respect for "Indigenous use of Indigenous data for Indigenous pursuits." The CARE Principles include *Collective benefit, Authority to control, Responsibility* and *Ethics*. *Collective benefit* supports Indigenous creation/use/reuse of data for policy decisions and evaluation of services in ways that reflect community values. *Authority to control* affirms Indigenous Peoples rights to determine Indigneous data governance protocols and be actively involved in stewardship decisions. The *Responsibility* principle acknowledges the importance of nurturing respectful relationships with Indigenous Peoples from whom the data originate, while the *Ethics* principle recognizes that Indigenous Peoples' rights and wellbeing should be the focus across data ecosystems and throughout data lifecycles.

As ONC upholds Indigenous partnerships for hosting environmental data, the data policy implementation plan and practices are informed by the CARE and OCAP Principles. ONC data stewards have completed training courses on OCAP™ and participated in the Portage Network's Sensitive Data Expert Group (n.d.), which works to develop practical guidance and tools for the management of sensitive research data. The team is developing plans to increase Indigenous data support through means such as integrating notices and labels relating to traditional knowledge and biocultural holdings. ONC actively participates in Indigenous data governance events and continues to evolve practices and implementations within Oceans 3.0 accordingly.

Data Restrictions

Most data within the Oceans 3.0 repository are provided under the Creative Commons CC-BY 4.0 license, which means these holdings are open and free for anyone to use (Creative Commons, 2021). However, for some datasets, ONC maintains agreements with the relevant data partners to clarify the data restriction details, with follow-on support for providing access to designated users within the contractual time frame of the data agreement. Even in the case of restricted data, metadata remain accessible. Embargoes may be established in some cases for the entire dataset, specific subsets, or most recent data (e.g., last 4 h). ONC's data access interfaces and services are generally designed to show the existence of datasets, even if access to the datasets requires specific permissions. Requests to access any restricted datasets are evaluated on a case-by-case basis.

Within the Oceans 3.0 framework, support has been implemented to handle requirements for access to, use and sharing of Indigenous datasets, which are defined by data agreements with providers.

QUALITY ASSURANCE LIFECYCLE, WORKFLOW AND TESTING

Quality Assurance/Quality Control Model

Ocean Networks Canada has developed and implemented a comprehensive process-oriented quality assurance (QA) model in combination with a product-oriented data quality control

(QC) model. This QA/QC model systematically intercepts and examines the instrument and data streams at various stages with the objective of minimizing human and/or systematic errors, thus ensuring high quality data workflow (see **Figure 7**). ONC's QA/QC methodology specifically addresses the QA/QC needs of a long-term dataset by ensuring data quality consistency within a single dataset and simultaneously among a collection of datasets at each site.

The following QA/QC stages monitor the performances of measurement systems, which eventually contribute to scheduling maintenance expeditions and calibrations of the instrument platforms. These processes are complementary to research and development of improved and new monitoring technologies.

Pre-deployment Testing

This stage includes all data/metadata QA/QC checks performed during pre-deployment testing for an instrument up to actual deployment.

Post-deployment Commissioning

This stage includes all data/metadata QA/QC checks from actual deployment to commissioning of the data from an instrument as good or compromised.

Automated Quality Testing

This stage includes all data QA/QC-related checks, real-time or delayed, performed via automated quality control procedures while the instrument is deployed.

Manual Quality Control Methods

This stage includes all data QA/QC checks performed via systematic manual data assessments and annotation routines.

Post-recovery Tests

This stage includes all post-calibration checks performed during post-recovery and servicing of an instrument.

Data Quality Assurance

Data quality assurance (QA) processes are preventive measures implemented to minimize issues in the data streams and inaccuracies, thus averting corrective measures required to improve data quality. The ONC data QA component includes processes to ensure that the instrument sensor network protocols are appropriately developed and observed. Examples of QA processes currently in place include periodic manual data review by ONC data specialists, inclusion of data assessment annotations and the completion of end-to-end workflow tasks.

Manual Data Assessment Annotations

Quality assurance on the quality-controlled data is accomplished by performing periodic manual data quality reviews followed by modification to the existing data quality flags as required. In addition, ONC data specialists add manual data assessment annotations of devices, sensors and other observatory components, reporting events or conditions that may affect the quality of ONC data. Such information includes instrument commissioning, sensor failures, changes in instrument calibration, and explanations for data gaps. Effort has gone into developing user-friendly interfaces and tools to facilitate annotation entry by data specialists and to effectively link the annotations through the time domain with corresponding data. External users can conveniently access and download the annotations through the Annotation Search tool and various links provided in the ONC data download interface.

Workflow Processes

By using an end-to-end workflow with systematic methodologies and processes, ONC ensures that the necessary pre-conditions for high-quality data are met. A workflow-process user interface facilitates the integration of knowledge among various teams within the ONC organization where teams work together to ensure that instruments are well-documented and provide the highest quality data possible.

Since 2013, ONC has employed an in-house software tool (shown in **Supplementary Figure 11**) that facilitates task management for all the network instruments affected in a given expedition or program (Jenkyns et al., 2013). Its development was motivated by the necessity to ensure all instruments are properly managed during a busy expedition season that requires input from domains of expertise distributed throughout the organization. Its design and implementation also establish records of events in an instrument's life cycle, and track ONC processes governing deployments, maintenance and recoveries.

Data Quality Control

Data quality control (QC) is a product-oriented process to identify and flag suspect data after they have been generated. QC includes both automated and manual procedures to test whether data meet necessary quality requirements. QC of ONC data includes three components. The first component evaluates real-time data automatically before data are parsed into the database. The second component evaluates near-real time or archived data using automatic delayed-mode testing. The third component is manual review, where an expert inspects the data for quality issues. The three components are discussed in more detail below.

Automatic Real Time Tests

Real time automated data qualification determines the initial validity of data prior to archival in the ONC database. The QA/QC test model follows conventions listed in the Argo quality controls manual (Wong et al., 2021) with additional tests developed at ONC. Qualifying the data prior to archival ensures that every reading with a QA/QC test has an associated QA/QC value.

The QA/QC architecture supports two types of automatic real-time QC tests: single-sensor range tests and dual-sensor relational tests. These tests are designed to catch instrument failures and erroneous data at regional or site-specific range values derived from various sources depending on test level (defined in the following section). In addition, quality flags are propagated to dependent or derived sensor data streams to ensure derived data are adequately quality controlled as well. Example listings of automatic real time tests are shown in **Supplementary Figure 12**; details of a range test for a fluorometer are shown in **Supplementary Figure 13**.

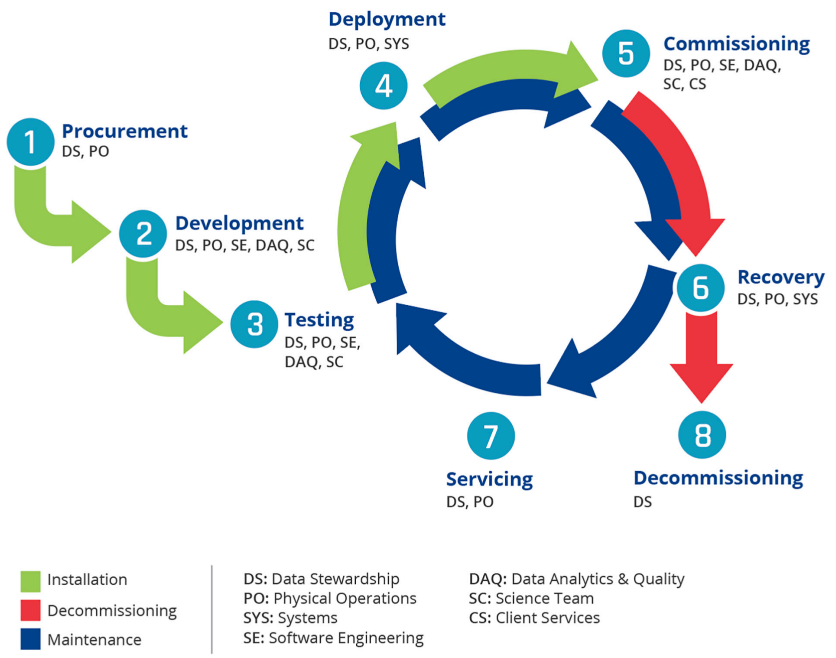

FIGURE 7 | ONC instrument life cycle and major process groups involved.

Automated Delayed-Mode Testing

Automated delayed-mode testing includes checks on data that can be applied in near real time or batch processed at set intervals. These tests require consecutive data where the central value is compared with surrounding values to determine its validity. The QA/QC test model supports tests such as spike detection and gradient steepness.

Manual Tests

Automated QC is a first pass at quality control, the results of which may contain both false positives and false negatives. For this reason, ONC data specialists conduct daily *manual tests*, by which all real time data are visually reviewed. In situations where data specialists notice issues with data visually, they isolate such data segments and perform an in-depth review to confirm whether automatic QA/QC tests were able to capture the instances and flag the data accordingly. If not, data specialists perform appropriate manual corrections to auto QA/QC flags.

An example situation requiring manual review of bad data points that were flagged as good, is with the automated *Spike Test*. This test is only able to capture a single erroneous point when applied as an auto test. However, there may be multiple erroneous data points subsequent to the initial instance. Such points can only be identified and flagged appropriately via manual review of data.

Another situation requiring manual review and flagging accordingly is the identification of potential drifts in the data. In general, automatic QA/QC tests, which are applied to single data points or very short segments of real time data, are unable to capture longer-term errors introduced gradually into the data from sensor drifts. This can only be addressed by data specialists periodically reviewing long term historical data visually, to identify potential drifts. Such data are flagged manually by ONC data specialists.

On occasion, in-depth reviews require consultation with ONC staff scientists to discuss potential natural events that may produce outliers. An example might be erroneously flagged data indicating presence of an unusual event, such as a marine heat wave or hypoxia intrusion. After consultation to confirm anomalies reflect actual events, data that may have been automatically flagged as “2 – probably correct” (see **Table 1**) could be reverted to “1 – good data.” As with all other manual QA/QC flagging, such changes are performed in delayed mode.

Manual QA/QC tests essentially follow the test criteria applied by auto QA/QC tests. The test criteria are developed by ONC data specialists through analysis of long-term data from specific sites and regions. Significant weight is given to the skill of the data specialist to capture potential issues visually. ONC data specialists

TABLE 1 | ONC quality control flags.

QC Flag	Description
0	No quality control
1	Data passed all tests
2	Data probably good
3	Data probably bad
4	Data bad
6	Insufficient valid data for reliable down-sampling (ONC defined flag)
7	Averaged value (ONC defined flag)
8	Interpolated value
9	Missing data

are subject matter experts on a variety of instrumentation and use their experience and knowledge to determine manual QA/QC flags that are not easily captured by automatic tests. These can include comparison with co-located instrumentation, drift analysis, seasonal events, stuck point values, and other tests. The underlying data stream used to derive the auto (and/or manual) tests will be validated against physical samples or shipboard and ROV cast data as and when they become available. However, availability of such data is limited.

Many problems are identified and corrected by the manual test process, including adjustment of automated QC test parameters. Within the ONC Quality Control terminology, manual QA/QC tests are considered as major tests (defined in next section).

Major Tests

A major test sets gross limits on the incoming data such as instrument manufacturer's specifications or climatological values. Failure of this test level is considered major and it is recommended that the flagged data should not be used. Specific tests that belong to this category include instrument-specific comparisons (against value ranges specified by the manufacturer for each physical sensor on an instrument) and regional-level tests (based on climatological values for a region and depth).

Minor Tests

Minor tests are based on local statistics derived from historical ONC data. If a minor test generates failures, the data are considered suspect and require further investigation by the user to decide whether or not to include these data in their analyses. Specific tests that belong to this category include single-sensor tests (compared against historical ranges for a specific site and station) and dual-sensor tests (utilizing two different sensors on the same instrument to catch dropouts and other sensor-specific errors).

Quality Control Flags

Quality information for individual measurements is conveyed by integrating the results from multiple types of test evaluations. The overall quality of the data is shown by integer indicators, or flags, which are standardized across all ONC data and are based on the Argo quality control flagging system (Wong et al., 2021), as well as including some ONC-defined flags (**Table 1**).

Overall quality flags are used to demarcate data values that fail one or more QC tests. This is achieved by subjecting the data to various levels of testing that generate a QC vector containing the output for each test. The final quality control flag is then determined as follows.

- If all tests achieve pass status, the final output flag assigned is *1* (Data passed all tests).
- If passed status is reported on major tests but failed reported on minor tests, the final output flag assigned is *2* (Data probably good). In cases where the Temperature-Conductivity tests are failed, the output assigned flag is *3* (Data probably bad).
- If failed status is reported on major tests, the final flag is *4* (Data bad).

In addition to using flags as quality indicators, the ONC flagging systems also provide information about how the data were processed, with flag *7* for averaging and flag *8* for filling gaps via interpolation. Note that averaged and interpolated data exclusively use *clean* data (all values have QC flag *1*). Users can determine the type of tests that have been applied to the data downloads by referring to the Data Quality Information section in the accompanying metadata file.

Quality Assurance/Quality Control Implementation Tools

Within the ONC data acquisition and delivery model, QA and QC procedures are applied at various stages as data flow from sensors to the end user. Various Oceans 3.0 tools and web interfaces have been developed for easy handling and linking this information to the data stream. Such tool developments are continuously improved and remain as work in progress. Both auto and delayed QA/QC tests are managed through a custom-designed QA/QC interface, which allows data specialists to search, display and filter test results for sensors and instruments.

Maintaining historical information over the lifespan of every ONC instrument is indispensable for delivering quality data. To serve this purpose, the design architecture of all the ONC tools related to data QA/QC ensures that all historical information pertaining to a device is accessible via a single link.

Ocean Networks Canada Quality Assurance/Quality Control Data Delivery Policies

Ocean Networks Canada delivers data to the end users in *clean* and *raw* data products or via web services that include QA/QC flags. For *clean* data products, all compromised data resulting from QA/QC assessments are removed and replaced with NaN (Not a Number) values. *Raw* data products deliver raw data (unmanipulated, preprocessed) with corresponding data assessment flags in separate columns. Data delivered via web services return the QA/QC flag values, but the onus is on the user to use the flags appropriately. Since there is a risk that real and potentially important phenomena will be ignored in fully automated QC models, the ONC data delivery policy emphasizes the need to maintain the raw unmanipulated data and offer the option of downloading raw data to the end user. Great care is also taken to ensure that valid data are not removed and that all QA/QC processing steps are well documented.

Data reliability is based, in part, on the capacity to reproduce data products. To this end, ONC data QA/QC model developers have carefully considered ways to preserve the original data in its raw form so that subsequent procedures performed on the data may be reproduced. Here, metadata act as a resource, holding valuable information about all QC procedures performed on the data (i.e., raw data, qualifier flags added, problematic data removed or corrected and gaps filled). Also included is all necessary information used to generate the data, such as the source file used, data-rejection criteria, gap-filling method, and model parameters. This information enables the data user to carefully scrutinize the data and determine whether data processing methods used by ONC are appropriate for their specific applications. Further, facilitating the review of uncorrected data through the ONC data distribution model helps end users perform their own quality analysis and identify real phenomena that may not be apparent in the corrected data.

DATA PRODUCT PIPELINE

As of Spring 2021, 299 distinct file-based data products were available for download through Oceans 2.0 (this total does not include data available via web services and interactive portals). Over the 2009–2021 time period, an average of 25 data products were created or revised annually, as shown in **Figure 8**. Data products are maintained in perpetuity, allowing for reproducibility, particularly via DOIs. This includes the ability to reproduce any historical version of a data product, particularly the more value-added and processed data products that are continually improved over time.

Data Products

Examples of data products include numerous forms of data plots, primarily in image formats, and many data file formats including self-describing and standard-adhering NetCDF formats, convenient MAT (MATLAB) files, accessible CSV files, manufacturer formats and raw data. These products are generated by Java or MATLAB codebases. Device manufacturers generally write their supporting software for standalone operation; usually for a PC laptop to connect, configure and download the data. To integrate with the network, ONC drivers emulate the device interaction and acquisition functions of the software, while ONC data products reproduce the initial manufacturer's product, including calibration, configuration and any metadata, as if the device were operated in the usual way, albeit continuously, with no limitations on power, data transfer and storage. No two device types are the same, even those produced by the same manufacturer. Support from the manufacturers has been very beneficial in the effort to integrate the hundreds of devices and data products to date. In general, for each device type, Oceans 3.0 offers at least one visualization product and the manufacturer's file product. Additional formats, including specialty products with increasing levels of refinement, are developed in response to user requests.

Data products are generated primarily on-demand, when requests are received from either the Oceans 3.0 web applications or the Application Programming Interface (API). As of July 2021, over 8600 graphical data visualizations were also pre-generated daily via scheduled jobs.

Depending on the data type, the data product processing pipeline converts device-specific source files, generic raw log files and/or parsed scalar data (from the database) into finished data products. Device-specific source files are usually acquired via file transfer (FTP, email, etc.). Generic raw log files include device output intermixed with logged commands and device response codes, as acquired by ONC device driver software. Some log files are stored in hex format, others in ASCII. As described in section Data Acquisition and Archival, incoming raw log files may be parsed into the scalar data system. Data products generated from the *scalar* data system have device independent format and options, while *complex* data products are generally specific to the device type. Consider the Teledyne Acoustic Doppler Current Profilers (AD) as an explanatory example. These ADCPs produce data via ONC device drivers that is stored as raw log files. Live incoming ADCP data is parsed in real-time producing scalar sensor data for temperature, tilt, and other state-of-health internal sensors, while the acoustic data is too

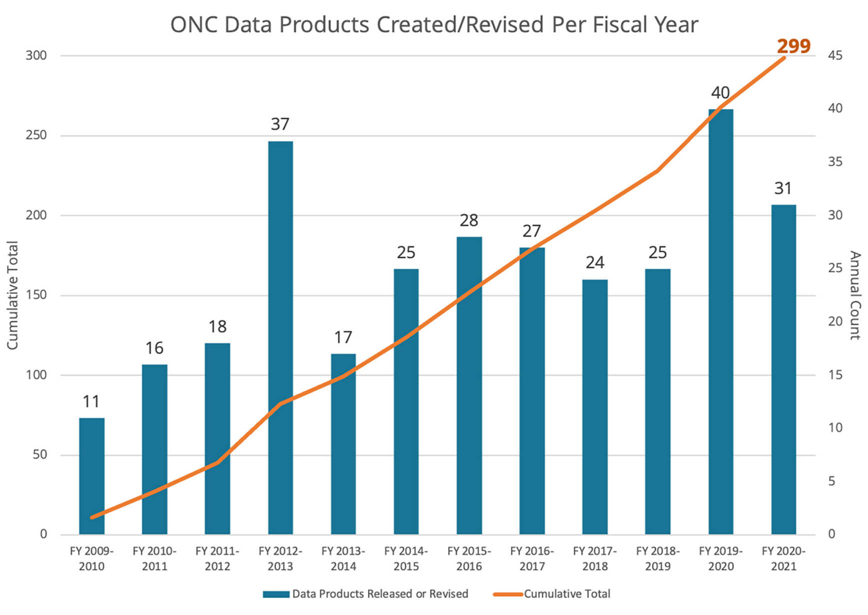

FIGURE 8 | Graph of ONC data products created and revised per fiscal year (blue bars) and cumulative total (orange line), 2009–2021.

complex to express as a single-reading in a unit of time. Instead, the data product pipeline processes the manufacturer format RDI files via a scheduled task; these are then stored in the file archive as an intermediary product and used to produce on-demand data products such as plots, MAT and NetCDF data products. If users request near real time complex data, most of the data product generation code is able to read raw live data directly from the Cassandra database, producing any normally pre-processed, intermediary formats on-demand. This mode is slower for processing large amounts of data, but it provides access to near real time data. The product generation code is also able to fill in any missing pre-processed data products on-demand as well. By using a combination of pre-processed stored formats and on-demand generation, the data product pipeline is optimized for both long time series and near real time data access.

Device-specific, manufacturer *complex* formats are necessary to support the diverse and numerous devices ONC operates. However, parsing some data into scalar sensors has many advantages over complex data products. Instruments with scalar sensors produce single values over time, such as temperatures or pressure readings. As described in detail in previous sections of this paper, incoming data streams are parsed, calibrated, quality controlled and stored within one of the Oceans 3.0 production databases, Postgres or Cassandra (Oceans 3.0 can be configured to use either or both of these database systems). The development of data products, visualization and interactive portals such as Plotting Utility (described in section "Data Discovery and Access") is much more easily practicable when drawing from standardized, database-stored scalar data.

In addition to what ONC classifies as *scalar* and *complex* data products, some value-added and processed data products combine these using data from the same or different source instruments. An example is the processed radiometer data product which combines the complex array data with scalar depth values acquired by a separate instrument to reproduce a manufacturer format file for easier processing. All products are available alongside the raw data and all formats. The processing steps for all data products are described in online data product documentation (ONC Data Products Wiki, n.d.).

MATLAB-based ONC data parsing and data product generations routines are provided to interested researchers upon request. Future plans for Oceans 3.0 include the publication of citable and persistently identified data product generation routines, which will advance efforts to support replicability by providing open-source code that can be run independently.

Long-Term Time Series

Once deployed in the marine environment, oceanographic instruments can undergo degradation, biofouling, sensor drift and outages. For this reason, instruments must be periodically replaced and refurbished, typically every year. Thus, to monitor oceanographic conditions at a location over an extended time period requires deployment and recovery of a series of instruments over years. The instrument sensors comprising the time series for a specific location are designated within Oceans 3.0 nomenclature as *primary sensors*. To generate data product files from long-running scalar time series at such a location, a number of operations are required. First, queries on the metadata database (Postgres) are used to obtain the full list of devices and primary sensors for the location. Next the data from each device deployment is pulled from the database (for scalar data) or from the file archiver (for complex data). Scalar data products offer gap filling with non-numerical values (NaNs) to ease analysis for the end user. Typically, long-running time series must also be partitioned into manageable file sizes (typically 1×10^6 lines for CSV files; 1 Gb for MATLAB and NetCDF files). The finished files are then packaged along with metadata files into zip files and made available for download by the end user. In this way, a continuous long-term time series product is compiled.

Long-term time series data can also be used to develop climatology data products, as exemplified in **Supplementary Figure 44**, which plots daily averages and statistical deviations for data gathered over a 12-year period (2009–2021). These plots and file products are pre-generated daily for Data Preview. The selection of primary sensors and locations comprising them are configurable via Task Management. New locations are added once 3 years of data is acquired; there were 22 locations supported at the time of publication.

Processing Options

A variety of processing options are offered to the user:

- *Resampling*: scalar data (and some complex data) may be offered with averaging, min-max and min-max average options. Resampling is applied using a simple box car algorithm, which in the case of averaging, is generally robust to aliasing. Each resample period box-car must meet a threshold of 70% data availability or it is QC flagged and shown as a NaN (not-a-number) value.
- *Cleaning*: *raw* or *clean* options are offered for scalar data products. Clean is the default where all data values that have been flagged as bad by the QA/QC algorithms are replaced by NaN values.
- *De-tiding*: for some datasets and data products, computational methods can be used to remove tidal signatures from the time series.
- *Special Options*: for complex data formats, a variety of special options are offered, including tilt compensation for ADCPs or color scale specification for hydrophone spectrograms. There are a total of 82 options available.

Low-Latency MATLAB Environment

Various approaches were investigated to address this problem. Eventually, an in-house solution was required and developed, named *MATLAB-as-a-service*. The concept is similar to the matlabcontrol open source Java API (Google, 2021) however, ONC's implementation is fully in-house with some improvements over matlabcontrol. It uses the official MATLAB Java API, maintains a configurable pool of MATLAB instances, and is fully integrated into Oceans 3.0, extending all the error handling, task management and configuration features. The pool manager maintains interactive MATLAB instances with startup, clean up/reset scripts so that the MATLAB environment is ready and waiting for any code needing to be run. Tasks and searches can be canceled from the Oceans 3.0 UI as usual. When errors occur, they are caught, notification emails are sent, issue tracking tickets are created, and the affected instance is shut down. The pool manager's maintenance thread asynchronously starts new MATLAB instances when the number running drops below the pool minimum and also ends instances when a time-to-live threshold is reached.

The result is a reliable, maintainable system with almost no start-up latency. Our testing shows the Data Preview (described in the following section) run-time for 8500+ search tasks is reduced by close to 60%, exceeding the amount expected from start up time latency alone (about 25%). The additional 35% reduction results from MATLAB's internal caching, which is not as effective when running in the one-and-done mode. The MATLAB instances do use more memory in this configuration, presumably because of their internal caching. The system is scalable with additional hardware as each task server has its own Oceans 3.0 full stack. Another benefit of the system is the ability to run more automated testing nightly without adding hardware. ONC's internal search automation tool runs 10000+ search tasks nightly in a QA environment comparing actual to expected results. Automated integration testing is essential when supporting nearly 300 data product formats with 82 option sets.

DATA DISCOVERY AND ACCESS

User Interface Tools and Data Visualization

Web Applications for Exploring and Visualizing Data

A variety of web-based applications have been developed as part of Oceans 2.0/3.0 to enable exploration and visualization of oceanographic data. These include the Data Preview, Plotting Utility, Dashboards, Search Hydrophone Data and other interfaces. Additional applications are under development. **Table 2** lists the major user-facing applications of Oceans 2.0/3.0, with principal uses and years of original release.

User Interface Tools Used for Development

Over its 15 + year (to date) development history, Oceans 2.0/3.0 has employed a variety of User Interface (UI) tools and frameworks for implementation. Over time it has made use of Dojo (2009), MooTools (2009), YUI (2011), jQuery (2013), React (2018) and Material-UI (2018).

Prior to 2018, Oceans 2.0 was built using the YUI (Yahoo!) Library and the jQuery Library to ease DOM manipulation. Beginning in 2018 new UI development is done using the React (Facebook/Meta) Library for web components and the Material Design System (Google) Library for style and color. Several advantages motivated this change. As YUI became outdated and was no longer supported, it was gradually supplanted by React and Material Design System, which are well supported. Additionally, ONC struggled to hire developers familiar with YUI, as the majority of young talented developers expressed preference working with the more modern Reach/Material development stack.

Following this change, when YUI-based pages needed fixes or small upgrades, YUI was still used to complete the work. However, when new features were needed for those pages, they began to be developed in React and Material and placed alongside the YUI display. New pages are now developed completely with the React and Material Libraries.

Data Search

Overview

Oceans 3.0 Data Search (shown in **Supplementary Figures 14–16**) provides data processing and visualization for both scalar and complex data products. The application employs a shopping cart metaphor, whereby users browse and select data sources, choose data products and processing options (e.g., averaging or min-max), and then request and download processed results with accompanying metadata reports.

The shopping cart approach allows users to create and download multiple searches, and for logged-in users, records of previous searches are retained. This makes it possible for users to start a search in one session (e.g., from the office) and later check in on progress with the request from somewhere else (e.g., home).

Use Cases

Browsing Data Archives

Data Search allows users to see the full scope of all instrument deployment locations, time periods, and data products available in ONC's extensive data archives. The map interface supports zoom-pan-scroll on networks and deployment locations, revealing the full density of deployments as users zoom to specific areas.

Targeted Search

The application's main use is for the case where users have specific locations, time periods, instrument sources or data types in mind, and wish to perform targeted searches to obtain specific data products.

On-Demand Data Product Generation

Ocean Networks Canada's 299+ data product types are all available for request and download via the Data Search application. Some of these products are retrieved directly from the file archive, while many are generated on demand, according to user-specified processing options.

Metadata

Upon fulfillment of every data request, an accompanying metadata file is generated, which includes information about instrument, sensor, date, time, geographical location, depth, and provenance of the requested data. Additionally, contact information for data stewards who can assist with data issues is provided.

Data Preview

Overview

Oceans 3.0 Data Preview (**Supplementary Figure 17**) displays visualizations of data from various time periods, including the previous 24 h, 30 days and over all time. As of 2021, approximately 8600 pre-generated data products were produced

TABLE 2 | Major user-facing Oceans 2.0/3.0 applications with principal uses and original release years.

Application	Purpose	Original Release
Data Search	Search, request, download data products	2009
Plotting Utility	Interactive visualization of scalar data	2009
SeaTube Pro	Search and playback of underwater video imagery	2010
Annotations Search	Queries for annotations associated with infrastructure assets and data streams	2010
Hydrophone Viewer	Search, display, download spectrograms of hydrophone data	2014
Data Preview	Display pre-generated data product visualizations	2015
SeaTube V3	Annotation, search and playback of underwater dives	2019
Dashboards	User-configured display of data widgets	2020
Geospatial Map	Browse, preview and download some types of data via map interface	2020

by daily scheduled jobs (the exact number varies). All products can be accessed via permalink and direct file requests in the API.

Use Cases

At-a-Glance Summary

Data Preview visualizations allow users to quickly review recent conditions and trends for locations and measurements of interest. These previews can be bookmarked (**Supplementary Figure 18**) for ease of sharing and single-click access. All displayed plots can be enlarged and downloaded to the user's computer.

For every time series plot, associated sensor and instrument metadata are provided in a summary tab (**Supplementary Figure 19**), listing the sensor(s) used to produce the data, listings for each instrument deployed at the location over time, and direct links to interactive plots for each associated variable (generated within the Oceans 3.0 Plotting Utility application).

State-of-the-Ocean Plots

These all-time summary plots of down-sampled data indicate trends and anomalies over the entire time period of data collection from a location.

Animated Loops

Some data products display a series of gif images that are animated and controllable to indicate changes over time. An example is the set of animations showing surface current magnitude and direction, as detected by coastal radar array systems.

Plotting Utility

Overview

Oceans 3.0 Plotting Utility (**Supplementary Figure 20**) is an interactive plotting application for visualizing scalar measurements in the data archive. The application allows users to plot data over time (**Supplementary Figure 24**), zoom in/out over time, change plot formats, specify display of minima/maxima and averages, and overlay data in different dimensions to compare variations over time. Logged-in users can also save and share plots via permalinks for 1-click access.

Use Cases

Interactive Visualization and Exploration of Scalar Data

Plotting Utility allows users to interactively visualize explore scalar data in the Oceans 3.0 database, plotting values as zoomable time series. Hovering the cursor over plotted values reveals a dynamic readout of exact values, dates and times. The plot is expandable and includes a clickable legend enabling users to hide/reveal data averages and min-max envelopes.

An Options dropdown menu allows users to choose between raw or clean source data (the QA/QC option), generate a PNG image of the plot, view numerical values of plotted data (**Supplementary Figure 26**, generally decimated from the full source dataset), configure plot properties (**Supplementary Figure 25**) and toggle the plot legend display.

Comparative Analysis of Overlaid Data

Multiple curves, either from different sensors on the same instrument or from different instruments, can be combined into single plots, enabling comparative analysis of variables over time, as illustrated in **Supplementary Figure 21**, Plot 1 and Plot 4.

Saving and Sharing Plots

Defined data time series plots can be saved by logged-in users within the application. These plots can then be retrieved as menu items in the Saved Plots tab of the interface. They may also be referenced via unique sharable permalinks or *Reference Links*, as shown in **Supplementary Figure 22**.

Displaying Live Data Streams

This application can be used to display near real time data readings from non-autonomous instruments. By selecting a relatively short time period for display (e.g., last 24 or 2 h), and setting Auto Refresh interval (illustrated in **Supplementary Figure 23**) to a desired frequency (e.g., every 15 s or 60 min), the displayed plot will be configured to automatically regenerate, with latest data values appearing on the right side of the plot.

SeaTube Pro and SeaTube V3

Overview

SeaTube Pro and SeaTube V3 (**Supplementary Figures 27, 28**) are streaming video player applications that display video from fixed cameras on ONC's networks as well as live and on-demand dive video from ROV cameras during maintenance and scientific expeditions. SeaTube Pro (first released in 2010) is a fully functional legacy application, which will eventually be deprecated. SeaTube V3 (first released in 2019) was an entirely new rebuild of the original application with enhanced capabilities and an improved UI. Both SeaTube applications are customized for creating, searching, and displaying annotations, comments associated with entries in published or custom taxonomies, and with other properties and events observed when the annotation was created. Annotations are described in more detail below, in section User-Contributed Content.

Use Cases

Dive Logging

One of SeaTube's primary use cases is to provide a record of expedition dives. Dive loggers working both on the expedition vessel (as shown in **Figure 9**) and on-shore watch the live ROV video stream in the SeaTube video player, and annotate engineering events as well as biological observations. For maintenance operations, annotations describe what actions were taken by the ROV operators. Authorized users are presented with a form to add or edit annotations. Annotations created here can include a taxon from several external taxonomies (WoRMS, WoRDSS, and CMECS) and custom internal taxonomies. An annotation with a taxon from an external taxonomy is displayed with a link to the taxon's details on the taxonomy's website.

Searching for Video

Video events can be found either by browsing, or by searching through annotations. Both SeaTube Pro and SeaTube V3 provide navigational tools for browsing by organization, expedition and dive. As of May 2021, SeaTube contained video from 1400 dives across 160 expeditions by ONC, NOAA, Ifremer and Fisheries and Oceans Canada. SeaTube Pro also includes a geographical tree menu for navigating to recordings from fixed-location cameras.

Videos from one or more expeditions can also be found by searching annotations. Annotations can be searched by comment text, author, taxonomy and taxon, and other attributes. The user can navigate from the search results directly to the video at the point the annotation was entered.

SeaTube Search (shown in **Supplementary Figure 29**) enables discovery of annotations from one or more expeditions. A user can constrain the search by selecting one or more dives, annotation authors and editors, searching for taxons from any supported taxonomy, or specifying comment text. After running the search, the user can switch to the video player and jump to the time of an annotation by clicking in the search results. Users can export search results to CSV or JSON, and can include snapshots of the video at the time of each annotation.

Managing Attributes and Taxonomies

Management tools allow dive administrators to customize SeaTube. Taxonomy Management allows creation of custom taxonomies from user-defined taxons or ones imported from CMECS, WoRMS, or other users' taxonomies. Attribute Management allows users to configure custom attributes (e.g., *depth, description, count*) to be attached to annotations or associated with taxons. These functionalities are described in detail in section User-Contributed Content.

Hydrophone Viewer

Overview

Oceans 3.0 Hydrophone Viewer (**Supplementary Figure 30**) allows users to browse visually through spectrograms representing passive acoustic data gathered from hydrophones. Visual patterns and signatures of acoustic events can be identified in these spectrograms and the associated data files can be downloaded directly from the Hydrophone Viewer interface.

Use Cases

Browsing Spectrograms

The main use of this application is for visually browsing through spectrograms, 1 day at a time. The table of 5-min spectrograms is scrollable and individual spectrograms enlarge/shrink on click to reveal more visual detail. Not all types of acoustic events are indicated by the default rendering parameters for these spectrograms, but many periods of acoustic activity can be more quickly identified by the trained eye for download and more in-depth inspection.

Downloading Hydrophone Data in Various Formats

Where available, archived hydrophone data can be downloaded in a selection of audio (WAV, FLAC, MP3, HYD) and spectral (PNG, PDF, FFT) data product formats. This shortcut is an alternative to downloading data via the Data Search application.

Searching for Annotated Hydrophone Data

For hydrophone data streams that have been annotated (whether manually or via automated algorithms) a simple search tool allows users to find specific 5-min periods associated with specific annotations.

Dashboards

Overview

Oceans 3.0 Dashboards provide an intuitive interface for creating displays of Oceans 3.0 data organized in ways that make sense to a user. It supports the display of time series, video and other data formats using a widget-based interface. A variety of users benefit from Dashboards functionality including experienced ONC staff members, who create their own custom displays for monitoring data, or educators wanting to highlight various data for their students.

A dashboard is defined as a visual tool providing an at-a-glance overview of a set of data. A widget is defined as an independent visualization of data that can be placed onto a dashboard.

Use Cases

Monitoring Data Streams

One use case is support for monitoring specific instruments. ONC staff members need to confirm their instruments are performing properly, Dashboards help them by displaying data from multiple instruments with different types of data on one page.

Community Pages and Displays

Another use case is to support simple creation of pages displaying highlights of community observatory data. A dashboard can also

FIGURE 9 | ONC dive loggers observing operations from the computer lab aboard the R/V Thomas G Thomson, 9 September 2015. Pictured from left: Ross Timmerman, Fabio C. De Leo, Reyna Jenkyns.

be used as a display in an educational or visitor facility to support exploration of selected data.

Sharing a Dashboard or Widget

A dashboard can be shared with another Oceans 3.0 user in read-only mode by specifying the user's email address. In addition, a dashboard can be published where it will be visible to any user. It is also possible for logged-in users to share individual embeddable widgets. Widget types are listed in **Supplementary Table 3**. Each widget within a dashboard includes a hover link that displays embeddable iframe code that may be included in external web pages (as shown in **Supplementary Figure 31**).

User-Contributed Content

Annotations

Oceans 3.0 uses annotations to add comments to infrastructure elements and data segments, or to mark data of special interest. Annotations consist of metadata attached to system resources: physical entities (instruments, topology connections, remotely operated vehicles), logical connections, events (dives or expeditions), and data products (instrument data, audio, video, plots). An annotation includes form-based content, its author, and the resource and time range to which the annotation applies. The fields available for an annotation's content are specific to the context in which the annotation is created and can be customized by administrators. These fields can include free text, selection and multi-selection from custom dropdown lists and trees, checkboxes and radio boxes, and entries from external taxonomies including WoRMS and CMECS.

Annotations are stored in the main relational database, with links to their annotated resource, allowing users to efficiently search for annotations and data according to resource type, resource, creation time and the contents of the annotation's form's fields. For example, a user could search for all annotations on a certain instrument's data, or for all annotations denoting *ship noise* in hydrophone data.

Annotations of scientific interest on instrument data are most often created by experts logging dive video, by citizen science users, and by AI tools that classify and identify patterns in data streams, such as whale calls in hydrophone data.

Digital Fishers

Citizen scientist annotations are created through the Digital Fishers web application (**Supplementary Figure 32**), a tool for crowd-sourcing the annotation of video data. A citizen user of Digital Fishers watches a series of short (typically 15-s or 1-min) video clips, and annotates each clip according to a custom vocabulary specific to the campaign, for example, by dropdown selection of the water visibility, sea floor type, presence of certain fish species and presence of any other objects. Context of the current video clip is provided in a sidebar with the date of the video and the latitude, longitude, depth, and a map showing the location of the camera.

More experienced users are provided with a more detailed vocabulary to choose from when annotating clips; where a new user selects from "flat" or "uneven" to describe the seafloor, a more experienced user is provided a structured hierarchy of terms to indicate the presence of methane hydrates, biogenic structures (sponges, corals, etc.), bubbles, mineral structures (carbonates, black smokers, etc.), and soft bottom structures (sediment, pits, etc.).

To encourage user engagement, Digital Fishers includes several game-like features that are unlocked based on the number of video clips the user has annotated. After certain numbers of annotations are contributed, they unlock a *card* with information about, and an illustration of, a marine species (example shown in **Supplementary Figure 33**). Every five cards, the user reaches a new *level* (five levels exist), providing them with a more complex vocabulary. A tutorial appears when each level is unlocked to introduce the user to new terms, and can be reviewed while playing. A user always has the option of operating as a lower-level user in order to annotate using the simpler vocabulary. Digital Fishers shows a leaderboard listing the people with the highest daily and all-time numbers of annotations submitted.

Videos in Digital Fishers are organized into campaigns, which are created and managed by scientists and network administrators. The campaign creator writes a mission statement describing the campaign's science goals (example in **Supplementary Figure 34**), and selects the annotation form and video clips to be used. Video clips are selected either by manually creating a list of segments by camera ID and time range, or by linking to a SeaTube playlist. A campaign is normally enabled during a date range specified by its creator, and can be enabled or disabled manually.

Digital Fishers tracks statistics about each campaign, which can be made available to administrators and campaign creators, providing breakdowns of the citizen users creating annotations and numbers of annotations and views of each clip.

Matabos et al. (2017) presented results of a campaign that compared crowd-sourced annotations with those produced by an expert fisheries biologist and an automated computer algorithm. Researchers found that volunteer annotators, with little prior experience, could with training and practice attain identification accuracies comparable to those of the expert. This study demonstrated the value of a hybrid combination of crowdsourcing and computer vision techniques as a tool to help process large volumes of imagery in support of basic research and environmental monitoring.

SeaTube

The SeaTube video player (described in section "Data Discovery and Access") allows users to view and annotate dive video recorded from Remotely Operated Vehicle (ROV) cameras during ONC's maintenance expeditions and NOAA's scientific expeditions. Additionally annotations can be made for video recordings from fixed cameras on ONC's networks. Expedition vessels typically do not have sufficient space for a full complement of scientific staff annotating the at-sea activities, and some of the logging needs to be performed on-shore. In order to support real time on-shore dive logging, live low-resolution video is streamed via satellite from the ship. Annotations are recorded by observers both at sea (from one or more expedition vessels) and on shore, and are collated together by an asynchronous messaging system, which ensures that annotations and other sensor data recorded on ship are archived even when the ship loses its Internet connection. The Oceans 3.0 video distribution and acquisition framework is illustrated in **Figure 10**. The data flow between multiple ships and shore-based systems is illustrated in **Figure 11**.

Observers annotating dive video in SeaTube are not restricted to the limited taxonomies used by citizen science users in Digital Fishers; instead, annotations can include taxons from scientific taxonomies (such as WoRMS for scientific annotations, shown in **Supplementary Figure 35**) and task-specific taxonomies (for example, for engineering annotations on maintenance expeditions).

Users also have access to predefined button sets to quickly create annotations, as shown in **Supplementary Figure 36**. Annotations created in SeaTube are linked to specific time stamps in the video.

Community Fishers

Community Fishers is a citizen science program that partners with First Nations and other communities and organizations to gather water profile measurements from their vessels for their ocean monitoring programs. The Community Fishers crews are equipped with a Conductivity-Temperature-Depth (CTD) instrument and an accompanying Android tablet running custom data acquisition software, as shown in **Figure 12**. Most CTDs support additional sensors as *piggy-backs* including oxygen, turbidity and chlorophyll sensors. The instrument sets are calibrated by the manufacturer and validated by ONC before initial distribution to community partners. They are subsequently validated annually and recalibrated when necessary. ONC conducts a rigorous initial training program and provides ongoing support to partners, in order to ensure higher quality data collection and prevent potential damage through misuse.

Each CTD device is typically deployed using a downrigger on a stationary vessel to lower the device through the water column to the seafloor, then retrieve it. After recovery, collected data are transmitted to the tablet via Bluetooth. Once the tablet comes within range of a WiFi network, the data are then uploaded to an FTP server on the ONC data acquisition framework. From this point forward, the process goes through the standard stages of parsing, calibration, QA/QC and packaging, as outlined in section Data Acquisition and Archival.

The Android app (screen capture shown in **Supplementary Figure 37**) has been designed as a turnkey system, with the aim of making it easy to use by non-technical operators on the water. The app reminds users to do things such as confirm GPS signal strength (or hand enter the latitude and longitude) and remove the cap on the oxygen sensor before deployment.

Data profiles are usually collected within predefined octagonal geospatial locations. In some instances, profiles are made in locations outside the area octagons, requiring location assignment by a data specialist.

After transmission to the shore system for processing, custom algorithms are used to find the relevant part of the data record; usually this is the downward moving *cast* through the undisturbed water. The software then analyzes the down-cast, collecting and averaging groups of readings into 1m pressure bins, which are used to create data profiles by calculating variables over depth. Data quality issues such as pauses in the down-cast, improper speed of lowering and ship heave are also detected and corrected by the software.

Geospatial Map

Data collected via the Community Fishers citizen science program can be accessed via the Oceans 3.0 Data Search

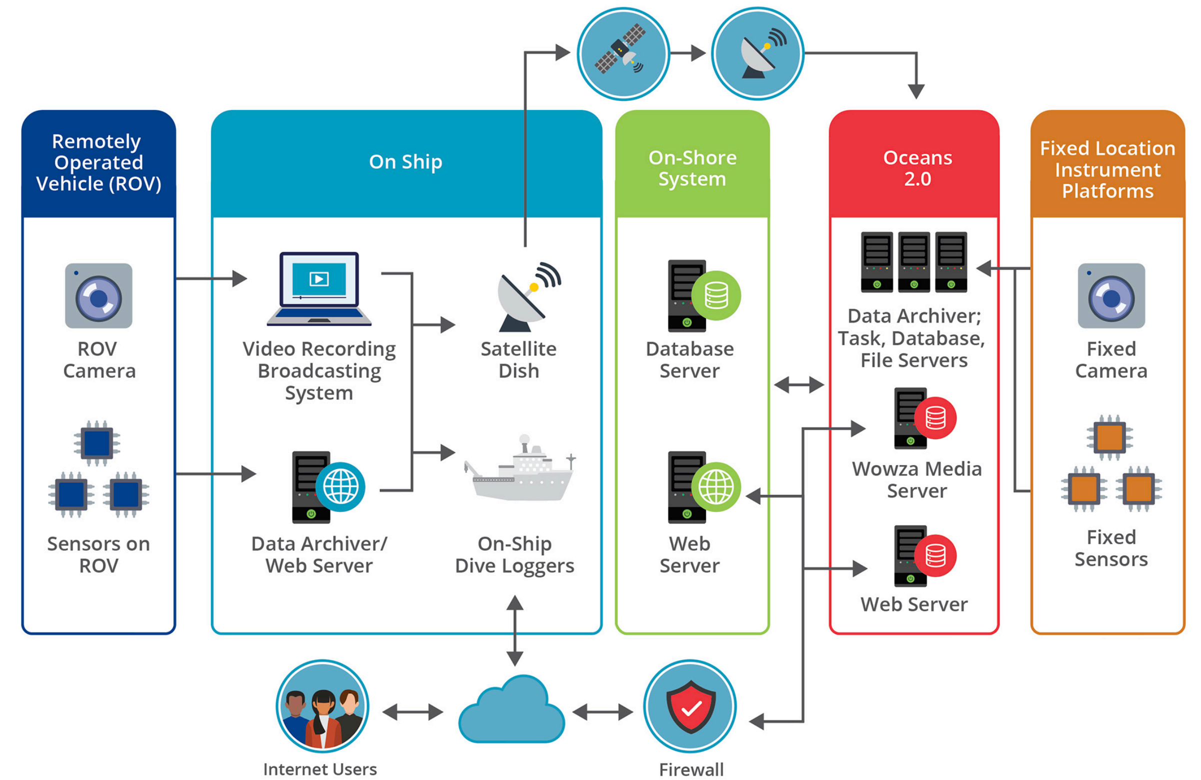

FIGURE 10 | Oceans 3.0 video data acquisition and distribution system. The two blocks at left illustrate video and data flow from the Remotely Operated Vehicle to on-ship systems. On-ship loggers write annotations during dives while connected to the on-ship system. The low-res video, sensor and annotation data are transmitted via satellite from ship to the Oceans 3.0 Data Acquisition Framework (DAF). Video and camera data also flow from fixed camera systems via cabled networks into the DAF (box at right). Web and media servers within shore stations and the ONC data center distribute video streams, sensor data and annotations to the cloud. Loggers who are not on ship can watch the real time video stream and contribute annotations that are time stamped and collated with ship-based annotations.

application, via the API and via Geospatial Map, a specialized application designed for preview and download of cast data. The interface was designed for use in bandwidth-limited locations and combines several methods for reducing bandwidth requirements, including the use of OpenStreetMap for the map background (this mapping platform is lighter and quicker to load than many others) and a *lazy loading* strategy, in which data plots are not loaded into the interface until selected by the user.

When the user clicks within an octagonal cast area, a pop-up window appears (illustrated in **Supplementary Figure 38**), displaying zoomable pre-generated thumbnail profile plots to reduce loading time. From there, the user may drill down into the full history of casts for a location and download cast data in text format, as shown in **Supplementary Figure 39**.

PROGRAMMATIC USE

Application Programming Interface

Oceans 3.0 includes a publicly accessible API, allowing users to access Ocean Networks Canada data via user-defined code. This API is guaranteed to be backward compatible and provides a number of RESTful (Fielding, 2000) services to discover and download data (Extensive details on these services are provided in the Oceans 3.0 public wiki[2]).

The services in the API are split into two groups: (1) Discovery and (2) Delivery.

Discovery Services

The purpose of Discovery services is to enable users to uncover terminology, organizing concepts and domain language used to structure data within the archive. Users can query the terms and infrastructure constructs used by Oceans 3.0, including:

- *Locations,*
- *Deployments,*
- *Devices,*
- *Device categories,*
- *Properties,* and
- *Data products.*

Each discovery service supports a set of filters with standardized codes; this makes it possible for the outputs of one service call to be used as filters for a subsequent call. These same codes can then be used in a delivery service to download data.

[2] https://wiki.oceannetworks.ca/display/O2A/Oceans+2.0+API+Home

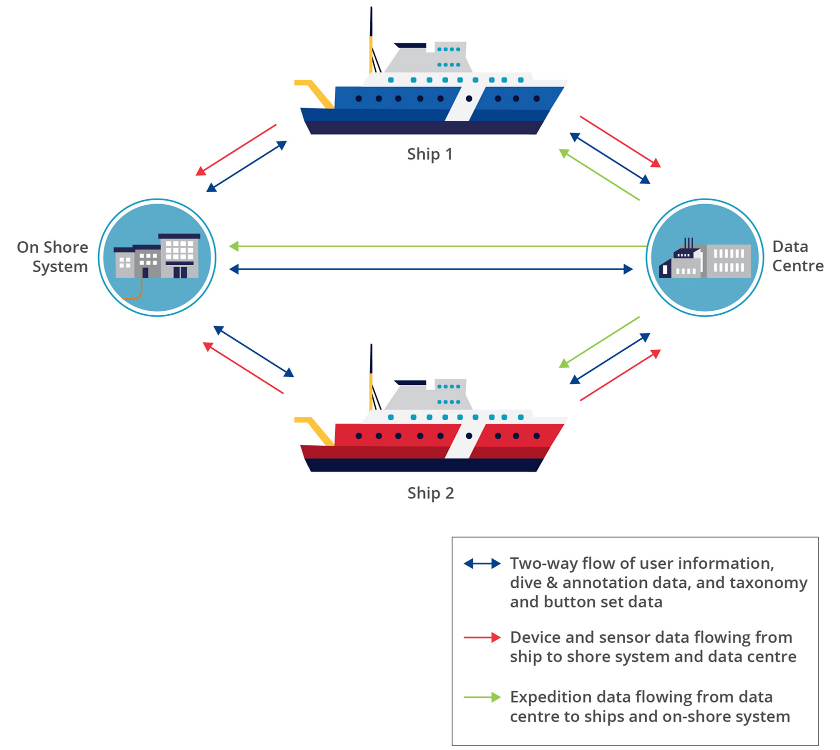

FIGURE 11 | Data flow between ships, the on-shore system and the data center. The SeaTube annotation system supports simultaneous annotations and data streams from multiple ships and shore-based loggers. There is a two-way flow or user information, dive and annotation data and taxonomy and button set configurations. Device and sensor data flow from ships to both the on-shore system and the data center. Expedition data flows from the data center to the ships and the on-shore system.

FIGURE 12 | Citizen scientists use ONC's Community Fishers app to collect oceanographic data within Pacheedaht First Nation waters in the Strait of Juan de Fuca, January 2020. Pictured from left: Tammi Peter, Leon Jones, Guy Louie. Leon Jones holds the Conductivity-Temperature-Depth (CTD) instrument used to collect readings, while Guy Louie holds an Android tablet with customized data acquisition software.

Example Discovery Calls
Devices service call to retrieve a list of all devices at the Barkley Hydrates location (locationCode BACHY):

- https://data.oceannetworks.ca/api/devices?method=get&locationCode=BACHY&token=YOUR_TOKEN_HERE

Locations service call to retrieve a list of all locations with a fluorometer (deviceCategoryCode FLNTU):

- https://data.oceannetworks.ca/api/locations?method=get&deviceCategoryCode=FLNTU&token=YOUR_TOKEN_HERE

Deployments service call to retrieve a list of all fluorometer deployments (deviceCategoryCode FLNTU) in the Barkley Canyon Axis location (locationCode BACAX):

- https://data.oceannetworks.ca/api/deployments?method=get&deviceCategoryCode=FLNTU&locationCode=BACAX&token=&token=YOUR_TOKEN_HERE

DataProducts service call to retrieve a list of all data product types available for fluorometer data (deviceCategoryCode FLNTU):

- https://data.oceannetworks.ca/api/dataProducts?method=get&deviceCategoryCode=FLNTU&token=&token=YOUR_TOKEN_HERE

Since multiple instruments or devices may be deployed to the same location over time, the API also supports calls to query specific oceanographic variables or properties over time at a location. The software then stitches together measurements of the same property across different devices deployed over time at the specified location.

Example Property Calls
Properties service call to retrieve a list of all properties measured by a particular CTD (deviceCode SBECTD16p7028):

- https://data.oceannetworks.ca/api/properties?method=get&deviceCode=SBECTD16p7028&token=YOUR_TOKEN_HERE

Properties service call to retrieve a list of all properties measured at the Barkley Hydrates location (locationCode BACHY):

- https://data.oceannetworks.ca/api/properties?method=get&locationCode=BACHY&token=YOUR_TOKEN_HERE

Delivery Services

The Delivery services are the methods used to request and obtain data. There are synchronous, asynchronous and direct delivery variants. The synchronous services support immediate delivery of scalar and raw data obtained from the real time acquisition system, whereas the asynchronous services support delivery of highly processed and/or large amounts of data.

Synchronous Delivery Services
Two synchronous services, *scalardata* and *rawdata,* return data in the response payload, supporting near real time access. Both services are designed around the *chunking* delivery pattern where the return is limited in size and provides the parameters to get the next *chunk*; the size is set to 100k records and 100 MB by default (whichever is exceeded first). The client iterates through the manageable chunks accumulating data. These services are provided by the task machine pool through a load balancer (this is a very recent change). These services have the option to request the latest data, while the *scalardata* service also offers resampling and aggregation.

Scalardata
Within Oceans 3.0 nomenclature, the term *scalar* is used to refer to simple data values, e.g., a temperature value from a specific time and location. Scalar data are stored in the Cassandra no-SQL database as tabular data. The *scalardata* service produces a JSON payload containing data values pulled from this database. Here is an example call to retrieve scalar data in JSON format from a specific Sea-Bird instrument (deviceCode SBECTD19p7027):

- https://data.oceannetworks.ca/api/scalardata?method=getByDevice&deviceCode=SBECTD19p7027&token=YOUR_TOKEN_HERE

Rawdata
This service retrieves unparsed, unprocessed raw data produced by instruments. This could be recently acquired data that have been stored temporarily in the Cassandra database or daily compilations of data that have been written into raw log files stored within the Oceans 3.0 Archive Directory file server (see section "Data Acquisition and Archival" for more background information on data storage).

Archivefiles
The *archivefiles* service allows users to search for available files in a location or from a particular device and download them. All types of files are accessible, including those acquired via file acquisition such as FTP, processed data products, etc. The *getListByLocation* method produces a list of data files for a given location code and device category code. The *getListByDevice* method produces a list of data files from a specific device. The lists generated by these two methods can then be parsed into individual files that may be retrieved via the *getFile* method.

Client Libraries

Ocean Networks Canada also provides client libraries for MATLAB, Python and R which wrap the service calls and simplify access to discovery and delivery services. Depending on the language required, these libraries are available using the appropriate public repository, for example, PyPi for the Python library.

Asynchronous Delivery Service – DataProductDelivery
The *dataProductDelivery* service mirrors the 3-step process used in the Oceans 3.0 Data Search application (see section "Data Discovery and Access") to specify a data request, run the request and then download the resulting data products. Thus, three

methods are provided: *request*, *run* and *download*. When making a *request* call, the user specifies device sources, time periods, data products and processing options. The method does not generate data in this first step, instead it validates the parameters and generates a new request ID. This request ID is then used for the second *run* method, which starts the data product generation process by adding the request to the Oceans 3.0 task queue and generating a new run ID. Finally, the download method uses the run ID to obtain the status of the run, whether *canceled*, *queued*, *error*, *running* or *complete*. Once the status has been set to complete the requested data product files can be downloaded from the FTP server.

User-Defined Tasks

Overview

Ocean Networks Canada users often want to perform their own processing on Oceans 3.0 data. However, the amount of data required for processing may be very large, requiring a lengthy time period for download to the user's environment. In order to minimize download time, Oceans 3.0 supports running the processing "close to the data" via user-defined tasks. "Close" refers to a minimized amount of time required to obtain data and make it available for processing.

User-defined tasks are run in a scalable cloud computing environment internal to ONC that enables users to upload and run their scripts (programs using Oceans 3.0 data) on ONC servers. This enables faster and more efficient data access which is particularly important for high-volume data such as acoustic or video data. Programs can be written in any of several languages including C/C++, Python, MATLAB, or R, and can be either scheduled or run on-demand. A user-defined task environment includes the Oceans 3.0 client libraries pre-installed, as well as other commonly used libraries such as the SciPy/NumPy scientific computing stack in Python. This set of libraries enables users to perform their desired scientific computing operations simply by calling the appropriate functions in their scripts. Oceans 3.0 includes system health monitoring features, including alerts for system admin staff when system resources are overloaded. The task machine pool can also scale to handle additional user-defined tasks, search requests and other processing as needed.

Users' Code

The most important ingredient of a user-defined task is a user's code. As a first step, users are advised to experiment, develop and test their code on their own machine with the supported languages, emulating the operational environment, while working with small amounts of downloaded data. Users need to make use of the Oceans 3.0 API, optionally through the client libraries.

Once the user's code has been developed and tested, the next recommended step is for the user to upload this code into the sandbox environment, where access to larger datasets is optimized. Both the user's development environment and the user-defined tasks runtime environment work the same way: data are downloaded to the working environment via the API, but that download is much faster within the ONC server environment.

User-Defined Tasks

When execution is transferred to the ONC server environment, the user's code is defined as user-defined tasks (example shown in **Supplementary Figure 40**) that are created using Oceans 3.0 Task Management interface (see section "Data Acquisition and Archival" for more on the Task Management interface). For each task, the user chooses the language used, uploads the source and any accessory files, provides the command to run the code and saves the task.

Running a User-Defined Task

Once the user-defined task has been created it can be run from the same screen. The status of the task can be monitored from the Task Management tab. Once the task is complete the results can be viewed in User's FTP Directory, which is also where search results and all products for users are stored (accessible via a link in the Oceans 3.0 main menu.) The results are organized under a directory with the task name. Depending on whether the task was run with the unzipped flag set to true or false the files generated by the task will either be stored in a data folder or in a.tar file.

Hydrophone Use Case

Hydrophones continuously collect data at very high rates over broad frequency ranges, resulting in very large data archives for each instrument. This data volume is compounded by the installation of tetrahedral hydrophone arrays, with four co-located instruments, which are used for directional location and tracking of sound sources such as ships or whales. For researchers wishing to analyze patterns or trends across multiple hydrophone arrays and over long time periods, data download becomes extremely impractical.

An example application might be searching through tens of thousands of hours of hydrophone recordings, using a classification algorithm to identify specific marine mammal call types. Another example could be the analysis of many months or years of hydrophone data in order to characterize the marine soundscape at a location. For applications such as these, the use of user-defined tasks running in the ONC server environment is the only practical approach.

Interoperability

When designing Oceans 3.0, ONC wanted to build a system that addressed the key requirements of Open Data, providing freely available, easily accessible data. When the FAIR principles (described in section "Metadata") were later formulated in the global data management community, they aligned well with Oceans 3.0's built-in support for Open Data allowing ONC to deliver data that are:

- *Findable*, through development of comprehensive search tools enabled by the underlying metadata structure.
- *Accessible*, through simple download of raw data or data products but also through visualization tools. This is the most developed user-facing aspect of Oceans 3.0.
- *Interoperable*, as a result of considerable efforts to make data shareable and usable by other third party analysis systems and tools. Interoperability starts with ONC's approach to managing internal data: the wide variety of supported

different instrument types requires standardization on many fronts such as with respect to timing or data transport formats, as described in section Architecture.
- *Reusable*. Reusability and reproducibility are enabled by a scheme that allows users to exactly specify a dataset and trace all alterations over time (e.g., re-calibration). To this end, Oceans 3.0 now implements citable, permanent Digital Object Identifiers attached to a unique version of a data segment (These are described in section Persistent Identifiers and Data Citation).

RESTful Web Services

In general, the Oceans 3.0 API strives to be *RESTful*, adhering to the REpresentational State Transfer (REST) software architectural style (Fielding, 2000). RESTful web services feature JSON or XML responses that are self-describing and contain information allowing the client to make sense of the response without prior or specialized knowledge. An interrogating user can explore the parameters and methods offered without too much difficulty. The Oceans 3.0 discovery services are a good example of this. Client code can also easily handle various contingencies as the responses are information rich.

Sensor Observation Service

In 2018, following a surge of interest in the Internet of Things (IoT) concepts and technologies, there was a strong motivation to provide Sensor Observation Service (SOS) interfaces for the various scalar instruments on the ONC infrastructure. This resulted in an effort to implement such compliant services with the help of SensorUP, a spinoff from the University of Calgary and advice from groups in Germany (in particular[3]). The services, including *GetCapabilities*, *DescribeSensor*, and *GetObservations* are still available and supported by Oceans 3.0 (Canarie Research Software, 2018). At the time of this writing, the 28-day availability rate for these services was 99.7%.

PERSISTENT IDENTIFIERS AND DATA CITATION

The current trend toward improved transparency and reproducibility in science is pushing researchers and institutions to develop new strategies for managing the data they produce. Increasingly, publishers insist on access to the datasets underpinning submissions (Ferguson et al., 2018), and national funding agencies are establishing policies (ESIP Data Preservation and Stewardship Committee, 2019) requiring the open sharing of data as a condition of awarding grants. These changes are driving the creation of new tools to ensure data are findable, accessible, and reusable and remain so into the future.

Persistent identifiers provide a long-lasting reference to a digital resource, including entities like articles, datasets, individuals and more. Depending on the entity, different types of identifiers, registries, relationships and accompanying metadata are typically used. A citation for the resource should follow established community conventions, including a reference to the persistent identifier.

Ocean Networks Canada has integrated persistent identifiers for datasets and organizations, with plans to expand to other entities in the future. For datasets, ONC is using DataCite Digital Object Identifiers (DOIs). For organizations, ONC is using Research Organization Register (ROR) identifiers. It is anticipated that more identifier systems will be integrated into Oceans 3.0 over time, especially those that are mature (Ferguson et al., 2018) and applicable to ONC.

Dynamic Data Citation

Persistent identifiers are relatively straightforward to create for static objects, such as a published paper or complete dataset. It is more difficult to affix identifiers to dynamic data that change over time, like ONC's continuously accumulating data streams, as the dataset is constantly evolving. To reliably and reproducibly cite dynamic data requires more detailed information about specific subsets of the data, such as the exact date and time the data were retrieved, and any search parameters used in selecting a particular subset. A new DOI is allocated for new versions of a dataset, along with provenance metadata that describe the reason and extent of the change. Even if preserving all previous versions of all data is beyond any institution's storage capacity, the landing page will remain available and will indicate relationships to any subsequent versions.

In February 2015, the Research Data Alliance (RDA) Working Group on Dynamic Data Citation released a set of 14 recommendations to guide best practices for persistently and reproducibly identifying these kinds of dataset. The recommendations rest on 3 pillars:

1. *Versioning*: Major changes to a dataset are marked with a new version number.
2. *Timestamping*: Queries made to the database are saved along with metadata about exactly when and how they were made.
3. *Query Preservation*: Persistent Identifiers (PIDs) are assigned not only to the whole dataset, but also to each time-stamped query used to extract a particular data subset from the repository's database.

Combining these strategies, it becomes possible to refine the parameters of a dataset until they exactly match its state when previously retrieved. New version releases mark changes to the dataset, whether to the data values or the ways in which they were processed. Finally, assigning a persistent identifier to each individual query – an actual data request sent to the database – allows previously accessed subsets to be re-created with ease, eliminating the need to painstakingly replicate complex search parameters by hand. ONC's solution represents one of the pilot implementations of these RDA guidelines (Rauber et al., 2021).

Data Set Landing Pages

Oceans 3.0 has implemented dataset landing pages, as shown in **Supplementary Figure 41**, that describe the high-level metadata associated with a dataset. Within this implementation, a dataset

[3] 52North.org

is defined as one deployment of one device, e.g., *Aanderaa Optode 3830 (S/N 911) deployed at Folger Passage on 11-Sep-2015, recovered 02-May-2017*. These dataset landing pages are linked and discoverable through the Oceans 3.0 User Interface.

Research Organization Registry

The Research Organization Registry (ROR) allocates unique, persistent identifiers to research organizations, much like ORCIDs for individual researchers. For example, the ROR ID for ONC is https://ror.org/05gknh003. As of August 2021, over 100,000 ROR IDs have been assigned since the registry launched in January 2019.

Persistent identifiers like ROR IDs ensure that research contributions are correctly attributed, by disambiguating entities which may be known by different names. When used within the scholarly communications and publication ecosystem, ROR IDs improve discovery, tracking, and linking of research outputs across platforms, organizations, and funders. RORs support the trend toward ensuring credit is given to all parties involved in producing research outputs but have been left out of traditional citations, such as funding bodies. When ONC mints a DataCite DOI for a dataset, the attribution metadata is associated with the ROR. In addition, attributions in the ISO 19115 metadata record (within the MD_DataIdentification class) also include the ROR details.

Dataset Citation

For data citations, ONC adheres to the ESIP Data Citation Guidelines for Earth Science Data, Version 2. The Oceans 3.0 Dataset Landing Page provides the specific citation text. For users or machines, Oceans 3.0 has also implemented a citation web service that returns citation text for a given DOI or Query PID, as illustrated in **Supplementary Figure 42**.

Linked Data and Repositories

Linked data are provided by frameworks for relationships between ONC's Oceans 3.0 datasets and other repositories or harvesters. The value of these relationships is to enhance discoverability of ONC datasets, as well as to provide enriched contextual metadata and complementary data resources. Elements that facilitate linked data include web services, metadata catalogs, and persistent identifier relationships. While ONC has direct involvement in facilitating some relationships, any harvester can leverage these utilities to incorporate ONC content as long as they adhere to licensing and restrictions.

As contributors to the Canadian Integrated Ocean Observing System (CIOOS), ONC uses a CKAN metadata catalog and ERDDAP system as a means for the CIOOS portal to harvest and provide access to these datasets. Once metadata records are available within CIOOS, they are harvested again by the Federated Research Data Repository (FRDR). Other portals where ONC metadata or data are made available include the Polar Data Catalogue, Listening to the Deep Ocean Environment[4] and Northwest Association of Networked Ocean Observing Systems (NANOOS).

In some cases, ONC is involved in data collection that may have all or part of the data archived with a partner institution. For example, some of the seismic instruments deployed on the NEPTUNE observatory have data streams feeding directly into the Incorporated Research Institutions for Seismology (IRIS). The corresponding metadata are provided by ONC, and the IRIS web services are used to retrieve the data from the Oceans 3.0 Data Search. Another example is a partnership with Ocean Tracking Network (OTN), whereby acoustic receiver data from ONC platforms are originally retrieved and archived within Oceans 3.0, but also shared with OTN who maintain the records on detected acoustic tags.

In other cases, ONC harvests data from other repositories where it may add value to ONC services. Examples include using web services to harvest from the Pacific Northwest Seismic Network (PNSN) for integration with ONC's earthquake detection algorithm, and from the Canadian Coast Guard for vessel tracking applications based on Automatic Information System (AIS) data.

ADVANCED FEATURES

Event Detection and Reaction

One of the key advantages of a real time sensor network infrastructure is the added ability to monitor, detect and react to predetermined events. Early this century, as the Ocean Networks Canada research infrastructure was envisioned and designed, the ability to include an event detection and reaction feature was part of the requirements. Although some initial ideas and suggestions were mentioned, no specific applications were identified at the outset, pointing to the need for the system to be as open and flexible as possible so that researchers would have the ability to define arbitrary event detection and reaction parameters running against arbitrary combinations of sensors.

This capability has since been implemented and can continuously monitor data streams from multiple sensors, checking whether their values, combined through specific formulas, match or exceed predetermined thresholds. Such a system has to be capable of performing an arbitrary number of such monitoring tasks in parallel for multiple users likely looking for widely varied phenomena.

The first major application of this capability was in support of ONC's instrument data quality control. Here, individual sensor values are continuously tracked for out-of-bounds values to be flagged. This is relatively straightforward for scalar sensors where, e.g., spike detection can be implemented using Short Term Average versus Long Term Average values to identify outliers. But data quality control can also take different forms: newly arrived short video clips from an underwater camera can be subjected to a quick automated examination to determine whether the video lights failed to illuminate as expected, resulting in black images. The detection of empty/black, out of focus or off-target video can trigger automatic QC flagging.

Beyond the use of the event detection system for data quality monitoring, the Oceans 3.0 event detection and reaction system can be used in real time to seek, identify and flag patterns in data

[4] http://listentothedeep.com/

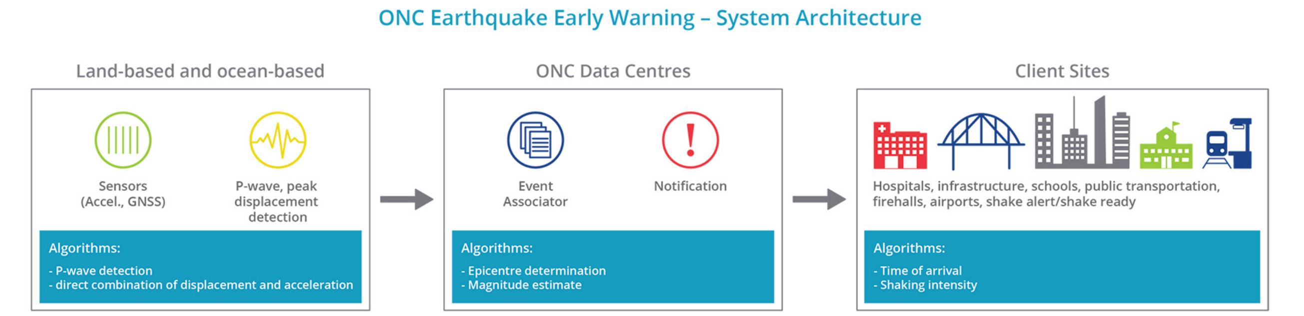

FIGURE 13 | High-level architecture of the ONC/NRCan earthquake early warning system.

streams. Examples are transient temperature phenomena or the identification of marine mammals. In these instances, advanced techniques extending beyond simple deterministic formulas can be used. In particular, data mining/neural network approaches can be employed for real time detection, identification and reaction to specific data patterns, such as is done in hydrophone data streams to detect marine mammals.

An especially complex case of event detection and reaction implemented in Oceans 3.0 is the simultaneous use of a large, geographically distributed seismic and Global Navigation Satellite System (GNSS) network to detect, characterize and alert for earthquakes within seconds of the first detected trigger. The ONC/Natural Resources Canada Earthquake Early Warning System (EEWS) (Schlesinger et al., 2021) was implemented over the course of 3 years and is undergoing a commissioning phase at the time of this writing. It integrates data from over 35 distinct sites where sensors have been installed (including land-based as well as ocean-bottom locations). A distributed processing architecture that fits the Oceans 3.0 approach (see section "Architecture") performs site-based parameter extraction and uses a messaging system to deliver those parameters to redundant data centers where detection, characterization and notification are implemented, as illustrated in **Figure 13**. Once commissioned, this system could provide a lead time of 60 to 90 s for notifying subscribers who implement pre-determined disaster mitigation reactions to impending shaking at their location. During the commissioning phase, a peer review committee was presented with the system description and provided with software details, results, analyses, and continuous improvement/maintenance plans. The committee will meet again at the end of the commissioning phase to provide its final approval. This EEW system will not be used to alert the public but will instead be provided to operators of critical infrastructure in the region who will be in a position to integrate dynamic reaction and alerting into their systems.

Data Mining, Machine Learning and Neural Nets

Generally referred to collectively as *Artificial Intelligence*, data mining, machine learning and neural network systems all seek to offer efficient means of identifying patterns in large data sets. Such systems perform two main functions, for which they use different techniques: detection and classification. In other words, first find "something" of interest (either pre-defined or simply deviating from the norm) and then attempt to determine what it is (typically based on a predetermined list of feature types or by identifying something that does not conform to any known patterns in the match database).

Data collected from real time ocean observing systems are well suited to the application of such techniques. With thousands of sensors reporting measurements every second, the accumulation of data in time series is substantial and quickly exceeds the capabilities of individuals to analyze, even with highly effective visualization tools. No less than 8 orders of magnitude in time scales (from seconds to decades) are present in the ONC data archive, allowing for the analysis of highly varied phenomena, from the random chaotic motion of water around the sensor to the impacts of climate forcing on the environment.

Additional time scales are involved for high sample rate instruments such as seismometers and hydrophones, which record at sampling rates around 100 kHz, resulting in 13 orders of magnitude in time scales after a few years of data collection. Other types of instruments producing time series of complex matrices present unique challenges as well; an example is a video camera producing no fewer than three large 2-D matrices (in red, green and blue wavelengths) 20+ times per second.

One of the first implementations of new data mining techniques in Oceans 3.0 was through the integration of the PAMGuard passive acoustic monitoring system specifically developed for the detection and identification of marine mammal vocalizations. PAMGuard is an open source system designed to provide a standard software infrastructure for acoustic detection, localization and classification of marine mammals, in order to help prevent and mitigate harm to these animals.

PAMGUARD (see[5]) has been integrated into Oceans 3.0, allowing users access to ONC's large library of acoustic data. Users who are familiar with the PAMGUARD software can upload the configuration for detection algorithms created in the PAMGUARD software and use ONC's library of acoustic data as the data source for detection. At the time of this

[5] pamguard.org

writing, the system was being used for whale detection at various locations monitored with ONC's data acquisition infrastructure. Because the PAMGUARD software is run on Oceans 3.0 servers co-located on the same network as the large sets of acoustic data, processing can be much faster than in situations when the user must download the acoustic data for processing.

TRANSITION FROM OCEANS 2.0 TO OCEANS 3.0

Oceans 2.0 was the cornerstone of Ocean Networks Canada since its inception, enabling the data that are collected to hold enormous value for ONC and end users. The time series is now of sufficient duration to observe decadal and climate-scale changes, while at the same time providing low-latency real time data useful for event-driven decision making such as Earthquake Early Warning. The ability to analyze data in the archive quickly and efficiently will help unlock new scientific discoveries.

The ability to have incoming data reviewed for quality by automatic processes and human experts ensures that the archive is fully qualified and supports a data collection process with minimal gaps. Efforts will continue to improve the autonomous characterization of data streams as they arrive onshore, thereby providing new metadata that describe the observations received from the instruments both in terms of their content and trustworthiness.

As ONC entered its 16th year of operations, Oceans 2.0 was growing beyond its original scope. The original user interfaces were expected to support three networks and eight seafloor nodes. Now, the archive includes data from an ever-proliferating list of locations. In the future, a new data discovery portal will be developed to integrate the existing apps, enabling users to find, preview and interact with the data much more easily. User interfaces will be updated to use the new Dashboards infrastructure, incorporating modern sharing and embedding features.

As the data volume continues to expand, outstripping users' ability to download and work on data within their own hardware, data summation and enrichment facilities are becoming increasingly necessary. How data are managed, shared and published is also changing. Publications now require the code and data to be accessible, facilitating the reproducibility of science. Support for persistent identifiers on data has been added recently, while persistent identifiers for code should be added (and extended to physical samples). Internal improvements necessary to support all of the above include geospatial data integration, distributed caching, code modularization, continuous integration processes and expanded automated testing.

Many of the proposed additions and improvements align with web 3.0 concepts (Rudman and Bruwer, 2016). As such, ONC renamed Oceans 2.0 as Oceans 3.0. Oceans 3.0 high level features will include cloud-based interactivity using distributed computing resources, and adding value to the data with artificial intelligence, which will augment and target user contributions and improve data-driven decision making. More specifically, this means better viewing, improved usability/accessibility to the data, improved searching, and more refined data products. Additionally, this entails data summation and event detection and classification by machine learning, plus expanded annotations. Furthermore, ONC is working toward improved functionality of the sandbox, including an expanded public API. After 16 years of operation, Oceans 3.0 will continue to grow through innovation, enabling ocean science and discovery.

DATA AVAILABILITY STATEMENT

The datasets encompassed in this article are available in Ocean Network Canada's online data repository (http://doi.org/10.17616/R3RW43), which can be accessed via: https://data.oceannetworks.ca/home.

ETHICS STATEMENT

Written informed consent was obtained from the individual(s) for the publication of any potentially identifiable images or data included in this article.

AUTHOR CONTRIBUTIONS

DO provided overall project coordination and drafted many sections of the manuscript. DA, BB, YC, PC, RJ, SK, TL, MM, MP, and MT contributed content and/or participated in reviews and edits. BB, DO, MS, RJ, and BP reviewed the article and provided final edits. DO, JM, and KO produced final figures. All authors contributed to the article and approved the submitted version.

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ORIGINAL RESEARCH
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Long-Term Monitoring of Diel and Seasonal Rhythm of *Dentex dentex* at an Artificial Reef

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Behavioral rhythms are a key aspect of species fitness, since optimize ecological activities of animals in response to a constantly changing environment. Cabled observatories enable researchers to collect long-term biological and environmental data in real-time, providing relevant information on coastal fishes' ecological niches and their temporal regulation (i.e., phenology). In this framework, the platform OBSEA (an EMSO Testing-Site in the NW coastal Mediterranean) was used to monitor the 24-h and seasonal occurrence of an ecologically iconic (i.e., top-predator) coastal fish species, the common dentex (*Dentex dentex*). By coupling image acquisition with oceanographic and meteorological data collection at a high-frequency (30 min), we compiled 8-years' time-series of fish counts, showing daytime peaks by waveform analysis. Peaks of occurrence followed the photophase limits as an indication of photoperiodic regulation of behavior. At the same time, we evidenced a seasonal trend of counts variations under the form of significant major and minor increases in August and May, respectively. A progressive multiannual trend of counts increase was also evidenced in agreement with the NW Mediterranean expansion of the species. In GLM and GAM modeling, counts not only showed significant correlation with solar irradiance but also with water temperature and wind speed, providing hints on the species reaction to projected climate change scenarios. Grouping behavior was reported mostly at daytime. Results were discussed assuming a possible link between count patterns and behavioral activity, which may influence video observations at different temporal scales.

Keywords: day-night rhythms, photoperiodism, imaging, cabled observatories, visual predator, temporal niche, habitat use, monitoring footprint

INTRODUCTION

Diel (i.e., 24-h based) and seasonal biological processes of species inhabiting temperate regions, are synchronized to changes in photoperiod length and overall levels of environmental illumination (Foster and Kreitzman, 2010; Visser et al., 2010; Helm et al., 2013; Kronfeld-Schor et al., 2013). In marine coastal fishes, the photoperiod light intensity are among the most important environmental variables controlling biological rhythms and overall phenology (Naylor, 2010). For example, environmental illumination determines the timing of activity of predators and preys, that perform their ecological tasks according to a trade-off between maximum opportunities of visual-based feeding and minimum mortality risk (Daan, 1981; Reebs, 2002; Brierley, 2014; Mittelbach et al., 2014). However, the exposure of marine costal ecosystems to solar light produces a seasonal co-variation of photoperiod length with other habitat variables that also affect biological rhythms. For example, temperature can have strong effects on fishes at day-night and seasonal scales (Reebs, 2002; López-Olmeda et al., 2006). Combined photoperiod length and temperature cycles regulate physiological processes over the day-night alternation, resulting in global growth and reproduction patterns at a seasonal level (Falcón et al., 2010; Bulla et al., 2017; Cowan et al., 2017). Nevertheless, many marine species can also follow the lunar or tidal cycle to carry out their biological processes within the lunar day of 24.8-h (Naylor, 2010). In particular, tidal rhythms in marine species were related to locomotion and reproduction (Wagner et al., 2007; Aguzzi et al., 2010).

The interaction of activity rhythms of all species within a marine community may affect the estimation of its overall biodiversity. This is particularly significant for ecologically important species, such as top-predators, that play a critical role in maintaining the structure and stability of communities and affect ecosystem functioning (Heithaus et al., 2008, 2012; Byrnes et al., 2021). Sampling should be repeated at a frequency sufficient to grasp the whole alternation between consecutive peak and through in population abundances as a product of massive rhythmic displacement (Aguzzi et al., 2015b). Moreover, that sampling has to be repeated in association with concomitant data collection to understand how photoperiod length, light intensity and other environmental variables modulate behavioral responses (Aguzzi et al., 2020d). Similar temporal effects exist on fish grouping behavior (Rodriguez-Pinto et al., 2020), whose strategy can be related to foraging, spawning and predator evasion (Ford and Swearer, 2013; Makris et al., 2019; Lear et al., 2021). Moreover, environmental modulation of grouping behavior of fish has been observed in association to photoperiod changes (Meager et al., 2012; Georgiadis et al., 2014). Changes on grouping behavior, driven by human activities such as fishing, could affect the ecosystem functioning, and have repercussions for biodiversity conservation and fisheries management strategies (Sbragaglia et al., 2021).

Data on the phenology of marine fishes, as a product of a variation in local abundances, can be studied by cabled observatories for their capability to perform high-frequency, continuous and long-lasting imaging along with a concomitant multiparametric oceanographic data acquisition (Snelgrove et al., 2014; Danovaro et al., 2017; Aguzzi et al., 2019, 2020a,b; Rountree et al., 2020). In particular, cabled systems have the capacity to host many environmental sensors at high resolution, collecting many habitat variables, thus giving a better instrumental field approach to fishes' ecological niches (Hutchingson, 1957). Stand-alone or lander-based cameras are also good tools to study those aspects of species (e.g., Langlois et al., 2020; Drazen et al., 2021). But, given to energy constrains, a limited set of environmental variables is usually acquired. Each environmental variable measured by the installed sensor (e.g., essential environmental variables) can add habitat information for each imaged species (Aguzzi et al., 2020b). Time-lapse imaging studies with that technology have been efficiently used to describe diel and seasonal patterns in fish counts as a proxy for behavior rhythms, resulting in projected abundance changes at all depths of the continental margin (e.g., Juniper et al., 2013; Doya et al., 2014; Matabos et al., 2014, 2015; Milligan et al., 2020). In fact, in the marine three-dimensional scenario of the seabed and the water-column, day-night and seasonal shifts in populations bathymetric distributions, displacement ranges, and overall activity, influence the number of collectable animals into our sampling windows (e.g., Aguzzi and Company, 2010; Scapini, 2014; Chatzievangelou et al., 2021). A variation in counted animals produce changes in estimated abundances for a species in comparison to all the others (i.e., evenness; Aguzzi et al., 2015b). When rhythmic abundance changes are not carefully considered at sampling, their effect transcend to the computed biodiversity (Doya et al., 2017).

The use of cabled observatories for the monitoring of economically or ecologically important fish species is of relevance for the international conservation strategy agendas (Aguzzi et al., 2020c). Here, we used a coastal cable observatory to video-monitor the 24-h and seasonal occurrence of a top-predator, the common dentex (*Dentex dentex;* hereafter refers to as *Dentex*), at an artificial reef at high frequency over almost a decade. This species represents an iconic study case also for its value in commercial and recreational fisheries (Marengo et al., 2014; Sbragaglia et al., 2020), and a previous time-lapse study at the same artificial reef using the same cabled observatory suggested a relationship of fish presence with temperature, salinity and photoperiod length (Sbragaglia et al., 2019). Here, we moved a step forward and attempted to measure the association of count patterns over the 24-h to the photoperiod length, scaling this phenomenon over the whole seasonal cycle (i.e., photoperiodism). In doing so, we evaluated which of the measured oceanographic and meteorological variables mostly affected the reported count patterns. At the same time, we innovatively quantified the occurrence and the temporal dynamic of grouping behavior, also relating this phenomenon to the environmental variation.

MATERIALS AND METHODS

The OBSEA Platform Location and Equipment

The coastal Seafloor Observatory (OBSEA[1]) is a cabled observatory platform located at 4 km off Vilanova i la Geltrú (Catalonia, Spain) at 20 m depth within the Colls i Miralpeix Natura 2000 area (Aguzzi et al., 2011; Del Rio et al., 2020; **Figures 1A,B**). The observatory is equipped with an OPT-06 Underwater IP Camera (OpticCam), which can acquire images/footages of the surrounding environment with a resolution of 640 × 480 pixels.

[1] www.obsea.es

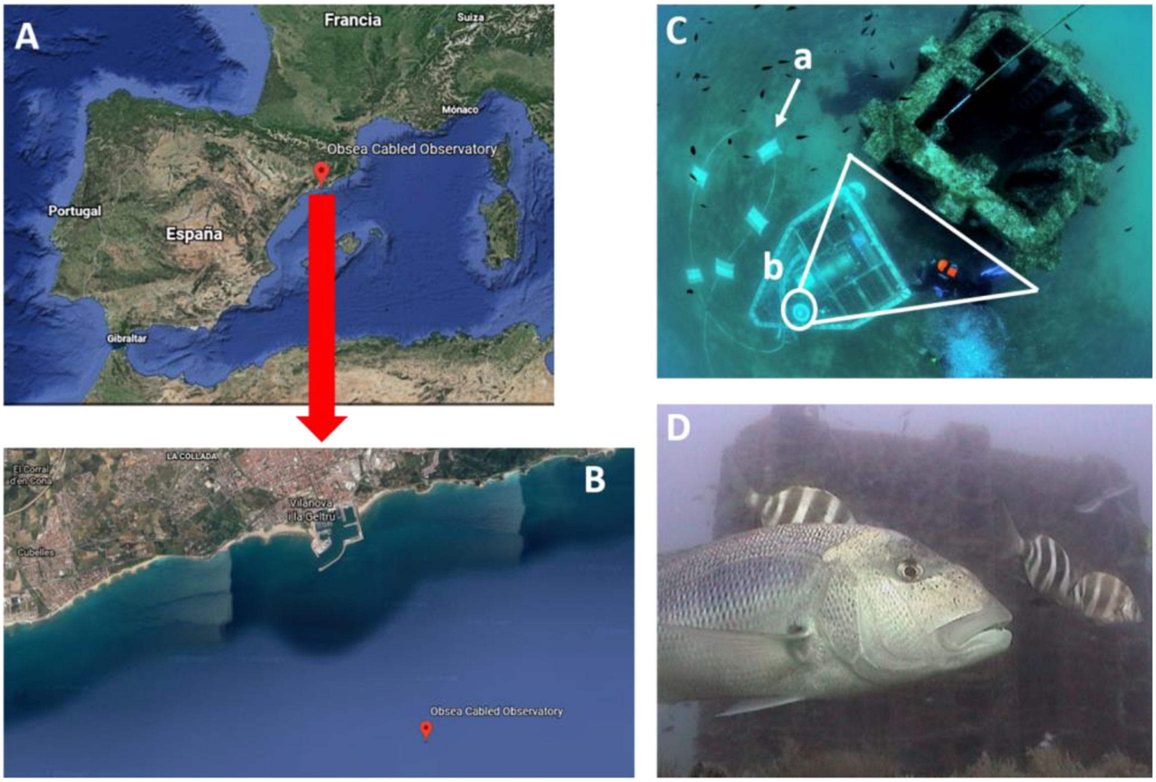

FIGURE 1 | Location of the OBSEA video platform in the NW Mediterranean **(A)** with specifications for the Catalan coasts, indicating its position off the harbor of Vilanova i la Geltrú **(B)**. The OBSEA platform is connected to shore with an Ethernet powering/data transfer cable **(C.a)**, camera focusing on the artificial reef **(C.b)**, where the number of individuals per photo of *D. dentex* can be observed and counted within a constant field of view **(D)**.

OBSEA is also equipped with two custom developed white LEDs (2,900 lumen; color temperature of 2,700 K), located besides the camera (with an angle of 120°) at 1 m distance from each other to allow image acquisition at night (Aguzzi et al., 2011). A procedure controlling the ON-OFF status of lighting immediately before and after image acquisition, was performed because of the artificial photic footprint on species (e.g., Aguzzi et al., 2010; Matabos et al., 2011). The lights were switched ON and OFF (lasting for 3 s) by a LabView application that also controlled their white balance.

Image Acquisition, Fish Counting and Environmental Data Processing

We acquired 70,254 images with a 30 min time-lapse mode, continuously during 8 years (2012-2019), preserving the same field of view, centered on the artificial reef at 3.5 m in front of the OBSEA (see **Figure 1C**). Individuals of *Dentex* were manually counted for each image (**Figure 1D**) by a trained operator following procedures by Condal et al. (2012) and Aguzzi et al. (2013).

Temperature (°C), salinity (PSU), and depth (m) were measured by the CTD probe installed aside the camera (Aguzzi et al., 2011). Furthermore, we collected data of air temperature (°C), wind speed (km/h), and wind direction (deg.) from the meteorological station located on SARTI (Development Center of Remote Acquisition and Information Processing Systems) rooftop in Vilanova i la Geltrú. We also gathered sun irradiance (W/m^2) and rain (mm) from the Catalan Meteorological Service station in San Pere de Ribes (6 km away from the OBSEA). Time series for all the environmental data compiled by selecting and extracting only readings contemporary to the timing of all acquired images.

We applied range filters for the fluctuation of environmental variables in order to remove out-layer data (i.e., due to instruments malfunctioning). Guillén et al. (2018) was referenced for water temperature and salinity (i.e., ranges of 11-28°C and 36.80-39.67 PSU, respectively), since authors have a 10 years' time series of readings from a nearby station in Barcelona (Spain). For air temperature and wind speed (ranges of 3-31°C and 0-60 km/h, respectively) we used an online website[2] with 30 years of hourly weather modeled data. Rain and solar irradiance were not filtered since downloaded from an Institutional and already filtered source[3].

Multivariate Analysis

Prior to the multivariate analysis, we transformed the number of individuals of *Dentex* per photo into nominal presence/absence

[2] www.meteoblue.com
[3] www.meteo.cat

response variable (Zuur et al., 2007). In order to obtain an optimized model for fish presence/absence, we then executed a correlation analysis on the environmental variables, to group the highly-correlated ones, removing the lesser representative from further analyses (Zuur et al., 2007). We used a General Linear Model (GLM) and a General Additive Model (GAM) using a binomial distribution, to identify which selected environmental variables mostly affected fish presence/absence, and compared the results between those analyses. We tested both methods because we did not have *a priori* reason for using a particular model.

We proceeded with the same multivariate analyses to describe the grouping behavior of *Dentex*. In order to do so, we firstly ranked images depending on variable number of pictured individuals (i.e., starting from 1). That frequency of groups of individuals was compiled into a frequency histogram plot. Then, we transformed the number of individuals into a nominal variable for grouping or not grouping behavior (i.e., "0" when in the photo there was only one individual, and "1" there was more than one individual). Then, we added this column of values to the temporal variables (i.e., hours, months and years), to detect any temporal pattern for this social behavior and identify which environmental variables affect it. We interpreted the data based on ethological common use of the wording (as per the general definition Pitcher, 1983). Thus, we consider the occurrence of the grouping behavior as the co-presence of fishes in the same field of view of the camera.

The correlation analysis was carried out with the library "PerformanceAnalytics," and GLM and GAM models were executed using the libraries "gdata" and "mgcv" of R software.

Time Series Analysis

In order to obtain a global overview of *Dentex* diel and seasonal behavioral rhythms across consecutive years, we first plotted the 8-years visual counts time series computing the means and standard errors (SE) values per each month of the time series. Temporal gaps in image acquisition were evidenced by line discontinuity. Time series analysis was performed separately for time series of fish counts and each relevant environmental variable for the presence/absence of *Dentex* evidenced by GLM and GAM modeling (see previous Section). All graphic outputs were again plotted in local time.

Waveform analysis was carried out to describe the diel and seasonal pattern of activity rhythm of the species. Waveforms computing was as follows: time series of visual counts were subdivided in 30 min time-series and averaged together over a standard 24-h period (i.e., 48 values per segment). A consensus averaged fluctuation over that standard 24-h period was then obtained by averaging all values of the different segments at the corresponding timings. The resulting means (± SE) were plotted to identify peaks and troughs in the waveform profile. The peaks temporal amplitude (i.e., the phase) was then computed according to the Midline Estimating Statistic of Rhythm (MESOR) method (Aguzzi et al., 2006), by re-averaging all waveform averages and the resulting value was represented as a threshold horizontal line superimposed onto the waveform plot. The Onset and Offset timings of activity (delimiting peaks intervals) were estimated by considering the first and the last waveform value above the MESOR. The peak was considered as continuous if no more than 3 values occurred below the MESOR (Aguzzi et al., 2020d). All waveform analyses were carried out using the library "ggplot2" of R software.

That waveform analysis was firstly conducted on the fish 8-years count time series and solar irradiance data, to visualize the general peaks as a proxy for the solar-driven, behaviorally induced changes in abundance as a product of behavioral activity (i.e., the photic character of the species ecological niche). Then, the same waveform analysis was repeated for each month and each season, by joining time series counts for winter (i.e., December, January, and February), spring (i.e., March, April, and May), summer (June, July, and August), and autumn (i.e., September, October, and November), to assess peaks' timings and amplitude variations as marker of photoperiodic regulation of behavioral rhythms. Moreover, to better describe the seasonal behavior of *Dentex*, and its relation with the photoperiod, we plotted the mean values (± SE) and MESORs of number of counts and solar irradiance of each month of the year. Finally, the same waveform analysis was performed for those environmental variables selected by models of presence/absence data (see previous Section).

Additionally, we assessed precisely the average values of those environmental variables selected by GLM and GAM modeling for presence/absence data (see previous Section) at *Dentex* waveform peaks crossing MESOR (see above), in order to add information on the species multidimensional niche (*sensu* Pocheville, 2015). At the same time, to better describe the environmental and temporal pattern of grouping behavior, we additionally plotted conditional densities of the environmental variables selected by GLM and GAM models of grouping or not grouping behavioral data.

An integrated chart depicting the temporal relationships of waveform peaks (i.e., the phases) in fish counts and the solar irradiance was created month by month over the whole 8 years of data acquisition (Aguzzi et al., 2012, 2015a). The values of each monthly waveform were compared with the respective MESOR through an inequality function in Excel (i.e., each waveform value per 30 min automatically resulted as "major" or "minor" in relation to the MESOR). All waveforms values identified as greater than the MESOR (i.e., the peak duration) were then plotted as horizontal continuous bar per each month. That operation was repeated for solar irradiance.

RESULTS

A total of 140257 photos should have been obtained during 8-years of monitoring (i.e., one per 30 min, from 2012 to 2019), but due to several malfunctioning problems creating gaps in the time series, we were able to analyze only 7,0254 photos (50.09% out of the total expected photos). The 95.99% of analyzed images (67438 photos) contained no *Dentex* (i.e., has "zero" as count value), and a few observations had high abundance (e.g., in only 5 photos there were more than 8 individuals; 0.18%).

We counted a total of 3,747 individuals of *Dentex*. The three months with the highest number of individuals were (**Table 1**): August with 649 number of individuals of *Dentex* (17.32%),

TABLE 1 | Monthly *D. dentex* visual counts number (N), average and relative percentage (%) out of the total within the 2012-2019 monitoring period.

	N	Average	%	MESOR	Onset	Offset	Irr. onset	Irr. offset	Water Temp. onset	Water Temp. offset	Wind speed onset	Wind speed offset
January	93	0.016	2.48	0.012	7:00	16:30	3.64	7.42	13.96	13.97	4.55	6.83
February	39	0.007	1.04	0.007	7:00	16:30	25.34	57.25	13.10	13.12	5.06	8.50
March	102	0.016	2.72	0.015	6:30	17:30	48.37	14.83	13.21	13.26	4.21	7.71
April	181	0.031	4.83	0.028	5:30	17:30	31.40	61.87	14.16	14.25	3.57	8.36
May	405	0.065	10.81	0.062	5:00	18:30	39.83	14.23	15.33	15.51	2.75	6.59
June	312	0.052	8.33	0.049	5:00	19:00	59.24	6.36	17.30	17.54	2.47	5.41
July	615	0.092	16.41	0.083	5:00	18:30	38.01	35.27	20.07	20.32	2.72	5.72
August	649	0.135	17.32	0.122	5:30	18:30	47.04	7.19	22.96	23.30	2.74	5.37
September	474	0.104	12.65	0.092	6:00	18:00	39.59	1.65	22.95	23.16	3.00	5.39
October	494	0.078	13.18	0.068	6:30	17:00	40.79	4.40	20.78	20.84	2.93	4.85
November	223	0.036	5.95	0.029	6:30	16:30	6.28	1.28	17.69	17.68	3.71	4.86
December	160	0.027	4.27	0.020	8:00	16:30	76.30	0.49	15.24	15.22	3.73	4.01
Total	3747	0.053	100	0.049	5:30	18:30	3.00	4.50	17.00	17.13	3.35	5.58

N was estimated by summing counts from all equivalent months in the 8-years' time series. Additional parameters per month are (i.e., averaging together equivalent months): Midline Estimated Statistic of Rhythm (MESOR), the starting and ending hours of the phase of activity (onset and offset, respectively), and average values of environmental variables selected by statistical models for presence/absence data of D. dentex at those onset and offset values.

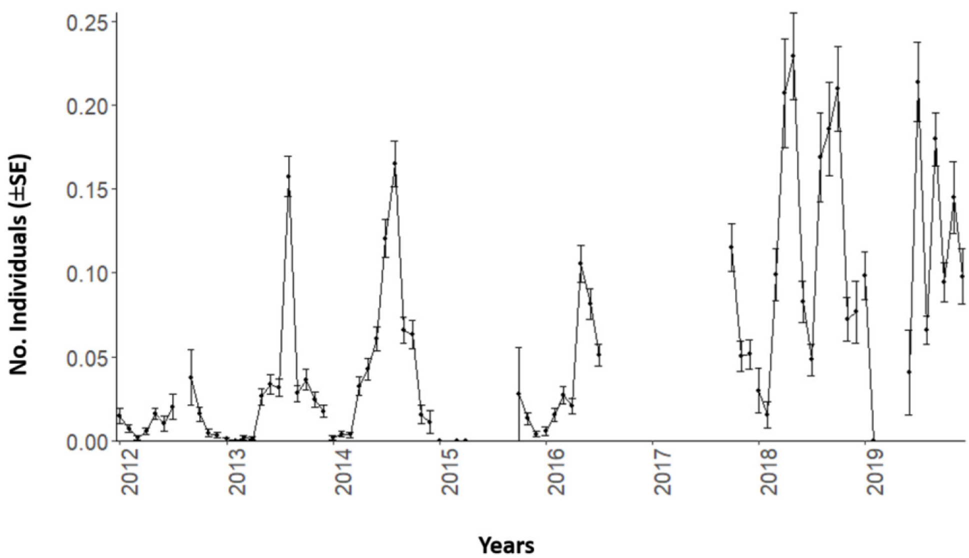

FIGURE 2 | Mean values and standard errors (± SE) per each month of the *D. dentex* counts time series during 8 years (from 2012 to 2019) of monitoring at the OBSEA video platform. Temporal gaps in image acquisition are evidenced by line discontinuities.

July with 615 counts (16.41%), and finally October with 494 individuals of *Dentex* counted (13.18%).

By compiling this time series into monthly estimates (± SE), we observed a consistent seasonal trend in *Dentex* counts (**Figure 2**). A major peak occurred in spring-summer and its height progressively increased over the consecutive years.

Multivariate Statistic

From the correlation analysis among the environmental variables, we observed a significant relationship between water and air temperatures (Correlation Index = 0.69) (**Figure 3**). Accordingly, we removed the air temperature as explanatory variable from the further analysis. We did not eliminate water temperature because it was considered a more biologically important variable for *Dentex*.

We observed that in both GLM and GAM models on presence/absence data all the variables were significant at the 5% level, except for salinity, wind direction and rain (**Supplementary Table 1**). Both approaches gave a model where water temperature, wind speed and solar irradiance were selected (**Table 2** and **Supplementary Table 2**). So, we selected these variables for the next time series analysis.

To study the grouping behavior of *Dentex*, we computed the percentage on the total number of images where it was present (2816 photos; **Figure 4**). Mostly, it was observed as solitary (2231 photos; 79.23%), but more rarely it appeared in

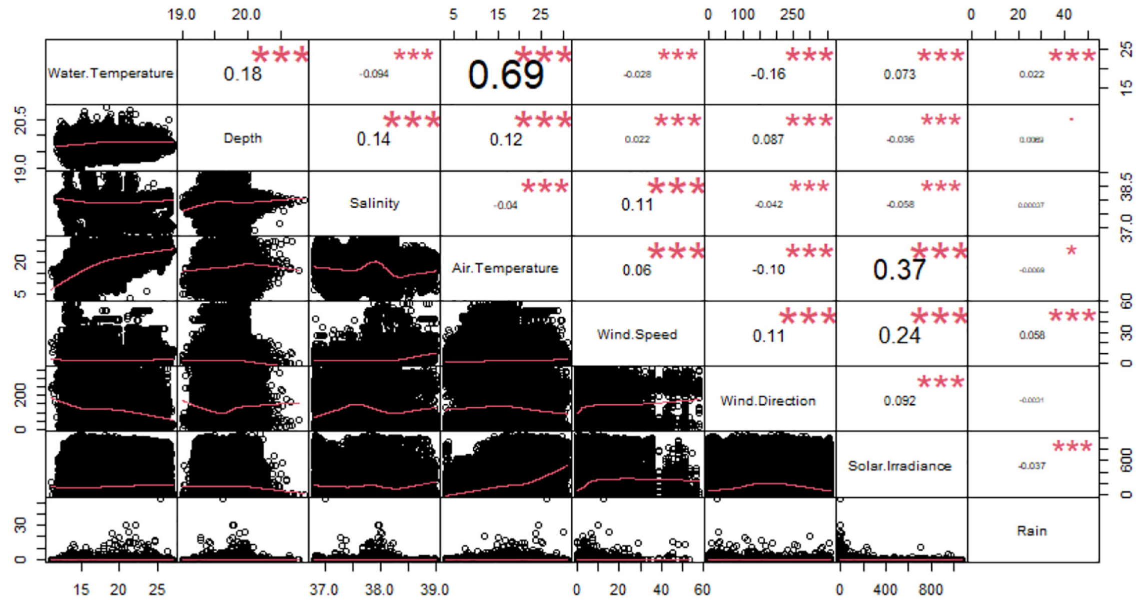

FIGURE 3 | Correlation chart among the environmental variables. The name of each variable is shown on the diagonal. Below the diagonal the bivariate scattered plots with the fitted line in red are displayed. Above the diagonal the value of the correlation plus the significance level as stars: to *p*-values of 0, 0.001, 0.1, 0.05, 0.1, and 1 correspond respectively "***", "**", "*", ".", and "".

pairs or in larger groups. In particular, in 395 photos (14.03%) it occurred in pairs, in 169 photos (6%) it occurred in groups of 3-5 individuals. Finally, it was observed in groups of 6-8 or more individuals (i.e., 16 and 5 photos respectively, equal to 0.57 and 0.18%). The maximum number of individuals in a single photo has been detected during 27th July 2019 at 8:00 in a group of 11 individuals.

Afterward, we carried out correlation analysis between environmental and temporal variables observing that there was a significant relationship between water and air temperature (Correlation Index = 0.69) (**Supplementary Figure 1**). As before, we removed air temperature as explanatory variable.

Then, we performed GLM and GAM models on the grouping or not grouping behavioral data (respectively when *Dentex* was observed alone or in group of two or more individuals) with the selected environmental and temporal variables. In both models all the variables were significant at the 5% level, except for wind speed and direction, solar irradiance, rain and hours (**Supplementary Table 3**). We observed in both approaches that water temperature, solar irradiance, hours, months and years were selected as relevant variables for the grouping behavior of the *Dentex* (**Table 3**) (**Supplementary Table 4**). It has to be noted that solar irradiance and month were slightly less significant than the other variables regarding the p-values (respectively Pr (> | z|) = $1.27*10^{-02}$ and Pr (> | z|) = $3.82*10^{-03}$).

We decided to report only GAMs upon GLMs results for both presence/absence and grouping or not grouping behavioral data, even if the two methods obtained same outputs, because GAMs models were considered an extension of GLMs.

Diel and Seasonal Fish Count Patterns

The waveform analysis on the 8-years' time series showed the occurrence of a solid diurnal peak, defining an increase

TABLE 2 | Results from the most representative GAM modeling for the presence/absence data of *D. dentex,* where metrics are also indicated: SE is the Standard Error of the estimated fitted mean parameter.

	Estimate	SE	*z* value	Pr (> |z|)
(Intercept)	−6.15	$1.16*10^{-1}$	−53.03	$< 2*10^{-16}$
Water Temperature	$1.42*10^{-1}$	$5.61*10^{-3}$	25.34	$< 2*10^{-16}$
Wind Speed	$2.63*10^{-2}$	$2.43*10^{-3}$	10.83	$< 2*10^{-16}$
Solar Irradiance	$1.21*10^{-3}$	$6.68*10^{-5}$	18.08	$< 2*10^{-16}$

z value is the value of the statistic used for testing the hypothesis that the regression coefficient is zero, and Pr (> |z|) is the p-value.

TABLE 3 | Results from the most representative GAM modeling for the grouping or not grouping behavioral data of *D. dentex,* where metrics are also indicated: SE is the Standard Error of the estimated fitted mean parameter.

	Estimate	SE	z value	Pr (> |z|)
(Intercept)	$-3.87*10^{2}$	44.6	−8.668	$< 2*10^{-16}$
Water Temperature	$6.18*10^{-2}$	$1.50*10^{-2}$	4.136	$3.53*10^{-5}$
Solar Irradiance	$-4.25*10^{-4}$	$1.71*10^{-4}$	−2.493	0.01267
Hour	$4.63*10^{-2}$	$1.30*10^{-2}$	3.575	0.00035
Month	$-6.57*10^{-2}$	$2.27*10^{-2}$	−2.893	0.00382
Year	$1.91*10^{-1}$	$2.21*10^{-2}$	8.61	$< 2*10^{-16}$

z value is the value of the statistic used for testing the hypothesis that the regression coefficient is zero, and Pr (> |z|) is the p-value.

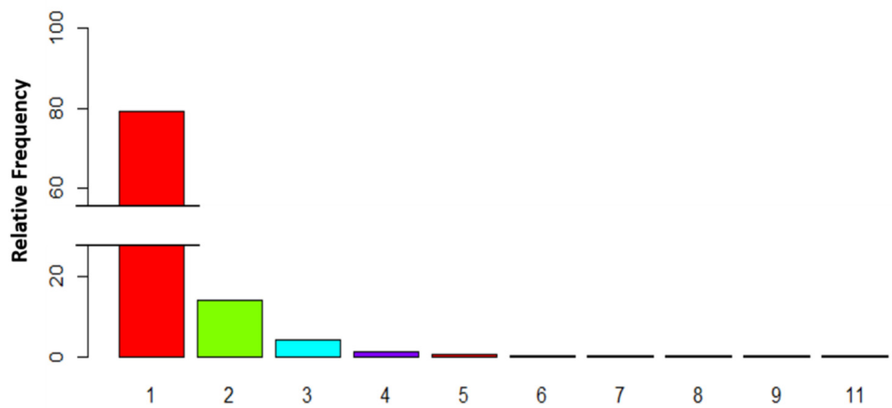

FIGURE 4 | Histogram depicting the relative percentage of images with variable number of individuals of *D. dentex,* where fishes of this species were present, as a quantification of grouping behavior.

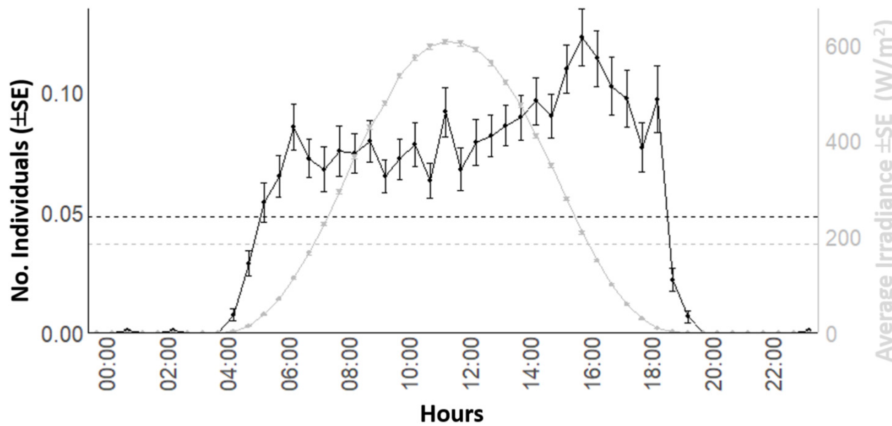

FIGURE 5 | Global waveform analysis output plot for the *D. dentex* visual count and solar irradiance time series from 8 years (i.e., 2012–2019) of monitoring at the OBSEA video platform. The dashed horizontal line is the MESOR.

of occurrence in the light hours (**Figure 5**). That waveform analysis repeated at the seasonal level (**Figure 6**) evidenced the photoperiodic regulation of occurrence with transient uni- and bimodality in counts peaks: crepuscular and diurnal peaks during respectively short and long photophases (i.e., autumn-winter *versus* spring-summer). Also peaks temporal limits are following irradiance temporal limits.

In the plotting of mean counts per month of *Dentex* vs. mean solar irradiance depicting the overall seasonal fluctuation trend in local abundance evidenced a general increase from winter to summer, with two peaks, a major on August and a minor on May (**Figure 7**). The increase of the solar irradiance follows a similar pattern but with a peak in June (**Figure 7**). In accordance, the waveforms MESORs values of *Dentex* for the different months (see **Table 1**) is increasing from February, when this average value is at the minimum, to August, when this average value is at the maximum (i.e., 0.007 and 0.122 individuals per photo, respectively). At the same time, the MESORs values of the solar irradiance are increasing from a minimum in December to a maximum in June (i.e., from 76.23 to 297.95 W/m^2, respectively) (**Table 4**).

In the integrated chart comparing *Dentex* waveforms peaks (i.e., means values higher than the MESOR as horizontal continuous band) (**Figure 8** and **Supplementary Figures 2**, **3**) we could observe counts increases form December to June, with onset and offset timings that shift form 8:00 and 16:30, to 5:00 and 19:00, respectively (see **Table 1**). For solar irradiance peaks amplitude also varied from December to May, with onset and offset at 8:00/15:00 and 7:00/16:30, respectively (see **Table 4**). The integrated chart (see **Figure 8**) indicated that *Dentex* counts followed the solar irradiance pattern, with values of onset and offset that could anticipate and are delayed to the irradiance onset of maximum 2 and 2.5-h, respectively.

In order to describe the photic niche of *Dentex*, we noted that the average values of irradiance when *Dentex* averaged counts start spiking (i.e., is becoming active) as the peak onset; these are between 3 and 76.3 W/m^2 (see **Table 1** and **Supplementary Figures 2, 3**). Inactivity (i.e., offset) occurs for average values

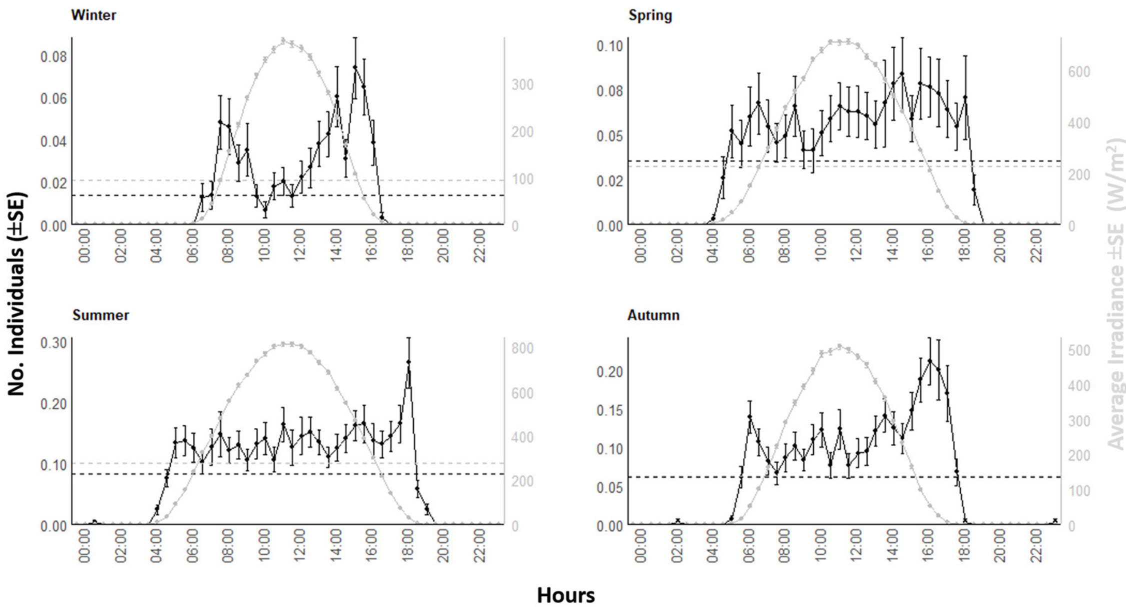

FIGURE 6 | Waveform analysis output plots for visual counts of *D. dentex* and solar irradiance during different seasons (i.e., winter, spring, summer, and autumn) from 8 years (i.e., 2012–2019) of monitoring at the OBSEA video platform. The dashed horizontal line is the MESOR.

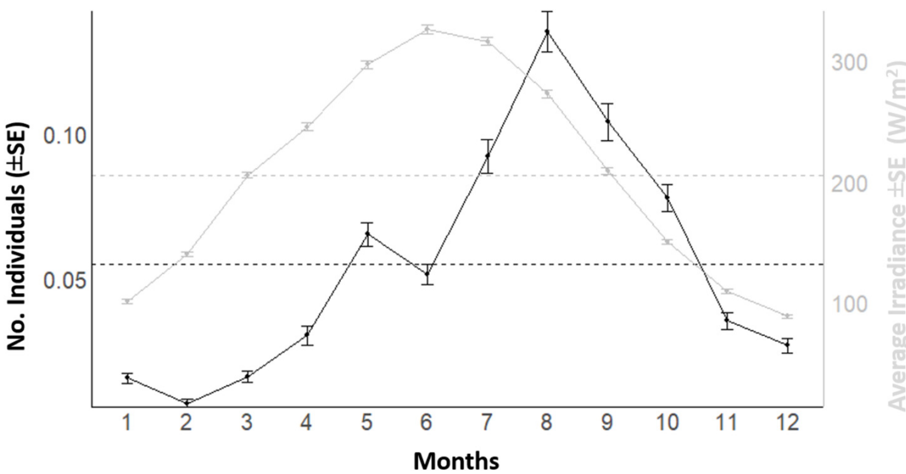

FIGURE 7 | Plot of mean counts (± SE) per each month of the year of *D. dentex* visual counts and solar irradiance recorded during 8 years (i.e., 2012–2019) of observations at the OBSEA. The dashed horizontal line is the MESOR.

of solar irradiance between 0.49 and 61.87 W/m^2 (**Table 1** and **Supplementary Figures 2, 3**).

Environmental Cycles

In **Table 4**, we reported MESOR values, onset and offset per each month of the year for the environmental variable previously selected by GLM and GAM models for presence/absence data (i.e., water temperature, wind speed, and solar irradiance). The temporal dynamic of those variables is described below, but not for solar irradiance that was already described (see previous Section).

The water temperature cycle (**Supplementary Figures 4, 5**) had a phase shift to early hours from January, with an onset and offset at 15:30 and 6:30 respectively, to December, with onset and offset at 0:00 and 17:00 respectively. Furthermore, we reported that the water temperature had a minimum and a maximum MESOR value in February and August (i.e., 13.11°C and 23.14°C, respectively). One should notice that those two months also correspond to the minimum and maximum for *Dentex*.

The wind speed cycle (**Supplementary Figures 6, 7**) followed the same pattern of solar irradiance and fish visual counts (see previous Section). Its onset anticipated its timing from

TABLE 4 | Midline Estimated Statistic of Rhythm (MESOR), onset and offset timings (hours) per each month, within the 2012-2019 monitoring period, for the environmental variables selected by GLM and GAM modeling for presence/absence data.

	Wind speed (km/h)			Water temperature (°C)			Solar irradiance (W/m^{-2})		
	Off-set	On-set	MESOR	Offset	Onset	MESOR	Offset	Onset	MESOR
January	23:30	11:00	5.52	6:30	15:30	13.96	15:30	8:30	86.91
February	23:30	10:30	6.34	3:30	15:30	13.11	15:30	8:00	121.94
March	21:00	10:00	6.15	23:30	11:30	13.24	16:00	7:30	181.39
April	19:00	9:30	6.21	23:30	13:30	14.20	16:00	7:00	220.02
May	19:30	9:00	5.62	23:30	10:30	15.43	16:30	7:00	269.95
June	20:00	8:30	5.09	23:00	11:00	17.43	16:30	7:00	297.95
July	19:00	9:00	4.87	21:30	10:30	20.20	16:30	7:00	288.77
August	20:00	9:30	4.61	22:00	9:00	23.14	16:00	7:00	245.68
September	19:30	9:30	4.80	21:00	10:00	23.04	16:00	7:30	186.15
October	20:00	10:00	4.08	20:00	13:00	20.78	15:30	7:30	131.59
November	17:00	7:30	4.37	7:30-15:00	0:00-11:30	17.69	15:00	8:00	94.42
December	16:30	7:00	3.18	17:00	0:00	15.22	15:00	8:00	76.23

January at 11:00 to June at 8:30. Whilst, the offset progressively delayed from December at 16:30 to June at 20:00. Furthermore, we noticed that wind speed has a minimum and a maximum MESOR value in December and February of 3.18 km/h and 6.34 km/h, respectively.

In order to describe the ecological niche of *Dentex*, we annotated the average values of the detected relevant variables from the statistical models when *Dentex* started and finished its active phase (i.e., onset and offset, respectively) (see **Table 1** and **Supplementary Figures 2–7**). Indeed, when this species started to spike (i.e., is becoming active) as the peak onset, the values of water temperature and wind speed were, respectively, between 13.1-22.96°C and 2.47-5.06 km/h (see **Table 1**). Instead, inactivity (i.e., offset) occurs, in average values, between 13.12-23.3°C water temperature, and 4.01-8.5 km/h wind speed.

Plotting conditional densities for the most important explanatory variables of the grouping or not grouping behavioral data of *Dentex* (i.e., the distribution of the nominal variable for the grouping behavior of *Dentex* given a certain value of environmental and temporal driver) (**Supplementary Figure 8**), we observed that *Dentex* form groups during the day or at dusk and down, but not during the night. Moreover. The frequency of grouping increased along the years of observation. No particular seasonal pattern along the months of the year has been observed for grouping behavior. Furthermore, we could not obtain particular information on the relationship between grouping and the environmental variables selected by the models for this behavior.

DISCUSSION

We described the occurrence of diel and seasonal behavioral patterns in a coastal marine top predator, *Dentex,* by analyzing 8-years of high-frequency and continuous time series of visual-counts plus concomitant multiparametric oceanographic and meteorological data. Firstly, we detected a relationship between fish counts and the solar irradiance as a proxy for rhythmic activity. Then, a seasonal variation in video-counts was evidenced with a major peak in August and a minor one in May, suggesting for local abundance changes, possibly linked to population dynamics (e.g., seasonal migration). Also, the species counts were significantly correlated to water temperature and wind speed. Finally, we detected the occurrence of grouping behavior correlated to solar irradiance and water temperature, suggesting an effect of the environment as a regulator of grouping behavior.

Limitations in Cabled Observatory Monitoring Strategies

Cabled observatories provide a spatially limited data acquisition (a single platform can provide a relatively narrow field of view of few m^2). Another problem is that with this methodology it is not possible to separate the influence of abundance variation from activity variation, and the first one certainly affects the results of the second. Anyway, general inferences can be made on activity rhythms with spatially limited sampling windows (Hansteen et al., 1997; Refinetti et al., 2007; Bu et al., 2016; Gaudiano et al., 2021). Even trawling, which is the more spatially representative tool, is still anyway limited in comparison to the real extent of marine species distributions (Cama et al., 2011; Sonnewald and Türkay, 2012; Ünlüoğlu, 2021). Furthermore, Campos-Candela et al. (2018) recently reviewed some methods to inference abundance from visual counts with cameras stating that averaged estimates of animal density do not show any substantial improvement after an adequate sampling effort (i.e., number of cameras and deployment time).

In our monitoring, fish were observed during daytime and this could cause more observations per day in summer than in winter, being the photoperiodic difference between months the cause for an increased probability in observing fishes in a summer day rather than in a winter day. In any case, there are diurnal species that are sampled more in winter for a reason that is related to an increase in their abundance and not to the

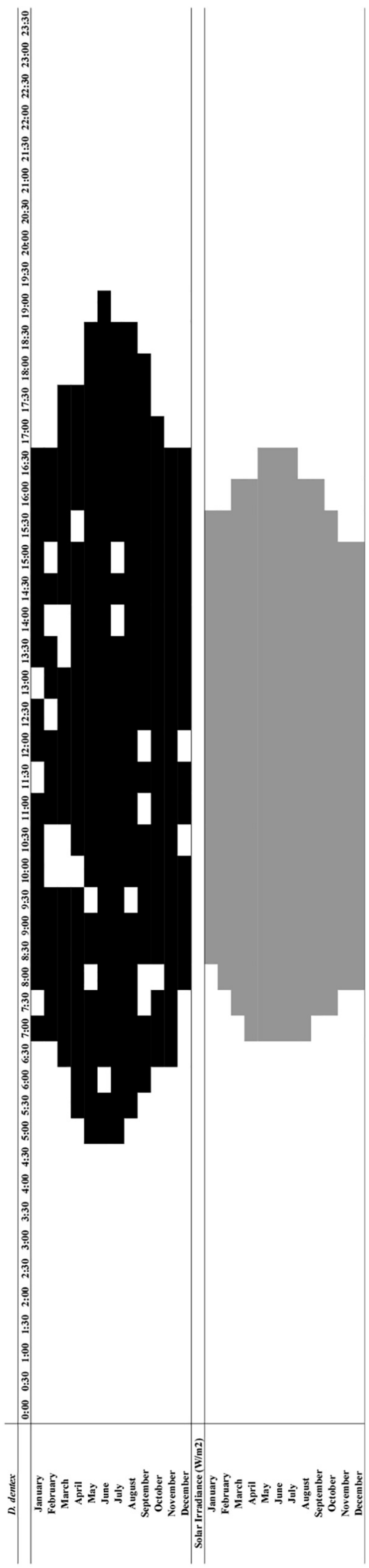

FIGURE 8 | Integrated chart depicting the temporal relationships of *D. dentex* active phase between months of the year (black), and periods of the diel cycle when the solar irradiance showed significantly increased values along the different months of the year (gray).

possible effect of increasing photoperiod (Condal et al., 2012; Aguzzi et al., 2015a). Here, it is difficult to methodologically distinguish this abundance/activity/photoperiod phenomenon with the present methodology.

In order to acquire more representative results on rhythmic movements and habitat use of fishes at the scale of species distribution a better spatial coverage in monitoring would be needed (Holt, 2009). Networks of cameras with synchronous image acquisition routines may be required to track the species movements across different levels of habitat heterogeneity (e.g., Doya et al., 2017; Aguzzi et al., 2020b; Rountree et al., 2020). Such a synchronous image acquisition could clarify if the peaks in video counts of *Dentex* in different areas are associated to a different habitat uses (e.g., preying vs. resting), and then could be used to relate this information to the activity rhythms. Inspiration on how to set the network monitoring may be drown from spatially extended surveys with camera traps, aiming at the visual census of fauna in terrestrial environments (e.g., Beaudrot et al., 2016; Norouzzadeh et al., 2018).

OBSEA data collection could be implemented with other complementary actions within the monitoring area, such as the classic visual census sampling by divers (Samoilys and Carlos, 2000; Grane-Feliu et al., 2019), and collected data could be cross-checked with information provided by telemetry. This technology allows the tracking of particular individuals over large period of times (Hussey et al., 2015; Villegas-Ríos et al., 2017; Brownscombe et al., 2020; Matley et al., 2021). Acoustic telemetry could help achieving continuous long-term tracking of single individuals to study the habitat use of fish species (Hussey et al., 2015; Dominoni et al., 2017; Lennox et al., 2017), overcoming the spatial and temporal bias of fixed-point video monitoring for a reliable evaluation of population demography and local biodiversity (Aguzzi et al., 2020a,b). It is impossible with fixed cameras imaging technologies to support for fish "site fidelity" when this area specificity is not a clear life trait of the species (e.g., territoriality, burrowing, etc.). We have no morphological tools to identify the individuals, whose position and orientation changes within the field of view. For this reason, we may need acoustic tagging coupled with imaging to enforce such a site specificity study.

Cabled observatory imaging equipment could have some monitoring footprint on coastal areas for the introduction of light at nocturnal image sampling, which can induce behavioral disturbance on the local fauna (e.g., Davies et al., 2015; Kurvers et al., 2018; Czarnecka et al., 2019; Lucena et al., 2021). Nevertheless, in our case it is unlikely that the OBSEA lightening system, active every 30 min for about 3 s, affected the reported *Dentex* count patterns, being the individuals of this species absent at nighttime all the yearlong (see previous Section). However, the environmental footprint of future long-term monitoring could be reduced with the use of acoustic multi-beam cameras (Aguzzi et al., 2019).

Despite the evidenced monitoring limitations, we would like to stress out that one positive aspect of cabled observatory use is the low-invasive character at data collection. For example, visual census obtained by divers implies a factor of disturbance on the organisms as human presence (Harmelin-Vivien and Francour, 1992; Januchowski-Hartley et al., 2011; Assis et al., 2013; Azzurro et al., 2013; Emslie et al., 2018; Pais and Cabral, 2018).

How to Interpret Day-Night Rhythms in *Dentex* Visual Counts

Counts peaks timing and amplitude followed the photophase. In our case, the interpretation of video-counts peaks in terms of increase or decrease activity should be carried out with precaution. A similar precaution is adopted when evaluating the ecological meaning of species peaks in catches or visual census; i.e., animals captures or spotting are provoked by their increased availability in the sampling area for their resting or because of their activity (Aguzzi and Bahamon, 2009; Aguzzi and Company, 2010). Notwithstanding, many species of fishes display activity rhythms (e.g., Eriksson, 1978; Muller, 1978; Helfman, 1986) that drive changes in abundance between day and night in coastal areas, as detected by different sampling systems and methodologies (e.g., Aguzzi et al., 2013; Hawley et al., 2017; Schalm et al., 2021). Diurnal, nocturnal, and crepuscular activity is often described as a product of fish behavioral response to solar irradiance variations (Helfman, 1986; Coles, 2014).

In this scenario, almost no *Dentex* was consistently detected at nighttime over several consecutive years. This observation suggests that video-counts peaks are a product of an increase activity at daytime. Laboratory data on fish behavior and physiology may provide a first insight on this phenomenon, assuming a link between visual counts and activity. Photoperiodic regulation of fish physiology and swimming behavior occur for the modulation that light intensity and temperature exert on the production of hormones (e.g., Pavlidis et al., 1999; Cowan et al., 2017; Sánchez-Vázquez et al., 2019). Fish melatonin measures environmental light levels and, as a result, variable rates of swimming occur (Saha et al., 2019).

A daytime activity increases for *Dentex* resulting in the increment of video-spotting at the OBSEA can be postulated for the following reasons. First, animals rest at nighttime within *Posidonia* seagrass beds (Zabala et al., 1992). Second, the species has a home range of less than 1 km^2 in specific period of the year (Aspillaga et al., 2019), with the exception of moments in which a migration may follow bathymetric changes related to optimal water temperature (Aspillaga et al., 2017; see next Section). Third, *Dentex* is a visual predator whose prey spotting is optimized during light hours (Marengo et al., 2014).

Our data suggest an increase of activity during daytime (and consequent resting at night), which implies a visual-oriented hunting strategy as already indicated by Marengo et al. (2014). This diurnal temporal character of *Dentex* ecological niche (i.e., *sensu* Hut et al., 2012) matches the daytime video-occurrence increases of its fish preys within the Spariformes order (Morales-Nin and Moranta, 1997), that were spotted at the OBSEA (Aguzzi et al., 2013), but also observed to be present in other Mediterranean areas (D'Anna et al., 1994; Azzurro et al., 2007; Lök et al., 2008; Witkowski et al., 2016). For example, *Diplodus vulgaris, Oblada melanura,* and *Spicara maena* are preys of *Dentex* (Morales-Nin and Moranta, 1997) with diurnal increases in presence and activity that are sustained also at twilight conditions (Santos et al., 2002; La Mesa et al., 2013; Witkowski et al., 2016). Predators and preys seek for temporal overlapping (predators) or avoidance (preys) of their activity phases over the 24-h cycle (e.g., Kronfeld-Schor and Dayan, 2003; McCauley et al., 2012; Kerr et al., 2015; Andersen et al., 2017; Olivares et al., 2020; Priou et al., 2021).

Seasonal Fluctuation in Fish Video-Counts

Here, we reported a seasonal rhythm in visual counts of *Dentex*, with a significant increase in August and a second minor peak in May, as consistent across multiple years. In the past study of Sbragaglia et al. (2019) at the OBSEA, the major peak in counts of *Dentex* on August was detected, but not the minor one of May. This points out the strategic importance of a prolonged monitoring activity at the OBSEA. That seasonal pattern has been also detected with recreational fishing data for the Italian coasts (Sbragaglia et al., 2020).

We interpreted the first large peak of August as the product of thermocline regulation on fish behavior. *Dentex* shows a preference for warm suprathermoclinal waters, whose shallowest depths (i.e., between 20-30 m) are usually reached in our monitoring geographic zone (i.e., the NW Mediterranean) in July and August (Aspillaga et al., 2017). The OBSEA is placed within that depth range and this fact may explain the count increase of summer.

Another explanation could be that *Dentex* seasonal counts increase are synchronized upon maximum abundances of its preys (see previous Section), that augment in the OBSEA area in spring-summer; e.g., *D. vulgaris* from June to October, *O. melanura* in May and June, and *S. maena* from May to July (Aguzzi et al., 2015a). Seasonally synchronic abundance changes may occur between fish predators and preys (Fox and Bellwood, 2011; Bustos et al., 2015; Mishra et al., 2020; Liu et al., 2021). Possibly, the presence of artificial reef structures nearby the OBSEA attract fish preys and consequently concentrate the presence of the *Dentex* as well.

We observed a second, minor peak of *Dentex* counts in May that can be discussed in relation to the phenology of breeding. If from one side, the species migrates deeper to reproduce in areas at 40-100 m depth from March to June (Marengo et al., 2014; Grau et al., 2016), from the other we did not observe a temporally concomitant drop in counts at the OBSEA location in May (as an indication for a deeper migration of individuals in that period). Possibly, some individuals that have finished the reproduction (or with no mature gonads), return (or stay) to shallower depths for foraging. In fact, regressing ovaries in females and late developing testes of *Dentex* were already reported during May (Grau et al., 2016).

Species Relationship With Water Temperature and Wind Speed

The oceanographic and meteorological monitoring was dedicated to understand the species tolerance to certain ranges in the variation of selected measured habitat variables, as an indication of the effects that climate change may exert on fish's phenology (Stevenson et al., 2015). Those ranges have a practical value for ecological monitoring, since indicate a roadmap to develop smart sampling procedures in marine species: i.e., the optimum time window when to expect a maximum presence of individuals, according to the fluctuation status of key environmental drivers (Aguzzi et al., 2020b).

Here, counts of *Dentex* were related to the water temperature, being the seasonal peak always reported above an averaged threshold of 13.1°C. A past study at the OBSEA with 3 years' time-series detected the increase in number counts of *Dentex* above 20°C (Sbragaglia et al., 2019). This highlight the importance of pursuing the monitoring activities at the OBSEA to better characterize the environmental preference of this species.

The importance of water temperature as environmental driver has already been described in many fish species (Vinagre et al., 2016; Van Der Walt et al., 2021). Temperature deeply affects fish presence (or absence), because it influences directly species physiological performance (Cussac et al., 2009; Freitas et al., 2016; Day et al., 2018; Waldock et al., 2019). *Dentex* can cope with temperature range above our reported threshold, as also indicated by the current trend of geographic expansion in the North Mediterranean (Orozco et al., 2011; García-Rubies et al., 2013). We confirmed that trend by a progressive increase in counts over the years (i.e., see **Figure 2**), which would possibly continue in the next decade, when temperature is expected to grow in the NW Mediterranean (Bahamon et al., 2020). This indicates the value of cabled-observatory assets to disclose the occurrence of progressive trends in population shifts beyond more contingent seasonal dynamics due to the climate forcing.

We found a significant relationship between *Dentex* counts and wind speed. This variable affects the population distribution in some fish species (Daskalov, 2003; Teo et al., 2007; Bakun and Weeks, 2008; Selleslagh and Amara, 2008; Brander, 2010; Kuparinen et al., 2010), based on upwelling nutrient inputs (Bakun and Weeks, 2008; Bellido et al., 2008; Brander, 2010) although this phenomenon is not relevant in a shallow costal area, such as the one where the OBSEA is deployed.

The changes in wind speed and direction could also affect indirectly other environmental variables, that consequently affect the marine biota. For example, it was observed that changes in wind affected salinity in the North Sea and in the Baltic Sea (Schrum, 2001), which had negative consequences on cod recruitment in both areas (Brander, 2010). In our case, salinity was not significantly associated to counts of *Dentex* nor to wind. Hence, the same dynamic reported for cod recruitment in the North Sea and Baltic Sea may not be valid in our case. Notwithstanding, wind speed may resuspend and mix seabed and water column nutrients at periods of blowing, hence influencing the coastal food web with the consequent overall increase of trophism at all predator levels of the trophic food web (Bellido et al., 2008). For the overall increase in pray abundance, *Dentex* counts may consequently increase at moments of wind blowing.

The Grouping Behavior of the Species

We reported data on the grouping behavior of *Dentex*, that showed a clear 24-h modulation. Here, the formation of groups of *Dentex* significantly occurred more during daytime (including twilight hours) than nighttime, given the broad phase relationship between all visual counts and solar irradiance as a proxy for diurnal activity rhythms (see previous Section). Differently, no peaking was reported over different seasons. A seasonality for *Dentex* grouping behavior was described in rocky coastal areas for juveniles during summer (Chemmam-Abdelkader et al., 2004; Sahyoun et al., 2013). We did not observe this phenomenon, but we could not resolve if our video-monitoring were composed by individuals in this stage of development, since no tools for body sizing (e.g., lasers) were present aside the camera; however, we can assume that the majority of individuals were adults. Indeed, for adults *Dentex*, groups of individuals may be detected during the spawning season in spring, between 40 and 100 m depth (Marengo et al., 2014), but, given the shallower depth of OBSEA deployment, we did not observe this phenomenon (see previous Section).

The grouping behavior of *Dentex* was associated to solar irradiance and water temperature. Grouping has been already broadly correlated to the environmental variation in previous works for different fish species (Félix-Hackradt et al., 2010; Meager et al., 2012; Georgiadis et al., 2014; Palacios-Fuentes et al., 2020). In particular, the formation of fish groups has been related to light intensity (Meager et al., 2012; Georgiadis et al., 2014) and to water temperature (Power et al., 2000; Davoren et al., 2006; Meager et al., 2012; Palacios-Fuentes et al., 2020). Also, the weak increase of grouping behavior reported across consecutive years of observations (see **Supplementary Figure 8**) is likely the result of the increasing abundance of this species in the OBSEA area (see also previous Section).

DATA AVAIALABILITY STATEMENT

The original contributions presented in the study are included in the article/**Supplementary Material**, further inquiries can be directed to the corresponding author/s.

ETHICS STATEMENT

Ethical review and approval was not required for the animal study because we did not actively sampled, nor manipulated, nor killed any animals. We just performed video imaging.

AUTHOR CONTRIBUTIONS

MF: conceptualization, formal analysis, investigation, writing-original draft, and writing-review and editing. VS: conceptualization and formal analysis. ET, JAn, IM and JP: formal analysis. JdRF: funding acquisition. MNC and DMT: data curation. JAg: conceptualization, formal analysis, and writing-review and editing. All authors gave final approval for publication.

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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.2022.837216/full#supplementary-material

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The EMSO Generic Instrument Module (EGIM): Standardized and Interoperable Instrumentation for Ocean Observation

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The oceans are a fundamental source for climate balance, sustainability of resources and life on Earth, therefore society has a strong and pressing interest in maintaining and, where possible, restoring the health of the marine ecosystems. Effective, integrated ocean observation is key to suggesting actions to reduce anthropogenic impact from coastal to deep-sea environments and address the main challenges of the 21st century, which are summarized in the UN Sustainable Development Goals and Blue Growth strategies. The European Multidisciplinary Seafloor and water column Observatory (EMSO), is a European Research Infrastructure Consortium (ERIC), with the aim of providing long-term observations *via* fixed-point ocean observatories in key environmental locations across European seas from the Arctic to the Black Sea. These may be supported by ship-based observations and autonomous systems such as gliders. In this paper, we present the EMSO Generic Instrument Module (EGIM), a deployment ready multi-sensor instrumentation module, designed to measure physical, biogeochemical, biological and ecosystem variables consistently, in a range of marine environments, over long periods of time. Here, we describe the system, features, configuration, operation and data management. We demonstrate, through a series of coastal and oceanic pilot experiments that the EGIM is a valuable standard ocean observation module, which can significantly improve the capacity of existing ocean observatories and provides the basis for new observatories. The diverse examples of use included the monitoring of fish activity response upon oceanographic variability, hydrothermal vent fluids and particle dispersion, passive acoustic monitoring of marine mammals and time series of environmental variation in the water column. With the EGIM available to all the EMSO Regional Facilities, EMSO will be reaching a milestone in standardization and interoperability, marking a key capability advancement in addressing issues of sustainability in resource and habitat management of the oceans.

Keywords: fixed-point observatories, multi-parametric monitoring, seafloor, water column, EMSO, EGIM, EOV

INTRODUCTION

Need for Long-Term Ocean Observation

The oceans provide food, mineral resources, energy, host a very rich biodiversity and regulate our climate. The sustainability of these services is subject to local and global scale changes including warming, deoxygenation, acidification, overfishing and pollution. Society has a strong and pressing interest in maintaining and where possible restoring the health and resilience of the ocean ecosystem. The measures to address these major challenges of the 21st century are encapsulated in the UN Sustainable Development Goals (Visbeck, 2018), the Blue Growth strategies and various statutory environmental programmes, such as, in Europe, the Marine Strategy Framework Directive (MSFD)[1] (Van der Graaf et al., 2012) or the OSPAR Commission[2]. To establish an initial assessment of the environmental status, to ensure consistency and allow for comparison, stakeholders throughout the ocean economy (civil society, research, industry, policymakers) require high-quality integrated observations in near real time, from the surface, through the water column, to sub-seafloor, over large spatial and temporal scales (Dañobeitia et al., 2020).

Effective ocean observation, forecast and monitoring of impacts, benefit from a clear guidance on the most relevant environmental factors to consider. The Global Ocean Observing System (GOOS)[3] sets out Essential Ocean Variables (EOVs), parameters which are feasible to measure across platforms, and provide relevant information for conservation and management (Miloslavich et al., 2018). Europe's Marine Strategy Framework Directive sets out eleven descriptors (The European Parliament and the Council of the European Union, 2008) to assess marine environmental status and establishes a strategy to preserve the marine environment and to protect resources of socio-economic value. *In situ* observatory technology has been underused in addressing these descriptors (Danovaro et al., 2016).

Long-term fixed-point observatories are indeed major contributors to a comprehensive description and understanding of the processes taking place in the oceans (Baptista et al., 2008; Favali et al., 2010; Levin et al., 2019; Weller et al., 2019). They provide multidisciplinary information on the variability of the oceans which are difficult to detect by other platforms (Bean et al., 2017). The continuous, high-resolution time series data makes long-term fixed-point observatories uniquely insightful in resolving decadal environmental trends required to understand effects of global climate change (Henson et al., 2016). They can record long-term variations over hours, days, months, seasons, years, as well as sudden, unpredictable events such as earthquakes and tsunamis (Lo Bue et al., 2021). Furthermore, the effective footprint estimated through modeling suggests that data from open-ocean observatories can be representative of wide areas for a variety of biogeochemistry parameters in surface waters (Henson et al., 2016).

European ocean observatories differ in their equipment and methodologies. Such technical and organizational heterogeneity has driven the need to establish a permanent and sustainable framework to adopt and develop standards and common tools. This will increase efficiency, optimize costs and resource allocations, enhance interoperability meeting the needs of scientists and generic users (Person et al., 2015). Independently operated, single discipline observatories to measure short-term change have been evolving into distributed infrastructures of multidisciplinary, long-term sustained regional installations. Global networks of ocean observatories are established and partners share a common strategic framework, scientific facilities, methods, equipment and expertise. Herein we describe the EGIM, a generic ocean sensor underwater system which has been developed through the collaboration of several nations with many ocean science disciplines and subsea observatories (e.g., Favali et al., 2015). We describe the system, from basic seagoing equipment through to data access, as defined in ESONET NoE, the European Sea Observatory NETwork of Excellence[4] (Ruhl et al., 2011). Furthermore, we discuss the scientific value of this generic system through the evaluation of initial oceanic deployments.

European Multidisciplinary Seafloor and Water Column Observatory

The European Multidisciplinary Seafloor and water column Observatory (EMSO) European Research Infrastructure Consortium (ERIC) is a distributed research infrastructure, consisting of 14 instrumented sites[5], also known as Regional Facilities, which measure a wide range of variables focused on the Essential Ocean Variables. Measurements are made throughout the water column to the seabed and address broad scientific disciplines including meteorology, physical oceanography,

[1] https://ec.europa.eu/info/research-and-innovation/research-area/oceans-and-seas/eu-marine-strategy-framework-directive_en

[2] https://www.ospar.org/

[3] www.goosocean.org

[4] https://en.wikipedia.org/wiki/European_Multidisciplinary_Seafloor_and_water_column_Observatory

[5] http://emso.eu/observatories/#overview

biogeochemistry, ecology and geo-hazards (Best et al., 2014, 2016; Lo Bue et al., 2021).

The EMSO Regional Facilities are distributed from the Nordic Seas through the mid-Atlantic Ridge across the Mediterranean to the Black Sea in a range of depths from oceanic abyssal plain to shallow water coastal sites (**Figure 1**). In the Atlantic, the distribution of EMSO Regional Facilities is constituted by EMSO-Azores, in the mid-oceanic ridge with focus on hydrothermal vent processes (e.g., Cannat et al., 2011), Porcupine Abyssal Plain-Sustained Observatory (PAP-SO), which provides long-term observations linking biogeochemical processes in surface waters through the water column to the abyssal benthos (e.g., Hartman et al., 2021) and the ESTOC site, north of the Canary Archipelago, which records long-term biogeochemistry time series (Santana-Casiano et al., 2007).

The EMSO Norwegian Regional Facility (NorEMSO) measures temporal and spatial changes in water masses in the Nordic Sea (e.g., Barreyre et al., 2020).

In the Mediterranean where most of the sites are cabled, the Regional Facilities are EMSO-Ligurian Sea, Western Ionian Sea and Hellenic Arc. EMSO-Ligurian Sea observes geo-hazards, biogeochemistry and physical oceanography at different locations ranging from 20 to 2,400 m water depth (e.g., Lefevre et al., 2019). The Western Ionian Sea Regional Facility has a focus mainly on geo-hazards and underwater acoustics (e.g., Monna et al., 2014). The Hellenic Arc Regional Facility monitors geo-hazards, physical oceanography and biogeochemistry (e.g., Lykousis et al., 2015). The Black Sea is monitored by the EuxRo buoys (e.g., Stanica and Melinte, 2020). At the time of the writing there are plans for the Regional Facilities on the Iberian Margin (Gulf of Cadiz).

There are also cabled sites in shallow water: Smart Bay (e.g., Gaughan et al., 2019), EMSO-Molène (Klingelhoefer et al., 2017) and OBSEA (e.g., del Rio et al., 2020) which provide real-time data and offer opportunities for more accessible *in situ* experimentation as well as development and testing of new technology.

FIGURE 1 | Geographical distribution of the EMSO Regional Facilities (open green circles) and test sites (solid green dots).

The EMSO ERIC's benefit is to add value to the Regional Facilities, taking advantage of the technologic and scientific excellence of each team to increase and harmonize the range of observed variables and enhance the interoperability. The development and deployment of the EGIM is a key step in completing this process.

EMSODEV (EMSO Implementation and Operation: DEVelopment of Instrument Module) Challenge

The Network of Excellence ESONET[4] efforts helped to frame the idea to categorize observatory design concepts into those which are generic to all major observation sites and those which are more specialized (Ruhl et al., 2011). This idea evolved to drive specifications for an instrumentation and infrastructure module which meet generic requirements for various disciplines and science issues, and can also serve as a framework to host new and more complex sensors to address more specific scientific questions. A major obstacle to accelerating infrastructure implementation, improving impact and lowering average annual operation costs was the adoption of generic requirements which could facilitate the harmonization of infrastructure including hardware and information handling.

The EMSODEV[6] EC project set out to construct a prototype and two replicated EGIMs with a set of core sensors. The concept was to not only set requirements, design the instrumentation, design data and power handling infrastructure, but also to prepare the EGIM full life cycle in the EMSO infrastructure and with important benefits regarding team building and technological capacity.

The design requirements and priorities for the prototype and early systems were constrained by a few principles. The EMSO strategic themes cover many disciplines and phenomena requiring a wide range of technical specifications. The design and selection of initial test cases for use of the EGIM was driven to demonstrate capability in both the water column and on the seafloor, together with the technical challenges of high data rate sensors and related interfacing. Additionally, the designs included both stand-alone systems with internal recording and power supply and cable systems with real time transmission of geophysical, acoustic and image/video data.

In this paper, we present a description of the EGIM system, features, set-up, operation and data management. We demonstrate, through a series of coastal and oceanic deployments, that the EGIM is a valuable ocean observation module, which can contribute to address questions which link physical, biogeochemical, biological and ecosystem variables and significantly enhance the capability of the existing observatories.

THE EGIM DESCRIPTION

Main Features

The EGIM serves EMSO ambitions for interoperability, flexibility and capability for future evolution, reliability and data quality

[6]www.emsodev.eu

standardization, to measure ocean variables throughout the Regional Facilities.

Standardization to Measure the Essential Ocean Variables Homogeneously Across EMSO

The central feature of EGIM is a standardized approach to measure a set of significant oceanographic variables: this is achieved by using consistent sensor and hardware specifications and deployment concepts, the same setting for each sensor, the same qualification and calibration methods and the same data format.

Compatibility With the Various Site Configurations, Deployment Scenario and Scientific Disciplines

Embedded in an easy-to-deploy frame, the EGIM meets very diverse implementation scenarios and multidisciplinary scientific purposes whilst keeping a generic design. It can operate on any EMSO Regional Facility, mooring line, seabed station both cabled and non-cabled, surface buoy and can host a variety of sensors. The EGIM can also be deployed as a completely independent system. In this case, it may be necessary to add buoyancy, an acoustic releaser and a set of beacons to recover the system from the surface. The specifications include a depth rating of 6,000 m so that any sensor could be deployed in all European seas. However, shallow ratings can be specified for given units.

Adaptable to Existing and New Technologies

The EGIM is open to user customization. The communication protocols with the sensors, the external communications and the power links are standard and non-proprietary, consequently, the EGIM can easily accommodate additional instruments and data types.

Building on Global Best Practice

The EGIM development process has benefited from EMSO community knowledge and extensive, operational experience of deployments at sea, and complies with the recommendations and best practices gathered by European Ocean Observing community (Pearlman et al., 2019), developed through projects such as the Best Practices Handbook by the project FixO3-Fixed-point Open Ocean Observatories[4] (Coppola et al., 2016) and the Network of Excellence ESONET[4] Label. The EGIM also complies with NF-X10-812 environmental test specifications (NF X10-812, 2013).

High-Quality Data

Full data lifecycle traceability is implemented to fulfill EMSO objectives of high quality and consistent measurements. It induces constraints to the purchasing and maintenance processes. Then, performing standardized tests and calibration is of prime importance to ensure interchangeability, compatibility and harmonization. Finally, the detailed information must be attached to the data sets as durable metadata.

The EGIM Sub-Systems

The EGIM is made of the sensors, an electronic core, power supply and an optional interface to optical cable, integrated in a compact frame (**Figure 2**).

The Core Sensors

The identification of scientific core parameter requirements has followed a decade-long investigation of scientific priorities and the potential for sensors to meet those requirements. The benchmark at the start of the EMSODEV[6] EC project was set by the Network of Excellence ESONET[4] in 2011, which included a set of seven generic variables and several other specialist ones (Ruhl et al., 2011). This benchmarking importantly included input from other related EU projects including the projects EuroSITES[5] Open-Ocean Observatory and the Hotspot Ecosystem Research and Man's Impact on European Seas (HERMIONE[7]). The previous exercise also referenced developing concepts such as the Global Climate Observing System (GCOS[8]) Essential Climate Variables. Refining the requirements which led to the construction of the first EGIM units included expert inputs *via* workshops (e.g., in Heraklion, Greece, 2015). The entire process was carried out with reference to relevance with multiple disciplines, detailed specification and wide existing usage. Commercial availability and Technology Readiness Level (TRL[9]), depth rating, and cost were also selection factors in what could be included in the first EGIM units.

The seven core parameters selected for the first EGIM units can be found in **Table 1**.

The Electronic Core

The electronic core of the EGIM is the COSTOF2 (2nd generation of COmmunication and STOrage Front-end), an optimal mix of innovation and reliability. Recently developed and already proven in long-term deployments, it benefits from more than 10 years deployment on EMSO-Azores of the previous generation of the instrument: the initial deployment was carried out in 2006 within the European project ASSEM – Array of sensors for long-term seabed monitoring of geohazards[5] (Legrand et al., 2019). Primarily designed for non-cabled applications, the system perfectly matches constraints of EMSO stand-alone Regional Facilities.

Within the EGIM, the electronic core provides adaptive power supply, measurement sequencing, data storage with redundancy, data time stamping with a clock common to all the sensors and high precision where necessary (less than 9.10^{-10} aging monthly), technical data such as internal temperature, internal humidity, power consumption, leakage detection and storage capacity to monitor the correct functionality of the module. The various bi-directional communications available on-board, underwater locally and remotely from the sea surface (**Figure 2C**) use standard and non-proprietary protocols. These protocols include serial and Ethernet, high-bandwidth contactless Wi-Fi

[7]https://en.wikipedia.org/wiki/Hotspot_Ecosystem_Research_and_Man%27s_Impact_On_European_Seas

[8]https://gcos.wmo.int

[9]https://it.wikipedia.org/wiki/Technology_Readiness_Level

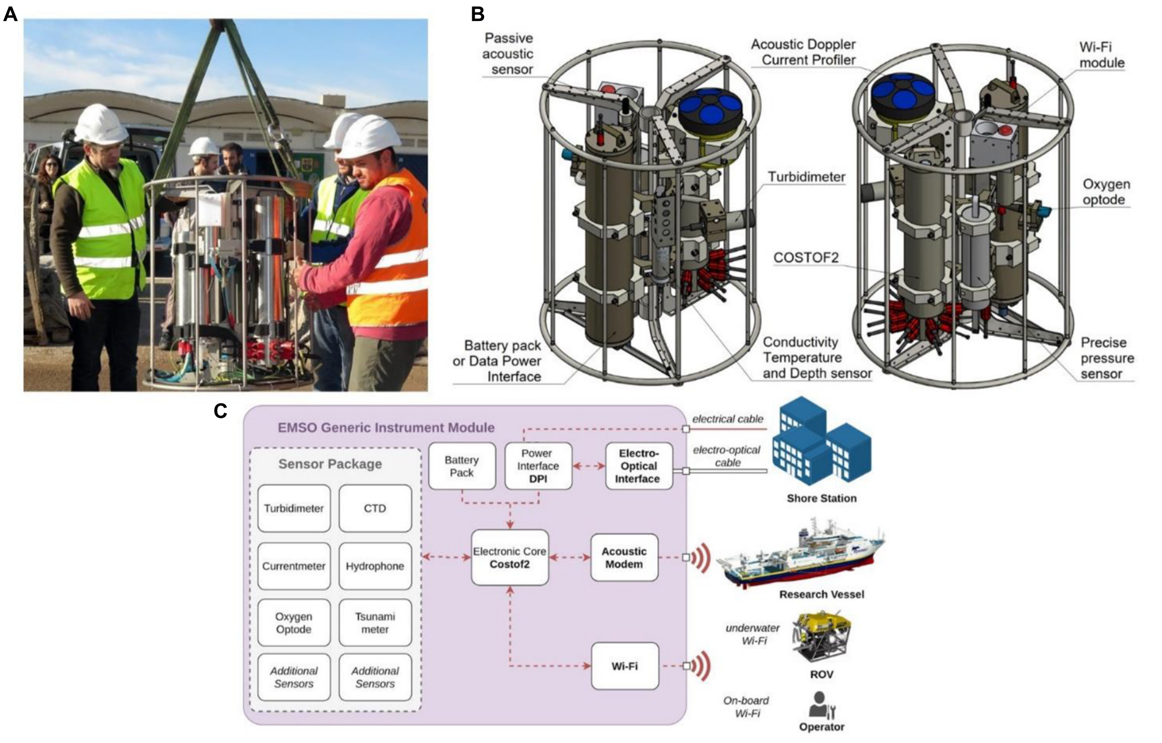

FIGURE 2 | (A) The EGIM assembled and ready for deployment **(B)** view of the sensors and components and **(C)** sensors diagram with communication services.

TABLE 1 | Specification for the first set of variables and sensors.

Parameter	Units	EGIM specifications			EGIM sensors models for EMSODEV units
		Range	Accuracy	Sensitivity	
Conductivity	S/m	0 to 7	0.001	0.00005	SeaBird SBE37-SIP
Temperature	°C	−5 to 35	0.005	0.0001	
Pressure	Bar	0 to 625	0.01% FSR	10^{-7} FSR	SeaBird SBE37-SIP and SeaBird SBE54 Tsunami
Dissolved oxygen	μmol/l	0 to 465	<8	<1	AADI-3005214831 DW4831
Turbidity and optical backscatter	NTU	0 to 150	0.1	0.02	Wetlabs NTUrdt
Currents velocity Current direction	cm/s^2 °	1 to 100 m	1% ± 0.5 cm/s^2 ± 2°	0.1 cm/s^2 0.01 °	Teledyne Workhorse monitor ADCP 300 kHz
Underwater sound	Hz V/μPa	20–200,000 Hz (0.1–100 Hz for geophysics)	1 V/μPa	−190 dB (re V/μPa)	Ocean Sonics icListen SB60L-ETH

operating *in situ* and optimized protocols for acoustic, inductive and satellite transmission.

The electronic core also provides the EGIM with customization and evolution capacities. With a user-friendly all-in-one configuration tool, users can adjust the configuration of the EGIM with regard to the deployment scenario and setup the instrument-specific parameters such as power consumption, event logging and acquisition duty cycle. With a Sensor Software Development on Kit, the users can develop new sensor interfaces thus contributing to extend the list of existing sensor drivers.

Protection Against Bio-Fouling

The EGIM can manage external antifouling systems and for non-equipped industrial sensors, it has a built-in active antifouling device based on micro-chlorinator. This feature is essential to ensure the data quality over time for oxygen, turbidity and images.

Power Supply: Power Converter Unit and Batteries Compatible

For standalone applications, the EGIM can be powered by primary lithium-thionyl chloride battery packs delivering a

28 V DC nominal voltage. For high voltage cabled installations, typically 300–400 V DC, a data-power interface unit converts the node power voltage to 30 V DC.

Optical Fiber Interface

Communication at cabled Regional Facilities uses optical fiber which can handle bidirectional large data traffic over long distances. In the world market of subsea optical connectors, EMSO has not yet been able to address standardization. Nonetheless, in order to provide a cost-effective solution, a dedicated module with an Ethernet optical converter was implemented in a separate canister to convert the signal transmitted via the fiber to Ethernet wire link accepted by the EGIM.

System Setup

In the EGIM, each sensor is placed in the best orientation and mechanical setting to ensure optimal performance (**Figure 2B**). The space in front of the optical and acoustic sensors is free from obstructions to avoid any interference, reflection or wave spreading shadowing. The Acoustic Doppler Current Profiler (ADCP) is placed vertically with respect to the seabed, facing either upwards or downwards.

The frame is compact (965 mm high, Ø 780 mm, weight 115 daN in air and 56 daN in sea-water), robust and easy-to-deploy (**Figure 2A**). The triple "C" shape central part handles the mechanical strains and vibration. The external protection rings and beams are exchangeable. For the first units, the frame was made of titanium, but other materials can be used depending on corrosion compatibility, mechanical constraints and operating depth.

The EGIM can easily be attached at the top or at the bottom to an external frame and the central space is intended as an interface to the pin used on moorings.

EGIM OPERATION AND DATA MANAGEMENT

Configuration and Operating Modes

The EGIM provides a high level of customization thus fits for various deployment scenario in non-cabled, autonomous and cabled conditions (**Figure 3**).

Non-cabled and Autonomous Modes

The non-cabled mode and the autonomous mode are configurations when the EGIM is battery operated with no, or few, external guidance and limited communication with the shore generally available through an acoustic link.

To manage the equipment (e.g., sensors, motors, pumps, antifouling devices) in these situations, the system relies on a set of non-proprietary sensor-specific drivers embedded in the EGIM electronic core COSTOF2.

The bi-directional communication services (see section "The Electronic Core") make it possible, to perform a final *in situ* check when deploying with a visiting/installing submersible, divers or an acoustic link, to adjust the acquisition routine and to recover scientific or technical data.

Cabled Mode

In cabled mode, the EGIM is connected to a shore station through an underwater electro-optical cable with an electro-optical converter at the end, offering continuous power supply and real-time, high bandwidth communication. The EGIM electronic core operates as a transparent junction box between the shore and the sensors, providing access to the sensors through the standard internet transmission control protocol (TCP/IP) and providing a serial to Ethernet converter for the instruments with no Ethernet interface.

The EGIM can face short-term failure in power supply and/or Ethernet communication and maintain the data series continuity: in case of power loss, the EGIM electronic core, running on internal backup batteries, switches from cabled to non-cabled mode and manages the system operation, regularly testing the connection with the shore (power and communication) to return to the nominal cabled mode. When the batteries are exhausted, the system turns to a secure mode with the sensors switched off and the electronic core in a sleep state.

In cabled mode, there is an option of associated on shore cyber-infrastructure available to the EGIM users' community to manage the real-time scientific and technical data and metadata acquisition, to access and monitor the EGIM throughout the deployment and to carry out the connection to any data infrastructure (**Figure 4**). The overall cyber-infrastructure has been designed to meet FAIR data principles (Wilkinson et al., 2016) meaning the data are Findable, Accessible, Interoperable and Reusable for machine to machine networking. It is composed of several virtual machines (VM). All the components and third-party software have open-source and permissive licenses. It uses Open Geospatial Consortium's Sensor Web Enablement (SWE) worldwide acknowledged standards, tools and services (Bröring et al., 2011), which are free and publicly available. This, in turn, makes linking of diverse sensors fast and practical: the Sensor Model Language-SensorML to describe the instrument and acquisition process metadata (Botts and Robin, 2014), the Sensor Web Enablement (SWE) bridge software to provide plug and play instrument integration (Martínez et al., 2017), the Sensor Observation Service (SOS)[10] (Bröring et al., 2012) to serve the sensor data and metadata in a standard and interoperable manner on the web and the Helgoland lightweight Sensor Web Viewer[11] to enable the exploration, visualization and analysis of sensor data.

Additionally, a Secure File Transfer Protocol (SFTP) handles the access and transfer of the huge acoustic raw data files (up to tens of gigabytes per day), and Zabbix[12] is used to monitor the EGIM and the cyber-infrastructure itself, providing real-time information about the system status and sending alarms when required.

[10]https://github.com/52North/SOS
[11]https://github.com/52North/helgoland
[12]https://www.zabbix.com/

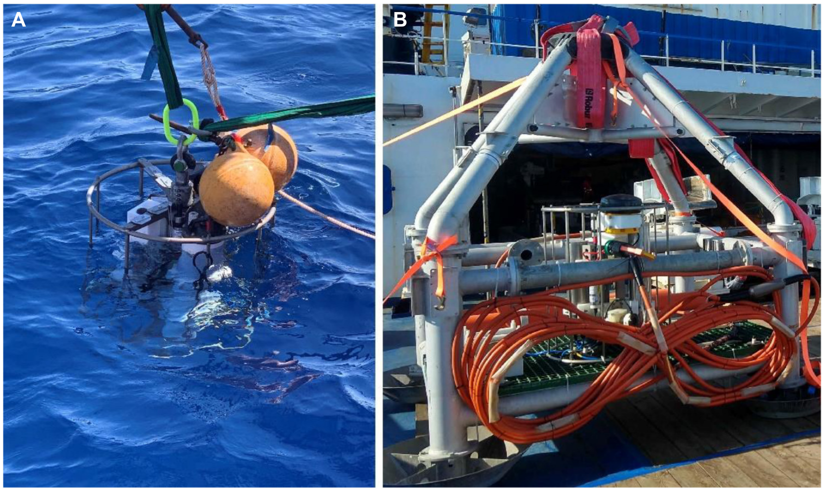

FIGURE 3 | The EGIM **(A)** in a mooring line during the deployment in autonomous mode on ESTOC test site and **(B)** inside the pyramidal frame used at Western Ionian Sea with the electro-optical converter and the 50 m electro optical jumper for the connection to the submarine cable of the infrastructure.

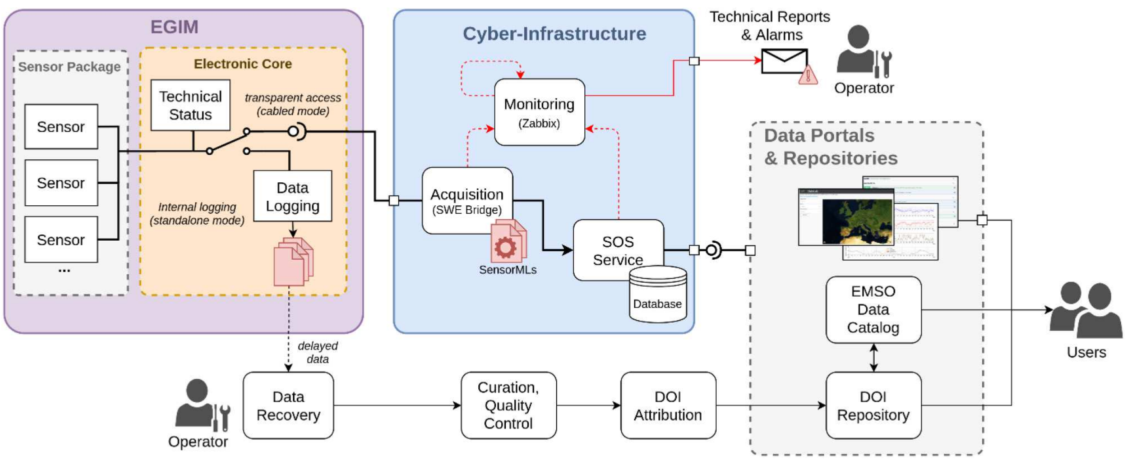

FIGURE 4 | Data flow from the sensor to the end user.

Data Management

EMSO legacy data is distributed over a variety of information systems which differ considerably from each other in terms of technology, formats and interfaces and with respect to their level of support for Findable, Accessible, Interoperable and Reusable (FAIR) data.

Within the project EMSODEV, the EGIM datasets were integrated into the existing infrastructures and published with DOIs in marine scientific data repositories open to the international community for archiving, publishing and long-term availability of data. The datasets are either in SEANOE[13] (French) or in PANGAEA[14] (German). Following the FAIR Principles, the data is freely available and usable under the terms of the license mentioned on the data set description.

As any EMSO datasets, the EGIM datasets were recorded in EMSO Metadata Catalogue[15]. The catalog system, mainly based on standards and interfaces defined within the Network of Excellence ESONET[4] and the project FixO3[4], acts as a "data broker" system which is capable of harvesting and extracting metadata from related data archives regardless of their standardization level. It is web based with a searchable metadata index designed to support discovery and use of data by humans as well as machines.

DEPLOYMENTS AT SEA

Following intensive laboratory tests which demonstrated the EGIM capability, a series of deployments at sea were used

[13]https://www.seanoe.org/

[14]https://www.pangaea.de/

[15]https://dataportals.pangaea.de/emso/

TABLE 2 | EGIM deployments up to date, with information about the EGIM setup; See general description in **Figure 2**, §3.1.1 for autonomous or non-cabled modes and §3.1.2 for cabled mode; (*) duration and depth expected for present or coming deployments.

Regional Facility	Water depth (m)	EGIM depth (m)	Start date	Duration (days)	Coordinates	Configuration
OBSEA	21	Seabed	01/12/16	75	41.1816° N 1.7522° E	Cabled
	21	Seabed	14/02/17	12	41.1816° N 1.7522° E	Simulated autonomous conditions, with a test cable enabling the monitoring of data and technical parameters
	21	Seabed	26/02/17	57	41.1816° N 1.7522° E	Cabled
EMSO AZORES	1,700	Seabed	20/07/17	390	37.2887° N 37.2881° W	Autonomous, with deployment and recovery by the ROV following the process on Azores
	1,700	Seabed	08/06/21	365*	37.291°N 32.279°W	Non-cabled with acoustic real time data transmission, serving sensors dedicated to seismology (seismometer, array of hydrophones and pressure gauge)
PLOCAN/ESTOC (Canary Islands Archipelago)	5	Seabed	13/02/19	47	27.9890° N 15.3683° W	Cabled, shallow water test with low voltage power supplied
	55	45	16/06/19	122	28.0278° N 15.3610° W	Autonomous, shallow water test on batteries
	3,650	3,580	05/12/19	192	29.1667° N 15.5000° W	Autonomous, powered on batteries
PLOCAN/La Palma Island (Canary islands Archipelago)	475	375*	30/10/21	90*	28,5857°N 17,9388°W	Autonomous, powered on batteries
CATANIA	2,100	Seabed	Delayed	365*		Cabled, equipped with a data-power interface (§2.2.4) and an electro-optical signal converter (§2.2.5), attached to an external frame fitting the deployment process on this Regional Facility

to evaluate the system in the wide variety of configurations (cabled and stand-alone) and environmental conditions (shallow water, deep sea, pelagic, benthic) found at EMSO observatories (see **Table 2**). The EGIM delivered useful data across a range of scientific themes, highlighting its value for specific science questions.

Correlation of Fish Activity and Biologically Relevant Oceanographic Variables at OBSEA

The EGIM was connected to the OBSEA cabled observatory[16], 4 km off Vilanova i la Geltrú (Spain) within *Coll i Miralpeix Marine Reserve and* Natura 2000 protected area (**Figure 5**). OBSEA focuses on scientific and technological experiments and time series studies which identify environmental influences on biodiversity (Aguzzi et al., 2013), upwelling phenomenon studies (Cusi et al., 2017) and development of new standards and protocols for marine sensor networks (del Rio et al., 2018; Martinez et al., 2021).

Beyond the tests in a coastal environment, the EGIM deployment at the OBSEA led to establishing a methodology to correlate fish activity and biologically relevant oceanographic variables. The EGIM provided data for salinity, temperature, sound velocity, water depth and dissolved oxygen (Toma et al., 2017) and two underwater digital cameras (a camera rotating over 360° and, five meters apart, a fixed camera) provided the fish activity observations around an artificial reef (del Rio et al., 2021).

Images were recorded every 30 min, for 3 months and data from days when divers visited the site, modifying the fish behavior, were excluded. To obtain a comprehensive richness list, all the individuals visible in the images were identified and classified to the lowest taxonomic level possible, using the latest scientific nomenclature (i.e., FISHBase[17]), deriving time series counts (Aguzzi et al., 2020a,b). Concomitantly, time series for all the environmental data were compiled by selecting and extracting only readings contemporary to the timing of the images.

Then, a waveform analysis was conducted (with 24-h segments of 30 min and averaged fluctuation calculated over 24-h) to assess the phase of the species activity rhythms (period of the day when the results of waveforms are above the MESOR, Midlines Estimating Statistic of Rhythm estimated by re-averaging all the waveforms values), separately for each species, for the total of counted fishes (i.e., the species assemblage) and the unclassified

[16] www.obsea.es

[17] www.fishbase.org

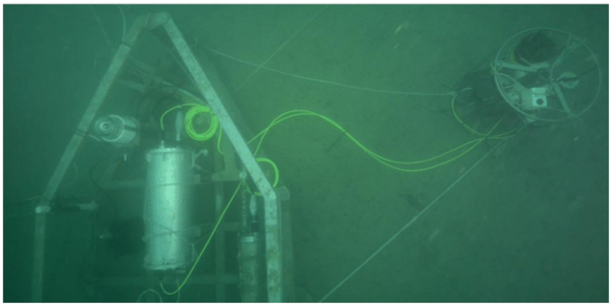

FIGURE 5 | The EGIM (right) connected to the OBSEA platform.

individuals, as well as for each oceanographic variable, in terms of peak timing.

An integrated chart of waveform phases (Aguzzi et al., 2020a) was used to determine the periods when the environmental variables and the activity of the studied species displayed significant increases (i.e., temporal coherence of rhythms and cycles as proxy for cause-effect relationships).

The integrated analysis (**Figure 6**) highlighted that fish which do not follow a general behavioral pattern in relation to the photoperiod likewise do not follow the general environmental ranges. The majority of species increase their presence during daytime, anticipating the increment in the fluctuation status for some of the recorded environmental variables (e.g., salinity and temperature, which progressively increment at the photophase, peaking at late day, for solar heating action and dropping at night).

EGIM deployment at OBSEA led to the setting of a new methodology to correlate fish diurnal/nocturnal behavior and environmental variables. Further data analysis will be conducted adding new entries such as trophic relationships (e.g., predators-prey relationships) and primary productivity (e.g., plankton concentration). Longer experiments are now required to confront the results with stronger variation of the environmental parameters and achieve conclusions about seasonality.

Dispersion of Hydrothermal Vent Fluids and Particles in the Near Seafloor Seawater on EMSO-Azores

EMSO-Azores is situated on the mid-Atlantic Ridge, at the Lucky Strike active hydrothermal vent field[18] (Ondréas et al., 2009) at about 1,700 m water depth, a site designated as a Marine Protected Area in the OSPAR Network in 2007. Initiated in 2010, EMSO-Azores is one of the few long-term monitoring sites for hydrothermal vent fields in the world (Glover et al., 2010; Cannat et al., 2011) and contributes to the understanding of the responses of these systems to environmental forcing.

The observatory supports sensors connected to two seabed stations which provide bi-directional acoustic communication with a surface buoy and the shore. SeaMon East is the station positioned at the base of the largest vent site of the field, Tour Eiffel. It records temperature and nephelometry and provides power to the TEMPO ecological module, placed near a diffuse venting area, 10 m to the north. TEMPO monitors the evolution of the hydrothermal fauna with a camera and measures several environmental variables (temperature, dissolved oxygen and iron concentrations).

The EGIM was deployed near the Tour Eiffel vent site, 25 m to the southwest of TEMPO and a TCM3 Lowell Instrument autonomous bottom current meter was deployed another 15 m to the south (**Figure 7**). Remotely Operated Vehicle (ROV) operations, including Wi-Fi underwater connections, were carried out a few days after deployment to check and complete the installation (Sarradin and Cannat, 2017). The EGIM was recovered during the MOMARSAT 2018 cruise (Cannat, 2018). Data was collected from all the sensors. Duration and frequencies of data acquisitions were defined to fit the power and data storage on board the EGIM.

On EMSO-Azores, the EGIM provided data (Sarradin et al., 2018a,b,c,d) valuable to the local hydrodynamic variability monitoring, complementing the data obtained by the other components of the observatory (Cannat et al., 2018; Laes et al., 2019; Sarradin et al., 2019) and improving the assessment of the dispersion of hydrothermal vent fluids and particles in the near seafloor seawater. Large variations in temperature and chemistry within venting areas can result from several mechanisms occurring in the shallow sub-seafloor (Cooper et al., 2000; Scheirer et al., 2006), but also from modulations by tides and currents (Tivey et al., 2002; Barreyre et al., 2014) and smaller-scale near-seafloor hydrothermal circulations (Schultz and Elderfield, 1997). Understanding these mechanisms requires the long-term monitoring of venting activity, but also of background seawater at reference points to discriminate between regional changes in water masses and local variation in venting activity (e.g., opening and closing of vents, sub-seafloor local processes).

The EGIM nephelometer measured low particle loads, just a little above the background dark value measured during calibration of the sensor (i.e., 48 NTU). Levels of turbidity were higher and more variable at SeaMon East, located on higher grounds and closer to Tour Eiffel vents, with peaks recorded in October, December, January, February and March (**Figure 8A**). Some of these peaks appear to match an intensification of venting activity in the nearby diffusion area, revealed by sharp increases in temperature and decreases in oxygen measured by the TEMPO (**Figure 8C**). Most variations, however, did not correspond with variations near the TEMPO vent indicating that SeaMon East also received particle loads from the main smokers located further up and to the north on the Tour Eiffel sulfide mount (**Figure 8A**). All nephelometry highs recorded at Seamon East, are tidally modulated and coincide with current reversion, with higher particle loads occurring at times of southern-directed currents (10B-C) which would transport material from the edifice toward SeaMon East. The EGIM data occasionally reveals small amplitude peaks (5 NTU; **Figure 8B** detail October) which clearly coincide with the larger amplitude variations recorded at SeaMon East (20 NTU or more) and are similarly correlated with tidal variations in current velocity and direction.

[18]https://vents-data.interridge.org/ventfield/lucky-strike

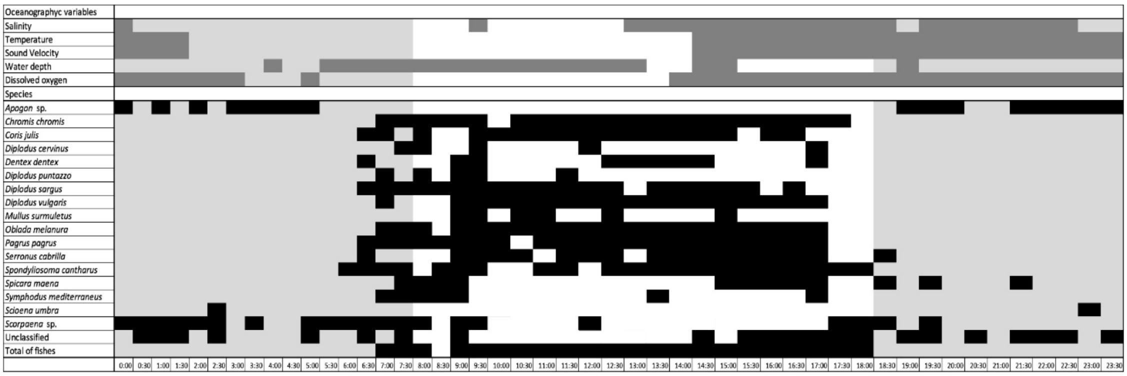

FIGURE 6 | Integrated chart of significant daily increases (mean values above the MESOR in each waveform plot) for the 5 biologically relevant oceanographic variables and visual counts of the 19 *taxa*, unclassified and total fish. Dark gray horizontal bars report values above the MESORs for the oceanographic variables, black horizontal are used for visual counts and light gray boxes show the duration of night hours.

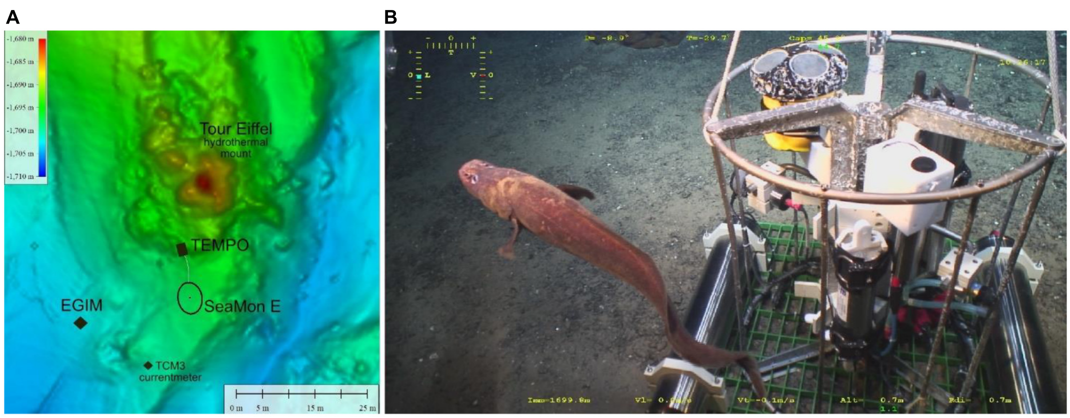

FIGURE 7 | (A) Map of the Tour Eiffel area at Lucky Strike (mid-Atlantic ridge) showing the location of the EGIM and the components of the EMSO-Azores observatory; **(B)** the EGIM.

Seawater temperatures measured by the EGIM and by SeaMon East are similar over the entire deployment period (i.e., 4–5°C). The dispersion radius of vent particles is therefore significantly larger than the effect that vent plumes might have on seawater temperature, which confirms the key role of currents on the near vent dispersion of hydrothermal particles (Girard et al., 2020).

This example shows how the EGIM, measuring surrounding background oceanic conditions, can complement the array of instruments and bring valuable information on the dispersion of vent particulate matter, a key parameter for the distribution of hydrothermal habitats (Girard et al., 2020).

Analysis of Acoustic Recordings From EMSO-Azores

The 3 months of acoustic data recorded by the EGIM on EMSO-Azores (duration was limited to match the energy available on the system; Sarradin et al., 2018e) were processed to search for acoustic events of interest under the LIDO[19] (Listening to the Deep-Ocean Environment) framework (André et al., 2011). As the data was recorded at a sampling rate of 4 kHz the analysis was limited to low frequency events, such as fish sounds or the lowest part of cetacean biosonar. Impulsive sounds, such as biosonar, were detected in a band between 500 and 2,000 Hz and short tonal sounds, such as whistles, with two detectors operating between 100–300 and 500–2,500 Hz. At this detection level, no distinction was made between biological sounds or self-noise, shipping sounds or other events. The detections serve to quickly browse over the dataset in order to find moments of interest. In addition to various animal sounds, some seismic events were identified, using the third-octave band sound pressure level measurements. Some results of the detections are shown below with links to access the database; **Figure 9** provides examples of biological impulse and short tonal signals and examples of other low frequency biological and natural.

A large number of marine mammal species can be found around the Azores Islands (Silva et al., 2003), making it an important area for conservation and monitoring. The EU focus

[19]http://lido.listentothedeep.com/

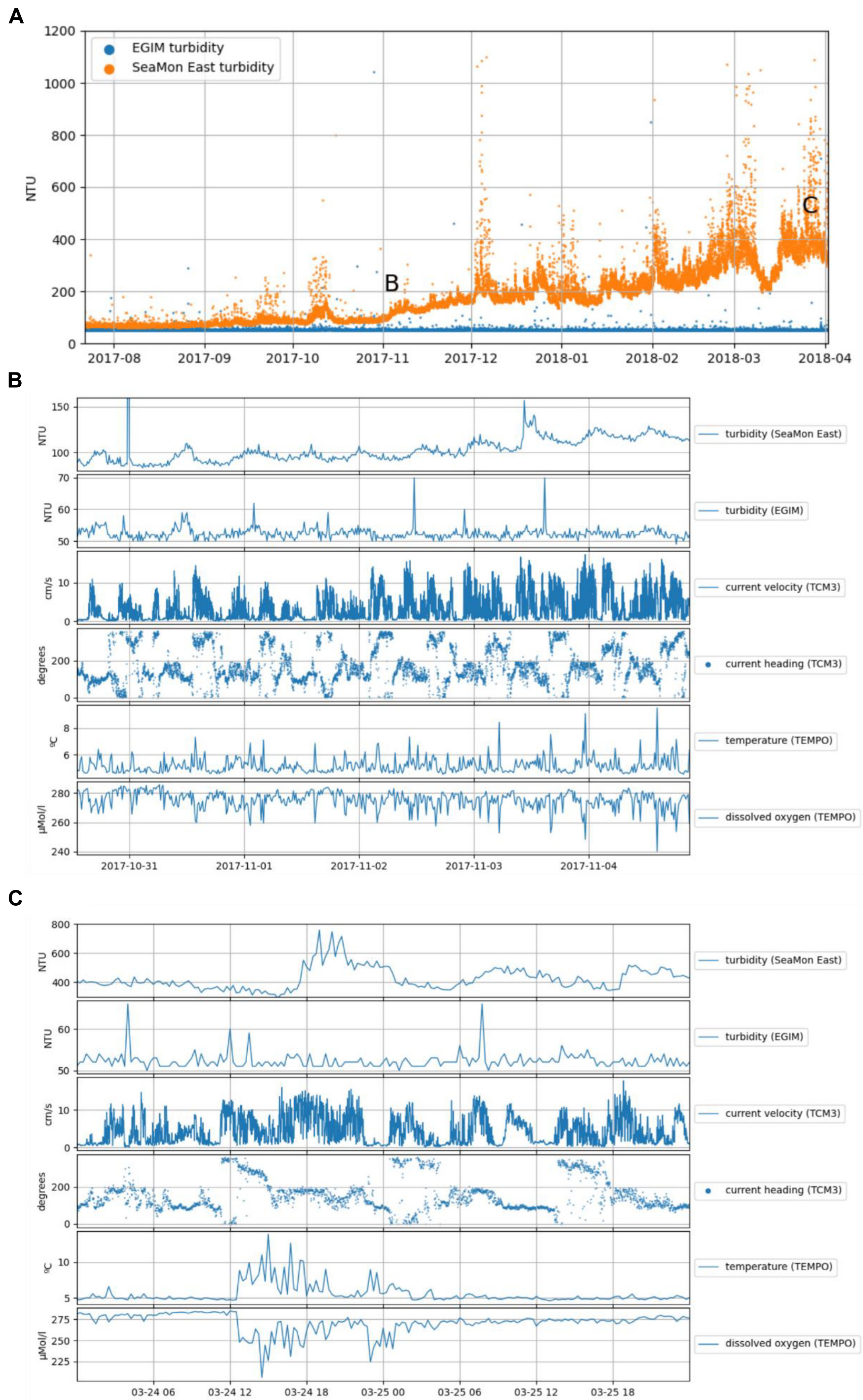

FIGURE 8 | (A) Evolution of turbidity measured by the nephelometers on the EGIM (blue) and Seamon East (orange) from 20 July 2017 to 4 April 2018. Details from the periods designated in panel **(A)** are shown in **(B,C)**. In **(B)** turbidity, currents, temperature and dissolved oxygen concentration from 30 October 2017 12:00 to 4 November 2018 18:00. In **(C)** turbidity, currents, temperature and dissolved oxygen concentration from 24 to 26 March 2018. Turbidity was measured by nephelometers deployed on the EGIM and the Seamon East. Current velocity and heading were recorded by the autonomous current meter. Temperature and dissolved oxygen concentration are from TEMPO (see **Figure 7A** for locations).

on underwater noise through the Marine Strategy Framework Directive (Van der Graaf et al., 2012) underlines the importance of standardized acoustic monitoring throughout Europe. The EGIM deployment at EMSO-Azores has been a very good test case with respect to interoperability and data accessibility, where data could be readily processed for instance for noise monitoring

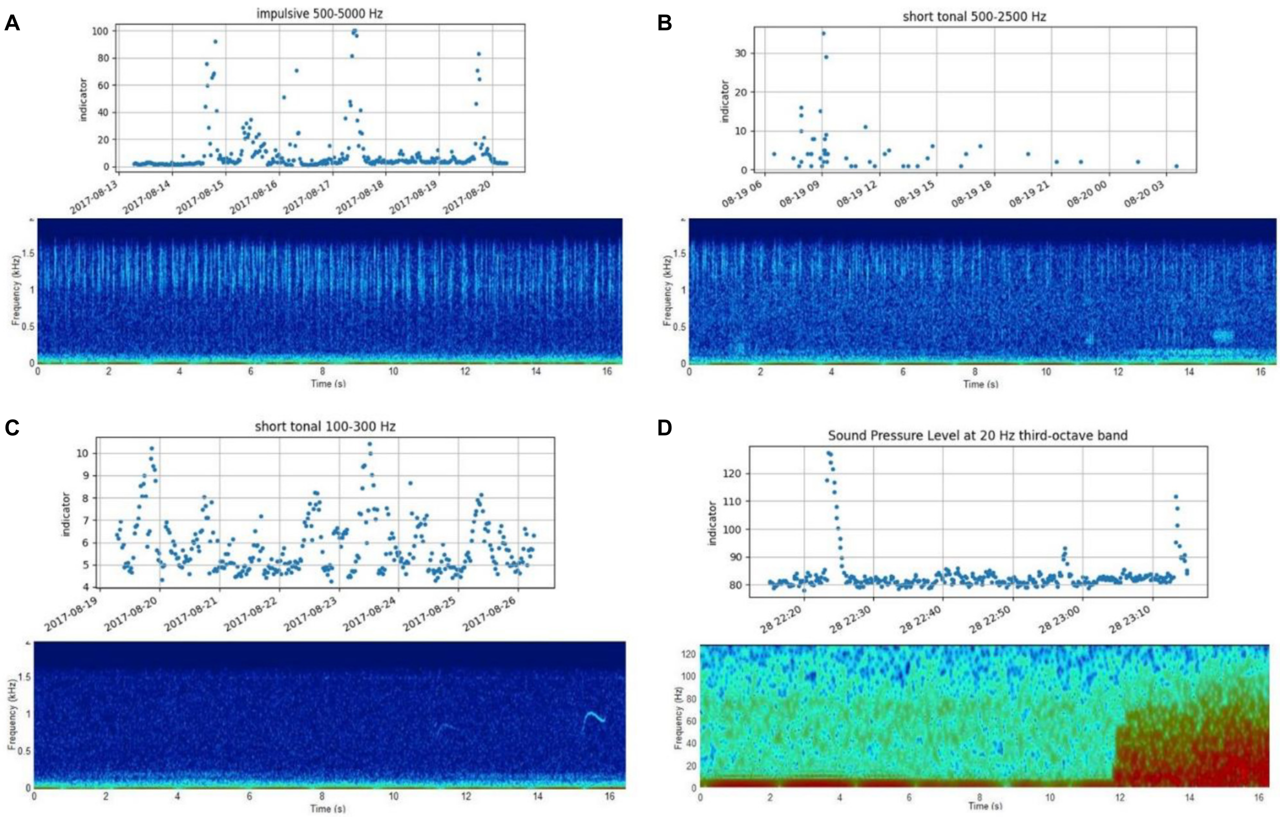

FIGURE 9 | Examples of acoustic events, each panel in this figure shows first in the dotted graphic the output of the data processing over almost 16.3 s segments with one dot per segment, for a particular detector or for example the sound level in a particular band. The second image in each panel is a spectrogram which shows a particular segment of interest (high detector value or high sound level): **(A)** the output of the impulse detector between 500 and 5,000 Hz and in the spectrogram signals which might be the lower part of sperm whale biosonar Play example A: (http://lido.listentothedeep.com/acoustics/index2.php?web=dataanalysis&rebuild&ts=1502604900&spp=0&width=0&time_unit=days&time_value=7&draw=67073:16843265:0:0-&grouping=none&metric_id=1&trend=0&spectrogram_timestamp=1502961658&spectrogram_platform=67073&spectrogram_segment=0&spec_id=1&overlay=1). **(B)** The output of the short tonal detector between 500 and 2,500 Hz which picked up various whistle-like signals Play example B: (http://lido.listentothedeep.com/acoustics/index2.php?web=dataanalysis&rebuild&ts=1503123300&spp=0&width=0&time_unit=days&time_value=1&draw=67073:16843012:0:0-&grouping=none&metric_id=1&trend=0&spectrogram_timestamp=1503133395&spectrogram_platform=67073&spectrogram_segment=1540559007&spec_id=1&overlay=1). **(C)** The output of a low frequency short tonal detector with a spectrogram showing at the bottom right-side croaker fish sounds Play example C: http://lido.listentothedeep.com/acoustics/soundlibrary/listenrt.php?idSeg=1540560833&idLoc=67073&idRun=176211&ts=1503163122&spec_id=3&class_id=16843025&data_id=0&tstart=1503159522&tend=1503249658. **(D)** Sound levels in the third-octave centered on 20 Hz clearly indicating an event of interest and a zoomed spectrogram at the start of a seismic event Play example D: http://lido.listentothedeep.com/acoustics/soundlibrary/listenrt.php?idSeg=1540774324&idLoc=67073&idRun=389685&ts=1506637399&spec_id=4&class_id=3492806916&data_id=0&tstart=1506633799&tend=1506641008.

purposes. Redeployment of EGIM at the Azores will allow to build-up a long-term time series, recorded and processed using identical procedures, providing an excellent Marine Strategy Framework Directive data set for following the evolution of underwater noise levels in the coming years and for monitoring cetacean presence in general.

Complementing the Long-Term Central-Eastern Atlantic ESTOC Time Series With Deep-Ocean Observation

ESTOC site is an open-ocean reference for the long term observation of the Central-Eastern Atlantic. It is located within the weak southward return flows on the Eastern side of the North Atlantic subtropical gyre, well outside of the highly variable eastern boundary with its strong coastal upwelling regime (although interaction with this regime exists). The site is sufficiently deep to encompass the Eastern subtropical North Atlantic's major water masses including the North Atlantic Deep Water (except the Antarctic Bottom Water current). ESTOC is windward of the Canary Islands and avoids wake effects of both the major currents and winds (Canary Current and Northeast Trade Winds). It is far enough from coasts and islands to serve as reference for satellite images and altimetry.

The time series observations at ESTOC (Delory et al., 2021a,b,c,d,e) complement our understanding of the biogeochemistry of the Subtropical North Atlantic by providing seasonally resolved, multi-year data from the eastern boundary of the gyre. The objective of the EGIM deployment on ESTOC was

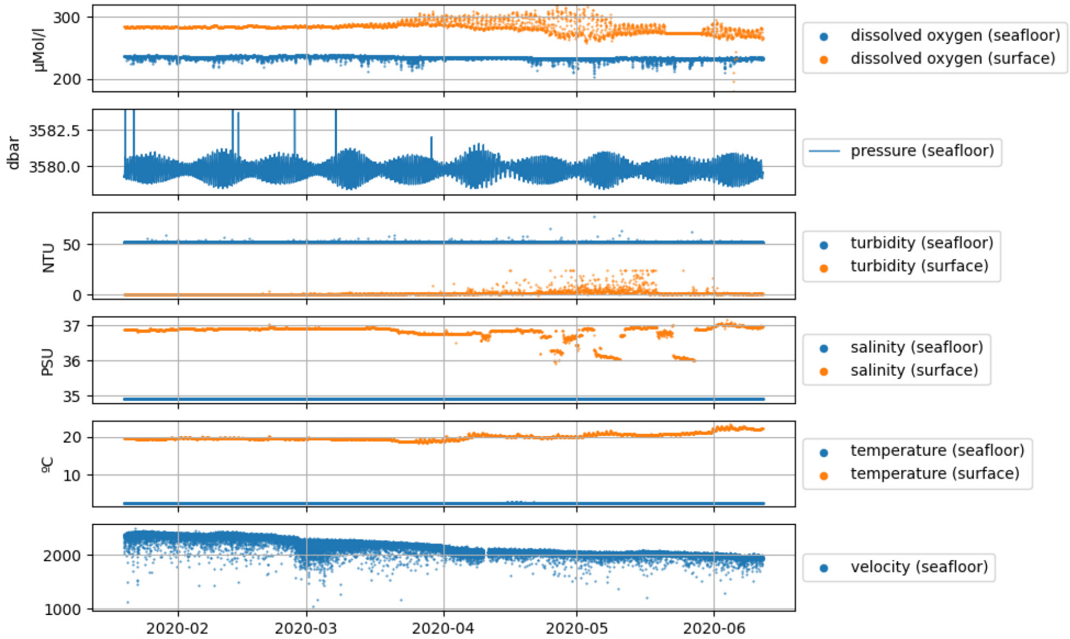

FIGURE 10 | EGIM (blue) and surface buoy (orange) observations of dissolved oxygen, pressure, turbidity, salinity and temperature at ESTOC, in 3,600 m depth. Pressure and current velocity are not measured at the surface.

to observe, for the first time after 20 years of operation, oceanic processes near the sea bottom, a measurement anticipated at the early stage of the FixO3[4] project.

The EGIM and the mooring line were deployed in free-fall, from RV Angeles Alvariño (Spanish Institute of Oceanography, IEO), 60 miles north of Gran Canarias. The mooring line is a 14 mm Dyneema® rope with a short 3 m chain at the bottom. The layout of the mooring line comprises from the bottom up: a mooring weight, two acoustic releasers used for recovery, the EGIM, configured in standalone mode 70 m above seafloor, and the flotation at the top of the line. In order to reduce velocity and mitigate the damage during descent due to drag on cables and connectors, a sea "para-anchor" (i.e., acting as a parachute) was attached to the floatation at the top of the mooring. According to the EGIM CTD (Conductivity Temperature and Depth sensor) records, the module took about an hour to reach the bottom, with an estimated average descent time of 1 to 1.5 m/s and the actual deployment depth recorded was 3,580 m (pressure sensor data).

Water samples and CTD casts were collected at two points at nearby locations at 3,620 m depth, for salinity (CTD and Autosal), temperature (CTD) and dissolved oxygen (Winkler). It appears that the data recorded for temperature, salinity and oxygen is relevant with the sampling of the near bottom water performed at deployment time (**Figure 10**).

The data series was not complete. The acquisition or the data recording stopped for about a month and resumed with nominal function. The hydrophone recorded for the first 11 h with good quality signals, then halted, most probably due to a human mistake on the time configuration. A complete expertise is underway but this deployment managed by a new team pointed out a necessary refinement of the human-machine Interface which has since been enriched with additional range controls.

It also confirmed the potential of measuring the time series of Essential Ocean Variables along the water column not only in the upper segment but also near the seafloor. Following the visions of FixO3[4] project, collecting such series is expected to be a common practice at several EMSO sites (EMSO-Ligure-Dyfamed, NorEMSO-Mohn, EMSO-Azores, EMSO-Hellenic Arc).

EGIM Deployments Outcomes

Lessons were learnt during the 19 month period when the EGIM was operated by 4 different teams at OBSEA, EMSO-Azores, Catania and ESTOC in real operational situations. These led to software updates and hardware improvements. The deployments demonstrated the capability of the equipment in different configurations and site-specific conditions including data collection in shallow water, deep water, in the water column and near the seabed. Different modes of deployment and maintenance including diver operation, ROV attendance and deployment as a free-fall lander demonstrated the versatility of the system. The case studies illustrated the benefits of the EGIM to enrich the analyses and expand the observation coverage of an observatory to other areas of the core EMSO Science Services under the themes of Geo-hazards, Climate Change and Marine Ecosystems. The addition of the EGIM to EMSO observatories also enabled greater integration of different data sets for the production of data products which are relevant to environmental monitoring such as Marine Strategy Framework Directive indicators.

CONCLUSION: THE EGIM, A CRUCIAL STEP TOWARD STANDARDIZATION AND INTEROPERABILITY FOR OCEAN MONITORING

Through the development of the EGIM, a deployment ready, upgradeable instrumentation that complies with EMSO best practices and recommendations, is available to EMSO Regional Facilities and to the wider marine science community (research and industry).

The EGIM will increase the service-provision capacity of the Regional Facilities and serve the EMSO ERIC aim of efficient collaborations at both EU and international level with related networks, Research Infrastructures, industry and other stakeholders. Issues such as networking, promotion of integrated scientific concepts, technical interoperability, common best practices and aligned services with other marine communities, are very high in the EMSO agenda. The EGIM is a direct contribution toward this endeavor, giving EMSO the leading role and the responsibility for the next steps in this direction.

The EGIM results demonstrate its value, particularly in standardization and interoperability in ocean observing. This is recognized by JERICO[20], the network of European Coastal Observatories which will develop a version of the EGIM specific to the coastal zone. It will be designed, built and tested hosting a core set of sensors, compatible with open standards for sensor and data interoperability, ensuring interoperability with EMSO standards but optimized to shallower water depths (e.g., depth appropriate pressure housings and greater focus on bio-fouling).

The EGIM is also acknowledged by ONC-Ocean Networks Canada (Heesemann et al., 2014). Ocean Networks Canada is indeed planning to use the EGIM in both the Canadian Arctic (Cambridge Bay) and Antarctica. This will include the deployment in standalone, in cabled mode and the test of the data stream transfer to Ocean Networks Canada Data Management System. This will meet the scientific aim to provide data to better understand and protect fragile Arctic marine ecosystems. The deployment, initially scheduled for the end 2019 was delayed and now strongly depends on the evolution of the COVID-19 pandemic.

The EGIM concept offers solutions for challenges faced by maritime industry operators. Marine renewable energy test site operators are interested in the concept of the EGIM as it would allow test sites from across Europe and globally to compare a standard set of core parameters *via* the same data sampling frequency, with the same sensors. Offshore industries require increased efficiency in environmental monitoring and impact assessment. For example, long-term monitoring of decommissioned oil and gas fields could be supported by *in situ* autonomous monitoring with a system like the EGIM providing a substantial improvement in the temporal resolution of environmental monitoring while potentially providing cost savings and reduced carbon emissions through reduced ship time (Jones et al., 2019). In ports and harbors the coastal version of the EGIM could provide data which would be useful for navigation and could enable operators to monitor port activities such as dredging and other engineering works.

There are a number of intermediary and consultancy companies involved in environmental monitoring which could avail of the capabilities of the EGIM. These companies could potentially use data gathered by the EGIM as an input to the creation or enhancement of value-added information products in the support of specific end users. These companies are generally involved in marine environmental monitoring and meteocean forecasting.

The EGIM is also a move forward to preparedness (a concept used in health pandemics and environment catastrophe fields), essential to cope with some of the targeted scope fields of the subsea observatories such as tsunami, volcanoes or underwater megathrust seismic events and large pollution events. The national and international operation management in response to a natural disaster calls for scientific expertise and the research data sets from adequate sensors (several of them already available on the EGIM) under short notice. For example, the tsunami in Indonesia in 2004 led to scientific studies with immediate answers if based on satellite data, but not so fast if based on underwater measurements (Tilmann et al., 2010). This event constituted one driver for EMSO and for similar projects in Japan (Matsumoto et al., 2017; Mochizuki et al., 2018), Canada and United States (Wilcock et al., 2018) to pave the way for better preparedness including sharing know-how, and proposing EGIM technologies ready for deployment to measure in any ocean environment. An interesting application of the deployment of an EGIM in this context occurred in September 2021 with the eruption of the Cumbre Vieja volcano off the coast of La Palma, Canary Islands, in the contact zone of recent lava flows with the Atlantic Ocean, and a second deployment could follow to observe the underwater volcanic eruption which began in May 2018 about 50 km East of Mayotte (Lemoine et al., 2020).

A second long and deep-sea deployment started on Azores in May 2021 and others are on the way. On Western Ionian Sea, the equipment is ready, awaiting a ship of opportunity and ESTOC (Canary Archipelago) confirmed the intention to redeploy the system.

Following the European Commission requirement, the EGIM intellectual property is governed through a Joint Ownership Management Agreement signed among the EMSODEV project partners[21]. IFREMER, as lead party of this agreement, was granted authorization to assist the first replications of the EGIMs post-EMSODEV project. In the near future, EMSO will manage procurement and replication.

The EMSO ERIC structure of Service Groups (Science, Data, Engineering and Logistics, Communications and Industry and Innovation) will support the EGIM in terms of updates, evolutions and supervision of user's contribution. This includes maintenance of the availability of the components, tracking instrument upgrades with a view to keep the system up to date with international standards. This also includes increasing

[20]https://www.jerico-ri.eu/

[21]Requirements are available at: https://intellectual-property-helpdesk.ec.europa.eu/regional-helpdesks/european-ip-helpdesk_en

deep ocean and biological data collection to enhance ocean observation (Levin et al., 2019): the coming developments for the EGIM scientific parameters include addition of biogeochemistry parameters (e.g., chlorophyll fluorescence/chlorophyll-A, pH, partial CO_2 pressure, partial CH_4 pressure and marine imaging systems).

These various perspectives underline that the EGIM can be considered as a milestone to meet the ocean monitoring need for standardization and interoperability and EMSO ERIC has endorsed the responsibility to go forward.

DATA AVAILABILITY STATEMENT

The datasets presented in this study can be found in online repositories. The names of the repository/repositories and accession number(s) can be found below: Data from the EGIM, EMSO-Canarias (ESTOC), 2020. SEANOE. https://doi.org/10.17882/83639, https://doi.org/10.17882/83643, https://doi.org/10.17882/83646, https://doi.org/10.17882/83642, and https://doi.org/10.17882/83645. Data from the EGIM, EMSO-Azores observatory, 2017-2018. SEANOE. https://doi.org/10.17882/56665, https://doi.org/10.17882/56528, https://doi.org/10.17882/56501, https://doi.org/10.17882/56525, https://doi.org/10.17882/56626, https://doi.org/10.17882/57005, https://doi.org/10.17882/69867, and https://doi.org/10.17882/69976. Annotated images capturing fish abundances during the first deployment of the EMSO Generic Instrument Module (EGIM) at the OBSEA cabled observatory from December 2016 to April 2017. PANGAEA, https://doi.org/10.1594/PANGAEA.936693. Data collected during the first deployment of the EMSO Generic Instrument Module (EGIM) at the OBSEA cabled observatory from December, 2016 to April, 2017. PANGAEA, https://doi.org/10.1594/PANGAEA.883072.

AUTHOR CONTRIBUTIONS

NL, HR, AG, EM, and JR started the project and established the frame. The group extended to JA, MC, ED, DE, RH, MM, GP, KR, J-FR, MS, JD, and PF reached an advanced version developing the context, the technological and IT aspects, the science use cases and the perspectives. EM took care of the charts. MA, JB, AC, MF, OG, SH, J-RL, JL, PP, JP, XR, DT, GM, BM, RS, and HW contributed to the work presented in the manuscript. All authors revised and enriched the manuscript, read and approved the submitted version.

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SANTORY: SANTORini's Seafloor Volcanic ObservatorY

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Submarine hydrothermal systems along active volcanic ridges and arcs are highly dynamic, responding to both oceanographic (e.g., currents, tides) and deep-seated geological forcing (e.g., magma eruption, seismicity, hydrothermalism, and crustal deformation, etc.). In particular, volcanic and hydrothermal activity may also pose profoundly negative societal impacts (tsunamis, the release of climate-relevant gases and toxic metal(loid)s). These risks are particularly significant in shallow (<1000m) coastal environments, as demonstrated by the January 2022 submarine paroxysmal eruption by the Hunga Tonga-Hunga Ha'apai Volcano that destroyed part of the island, and the October 2011 submarine eruption of El Hierro (Canary Islands) that caused vigorous upwelling, floating lava bombs, and natural seawater acidification. Volcanic hazards may be posed by the Kolumbo submarine volcano, which is part of the subduction-related Hellenic Volcanic Arc at the intersection between the Eurasian and African tectonic plates. There, the Kolumbo submarine volcano, 7 km NE of Santorini and part of Santorini's volcanic complex, hosts an active hydrothermal vent field (HVF) on its crater floor (~500m b.s.l.), which degasses boiling CO_2–dominated fluids at high temperatures (~265°C) with a clear mantle signature. Kolumbo's HVF hosts actively forming seafloor massive sulfide deposits with high contents of potentially toxic, volatile metal(loid)s (As, Sb, Pb, Ag, Hg, and Tl). The proximity to highly populated/tourist areas at Santorini poses significant risks. However, we have limited knowledge of the potential impacts of this type of magmatic and hydrothermal activity, including those from magmatic gases and seismicity. To better evaluate such risks the activity of the submarine system must be continuously monitored with multidisciplinary and high resolution instrumentation as part of an *in-situ* observatory supported by discrete sampling and measurements. This paper is a design study that describes a new long-term seafloor observatory that will be installed within the Kolumbo volcano, including cutting-edge and innovative marine-technology that integrates hyperspectral imaging, temperature sensors, a radiation spectrometer, fluid/gas samplers, and pressure gauges. These instruments will be integrated into a hazard monitoring platform aimed at identifying the precursors of potentially disastrous explosive volcanic eruptions, earthquakes, landslides of the hydrothermally weakened volcanic edifice and the release of potentially toxic elements into the water column.

Keywords: Kolumbo, hydrothermal vents, monitoring, submarine volcano, Santorini, marine technological innovation

INTRODUCTION

About 80% of volcanism on Earth is submarine (Crisp, 1984), mainly in subduction-related arc and mid-ocean ridge (MOR) geodynamic settings. The deep-seated mantle processes and associated volcanic activity are primary drivers of the chemical and biogeochemical evolution of the global oceans. Submarine volcanism is often associated with seafloor hydrothermal activity and degassing of high-temperature magmatic volatiles, presenting both potential hazards and opportunities for the future, such as mineral deposit formation that are the focus of intense debate over marine resources (e.g., Beaulieu et al., 2017).

Hydrothermal activity also supports an astonishing diversity of seafloor vent ecosystems influencing global carbon and nutrient cycles (Van Dover et al., 2002; Sander and Koschinsky, 2011; Hawkes et al., 2015), aspects that have been widely studied in different geodynamic settings (Lupton et al., 1990; Taran et al., 1992; Lilley et al., 1993; Tsunogai et al., 1994; von Damm, 1995; von Damm et al., 1995; Butterfield et al., 1997; Lupton et al., 2006; Lupton et al., 2008; Lupton et al.,2009; Caracausi et al., 2005a; Lan et al., 2010; Hannington et al., 2011; Kilias et al., 2013; Rizzo et al., 2016a; Rizzo et al., 2019; Bravakos et al., 2021). Most of the known modern seafloor hydrothermal systems, with their associated mineral deposits and chemosynthetic microbial biomes, occur at MORs and mature back–arc spreading centers, typically at water depths of 2000 to 4000m (e.g., Butterfield et al., 1990; Lilley et al., 1993; Von Damm, 1995; Von Damm et al., 1995; Lupton et al., 1999; Price and Giovanneli, 2017).

The least studied seafloor hydrothermal vent sites are associated with shallow submarine arc volcanoes and arc–related rifts in subduction–related settings (Taran et al., 1992; Tsunogai et al., 1994; Lupton et al., 2006; Lupton et al., 2008; Lan et al., 2010), which typically occur at a much shallower water depth (<1000m). These vigorously degassing, submarine hydrothermal systems are associated with significant and dangerous volcanic and seismic activity and are more likely to impact the marine environment near-coastal populations (Dando et al., 1995; Zimanowski and Büttner, 2003; Puzenat et al., 2021; Mei et al., 2022). The cabled sea-floor observatory deployed off the coast of Panarea hydrothermal system (Aeolian Arc, South Tyrrhenian Sea, it was exploded in November 2002) at a depth of 24m, is at the moment the only monitoring system installed in the Mediterranean Sea which automatically transmits data of chemical and physical signals (T, EC, pH, dissolved CO_2, acoustics) to shore (Caracausi et al., 2005a; Caracausi et al., 2005b).

Research on shallow submarine arc volcanoes is still in its infancy despite their potentially severe hazards. In the Mediterranean, the Aeolian Island Arc of the Tyrrhenian Sea (Caliro et al., 2004; Caracausi et al., 2005a; Chiodini et al., 2006; Capaccioni et al., 2007; Heinicke et al., 2009; Tassi et al., 2009; Monecke et al., 2014; Petersen et al., 2014; Tassi et al., 2014; Tassi et al., 2015; Esposito et al., 2018) and the Hellenic Volcanic Arc of the Aegean Sea (Dando et al., 2000; Nomikou et al., 2012; Nomikou et al., 2013; Carey et al., 2013; Kilias et al., 2013; Cantner et al., 2014; Christopoulou, et al., 2016; Ulvrova et al., 2016; Rizzo et al., 2016a; Rizzo et al., 2019; Puzenat et al., 2021; Daskalopoulou et al., 2022; Kilias et al., 2022) have attracted lots of attention, as very little is known about their volcanic and hydrothermal activity and impacts over intermediate and longtime scales. Nevertheless geological and historical records point to many catastrophic events that have had a broad impact throughout Southern Europe (Druitt et al., 1999).

At global scale, *in situ* seafloor observatories for long-term monitoring of submarine volcanoes have been developed at a number of locations, such as the Azores node of European Multidisciplinary Seafloor and water column Observatory (EMSO: Colaco et al., 2011; Best et al., 2014; Escartin et al., 2015), Axial Seamount in the NE Pacific, which is part of the U.S. National Science Foundation (NSF)-funded Ocean Observatories Initiative (OOI) Cabled Array that captured the 2015 eruption (Nooner and Chadwick, 2016; Wilcock et al., 2016; Trowbridge et al., 2019; Cabaniss et al., 2020), the Ocean Networks Canada cabled observatory at Endeavour Ridge (Kelley et al., 2014), and also the Mayotte deep-sea eruption (North Mozambique channel) with an observatory being put in place by France (Feuillet et al., 2021). Several of these observatories have successfully captured changes in the dynamics and evolution of submarine volcanism. For example, the 2015 Axial Seamount eruption was successfully forecast within a 1-year time window on the basis of volcanic deformation, ascribed to pressurization of a magma reservoir at depth, and was captured in real time by the OOI Cabled Array (Nooner and Chadwick, 2016). A combination of deformation and seismic monitoring are being used to attempt to forecast the next eruption (Chadwick et al., 2022).

This paper is a design study, which reports on a joint effort of a multinational team of Earth and Ocean scientists to build a new seafloor observatory (SANTORini's seafloor volcanic observatorY, SANTORY) that will be developed and installed within the crater of the submarine Kolumbo volcano (Nomikou et al., 2012; Nomikou et al., 2013) to monitor its activity and mitigate the hazards it poses to the neighboring densely populated volcanic island of Santorini.

SANTORY represents a new research priority for a combination of reasons:

Geochemical diversity: The Kolumbo shallow-seafloor massive sulfide (SMS) hydrothermal mineralization shows a range of elements and minerals, including those with security of supply issues (e.g., Sb, Sr, barite), and those that may have potential environmental implications (Tl, As, Sb, Hg), in areas exploited by fishing and tourism, if not managed. Understanding the geochemistry of these occurrences and the potential toxicity impact associated with their preservation and/or discharge, needs greater scientific focus.

Geological and Environmental diversity: The Kolumbo volcanic terrain includes nearly exposed volcanic flanks and sheltered crater within relatively shallow waters of European Exclusive Economic Zones (EEZs) making related geohazards more dangerous than those in international waters. Moreover, it is a dynamic environment with changing sediment inputs from islands and continental landmasses, and variable topographies and seismic activity which affect rates and levels of mass wasting. These factors affect seafloor toxic-metal budget and liberation potential.

Near-term submarine biotechnology potential: Environments such as Kolumbo are unique locations of high biological productivity, and high degrees of endemism, of added value to global biomedical research. The Hellenic (South Aegean) Volcanic Arc has been described as the largest 'submarine volcanic ecosystems, a significant resource of novel genes and pathways with potential submarine biotechnological applications (Chrousos et al., 2020).

STUDY SITE: SANTORINI-KOLUMBO VOLCANIC FIELD

A linear feature in the southern Aegean Sea known as the Christiana–Santorini–Kolumbo (CSK) rift (Nomikou et al., 2019) (**Figure 1**) hosts one of the most important volcanic fields in Europe, having erupted more than 100 times in the last 400.000 years (Druitt et al., 1999). Running in a NE–SW direction, it includes several volcanic centers of late Pliocene to Pleistocene age as part of the larger east–west trending Hellenic subduction zone, north of the island of Crete. The CSK rift lies in a 100 km long, 45 km wide zone of *en echelon* NE–SW-trending rifts, including the Santorini–Amorgos Tectonic Zone (Nomikou et al., 2018). It hosts volcanic centers that include the extinct Christiana Volcano and associated seamounts, Santorini caldera with its intracaldera Kameni Volcano, Kolumbo Volcano, and 25 other submarine cones of the Kolumbo chain, which extends NE along the floor of the Anhydros Basin. Kolumbo is currently the most volcanically active part of the CSK (Nomikou et al., 2012; Hooft et al., 2017). The world-known Santorini volcano is a globally significant volcanic center, with numerous large-volume explosive eruptions over the last 600.000 years (Druitt et al., 1999). It is widely renowned for its 3600 BP Minoan eruption, which is thought to have had a significant impact on the homonymous Minoan civilization (Crete), in the Eastern Mediterranean Sea, because of the subsequent earthquakes and tsunamis (Dimitriadis et al., 2009; Ulvrova et al., 2016; Nomikou et al., 2016).

The Kolumbo volcano, a 3 km diameter cone with a 1700 m wide crater, is the most prominent entirely submarine volcanic feature of the CSK rift. The crater's rim is currently as shallow as 18 m below sea level, and the flat crater floor is 505 m below sea level (**Figure 2**). At least seventy people who were either at sea or along the NE coastline of Santorini died of asphyxiation due to acidic gases released by an intense eruption from Kolumbo in 1650 AD (Cantner et al., 2014; Fuller et al., 2018). In addition, a large tsunami on the 29th of September 1650 caused widespread damage on Santorini and on other islands within a 150 km radius (Ulvrova et al., 2016).

The first detailed bathymetric map of the Kolumbo volcano was produced in 2001 using the 20 kHz SB2120 swath system on R/V Aegaeo (Nomikou et al., 2012; Nomikou et al., 2013). More recently in 2015, bathymetric data were also acquired on-board the R/V Marcus Langseth using the Simrad Kongsberg EM122, 12 kHz multibeam echo sounder. In 2017, high-resolution AUV (Autonomous Underwater Vehicle) data were collected during POS510 cruise, in 7 missions of AUV Abyss (GEOMAR) (Hannington, 2018), under the framework of the collaborative project "ANYDROS: Rifting and Hydrothermal Activity in the Cyclades Back-arc Basin" (**Figure 2**). The AUV mapping allows a 2m resolution that can identify seafloor geomorphological features that are not visible in conventional ship-based multibeam data. The new bathymetric map of Kolumbo volcano (Nomikou et al., 2019b) reveals: a) the abrupt inner slopes of Kolumbo crater, b) the almost flat seafloor surrounding the active vent field at the northern part of the crater floor (485 m depth) c) dykes exposed in the inner slopes, d) the mass-wasting deposits in the inner slopes, e) the curvilinear scarps with inward dipping faces at the W-NW rim of the crater.

Kolumbo is the most active volcanic center in the area and is considered the most dangerous submarine volcano in the Mediterranean Sea, partly because it is prone to explosive activity. At present, Kolumbo is only monitored sporadically during isolated oceanographic missions, and therefore nearby highly populated areas are vulnerable to significant risks from the volcano (such as earthquakes, tsunami, landslides). Current knowledge mainly concerns Kolumbo's hydrothermal activity as a source of potentially toxic metal(loid)s, climate-critical gases,

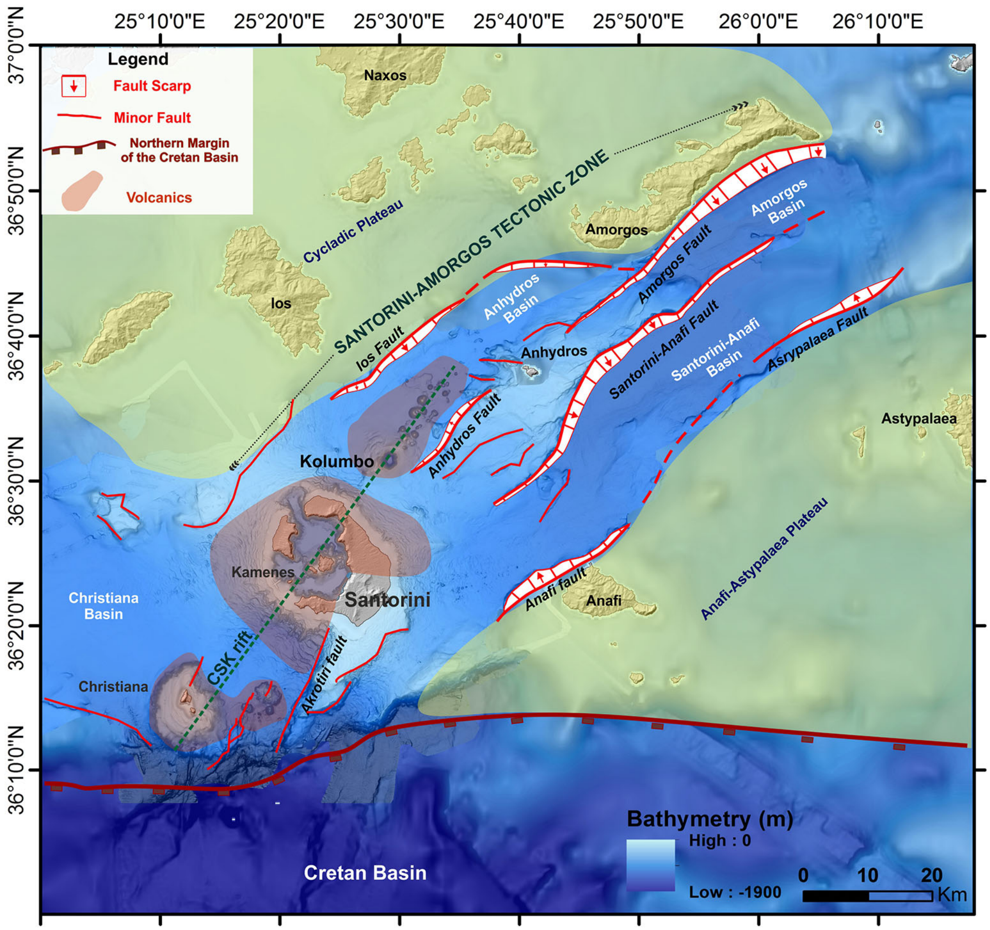

FIGURE 1 | Christiana-Santorini-Kolumbo rift (South Aegean Sea, Greece) (Nomikou et al., 2018; Nomikou et al., 2019).

as well as natural radioactivity (Jamieson et al., 2013; de Ronde et al., 2019; Neuholz et al., 2020; Klose et al., 2021).

The hydrothermal system within its caldera (Sigurdsson et al., 2006; Kilias et al., 2013), emits an important but poorly quantified flux of mantle-derived gases together with aqueous fluids venting at 265°C (Carey et al., 2013; Klaver et al., 2016; Hannington, 2018; Rizzo et al., 2016a; Rizzo et al., 2019) (**Figure 3**). The emitted gases composed of nearly pure CO_2 and other trace gases (e.g, H_2S, CH_4, H_2, CO) common to hydrothermal systems at active volcanoes. Noble gases are present in trace concentrations, and helium ($^3He/^4He$) ratios of up to 7 Ra, with a Mid-ocean ridge basalts: MORB-like signature, are the highest reported along the Hellenic volcanic arc (Rizzo et al., 2016a; Rizzo et al., 2019). In Kolumbo gases, a remarkable concentration of Hg(O) has also been found (Rizzo et al., 2019), suggesting active magmatic-hydrothermal degassing activity of this volcano that poses several hazards for the area; this is confirmed by elevated contents of Hg fixed in hydrothermal sulfide minerals deposited in seafloor hydrothermal deposits (see below).

The Kolumbo crater hosts an active shallow-marine, boiling hydrothermal system currently forming the only known polymetallic seafloor massive sulfide (SMS) deposits associated with continental margin volcanism, with high contents of potentially toxic, volatile metal(loid)s (VTML), i.e., Ag, Hg, As, Sb, Pb and Tl (Kilias et al., 2013; Kilias et al., 2016). The VTML are contributed to the Kolumbo hydrothermal system, possibly *via* active degassing of a shallow magma chamber and the shallow submarine hydrothermal venting (de Ronde et al., 2005; Hannington et al., 2005; Kilias et al., 2017). High VTML contents are variably distributed in sulfide minerals (pyrite, marcasite, galena, sphalerite, chalcopyrite, Pb-Sb sulfosalts, stibnite, and orpiment- and realgar-like As-sulfides) which constitute potential natural source of VTML to the overlying seawater column (Kilias et al., 2016; Fuchida et al., 2017; Zegkinoglou et al., 2019a; Fallon et al., 2019; Zitoun et al., 2021) (**Figure 4**).

In terms of radioactivity, the amount being released by Kolumbo is largely unknown, as is the case with most submarine volcanic systems featuring hydrothermal activity

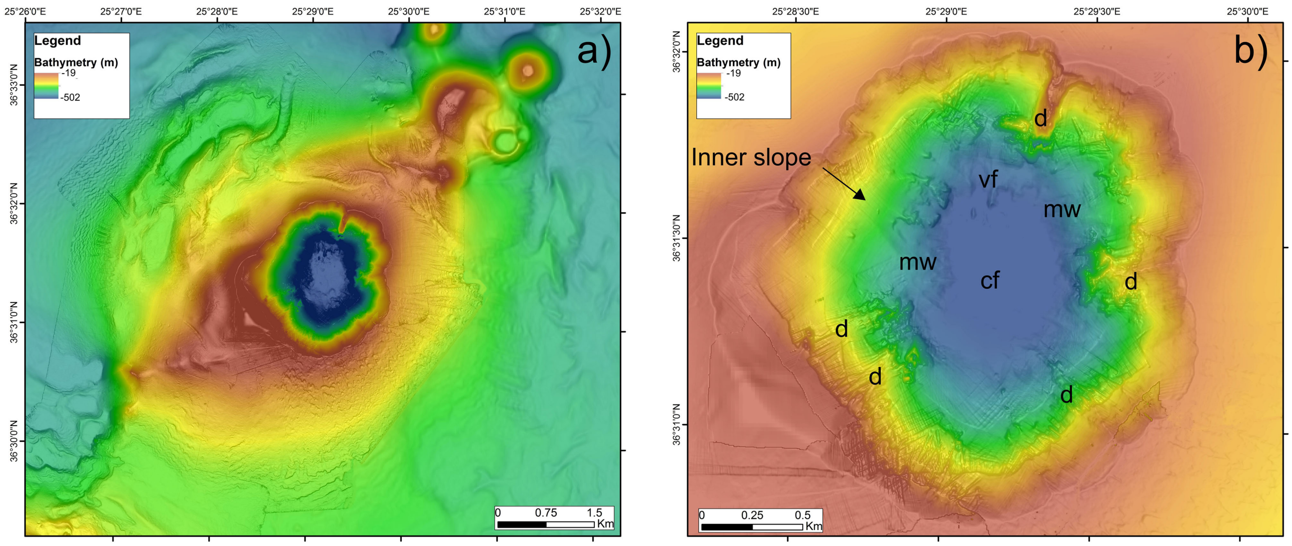

FIGURE 2 | **(A)** An AUV high-resolution bathymetric map of Kolumbo volcano **(B)** An AUV high-resolution map of Kolumbo crater (High resolution bathymetric data were collected by GEOMAR's AUV Abyss during mission POS 510, Hannington, 2018). d, dyke; cf, crater floor; mw, mass wasting deposits; vf, vent field.

around the world. Natural radioactivity stems mainly from naturally occurring long-lived radioactive uranium and thorium daughters, which are produced in the mantle and can be released to the water column by hydrothermal fluids. The presence of VTML may also suggest the presence of the heavier and radioactive Ra isotopes in the dynamic hydrothermal processes, despite the latter have not been studied in Kolumbo. Among these natural radioactive emitters, important radio tracers present in HVF are the gaseous radon (^{222}Rn) and the thoron (^{220}Rn), which can easily escape the mantle and the sediment layer *via* diffusion and transfer processes. The study of their kinetics in the marine environment can offer valuable information on the dynamics of the system, and radon and thoron releases may be seismic precursors (Hwa and Kim, 2015). With SANTORY, we expect to close this knowledge gap worldwide using long-term, *in situ* monitoring, overcoming the remoteness and the harsh conditions of Kolumbo, by installing and operating a novel, high-resolution γ-ray spectrometer.

The Kolumbo volcano has a number of unique attributes that make it attractive for an observatory: i) it is ideally located and very accessible; (ii) it shows significant magmatic and hydrothermal activity; iii) it hosts a unique physical and chemical environment, owing to its deep, nearly vertical-walled crater; iv) the high-temperature hydrothermal vent field is an extreme environment emitting high concentrations of VTML that are partly fixed in polymetallic hydrothermal sulfide chimneys and mounds, and also released into the seawater column in unknown quantities, causing also build-up of hydrothermally emitted CO_2 resulting in persistent acidic conditions; v) the observed metal(loid) enrichment highlights the significance of shallow submarine hydrothermal vent activity as a potential source of toxic metal (loid)s in natural areas extensively exploited by tourism and fishing; vi) the hydrothermal vents are habitats for extremophiles that are not found or only detectable in very low numbers in other active vent fields; and (vii) of particular interest is the opportunity to assess changes in habitat conditions (e.g., *via* genomics) and the release of toxic elements due to volcanic and hydrothermal activity unrest.

DESCRIPTION OF THE PLANNED OBSERVATORY

The SANTORY observatory aims to monitor the current activity at Kolumbo volcano and link these findings to ongoing observations of the wider Santorini Volcanic Complex, by developing and integrating state-of-the-art technology for *in situ* monitoring along with discrete sampling and measurements (**Figure 5**).

The heart of the observatory will include moorings with spectral imaging capabilities, *in situ* operating sensors, including chemical sensors, pressure gauges coupled with tiltmeters, fluid/gas samplers triggered by ROV's, and purpose-built sensors to record physical and chemical parameters in diffuse hydrothermal flows. Chemical sensors will include autonomously operating mass spectrometers to characterize dissolved volcanic gases in the water column, while operating continuously different timescales (e.g., days to weeks). A stand-alone observatory deployment is planned at the crater bottom, together with an OBS, to collect high-frequency data form a wide range of probes (pH, T, EC, dissolved CO_2, CH_4 and O_2, acoustics). Monitoring will be conducted through long-term deployments of the instrumentation, that will record continuously, and with instrument recovery during recurrent cruises (e.g., 1 yr). This approach will provide time series to

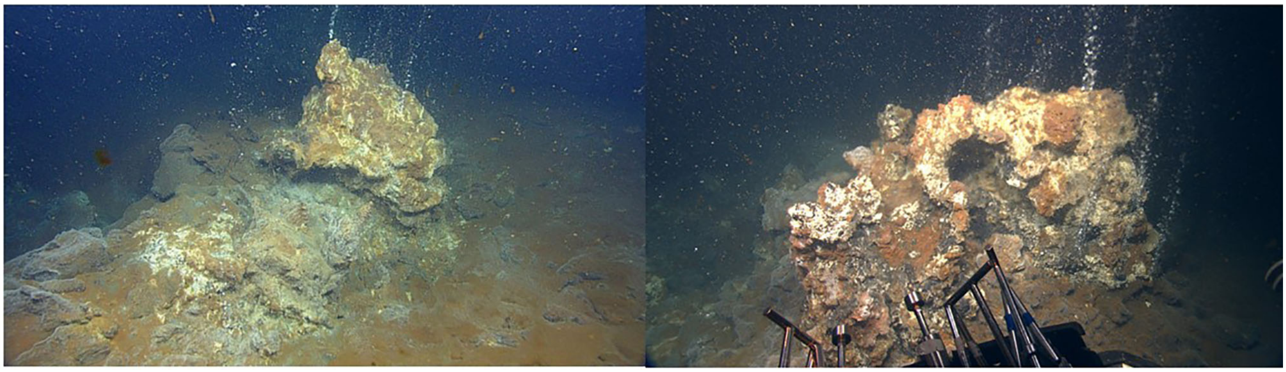

FIGURE 3 | ROV captured photos (E/V Nautilus Leg NA-007) (Carey et al., 2011) of active high–temperature (max 265°C) Kolumbo hydrothermal sulfide mounds, vigorously discharging boiling fluids and gases (>99% CO_2) (Carey et al., 2013b; Kilias et al., 2013).

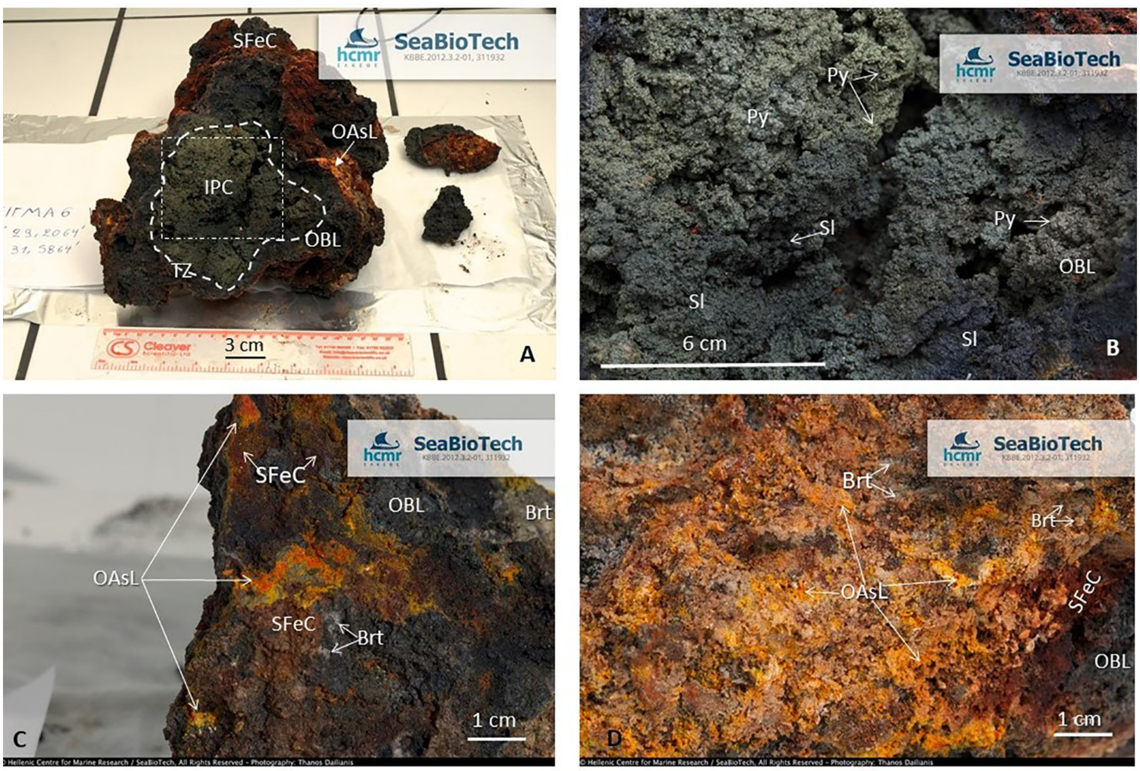

FIGURE 4 | Ex situ photographs of a typical recovered Au-rich SMS chimney (Au up to 32 ppm; Au/(Cu+Zn+Pb) = 1.9), enriched in potentially toxic, volatile metal (loid)s (As, Sb, Pb, Ag, Hg, Tl) (VTML), Kolumbo hydrothermal vent field (Kilias et al., 2013). All sulfide phases are variably enriched in Au and VTML. **(A)**. Basal cross section of chimney showing typical pattern of sulfide phase zonation. **(B)** Enlargement of the squared area of **(A)**, showing the IPC texture that is dominated by fine-grained botryoidal masses of pyrite surrounding fluid flow channels. **(C, D)**. Outermost skin of the OBL (dark bluish-black), composed of patches with red, orange, and yellow auriferous orpiment-, and realgar-, like phases (OAsL), associated with barite; these As-phases show evidence of oxidative weathering in the form of local, dark brown SFeC. Py, Auriferous As-pyrite; Brt, barite; Sl, polymetallic sulfide aggregates; IPC, Inner Pyrite Core; OBL, Outermost Barite Layer; TZ, Transition Zone; OAsL, Outer As-rich Layer; SFeC, Surface Fe-oxyhydroxide rich Crust. “SeaBioTech” EU-FP7 project (Grant No. 311932), are thanked for funding the sampling.

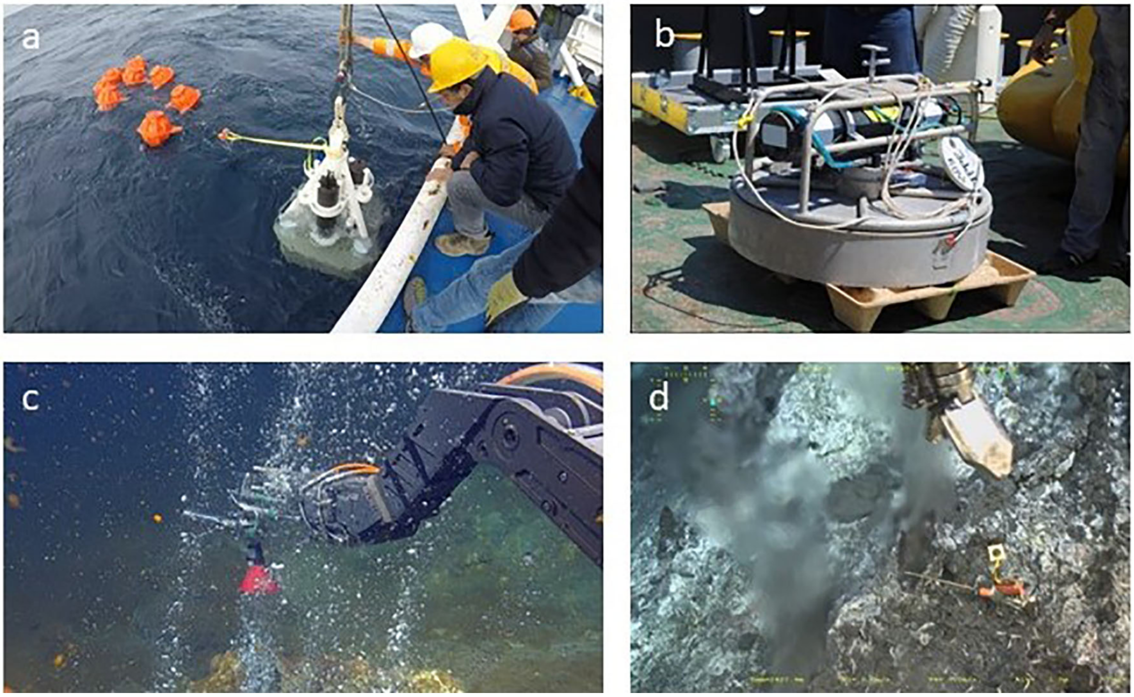

FIGURE 5 | Some of the novel sensors and monitoring systems that will be deployed in the SANTORY observatory: **(A)** automated seafloor system for geochemical multi-parametric monitoring (i.e., dissolved CO_2, H_2S, O_2, temperature, pressure, conductivity, pH, water column current, and turbidity, hydrophone) (Longo et al., 2021a), **(B)** IPGP (France) pressure gauge deployed at Santorini during the 2012 Caldera cruise (Vilaseca et al., 2016) measuring vertical seafloor movements, **(C)** discrete gas-tight sampler above Kolumbo vent (Carey et al., 2013), **(D)** Temperature sensor deployed at the Lucky Strike hydrothermal field during the Bathyluck 2009 cruise (Barreyre et al., 2012).

investigate processes with temporal variabilities spanning from less than a day to over a year. The installation of the SANTORY sensors and monitoring systems will be done based on the morphology and distribution of hydrothermal features in the area. This fine-scale geological knowledge is required to both provide a precise context necessary to properly interpret the acquired time series of both data and sampling (fluids and ecosystems primarily), while securing that mesurements are performed at the same locations. The on-site submarine monitoring will be complemented with on-shore land-based seismographs installed on Santorini Island. The proximity of Kolumbo to Santorini ensures high accuracy in seismic monitoring without the need to install OBS inside the volcanic cone, which increases the cost and complexity of operation. **Tables 1**, **2** provide information of the planned activities.

Imaging Data

Observing the flow rates of active hydrothermal vents and chimney growth rates as well as correlating this information with the overall activity of the Kolumbo system is crucial for monitoring. Up to now flow rates have been measured quite sporadically during costly underwater expeditions with supporting surface vessels (Carey et al., 2011; Nomikou et al., 2012; Carey et al., 2013; Nomikou et al., 2013). In SANTORY the goal is to design, develop and deploy optical imaging systems to document active processes the seafloor, and in particular hydrothermal dynamics and links to associated ecosystems. Two type of imaging systems will be designed and deployed.

i) A stand-alone, underwater optical video system with associated light sources, will be developed to monitor the main Kolumbo hydrothermal vents. The system will be designed to capture short video sequences (a few minutes) at regular time intervals (e.g., every 4-6 hours), an approach successfully deployed at other deep sea hydrothermal observatories (e.g., EMSO-Azores).

ii) SANTORY will deploy an autonomous submarine imaging system comprising spectral and optical RGB color sensors, and deployable also by ROV, to characterized accurately seafloor reflectance, and hence infer physical and chemical properties to obtain detailed seafloor composition maps. The spectral imaging system will be developed based on integrated and synchronized high-end VNIR and high-resolution RGB video cameras. Distortion and vignetting of frames requires processing (Vakalopoulou and Karantzalos, 2014; Kandylakis et al., 2015) to reconstruct the spectral reflectance of the seafloor that accounts for ambient light conditions, ROV lighting sources and the inherent optical properties of the surrounding water column. This is achieved exploiting a combination of visible and

TABLE 1 | Activities to be performed in SANTORY by continuous measurements.

AIM	DATA TYPE	METHODOLOGY	RESULTS
document processes occurring at the seafloor	Imaging data	stand-alone, underwater optical video system	capture short video sequences (e.g., 4 min duration), several times per day (e.g., every 4 hours) for extended periods of several months with periodic downloading of the images.
exploit the combination of visible and near-infrared (VNIR) spectra	submarine spectral imaging system	integrated and synchronized high-end VNIR and high-resolution RGB video cameras.	reconstruct the spectral reflectance of the seafloor by accounting for ambient light conditions, ROV lighting sources and the inherent optical properties of the surrounding water column
detect changes in fluid flux, volcanic tremor, chimney growth	Geochemical records (CO2, O_2, pH, EC, T) acoustic signals (Hydrophones)	stand-alone multi-parametric geochemical recording system	Long time series of geochemical parameters and acoustic signals
fluxes of radon and/or thoron commonly associated with volcanic emissions	Radionuclides coupled with chemistry	prototype underwater γ–radiation spectrometer	radioactivity levels in close proximity to the vents correlation of radiotracers to seismicity/venting
fluctuations related to volcanic processes, tectonic deformation, or seismicity, tidal forcing	Temperature variations of the hydrothermal outflow	stand-alone low/high temperature recorders	temporal variability at tidal frequencies exploited to understand the subseafloor permeability structure
differential vertical displacements	pressure gauges and tiltmeters placed on benchmarks and anchored to the seafloor	Pressure gauges and tiltmeters coupled to the temperature sensors	

Columns display the aim, the recorded data, the methodology and the collected results.

TABLE 2 | Shore-based activities performed by periodical samplings.

SAMPLING AIM	PERIODICITY	METHODS	AIMS
sulfide mineralogy	Once a year	optical microscopy and scanning electron microscopy with energy dispersive X-ray (SEM-EDS) analysis, an electron microprobe (EMPA), micro-X-ray fluorescence (µXRF), LA-ICP-MS analysis, and secondary ion mass spectrometry (SIMS)	Assessment of subsequent oxidative weathering, dissolution and release of VTML and potential toxicity
Biological sampling	Two times per year	standardized protocols for sampling, environmental DNA extraction and analysis through specific gene markers (i.e. amplicon sequencing of the 16S rRNA gene)	Microbial diversity and function
geochemical characterization	Two times per year	Chemical and isotopic composition of gases and thermal waters (gas-chromatography, Mass spectrometry for stable isotopes and nobles gase; major and trace elements	Origin of the vented gases; Gas-water interactions; Chemical and isotopic fractionation

Columns display the sampling aim, its periodicity, the analytical methods and techniques and the expected results.

near-infrared (VNIR) spectra through geometrically and spectrally consistent seafloor mosaics to accurately map biotic and abiotic cover.

Geochemical Parameters

iii) Santory will simultaneously measure key physical and geochemical parameters of the vent sites, including dissolved CO_2, H_2S, O_2, temperature, pressure, salinity, conductivity, pH, water column current, turbidity and passive hydro-acoustics. The resulting time-series will be compared with other recordings such as volcanic tremor, changes in fluid flux, and chimney growth. These deployments will include a new stand-alone multi-parametric geochemical recording system will be deployed on the seafloor to collect these data consisting of a suite of probes with both slow and fast cycling times (Longo et al., 2021a; Longo et al., 2021b) insuring multi-parameter characterization of specific sites.

iv) Santory will specifically monitor *in situ* the concentration of dissolved CO_2 in the water column above the hydrothermal vents and on the crater floor using highly accurate pCO_2 sensors. Deployed both at the seafloor and on mobile platforms (e.g., ROVs during recovery cruises), these data will provide both the temporal variability and constrain the 3D pCO_2 structure, that is required to his will allow us to map the distribution and variability of CO_2 concentration dissolved in the water column above the vents and reconstruct the flux of gas emitted from the crater bottom, with implications for the budget of the emitted volcanic species. The flexible design allows deployment from different platforms (e.g. ROV, long-term deployments on seafloor observatories, buoys and moorings and profiling applications using water sampling rosettes). Samples stored in the gas-tight samples will be analyzed for major and trace elements in on-shore laboratories.

v) Complementing the continuous chemical monitoring, discrete gas-tight samplers deployed by ROVs will collect hydrothermal fluids from the vents at the crater bottom. Samples stored in glass and stainless-steel bottles will be analyzed onshore to study the chemistry of magmatic volatiles (CO_2, N_2 and CH_4) and the isotopic composition of noble gases (He, Ne, Ar).

Combined chemical monitoring and sampling will: i) deepen our knowledge of the origin of the emitted fluids; ii) allow comparisons to recognize changes and determine the cause; iii) constrain changes in the state of activity of the volcano. The main goals are: (a) to decipher whether potentially toxic trace VTML elements are released in the seawater column.; (b) to investigate the partitioning of trace VTML elements between hydrothermal fluids and sulfide minerals; and (c) to investigate whether precious trace elements (i.e., Au) are possibly transported in colloidal suspensions in boiling diffuser hydrothermal fluids. Sampling protocols and analytical methods for major and trace element analysis of fluids and particulate solids are detailed in Gartman et al. (2018); Hannington and Garbe-Schönberg (2019) and Evans et al. (2020) (see also below "*Shore-based mineralogical and geochemical analyses*").

Radionuclides Coupled With Chemistry

vi) In addition to variations in CO_2, H_2S, and O_2, we expect measurable fluxes of radon and/or thoron commonly associated with volcanic emissions (Jamieson et al., 2013; Hwa and Kim, 2015; de Ronde et al., 2019; Neuholz et al., 2020; Klose et al., 2021). A prototype underwater γ–radiation spectrometer will be developed for operation on the seafloor observatory to monitor these fluxes together with other physical and chemical data. In addition to stand-alone detectors, SANTORY will deploy γ–detectors on ROV to provide real–time, *in situ* monitoring of radioactivity levels near the vents. In addition to monitoring dynamics of radon/thoron emanation from the volcanic vents, several applications for the instruments are envisioned, including radioisotope tracing experiments, (e.g., correlation of radiotracers to seismicity/venting), subseafloor hydrogeological studies, and sediment dating (Jamieson et al., 2013; de Ronde et al., 2019; Neuholz et al., 2020; Klose et al., 2021). The main effort in SANTORY is to introduce new types of detectors that are smaller, more efficient and less power–consuming, to offer continuous monitoring and new opportunities for scaling up the design and interoperability with other instruments.

Physical Parameters

The hydrothermal activity is influenced by both the dynamics of the overlying ocean, and by subseafloor geological processes. Monitoring of the hydrothermal activity will thus be coupled with monitoring of physical parameters, in order to understanding the links (or lack of) between the different time-series and identify the processes behind any hydrothermal temporal variability.

vii) Temperature variations of the hydrothermal outflow at different vents and areas of the crater floor will be measured with stand-alone low/high temperature recorders. Hydrothermal fluid temperature in these systems often shows fluctuations that may be related to volcanic processes, tectonic deformation, or seismicity (Sohn et al., 2009), in addition to tidal forcing (Barreyre et al., 2012; Barreyre et al., 2014), or variations in the rate of recurrent boiling and hydrothermal fluid-seawater mixing (Gartman et al., 2019). In particular, the temporal variability at tidal frequencies can be exploited to understand the subseafloor permeability structure of these systems (e.g., Crone and Wilcock, 2005; Barreyre et al., 2022).

viii) Pressure gauges and tiltmeters, placed at the rim and within the crater, and coupled to temperature sensors, will recorddifferential vertical displacements, while current meters will monitor currents water within the crater. A prior study in Santorini caldera recorded seiches and seasonal events (e.g., Vilaseca et al., 2016), and these diurnal and seasonal oceanographic fluctuations have been shown to modulate the temperature of the outflow at the seafloor, particularly in the case of diffuse hydrothermal flow (Barreyre, et al., 2014; Barreyre, et al., 2018). The bottom pressure gauges and tiltmeters will be placed on benchmarks and anchored to the seafloor using an ROV. The tiltmeters measure instrument inclination along two horizontal axes with high resolution (Fabian and Villinger, 2008). Internal temperatures of the instruments are also monitored to correct pressure measurements. These stations will be installed both within and outside the crater.

Shore-Based Mineralogical, Geochemical and Biological Analyses

SANTORY *in-situ* monitoring will be accompanied by shore-based measurements on samples collected. Laboratory work will provide details on various parameters that are not time-sensitive in terms of hazard risk estimation, but will clarify the effects of the active volcano on the formation of its ecosystem: geochemical processes, biomineralization, and more.

ix) Sulfide mineralogy (i.e., mineral abundances and their VTML content) is the main control on trace element distribution, chemical speciation and bioavailability of VTML, and is key to assessing subsequent oxidative weathering, dissolution and release of VTML and potential toxicity. Sulfide mineralogy and chemistry at a high spatial resolution and per-mineral basis will be determined using a combination of optical microscopy and scanning electron microscopy with energy dispersive X-ray (SEM-EDS) analysis, an electron microprobe (EMPA), micro-X-ray fluorescence (μXRF), LA-ICP-MS analysis, and secondary ion mass spectrometry (SIMS). Integrated micron-scale maps of the texture, chemistry and mineralogy of sulfides that will be produced, will allow determination of detailed paragenetic relationships, quantitative understanding of the mineralogical sequestration of VTML, VTML distribution among the main sulfides and accessory phases contained in SMS.

Such detailed mineralogical data will be used for the determination and quantification of the mineralogical changes through time seen between the pristine hypogene sulfide assemblages and degraded material from the inactive and extinct SMS deposits due to oxidative weathering. Mineral associations are important as contact between certain minerals could lead to galvanic reactions that are known to affect sulfide dissolution rates by more than an order of magnitude during oxidative weathering (Vera et al., 2013; Fuchida et al., 2017; Hauton et al., 2017; Fallon et al., 2017; Fallon et al., 2018; Fallon et al., 2019). Furthermore, detailed SEM and LA-ICPMS will be undertaken on secondary products to document the fate of sulfide-hosted trace metals released during the weathering process. This has been documented for terrestrial systems, but such studies are lacking in SMS on the seafloor. Whole-fluid sample treatment protocols and major and trace element analysis by inductively coupled plasma mass spectrometry (ICP-MS), and analysis of solid particles from nano-to-macro scale, by diffraction (XRD), Scanning electron microscopy/energy dispersive X-ray spectroscopy (SEM/EDS), and Transmission electron microscopy (TEM/ED), are detailed in Gartman et al. (2018; Gartman et al., 2019), Hannington and Garbe-Schönberg (2019) and Evans et al. (2020).

x) Moreover, the associated chemosynthetic microbial biomes and the presence and risks of potential pathogens are poorly known (e.g., Oulas et al., 2016; Christakis et al., 2018; Mandalakis et al., 2019; Bravakos et al., 2021). Together with the geochemical and isotopic characterization, samplers for water and microbial mat collection will be also deployed at the vents and the collected samples will be further processed in the lab. We will integrate genomic approaches in marine microbial observation by combining standardized protocols for sampling, environmental DNA extraction and analysis through specific gene markers such as the amplicon sequencing of the 16S rRNA gene which is a common taxonomic marker for both bacteria and archaea.

EXPECTED RESULTS-DISCUSSION

With SANTORY, we expect to obtain high-frequency information on changes in the underlying permeability structure and fluid output of the Kolumbo volcanic system, including potential impacts on the local environment.

SANTORY will provide geochemical, mineralogical, physical and biological data, over an extended period of time, to address a broad range of scientific topics, including:

- Invest on innovative, next–generation technology and the latest developments in marine genomic observation, to monitor active shallow (<500m) hydrothermal field processes and assess volcanic and seismic hazards (e.g., landslides, tsunamis)
- Constrain the processes that modulate and control the temporal variability in hydrothermal activity
- Understand the interdependencies that this variability imparts on the associated ecosystems
- Determine the different parameters of the system that could be used to evaluate major changes that may indicate risks (e.g., enhanced magmatic and associated hydrothermal activity)
- Develop and adapt monitoring strategies coupled with instrumental development.
- Determine the largest controls of potentially toxic, volatile trace metal(loid) (VTML) distribution, with direct effect on subsequent dissolution and potential toxicity
- Determine the potential toxicity impact of the dissolution and release of VTML *via* the process of oxidative weathering of the Kolumbo SMS, i.e., mineralogical changes and diagenesis on the seafloor induced *via* protracted interaction of SMS with oxidizing seawater when hydrothermal activity ceases temporarily (inactivity) or permanently (extinction).
- Decipher the potential toxicity producing changes of fine SMS-bearing hydrothermal vent–detritus dispersed in the oxidizing seawater column by eruptive or landslide disturbances, i.e., submarine eruptions, steam-blast eruptions, failure of hydrothermally weakened volcanic edifices etc.
- Investigate the partitioning of volatile trace elements (As, Ag, Hg, Sb, Pb, Tl) between hydrothermal vent fluids and sulfide and sulfosalt minerals, and analysis of the fundamental controls of trace element fixing in modern SMS minerals.
- Constrain the rate of magmatic inputs using the geochemical features of the vented fluids.
- Follow the circulation of hydrothermal fluids in fractures and conduits using acoustic data.

While some of the above scientific objectives are shared across existing submarine observatories, SANTORY is unique in that it focuses on a summit crater of an active submarine volcano at a shallow water depth where continuous phase separation is taking place, and where phreatomagmatic processes can have significant impact in nearby areas. In addition to monitoring and sampling of volcanic gases, the dangers of shallow magmatic-hydrothermal activity, as recently observed in Tonga, will be explicitly addressed.

Establishing the nature of the threat will be achieved by observing long- and short-term fluctuations in (i) the thermo-barometric conditions of the hydrothermal system; (ii) hydrothermal influences on seawater (bio) geochemistry, and (iii) changing subseafloor permeability. The pressure gauges coupled with tiltmeters and an array of benchmarks will be the first geodetic network to monitor ground movements in this type of setting that can be compared to fluid and gas fluxes. Quantification of the budget of CO_2 emitted from the vents coupled to the time variability of selected key tracers of magmatic degassing, will be compared with other active hydrothermal systems on Earth.

Furthermore, gases emitted from the degassing vents are made of nearly pure CO_2 that dissolves in seawater within 10 meters above the vent (Carey et al., 2013). Therefore, the water column above the bottom of Kolumbo crater contains dissolved volcanic gases (mostly CO_2, H_2S, CH_4, H_2, CO, noble gases) with a concentration that progressively decreases toward the ocean surface.

Until the SANTORY observatory, gases emitted from Kolumbo have only been sampled sporadically, limiting the possibility of recognizing changes in the state of activity of the volcano. A higher frequency of sampling, as planned during this project, will allow a temporal monitoring of some key geochemical parameters to provide information on possible magma recharges at depth. These are: i) the flux of CO_2 emitted from the crater vents, which is known to increase days to weeks before volcanic unrest, for example as observed at Stromboli volcano (Inguaggiato et al., 2011). A higher degassing of CO_2 would also induce a lowering of the pH in hydrothermal waters and in the water column above the vents; ii) the $^3He/^4He$ ratio is known to increase months before an eruption starts, due to the intrusion from the mantle into the crustal plumbing system of a volcano of more primitive and ^{3}He-rich magma batches. This behavior has been observed in many volcanoes on Earth (e.g., Etna, Rizzo et al., 2006; Stromboli, Rizzo et al., 2015;

Turrialba, Rizzo et al., 2016b; Ontake, Sano et al., 2015) and would be expected also for Kolumbo in case of its reactivation; iii) temperatures and pressures within the hydrothermal system are expected to increase weeks before an unrest phase starts, as observed in 2002 before and during the submarine degassing crisis of Panarea volcano (e.g., Caliro et al., 2004).

Furthermore, in concert with abrupt changes in the physical-chemical properties of seawater caused by volcanic discharge, we need to sample the hydrothermal plumes above and in the near-field of the KHV in order to understand the potential toxicity-producing modification processes of fine SMS-bearing vent–detritus, which may be released and dispersed in the seawater column *via* episodic plumes, which may be caused by eruptive or landslide disturbances, i.e., submarine eruptions, steam-blast eruptions, failure of hydrothermally weakened volcanic edifices etc. (e.g., El Hierro) (Fraile-Nuez et al., 2012). Hydrothermal plume sampling protocols and analytical methods are detailed in Kleint et al. (2022).

Detailed study of actively forming to mature extinct SMS, and episodic plumes of fine SMS-bearing vent–detritus, is therefore needed to give us new and temporally constrained insights into these processes on the seafloor and in the water column, particularly the fate of environmentally hazardous SMS-derived potentially toxic, metal(loid)s.

Shore-based studies will employ next-generation sequencing technologies to study the benthic communities in relation to possible changes in chemosynthetic energy sources from hydrothermal venting. Until the SANTORY observatory, sampling for microbial diversity was performed sporadically. Despite the vital role of microorganisms in hydrothermal vent ecosystems, only recently have bio-geochemical (Kilias et al., 2013; Christakis et al., 2018) and metagenomics and genomic investigations (Oulas et al., 2016; Mandalakis et al., 2019; Bravakos et al., 2021) been performed at Kolumbo volcano. These investigations revealed that both Kolumbo crater and Santorini caldera harbor highly complex prokaryotic communities (Oulas et al., 2016; Christakis et al., 2018) and microbes with an enhanced co-tolerance to acidity and antibiotics (Mandalakis et al., 2019; Bravakos et al., 2021). The observatory will enable microbiologists to locate and revisit specific microbiological features of the vent field, to study the microbial communities' composition, structure and response to changes in the volcanic/hydrothermal system and to understand the physicochemical factors that shape the antibiotic resistome. These results will help to identify and forecast ecological changes of active submarine volcanic systems and will establish baselines and protocols for fast assessment of volcanic ecosystem diversity and structure.

Thus, a higher frequency of sampling for microbial communities within the framework of SANTORY observatory would allow a better understanding of a) how biodiversity and microbial communities' stability are linked to chemosynthetic energy sources of HVs b) the extent to which extreme ecosystems may serve as reservoirs of resistance mechanisms, and c) the effect of bioleaching of sulfide minerals during oxidative weathering.

Scientific Impact

We expect to comprehend the links between deep-seated geological processes that have associated risks and their expression in the hydrothermal activity we monitor at the surface. In particular, our goal is to document the temporal variability of a dynamic system and identify significant events that cause changes in the behavior of the system. Hence monitoring, as proposed here, becomes a key component of risk assessment as already happened for the island of Panarea which is a tourist place similar to Santorini, but after the 2002 submarine explosion is monitored due to the large seasonal hazard variability.

At Panarea, coupling the results of periodical geochemical investigations with acoustic data recorded by the sea-floor observatory, it was possible to detect how the deep magma chamber of Stromboli volcano is responsible for the activity changes of the hydrothermal system (Heinicke et al., 2009; Longo et al., 2021a). With this background the data provided by SANTORY observatory will gain a better insight into the dynamics of the hydrothermal system and their relationships with changes of the deep magmatic activity with a positive impact on the risk mitigation for the Santorini area.

There will be a strong exchange of information between SANTORY and the upcoming IODP Expedition 398: Hellenic Arc Volcanic Field on-board the JOIDES Resolution from December 5 2022 to February 6 2023 (Druitt et al., 2022). The Expedition 398 will help SANTORY as:

1. Drilling on the flanks of Kolumbo will provide samples of quenched magma from the different Kolumbo eruptions. The phenocrysts will contain melt inclusions that can be analysed for volatile elements and trace metals. The samples will thus give a database of the contents and compositions of magmatic volatiles, metal and metalloids in the magmas that are the source of the fluids emitted in the crater. The samples will include the magmas of intermediate to silicic composition that are erupted in quantity, but it is possible that some basalts feeding the Kolumbo magmatic system are also sampled, either as lava, scoria or mafic inclusions in silicic magmas.
2. Drilling will also tell us about the nature of the Kolumbo eruptions and the hazards from them. As such, fusion of the drill data with the observatory data will give us a full picture of the state of the volcano in different regimes (Plinian, inter-plinian) to input into hazard and risk assessments.
3. Drilling at Kameni will allow us to compare and contrast the two systems.

- Why is there this large heat and fluid flow at Kolumbo but not at Kameni. Are fluids somehow channeled NE-wards towards Kolumbo?
- How do the fluid compositions and hydrothermal processes compare and contrast?
- How do the biospheres at Kameni and Kolumbo compare and contrast, and why?

Moreover, project outcomes will benefit scientific research at an international level by complementing and enriching monitoring practices developed in other world regions with different depths e.g.

the shallower (<100 m b.s.l.) hydrothermal system of the Panarea volcano (Aeolian volcanic arc, Italy) (Heinicke et al., 2009; Longo et al., 2021b and references therein), where in the last decade a multi-parametric system of sensors has been deployed to monitor seafloor activities. In the mainframe of the EMSO-ERIC initiatives, a Panarea-like cabled observatory, would be the next step for the research team of SANTORY. Foreseen synergies will be established or strengthened in the framework of SANTORY with the ones with top–rank, internationally leading institutes that already have established scientific activity and/or have executed cruise expeditions successfully relating to marine geohazards in Mediterranean. SANTORY will additionally linked with complementary projects, such as the EU H2020 Pathfinder RAMONES which aims at investing on novel robotics capabilities for the exploration of the marine ecosystems (Mertzimekis et al., 2021).

Social Impact

SANTORY plans to: i) Establish a monitoring protocol and advise policy makers on scenario planning and possible strategies for hazard mitigation in underwater volcanic systems; ii) Invest on open–access data by creating an Open Data Hub for keeping local citizens, visitors and scientists informed about potential hazards related to submarine volcanoes and associated shallow hydrothermal vents; iii) Educate the general public and disseminate scientific information *via* outreach activities; iv) Train early–career researchers and students; v) Develop and integrate innovative monitoring technologies to promote surveillance of submarine arc volcanic areas located close to Mediterranean touristic islands.

The SANTORY Open Data Hub will implement a user-friendly, cross-platform and open-source toolkit (with algorithms and applications) that is integrated closely with the acquired datasets and exploits emerging visualization tools. The SANTORY Open Data Hub will be linked to major initiatives, such as the EMSO, the U.S. National Science Foundation's Ocean Observatory Initiative (OOI) and the Ocean Networks Canada observatory to encourage collaborations in infrastructure, architecture, and interoperability. Moreover, it will develop different strategies and protocols for underwater hazard monitoring targeting specialist and non–specialist audiences. Finally, SANTORY will provide scientists, policymakers and stakeholders at all levels (local, national and EU/International) with data for interregional monitoring protocols, hazard warning codes, services to the local authorities and the public and guidance for mitigating societal impacts (e.g. timely evacuation) of natural hazards for populated areas. SANTORY will be a novel communication platform, using virtual and augmented reality and mobile platforms to promote the fascinating world of active underwater volcanic ecosystems on the EU's shores.

THE FUTURE

SANTORY will be a reliable source of novel new data regarding the links between deep-seated geological processes that have associated hazard risks and their expression in the hydrothermal activity we monitor at the surface. More in particular, our goal is to establish the expected temporal variability of a dynamic system vs significant events that indicate changes in the fundamental behavior of the system. Hence monitoring, as proposed here, becomes a key component of risk assessment. In addition, reference monitoring protocols in the sense of combining active volcano measurements with Santorini's on-land data (e.g., seismic, geodetic, geochemical), will provide the necessary impetus for understanding the long–term threat and developing novel risk assessment mechanisms.

The cataclysmic eruption of Hunga Tonga–Hunga Ha'apai submarine volcano, unlike anything seen in the modern scientific era, destroyed Tonga on 15 January 2022, and has shown that submarine volcanoes will continue to pose a hazard (Witze, 2022). Submarine volcanoes are understudied, therefore SANTORY is a largely hoped for addition to an emerging technological tendency, demonstrated by the installation of submarine cabled observatories in Mozambique, Japan, Taiwan Norway, China, and Canada, as well as the Mediterranean (Delaney and Kelley, 2015; Trowbridge et al., 2019; Feuillet et al., 2021). A cabled volcanic observatory, such as the NSF-funded observation OOI at Axial seamount, at Santorini, would be the next step for the research team of SANTORY.

We envision the future development of a network of similar seafloor observatories in the Mediterranean offering a new perspective for oceanography and ocean management in the region.

DATA AVAILABILITY STATEMENT

The raw data supporting the conclusions of this article will be made available by the authors, without undue reservation.

AUTHOR CONTRIBUTIONS

PN, PP, AR, SP, MH, SK, DP, JE, KK, TM, VA, MK, LG, and FI conceived the study. DL helped in figures preparation. All of the authors contributed to the preparation and editing of the final manuscript. All authors contributed to the article and approved the submitted version.

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Assessing the Image Concept Drift at the OBSEA Coastal Underwater Cabled Observatory

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The marine science community is engaged in the exploration and monitoring of biodiversity dynamics, with a special interest for understanding the ecosystem functioning and for tracking the growing anthropogenic impacts. The accurate monitoring of marine ecosystems requires the development of innovative and effective technological solutions to allow a remote and continuous collection of data. Cabled fixed observatories, equipped with camera systems and multiparametric sensors, allow for a non-invasive acquisition of valuable datasets, at a high-frequency rate and for periods extended in time. When large collections of visual data are acquired, the implementation of automated intelligent services is mandatory to automatically extract the relevant biological information from the gathered data. Nevertheless, the automated detection and classification of streamed visual data suffer from the "concept drift" phenomenon, consisting of a drop of performance over the time, mainly caused by the dynamic variation of the acquisition conditions. This work quantifies the degradation of the fish detection and classification performance on an image dataset acquired at the OBSEA cabled video-observatory over a one-year period and finally discusses the methodological solutions needed to implement an effective automated classification service operating in real time.

Keywords: concept drift, automated fish classification, automated fish detection, deep learning, underwater imaging, underwater observing systems, cabled observatories

INTRODUCTION

The oceanic seabed and the overlying water masses constitute the largest and yet the less explored biome on Earth (Danovaro et al., 2020). Today, the marine science community is engaged in the exploration and monitoring of biodiversity and its processes (e.g. reproductive cycles, population growth and mortality dynamics and migrations) in relation to environmental control and growing anthropogenic perturbations (Levin et al., 2018; Levin et al., 2019). However, the marine environment is hostile to the prolonged human presence and *in situ* experiments, especially when the depth of the sea increases (Rountree et al., 2020), and the monitoring actions often need the assistance of expensive support vessels. Within this operational context, it is not easy to plan campaigns for data acquisition that extend for long periods, reducing data sampling capability and repeatability (Raffaelli et al., 2003). So, accurate monitoring of marine ecosystems requires the development of innovative and effective technological solutions to allow a remote and continuous collection of high-frequency physical, chemical and biological data (Aguzzi et al., 2010; Aguzzi et al., 2015; Dañobeitia et al., 2020; Painting et al., 2020).

In this regard, cabled fixed observatories and their docked mobile platforms (e.g. crawlers and AUVs), all equipped with camera systems and multiparametric bio-geochemical and oceanographic sensors, allow for a non-invasive acquisition of biological and environmental data, at a frequency of seconds or higher, over consecutive years (Aguzzi et al., 2019; Del Rio et al., 2020). This biological and environmental highly integrated monitoring activity is about to produce new relevant ecological information to sustain innovative ecosystem management approaches and policies (Danovaro et al., 2017). Those data refer mainly to megafauna species identification and their individual counts (e.g., Juniper et al., 2013; Bicknell et al., 2016; Danovaro et al., 2020).

Many marine observing systems acquire and store terabytes of data that need to be processed (Painting et al., 2020). As a consequence the marine research community is urging for the implementation of services, based on artificial intelligence methodologies, aimed at the automated extraction of relevant biological information, especially from image data (e.g. animals identification, tracking, classification and counting) (Marini et al., 2018b; Canonico et al., 2019; European Marine Board, 2020; Aguzzi et al., 2020; Lopez-Vasquez et al., 2020; Beyan and Browman, 2020; Malde et al., 2020; Zuazo et al., 2020). The achievement of this goal can be resumed by the definition of novel self-aware observing systems capable of sensing the surrounding environment and intelligently processing the acquired data (Aguzzi et al., 2022; European Marine Board, 2020; Jahanbakht et al., 2021), also through edge computing techniques (Shi et al., 2016; Marini et al., 2018a) to process the acquired data onboard intelligent observing systems. Such an on-board processing approach needs to face the problems of multiparametric data acquisition and integration, relevant knowledge extraction and interpretation, transmission latency and bandwidth lack, when the information is remotely sent to a shore server (European Commission, 2018; Malde et al., 2020; European Marine Board, 2020;Jahanbakht et al., 2021; Aguzzi et al., 2022).

Species detection and classification in a real-world scenario requires supervised-learning methods that allow a computer system to automatically make predictions based on a series of examples (e.g., see Marini et al., 2018a; Marini et al., 2018b; Lopez-Vazquez et al., 2020; Malde et al., 2020). Unfortunately, the effectiveness of such automated approaches incurs into the "concept drift" phenomenon, consisting in a progressive decrease over time of the detection and classification performance (Hashmani et al., 2019; Jameel et al., 2020; Din et al., 2021). The concept drift is largely investigated in the community of computer vision and artificial intelligence, but very few contributions are available in the marine science context (Langenkämper et al., 2020; Kloster et al., 2020).

This work analyses and quantifies the degradation of the fish detection and classification performance on the image data acquired at the OBSEA cabled video-observatory (Del Río et al., 2020) over a one-year period. Images were analysed by using deep learning methodologies aimed at fish detection and classification, and the experiments, for assessing the performance degradation, were designed to reproduce an automated classification service installed on the observatory. A ground-truth dataset was generated through the visual inspection of the image dataset, and every fish was tagged with its corresponding bounding box and its species label. The ground-truth dataset was used for training the algorithms on the first four months of the image data stream of the observatory, then the detection and classification performance was evaluated on a monthly basis on the remaining data. The results show a continuous degradation of both the detection and the classification performance over the studied period. Finally, the methodological approaches for mitigating the concept drift phenomenon are presented and discussed.

MATERIALS AND METHODS

Study Area

The Western Mediterranean Expandable SEAfloor Observatory (OBSEA; http://www.OBSEA.es) is a cabled video-observatory located at 20 m depth, 4 km off Vilanova i la Geltrù (Catalonia, Spain) (Aguzzi et al., 2011; Del Río et al., 2020) (**Figures 1A–C**). The observatory is equipped with an Underwater IP Camera (OPT-06; OpticCam), acquiring colour images/video footage with 640 x 480 pixels resolution (see next section). Two custom white LEDs (2900 lumens; colour temperature of 2700 K) are located beside the camera, at 1 m distance from each other, projecting the light beam with an angle of 120°. Light ON-OFF (lasting for 3 s) occurs immediately before and after image acquisition by a LabView application that also controls their white balance.

With this setup we acquired 14025 images, one image every 30 minutes between January and December 2014, constantly focussing on the artificial reef, located 3.5 m from the camera. A change of camera occurred on December 11, 2014. The new one was an Axis P1346-E camera, acquiring colour images/video with 3 megapixels resolution. **Figures 1D, E** shows two examples of acquisition conditions characterised by turbid water and biofouling on the porthole of the camera (i.e., growth of algae or other encrusting organisms) and an image acquired during the night using the artificial lights of the observatory.

Ground-Truth Definition

The images acquired at the OBSEA were visually inspected by a trained operator, in order to recognize the fish specimens, within the field of view, by following the procedures described in Condal et al. (2012) and Aguzzi et al. (2013).

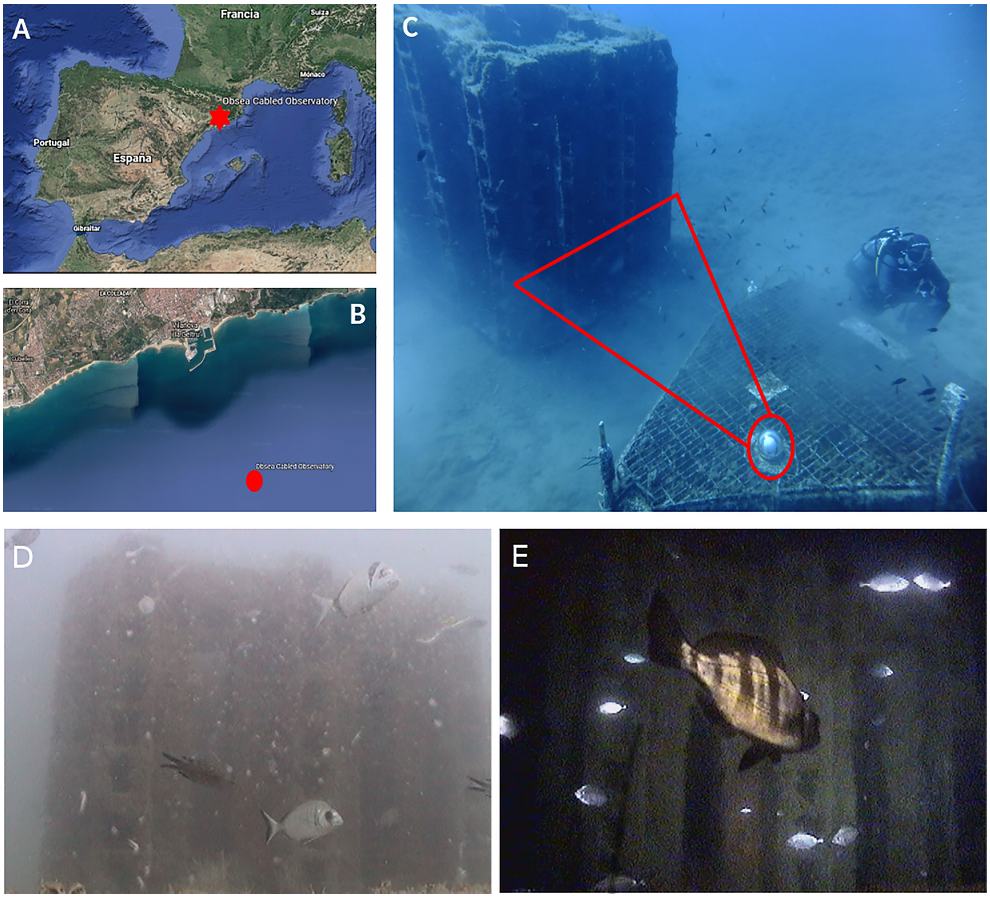

FIGURE 1 | The location of the OBSEA observatory in the Mediterranean Sea **(A, B)**; The field of view of the camera installed in the observatory **(C)**; Two examples of images acquired by the OBSEA camera, during the daylight **(D)** and during the night **(E)**, using the artificial lighting system of the observatory.

For each individual in the image, a bounding box was drawn and labelled with the corresponding species. The results of this manual processing were encoded into a text file including: the image file name, the corresponding timestamp, the position of the four vertices of the oriented bounding-box and the species label.

The biofouling phenomenon and the water turbidity, sensibly affects the automated recognition of fishes (Marini et al., 2018b) and presents difficulties also during the visual inspection of the images (see **Figure 1D** as an example). The inspection was also difficult to perform when the individuals appeared too far from the camera or during the nighttime, when the field of view was illuminated only by the lighting system of the observatory. Those individuals, whose species could not be attributed with sufficient confidence, were included in the "unknown" category.

The visual inspection task resulted in 62038 individuals, of which 29497 belonged to 30 species, with very different abundances. **Table 1** summarises the taxonomic names of those species (Condal et al., 2012; Aguzzi et al., 2013; Aguzzi et al., 2015).

Automated Image Fish Classification

The image content classification was performed by using a Deep Learning (DL) approach (LeCun et al., 2015), following the current trend in the scientific community (Malde et al., 2020). The DL methods are well suited for image classification and achieved human-like performances in many visual tasks, as reported in many surveys (e.g., He, 2020). Among the Convolutional Neural Network (CNN) architectures proposed in literature, we have chosen to experiment the fish classification problem with ResNet (He et al., 2016), as it is a compact, effective and consolidated network (Tan and Le, 2019) and because demonstrated good performance by winning the ImageNet competition in 2015, a large classification competition on over 1000 classes and 10 million images[1].

Differently from the traditional approaches for image classification, DL operates directly on pixel values, without any kind of pre-processing or feature extraction stage, and learns the optimal mapping between data (i.e. images) and object classes (i.e. fish species) (LeCun et al., 2015). Moreover, CNN can be

[1]https://image-net.org/challenges/LSVRC/2015/

TABLE 1 | Species expected and observed in the OBSEA site: list by scientific names and the number of observed individuals.

Code	Scientific name	Individuals	Code	Scientific name	Individuals
f1	*Diplodus vulgaris*	10623	f16	*Symphodus tinca*	12
f2	*D. sargus*	2362	f17	*S. mediterraneus*	206
f3	*D. puntazzo*	272	f19	*S. cinereus*	104
f4	*D. cervinus*	558	f23	*Coris julis*	1818
f5	*D. annularis*	106	f24	*Thalassoma pavo*	6
f6	*Oblada melanura*	6731	f25	*Serranus cabrilla*	409
f7	*Dentex dentex*	667	f26	*Epinephelus marginatus*	4
f8	*Sparus aurata*	47	f27	*Sciaena umbra*	38
f9	*Sarpa salpa*	289	f28	*Seriola dumerili*	97
f10	*Boops boops*	18	f30	*Gobius vittatus*	2
f11	*Spondylosoma cantharus*	631	f31	*Apogonidae*	555
f12	*Pagrus pagrus*	76	f32	*Atherinidae*	24
f13	*Pagellus* sp.	3	f36	*Mugilidae*	1
f14	*Spicara maena*	1247	f38	*Murena helena*	4
f15	*Chromis chromis*	2771	f39	*Scorpaena* sp.	86

used in different application contexts through the transfer learning approach (Pan and Yang, 2010; Rawat and Wang, 2017), where the neural network can be trained for a general purpose task and then specialised to a more specific task only, by changing a small part of its architecture.

Taking advantage of the transfer learning approach, we experimented with a few ResNet networks, pretrained on more than a million images from the general purpose ImageNet database[2] and then selected the ResNet18 (He et al., 2016) as the main fish species classification algorithm.

For training the specialised fish classifier, the ground-truth dataset was structured according to both the fish species and the acquisition date, as reported in **Table 2**. Images of fishes far from the camera were not considered in the training process. This is because the reduced size of the image regions containing these specimens do not provide enough information to effectively characterise the fish species. Differently, a human observer performs classification of fish species in the image not based only on the pixel values, but based also on previous experience and *a priori* knowledge of the time and space distribution of individuals (Sbragaglia et al., 2019).

Moreover, we observed that, even if the total number of classes was high, there were too few observations for certain species, making the learning process not effective. As a consequence, we decided to carry out the classification experiment only on the categories with a number of individuals larger than 200, in order to reduce the class imbalance. For this reason, we focused on the following 14 classes: f1, f2, f3, f4, f6, f7, f9, f11, f14, f15, f17, f23, f25 and f31, whose temporal distribution is represented in **Figure 2A**, and a representative individual of each species is reported as an example in **Figure 2B**.

Although the temporal distribution of specimens was very inhomogeneous (see **Table 2** and **Figure 2**), we decided to keep the data sets unbalanced in order to reflect a real-word image-monitoring situation, where the abundance of a species in the environment naturally depends on several and unpredicted factors.

The image dataset described in **Table 2**, was split into training and validation sets as detailed in the next sections. This partition was made for each class, in order to mirror the relative abundance of each species. Solutions were also adopted for minimising the overfitting on the training set and maximising the generalisation capability of the classifier: shuffling the training dataset at every epoch; augmenting the data by random image flipping along horizontal or vertical direction; setting a learning rate decay option (a piecewise decay starting with an initial value of 10-3 and a drop factor of 0.1 after 5 epochs).

To evaluate the performance of the classifier, a confusion matrix was calculated (Lopez-Vazquez et al., 2020; Zuazo et al., 2020; Harrison et al., 2021). The entry (i,j) of the matrix represents how many individuals belong to the class *i* have been classified into class *j*. The more the matrix entries are concentrated on the diagonal, the better is the classification performance. Besides the confusion matrix, other five criteria were used to evaluate the classification performance (Fawcett, 2006):

- the recall or True Positive Rate (TPR), as the number of individuals correctly classified in a given class (TP), with respect to the total number of individuals in that class (P), defined as $recall = TPR = \frac{TP}{P}$;
- the False Negative Rate (FNR), being complementary of the TPR and representing the number of individuals of a given class wrongly classified in other classes (FN) with respect to the total number of individuals in that class (P), defined as $FNR = 1 - recall = \frac{FN}{P}$;
- the precision, being the number of individuals correctly classified in a given class (TP) with respect to the total number of individuals classified in that class plus individuals of other classes wrongly classified in that class (FP), defined as $precision = \frac{TP}{TP+FP}$
- the False Discovery Rate (FDR), being complementary of precision and representing the number of individuals wrongly

[2] https://www.image-net.org/

TABLE 2 | The monthly occurrence of fish individuals per species and months.

Species	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec	Total
f1	141	93	292	351	1242	836	500	995	2569	2937	221	29	10206
f6	1199	1417	794	578	266	485	244	262	285	278	265	648	6721
f15	42	93	44	153	385	479	266	270	198	377	94	370	2771
f2	88	77	41	28	91	106	232	648	534	428	71	8	2352
f23	51	32	68	138	227	513	273	185	153	130	38	4	1812
f14	126	34	56	81	136	202	18	4	2	4	218	364	1245
f7	4	4	0	55	58	78	153	164	93	50	6	2	667
f11	27	70	19	8	6	0	2	36	52	196	161	52	629
f4	7	9	8	9	19	2	141	191	141	20	7	2	556
f31	8	0	0	0	0	0	9	2	158	273	103	2	555
f25	5	0	2	0	6	7	74	45	122	106	42	0	409
f9	0	0	0	2	2	14	6	259	5	0	1	0	289
f3	31	15	47	25	26	14	42	36	4	12	5	15	272
f17	0	0	3	14	36	46	48	20	12	23	3	0	205
Total	1729	1844	1374	1442	2500	2782	2008	3117	4328	4834	1235	1496	28689

classified into a class (FP) with respect to the total number of individuals wrongly classified in that class plus the individuals correctly classified in that class (TP), defined as $FDR = 1 - precision = \frac{FP}{FP+TP}$;

- the accuracy, being the total number of correct classifications performed on the whole dataset with respect to the total individuals of the dataset, defined as $accuracy = \frac{TP+RN}{P+N}$.

Automated Image Fish Detection

While the image classification task is aimed at associating a class label to each relevant subject (i.e. the identified fish), the image detection task is aimed at recognizing the relevant subjects without associating them with the class they belong to. In this work, the object detection task is aimed at recognizing the fish specimens (without any class labelling) with respect to the image background. As for the image classification task, the image detection task can be achieved using the DL approach (Cui et al., 2020). Among the DL methods suitable for the image detection task, we selected the FasterRCNN network, which has proven to be very effective in several competitions, like for example the ImageNet Large Scale Visual Recognition Challenge[3]. Although the object detection task seems to be simpler than the classification task, within the CNN computational paradigm, the FasterRCNN detection method is built upon a classification network (e.g. the ResNet), adding more layers to compute the bounding box of each object inside the given image (Ren et al., 2015; Li et al., 2017).

Within the fish detection task, the fasterRCNN was trained for detecting a single fish against the image background. Images where one or more fishes overlap other fishes were not used for training. In this way, the detection algorithm learned the fish shape features shared among all the individuals used for the training, without an explicit reference to a specific species. The fish detection performance was estimated by comparing the bounding box coordinates automatically extracted from the images with those encoded in the ground-truth dataset through the use of the Intersection over Union (IoU) approach (Zhu et al., 2021).

Classification and Detection Experiments

Three experiments were designed in order to assess the degradation of the detection and classification performance.

In the first experiment, the full image dataset was split into two random partitions, 50% for training and 50% for testing, with the aim of assessing the global performance of the classification approach. Aim of this experiment was the assessment of the generalisation properties of the ResNet18 classifier in real applications, where no hypothesis can be assumed on the species assemblage and on the quality of the acquired images.

The aim of the second experiment was the simulation of an automated classification service, where the data stream is processed in real-time for the production of time series abundance of fish species. In this second experiment, a different training set was designed. For each species, the 30% of the individuals were randomly sampled from the first four months of the one-year image set and then used for training the fish classifier. The remaining images were used to test the performance of the learnt classifier on a monthly basis, in order to evaluate the possible degradation and its temporal progression.

For both experiments, only the fully connected final layers of the ResNet18 network were trained, for 10 epochs, by shuffling the elements of the training set after each epoch with the aim to ensure that the network sees training data of all classes mixed arbitrarily. To minimise the loss function during the training phase, we used the stochastic gradient descent algorithm, with mini batches of 16 elements and a constant learning rate equal to 0,001. The training was performed on a GPU (NVIDIA GEFORCE RTX 2070) and each experiment lasted about one or two hours, depending on the size of the dataset itself.

The third experiment was aimed at assessing the degradation of the fish detection performance. Similarly to the previous experiments, the fish detection network (fasterRCNN) was trained by randomly sampling the 30% of fish specimens, occurring in the first four months of the dataset. The obtained fish detector was then tested on the remaining data, providing detection accuracy over time as in the experiment n.2.

[3] https://image-net.org/challenges/LSVRC/2015/

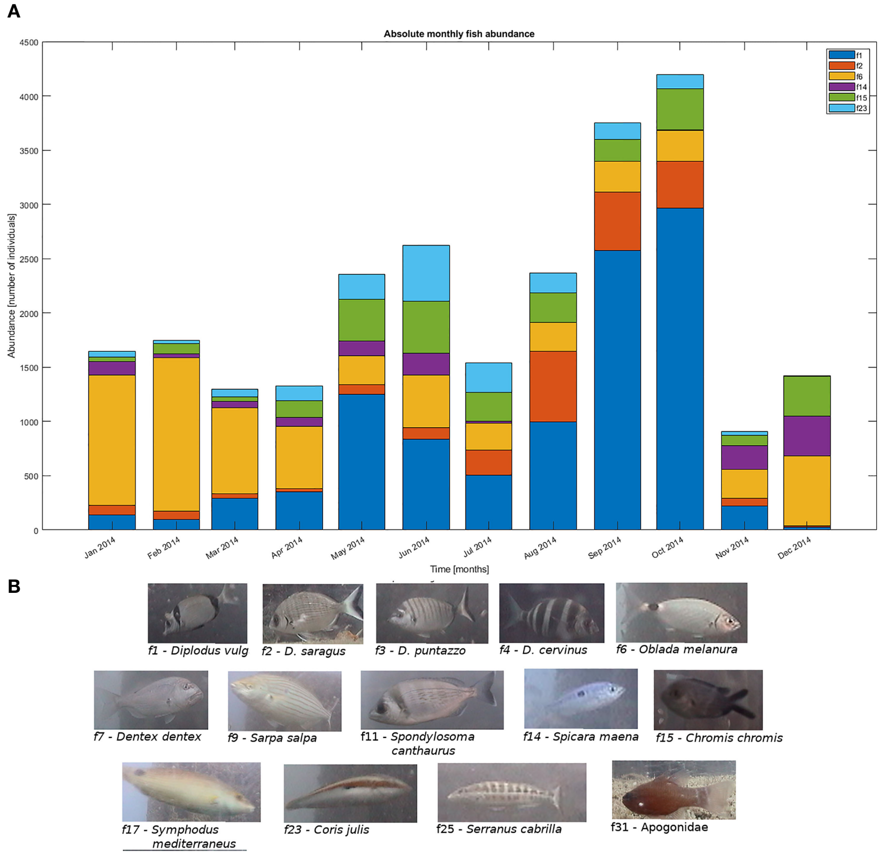

FIGURE 2 | **(A)** Temporal distribution of the species covering the 90% of the whole set of species reported in **Table 2**; **(B)** Representative individuals of the fish species presented in **Table 2**.

RESULTS

In this section, we report the results obtained by the ResNet18 for automatic fish classification and by FasterRCNN for automated fish detection.

Experiment n.1

Fish classification with training on a randomly sampled dataset: The confusion matrix resulting from this experiment is shown in **Figure 3**. The data partition being completely random and unrelated with time, this result represents an estimate of the best performance achievable with this kind of images. The overall accuracy is 93.7% and only 4 classes (i.e., f3, f9, f11 and f17) have an FNR larger than 20%. The results obtained in this experiment were considered the benchmark required to compare the time-dependent tests performed in the second experiment.

Experiment n.2

Fish classification with training on a time-ordered dataset: The confusion matrix for this experiment is shown in **Figure 4**. The overall accuracy is 72.6% and many classes show poor global performances. For these classes, the first 30% of images used for the training phase does not carry enough information to produce a classifier capable of generalising the whole yearly data stream. **Figure 5** shows the monthly accuracy of the classifier, clearly expressing how classification performance decreases over the time.

A sensible drop of classification performance occurred in December (see **Figure 5**), due to a hardware change in the acquisition system, where a new camera with a different colour balance mechanism substituted the old one. **Figure 6** shows few image examples of individuals belonging to the same species, acquired with the old and the new camera, just showing an improvement of the image quality. Removing the data gathered in December, the mean accuracy rises from 72.6% to 88.8% showing a sensible incrementation of the detection performance.

Experiment n.3

Fish detection with training on the time-ordered dataset: Within this experiment all the available data was used, including those fishes whose class was undetermined (i.e. the unclassified category). This experiment produced an average recall equal to 72.6%. The **Figure 7** depicts the distribution of the recall over the different months of the year, showing a decay of performances over time, similar to experiment two, while the **Figure 8** shows some examples of fish detection, where the red boxes represent

Confusion Matrix for Validation Data

True Class \ Predicted Class	f1	f11	f14	f15	f17	f2	f23	f25	f3	f31	f4	f6	f7	f9		
f1	4986	1	5	19		46	3			3	3	30	4	3	97.7%	2.3%
f11	22	198	10	26	3	22	2	2	2		4	22		1	63.1%	36.9%
f14	2		558	14		5	11			2		27	3		89.7%	10.3%
f15	13	5	16	1327		6		2				14	2		95.8%	4.2%
f17	2	2	6	13	63	2	2	2		2		6		2	61.8%	38.2%
f2	54	8	2	14		1057	3	1	7	1	1	20	4	4	89.9%	10.1%
f23	17		16	14	2	3	840	8	2		1	1	2		92.7%	7.3%
f25	3	1	5	4			15	175				1			85.8%	14.2%
f3	13	4	1	4		42			62		2	6	2		45.6%	54.4%
f31	1	2	1	16	6		1	2		242		6			87.4%	12.6%
f4	2	3	1	8		8	1				240	14	1		86.3%	13.7%
f6	30	5	42	21		24	3	1		3	1	3227	3		96.0%	4.0%
f7	3	5	8	2		4	1		2			6	300	2	90.1%	9.9%
f9	2		5		1	22	3					7	4	100	69.4%	30.6%
	96.8%	84.6%	82.5%	89.5%	84.0%	85.2%	94.9%	90.7%	82.7%	95.7%	95.2%	95.3%	92.3%	89.3%		
	3.2%	15.4%	17.5%	10.5%	16.0%	14.8%	5.1%	9.3%	17.3%	4.3%	4.8%	4.7%	7.7%	10.7%		

FIGURE 3 | Confusion matrix resulting from the first classification experiment (50%-50% training/test partition). The two columns on the right of the confusion matrix represent the recall (blue) and the False Negative Rate (orange), respectively; the two rows below the confusion matrix represent the precision (blue) and the False Discovery Rate (orange), respectively.

Confusion Matrix for Validation Data

True Class \ Predicted Class	f1	f11	f14	f15	f17	f2	f23	f25	f3	f31	f4	f6	f7	f9		
f1	6297	35	38	74	1	200	2	2	2	18	19	407	6	43	88.1%	11.9%
f11	93	93	20	82	8	33	10	3	5	10	2	54	17	10	21.1%	78.9%
f14	16	85	318	88	3	139	94	6		2	4	80	26	10	36.5%	63.5%
f15	55	52	88	1520	8	132	18	6		14	10	22	11	4	78.4%	21.6%
f17	4		2	17	45	4	26			32		6	2	5	31.5%	68.5%
f2	295	33	14	44	2	895		3	4	2	20	291	17	26	54.4%	45.6%
f23	54		13	26		10	1084	38		17	7	7	7	5	85.5%	14.5%
f25	7	2	4	6		2	35	210		3	4		1	12	73.4%	26.6%
f3	23	4	10	11		100	4	2	23	1		4	4	4	12.1%	87.9%
f31	6	8	2	21		11	2		1	315		20	2		81.2%	18.8%
f4	16	8	2	12		9		5	4		307	5	12	9	78.9%	21.1%
f6	344	219	371	154	3	488	10	3		18	7	3054	24	10	64.9%	35.1%
f7	11	4	2	10		57	4	2	2	4	10	18	314	29	67.2%	32.8%
f9	11		6	12		49	4			2		14	5	99	49.0%	51.0%
	87.1%	17.1%	35.7%	73.2%	64.3%	42.0%	83.8%	75.0%	56.1%	71.9%	78.7%	76.7%	70.1%	37.2%		
	12.9%	82.9%	64.3%	26.8%	35.7%	58.0%	16.2%	25.0%	43.9%	28.1%	21.3%	23.3%	29.9%	62.8%		

FIGURE 4 | Confusion matrix resulting from the second classification experiment (30%-70% training/test partition). The two columns on the right of the confusion matrix represent the recall (blue) and the False Negative Rate (orange), respectively; the two rows below the confusion matrix represent the precision (blue) and the False Discovery Rate (orange), respectively.

the ground-truth bounding boxes, and the yellow boxes represent the bounding boxes automatically detected.

DISCUSSION

In this work, we assessed the problem of the concept drift for the automated classification and detection of fishes at a coastal cabled observatory. The results of the proposed study confirmed that an effective underwater monitoring system can be realised by exploiting an automatic learning procedure based on the DL approach, being able to count individuals and classify them in a way similar to what could be done by a human expert. The results obtained in the experiment shown in **Figure 3**, prove that the system is robust with respect to the fish shapes variations and motion. It is also robust to the light changes due to the day/

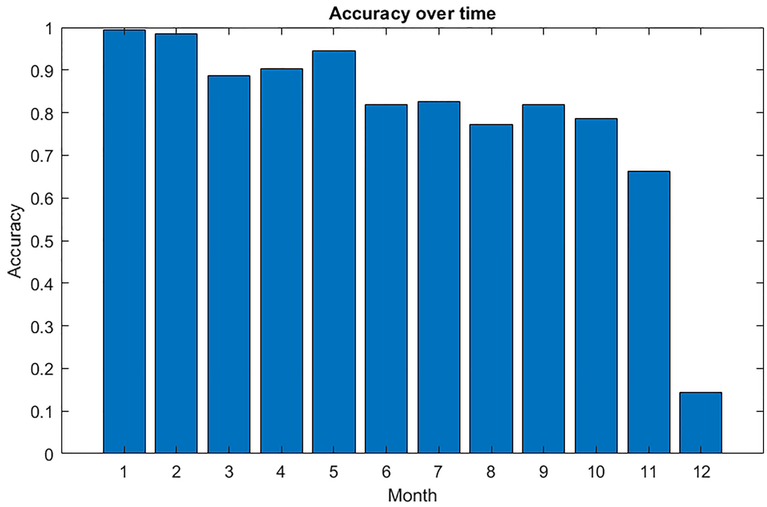

FIGURE 5 | Monthly progressive decrease of the averaged accuracy resulting from the experiment N.2 (30% training, 70% test).

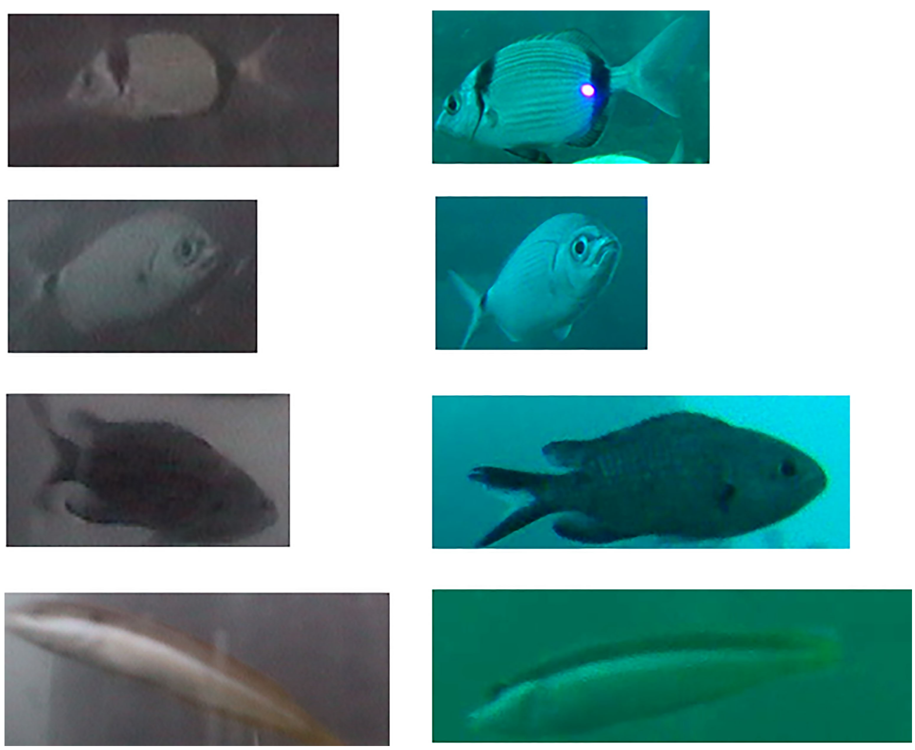

FIGURE 6 | Four examples of fish images before (left) and after (right) the substitution of the OBSEA camera with the new one with improved colour balance.

night and seasonal photo-period dynamics, as well as to the application of the artificial lighting system of the observatory. Nevertheless, both the classification and detection algorithms showed a concept drift when the data was streamed over a long (i.e. months) time period (see **Figures 4**, **5** and **7**). Such a drift is caused by both natural and artificial factors. Though the camera was periodically maintained, the drop of performance was caused both by the presence of fouling onto the porthole, due

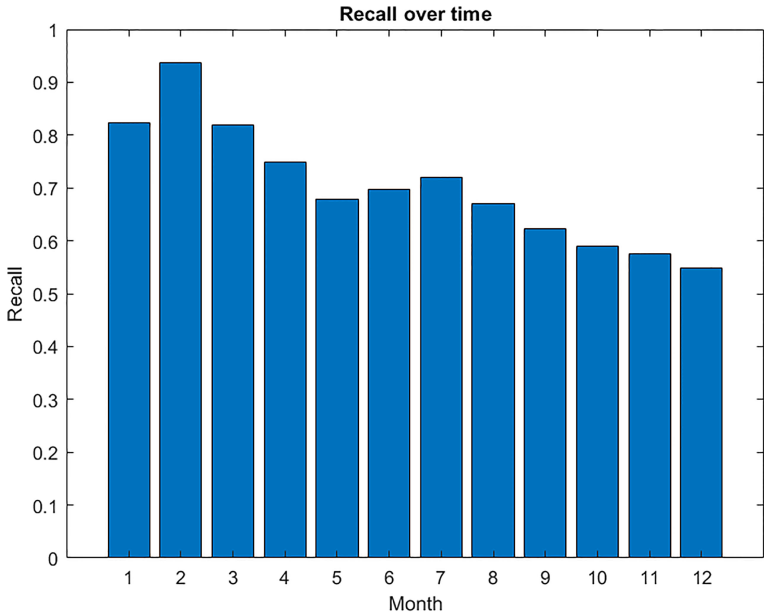

FIGURE 7 | Monthly averaged recall for fish detection with the progressive decreasing trend.

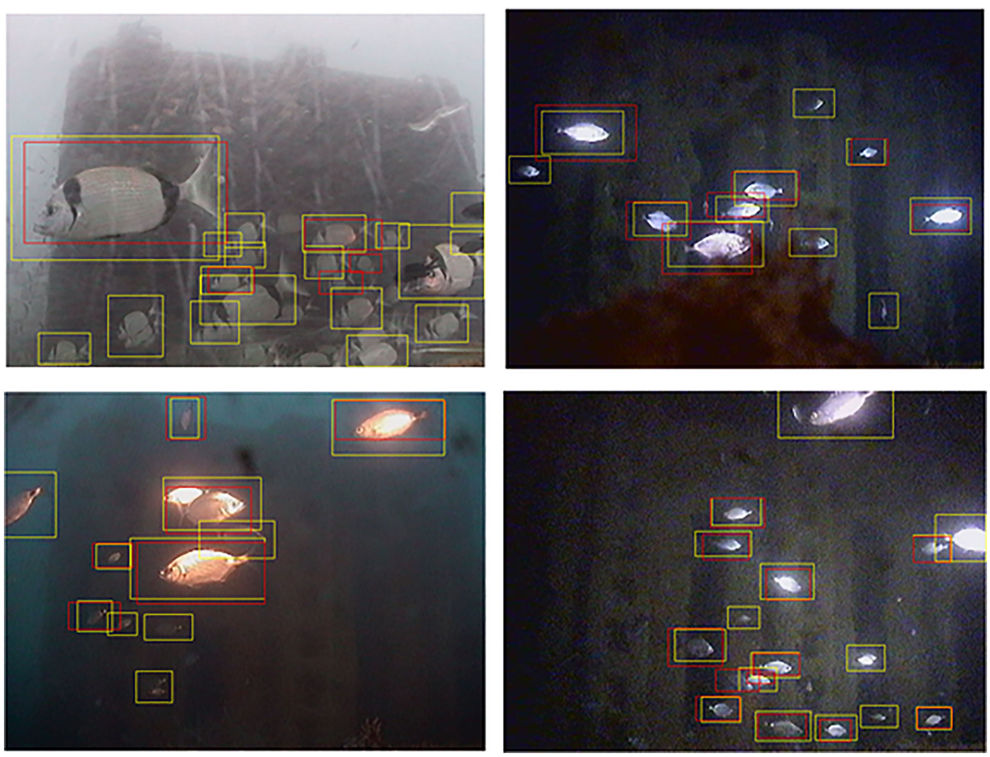

FIGURE 8 | Four examples of automated fish detection. The red boxes represent the ground-truth bounding boxes, while the yellow boxes represent the automated fish detection.

to the natural increase of the seasonal temperatures, and by the change of the species present in the surrounding of the observatory, as reported in **Figure 2A**. In fact, during the training phase of the classification and detection experiments the number of specimens and the proportion among the species changed sensibly with a prevalence of specimens of the species *Oblada melanura* (f6) in the first three months and an increase of fishes of the species *Diplodus vulgaris* (f1), *Diplodus saragus* (f2), *Chromis cromis* (f15) and *Coris julis* (f23), in the remaining months used as test set. Very variable numbers of individuals for different video-detected species are usually reported in coastal image monitoring with fixed cameras. In fact, species assemblages can be affected by relevant variations over the year, depending on seasonal biological and physical parameters (Aguzzi et al., 2013; Aguzzi et al., 2015; Sbragaglia et al., 2019). Moreover, a sensible drop of classification performance occurred in December (see **Figure 5**), when a new camera with a different colour balance mechanism substituted the old one. The classifier was trained before the change of the camera and could not manage this modification. As a consequence, the accuracy dropped down significantly. A different behaviour resulted for the fish detection task (**Figure 7**), where the effect of the concept drift is sensibly reduced with respect to the fish classification task. The detection algorithm was trained in order to recognize a fish with respect to the image background, without taking care of the visual characteristics needed to discriminate among species. As a consequence the concept drift effect, caused by the change of the camera setup, was sensibly mitigated. In fact, even if the image colour balance changed in December, the detection algorithm was still capable of detecting the learnt fish shapes.

Fixed cabled observatories like the OBSEA platform, that is part of the Joint European Research Infrastructure of Coastal Observatories (JERICO) and is a testing site of the European Multidisciplinary Seafloor and column Observatory (EMSO), have high costs for deployment and maintenance. The automated services for producing valuable scientific knowledge are recognised to be relevant tools for optimising cost/benefit of the infrastructure (Aguzzi et al., 2019). Nevertheless, the

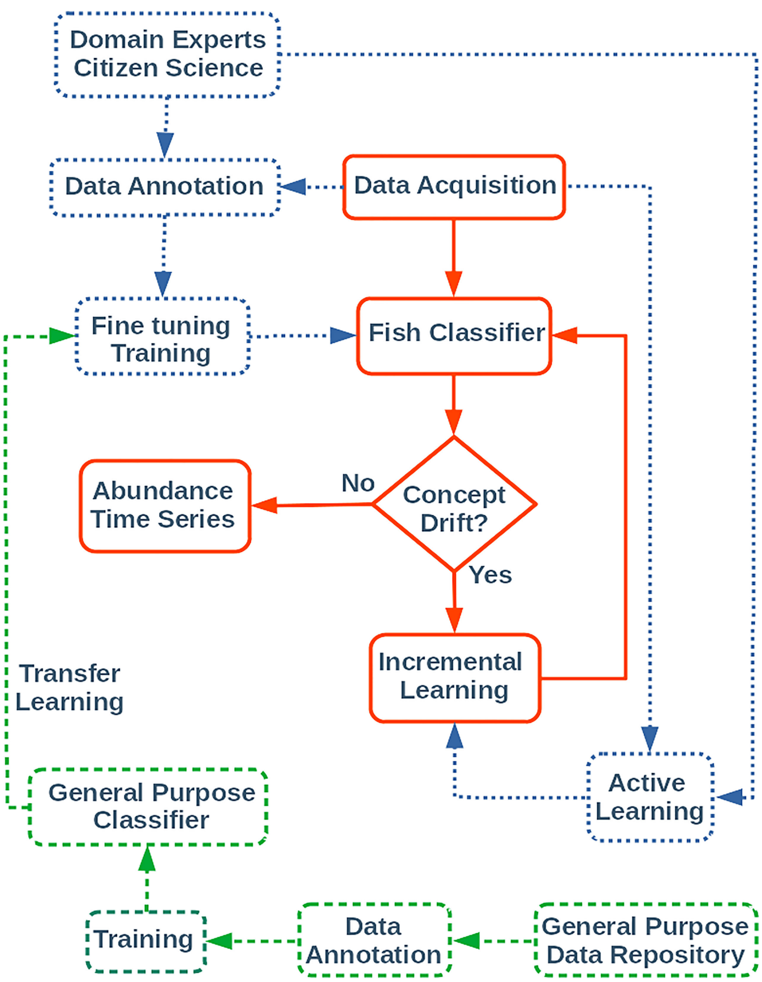

FIGURE 9 | The complete fish classification pipeline for a future automated service at the OBSEA observatory. The continuous red lines and boxes describe the automated service; the dotted blue lines and boxes represent annotation and training activities; the dashed green lines and boxes represent the transfer learning activities.

reliability of such services to provide an effective tracking of life components in marine ecosystems, is not yet proven at present and the solution of the concept drift phenomenon is an obstacle that needs to be urgently addressed.

Although the concept drift is a major concern for the definition of automated services, very few studies address this problem in the field of marine monitoring (Lagenkämper et al., 2020; Kloster et al., 2020). The recent literature in the computer vision and machine learning community proposes several general purpose approaches useful to mitigate the concept drift problem (Langenkämper et al., 2019). Among those, promising research directions include active learning (Brust et al., 2020; Wu et al., 2020) and incremental learning (He et al., 2020; Zhou et al., 2021), with specific attention to emerging trends in self-supervised and few-shot learning (Jaiswal et al., 2021; Ohri and Kumar, 2021). The active learning approach consists in techniques aimed at minimising the effort of human experts in selecting new valuable unlabelled examples. These are used for training a classifier based on machine learning, while the incremental learning, depending on the classifier architecture, uses a selected set of new examples to dynamically improve classifier performance. Self-supervised and few-shot learning are novel methodologies that strongly reduce the use of positive and negative examples during the training of a machine-learning based algorithm.

In the context of cabled observatories, the creation of a training dataset for fish detection and classification is a bottleneck, even if active learning sensibly reduces the effort for labelling the acquired images. This process can be further improved by combining active learning with the crowd sourcing data and labelling, produced by citizen science activities as discussed in Støttrup et al. (2018) and DiBattista et al. (2021). In this case, several categories spanning from students to professional fisherman or amatorial divers can efficiently contribute to the labelling of the acquired images and combine this effort with active learning techniques to select the most relevant images for training/updating the classifier, as discussed in Sayin et al. (2021).

The new minimal and effective training set generated through an active learning task can be combined with an incremental learning technique for updating the classifier (Delange et al., 2021; Liu et al., 2021). The major challenge of the incremental learning task is to improve the classifier even by learning new classes, possibly characterised by few instances, without a catastrophic forgetting of the previously acquired discrimination capabilities. This capability is critical, especially when the input data originates from a continuous stream as in the case of the OBSEA cabled observatory (Delange et al., 2021; Din et al., 2021; Mai et al., 2022).

Figure 9 summarises the whole pipeline that could be implemented for creating an automated service for a cabled observatory. In the proposed diagram, the red lines and boxes represent the tasks involved in the automated classification of the acquired images and in the production of the abundance time series for each species detected. As discussed in Section 2, the Fish Classifier is obtained through a fine-tuning training activity (dotted blue lines and boxes), aimed at specialising a classifier previously trained on a general purpose image dataset, within a transfer learning approach (dashed green lines and boxes). The fine-tuning training activity is based on the annotation of the acquired images by expert biologists, and since the annotation task is really time consuming also citizen science activities could be useful to ease the ground-truth generation process. According to the literature, the incremental learning task could be activated when the average classification confidence of the organisms contained in the images decreases below a given threshold or when the number of unclassified organisms exceeds a given threshold (Zhou et al., 2021; Mai et al., 2022). The number of unclassified organisms could be estimated using the confidence level for each class already provided by the classifier. In this case, a new training set obtained through an active learning approach can be considered for updating the fish classifier.

Finally, the machine learning procedures used for the image analysis can be easily generalised to other types of marine organisms, as these methodologies are in no way linked to the specific image details and can be applied to any type of visual-based observing system.

DATA AVAILABILITY STATEMENT

The time series of specimen counts per species, obtained through the visual inspection of the image dataset, is provided as a supplementary material (only the images containing at least one specimen are reported). The image datasets analysed for this study can be accessed by contacting the OBSEA observatory [https://www.obsea.es/] on reasonable request.

AUTHOR CONTRIBUTIONS

SM, EO, JA, and JR have conceived research activity. MF produced the ground-truth by visually inspecting and tagging the images. EO and NG implemented the classification and detection algorithms. EO and SM defined the experiments for the concept drift assessment. EO, SM, JA, and JR wrote the manuscript. All the authors reviewed and edited the manuscript. All authors contributed to the article and approved the submitted version.

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Performance of Seismic Observation by Distributed Acoustic Sensing Technology Using a Seafloor Cable Off Sanriku, Japan

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Recently, the distributed acoustic sensing (DAS) measurement, which utilizes an optical fiber itself as a sensor, becomes popular for various fields and is being applied to seismic observations. The shortest spatial sampling of DAS observations reaches a few meters, and the total measurement distance becomes greater than 50 km. A high temporal sampling rate is achieved. Due to these characteristics, a DAS measurement allows for a dense seismic observation as a linear array. Applying a DAS measurement to the seafloor cable is advantageous because the quantity of data can be significantly increased in a marine area. A seafloor seismic tsunami observation cable system using an optical fiber for data transmission was deployed off Sanriku by the Earthquake Research Institute, the University of Tokyo in 1996. This seafloor cable observation system has spare fibers for extension. Beginning in February 2019, we made several DAS observations using the spare fibers of the seafloor system. Consequently, many earthquakes were recorded. Small earthquakes with a magnitude of 1.8 occurring near the cable system were recorded by the DAS system. The arrivals of P- and S-waves of the earthquake with a magnitude of 3 were clearly seen using the phase data from the DAS measurement. In addition, a teleseismic event with an epicentral distance of approximately 2,300 km and a magnitude of 6.6 was clearly observed. Because there are conventional seismometers in the Sanriku cable system, we compared records from the DAS measurement with those from the seismometer. The DAS records and the data by the seismometer showed a high coherency. The noise levels of the DAS measurement were evaluated, and there was little temporal variation of the noise levels. A spatial variation of ambient seismic noises was revealed using a spatially high-density observation with a long distance. In November 2020, a seismic survey using the DAS system and airguns was carried out, and the DAS system clearly recorded signals from the airguns. We also compared these data from the DAS system with that of the seismometer. Both records had the same characteristics, although P-wave arrivals on the DAS records have smaller amplitude.

Keywords: distributed acoustic sensing (DAS), seafloor cable, seismic ambient noise level, optical fiber sensing, microearthquake observation, controlled seismic source survey

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INTRODUCTION

The distributed acoustic sensing (DAS) measurement is a technology measuring the sensing strain or strain rate of an optical fiber using the optical fiber itself as a sensor. Initially, the DAS measurement had been applied to security surveillance, the monitoring of pipeline, and traffic monitoring (Owen et al., 2012; Dou et al., 2017). Later, for seismic explorations, such as vertical seismic profiles in a field of resource surveys, the DAS measurement began to be applied (Daley et al., 2013; Mateeva et al., 2014; Karrenbach et al., 2019). Because the DAS measurement provides spatially high-density data, a seismic observation for natural earthquakes on land has been conducted using the DAS measurement (e.g., Lindsey et al., 2017). In addition, the DAS measurement is useful to provide the information related to shallow structures (e.g., Zeng et al., 2017). Recently, the DAS measurement was applied for seafloor observation using a seafloor cable containing optical fiber (Lindsey et al., 2019; Shinohara et al., 2019; Sladen et al., 2019; Ide et al., 2021; Lior et al., 2021; Matsumoto et al., 2021). In addition, the DAS measurement was also used for the studies of other topics, such as microseisms and ocean waves (e.g., Williams et al., 2019).

The DAS measurement is an optical fiber sensing technology. A coherent laser pulse with short duration is transmitted intermittently to a single-mode optical fiber for the DAS measurement, and Rayleigh scattering occurs at inhomogeneity within the optical fiber. The backscattering light is observed at the point where the coherent laser pulse is transmitted (Posey et al., 2000). When a fiber has a small deformation due to its movement, the distance between the two scatterers where Rayleigh scattering occurs is changed. The distance of the scatterers is measured using interferometry technology. The distance of the scatterers is expressed using the phase difference between two scattered lights by optical interferometry. The travel time of a light indicates a distance to a measurement point from the laser light source, and a distance between two scatterers that is called a gauge length, for an interference measurement, corresponds to the spatial resolution of the DAS measurement. A recent interrogator has a spatial resolution of a few meters. Due to a repetition of an interference measurement with very short time intervals, a spatial measurement interval, which is usually called as a channel interval, becomes a few meters, and a measurement with a long distance on a fiber can be performed. This results in a long linear measurement array with a measurement interval of a few meters. The total length of the DAS measurement reaches more than 50 km at the present, although the recording performance of the DAS measurement seems to decrease with a distance greater than 50 km from an interrogator generally. Seismic observations using the DAS technology, which measures a strain on a fiber using interferometry, have become popular because spatially high-density data can be obtained. DAS measurements have become increasingly accurate, and the progress of the technology accelerates the increase of obtained data quality. Therefore, various sophisticated data analyses can be applied to recent DAS data; however, for data processing, DAS measures strain wave fields, which are different from those from conventional seismic measurements using the devices based on the pendulum principle.

The Earthquake Research Institute, the University of Tokyo is carrying out seafloor seismic observation using two seafloor cable observation systems off Sarinku, northeastern Japan, in the source region of the 2011 Tohoku-oki earthquake with a magnitude of 9. One system using conventional communication technology was installed in 1996 and another system using Internet technology for data transmission and system control was deployed in 2015 (Shinohara et al., 2021). The first system installed in 1996 has a total length of approximately 120 km. Three three-component seismometers and two tsunami-meters (pressure gauges) are connected in the line (**Figure 1**). The seafloor cable was buried using a plough-type burial machine simultaneously with the cable deployment in the region where the water depth was less than 500 m. A remote-operated vehicle buried the cable just after the deployment of the system in the range of the water depths from 500 to 1,000 m. The burial depth was estimated to be less than 1 m below the seafloor. The data from the scientific sensors are digitally transmitted to a landing station in Kamaishi, Iwate prefecture, using optical fibers in the seafloor cable, and each sensor uses a dedicated optical fiber. One optical fiber is used for the delivery of a timing clock to each sensor system. The seafloor units synchronize with the timing clock, which is generated by a Global Positioning System (GPS) receiver on the landing station. Because the seafloor cable of the 1996 system has 12 optical fibers, six spare (dark) optical fibers, including the system for future extension, are available. The seafloor cable in the 1996 system has dispersion-shifted single-mode optical fibers with a wavelength of 1,550 nm, and therefore, the spare fibers are suitable for the DAS measurement. Because the spare fibers have no repeater or connector on the seafloor, the DAS measurement can be performed up to the seaward end of the seafloor cable. In addition, the records from the DAS measurement can be compared to those obtained by three seismometers installed in the 1996 cable system. We carried out phase-based DAS measurements using a spare fiber of the Sanriku system beginning in February 2019.

OBSERVATIONS

In February 2019, we made the first pilot observation of a DAS measurement using a dark fiber of the Sanriku seafloor observation system. Prior to the DAS measurement, we confirmed a good condition of the dark fibers using an optical time domain reflectometer (OTDR). The OTDR also sends laser pulse light into an optical fiber and observes backscattered light from inhomogeneity in an optical fiber. Unlike a DAS using interferometry, the OTDR uses the intensity of the backscattered light and a travel time to check the conditions of an optical fiber. The phase-based DAS interrogators have been used through the observations using the Sanriku seafloor observation system. An interrogator for the DAS measurement was installed in the landing station temporarily. A commercial DAS measurement system model N5200A from AP Sensing GmbH was used (Cedilnik et al., 2019). N5200A outputs phase data as a result of the interferometry and can measure strain for a long range of more than 70 km. Data were recorded for 100 km in length with a spatial

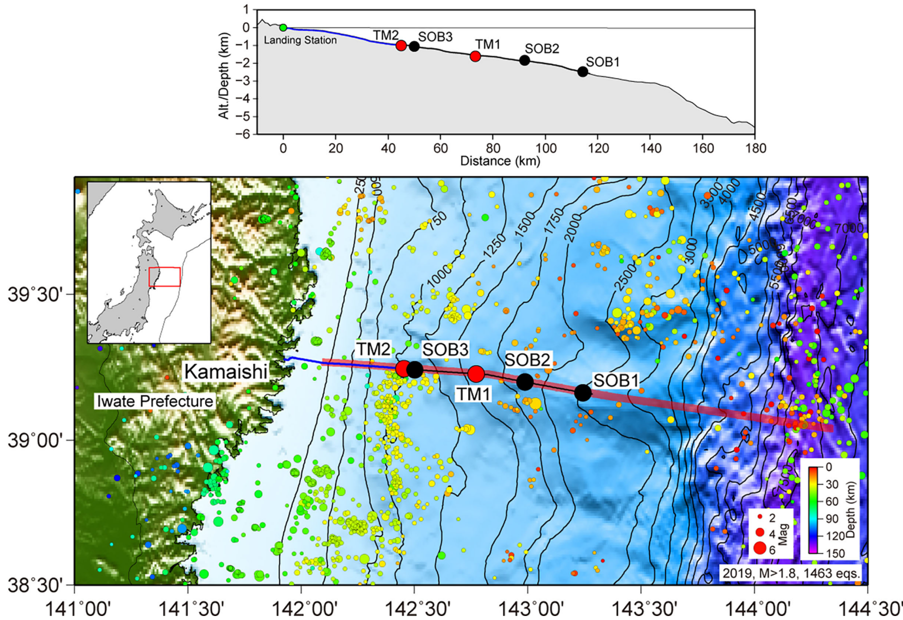

FIGURE 1 | The seafloor cable observation system off Sanriku installed in 1996. Upper: depth profile of the cable system. The seafloor gradually deepens toward the Japan trench. Lower: the position of the seafloor cable. Black and blue lines indicate the cable route of the 1996 system. Blue lines denote a segment where the cable is buried. Black and red circles show the positions of the seismometers and tsunami-meters. Translucent red lines indicate the profile of the seismic survey using an array of large airguns. Colored circles denote epicenters of earthquakes with magnitudes greater than 1.8 occurring in 2019. Size and color of circles indicate magnitude and depth of events, respectively.

sampling interval of 5 m and sampling frequency of 500 Hz. The gauge length was set to 40 m. The laser light with a wavelength of 1,550 nm was used for the interferometry. The DAS interrogator generated phase data that are obtained from the interferometer for backscattered lights and frequency band-extracted (FBE) data, which indicate the energy of the strain rate in a frequency band as a function of distance from the interrogator and time. Both kinds of data were collected continuously for approximately 46 h. The data were stored in the hard disks in the recording system. We copied the data of a total capacity of approximately 4 TB to an external disk after the observation.

For long-term seafloor seismic monitoring, an experimental measurement for a long-term observation was carried out in 2019. For the observation, N5200A was also used. The recording period basically depends on the capacity of a recording device. We succeeded in a obtaining a continuous DAS measurement for approximately 2 weeks using the same type of the interrogator for the measurement in February 2019. The DAS measurement using the Sanriku seafloor cable system began on November 18, 2019, and the measurement was completed on December 2, 2019. We set the same recording parameters as those of the measurement in February 2019. To reduce the dataset, a total length of the measurement was set to 48 km for the first day and extended to 70 km after the second day. The total capacity of the dataset reached 17 TB over approximately 2 weeks.

In March 2021, we performed the DAS measurements using a different interrogator on the Sanriku seafloor observation system. We used the commercial DAS system model QuantX from OptaSense Ltd., Farnborough, Hampshire, UK for this observation. The interrogator QuantX is also a phase-based DAS system with a maximum range of 100 km. The interval of the channel is 2 m; therefore, 50,000 channel data can be obtained. The aim was to obtain spatially long-range data. The interrogator was also installed in the cable landing station temporarily, and the length of data collection (array aperture) was set to 50 or 100 km. The data were recorded with various values of parameters, such as gauge length and ping rate, to evaluate the data quality. The wavelength of the interferometry was 1,550 nm. The total recording period was approximately 35 h. On the first day, we tuned the system using various tests and performed overnight recording with a gauge length of 100 m and spatial sampling interval of 2 m. Because the total channel number was 50,000, the total spatial length became 100 km. On the next day, an observation with a gauge length of 200 m and a spatial sampling interval of 1 m was carried out through the night. The ping rate was 500 Hz, and the data were decimated to the temporal sampling rate of 250 Hz through the observation. The system could store the data to an internal disk and external disk concurrently during the observation. The data size was approximately 3.4 TB.

A seismic survey using controlled sources and a DAS measurement on a seafloor optical fiber cable was carried out (**Figure 1**). The objectives of the survey were to evaluate the DAS data for seismic surveys and to obtain a seismic structure beneath the seafloor cable with a high resolution. The survey was performed from November 3–8, 2020, using the R/V Hakuho-maru belonging to the Japan Agency for Marine-Earth Science and Technology. For controlled seismic sources, we used two types of seismic sources. One was an array of four large airguns (Bolt 1500LL). Each 1500LL airgun had a chamber volume of 1,500 in^3. The other was two GI-guns from Sercel Inc. Each Generator and Injector (GI)-gun had a capacity of 355 in^3. Shooting the large-airgun array was carried out on November 5 and 6 along the profile with a length of approximately 200 km (**Figure 1**). The shot interval was approximately 40 s. Two GI-guns were shot on November 6 and 7. The shot interval of the GI-gun was 20 s, the length of the profile was approximately 90 km, and the cruising speed was 4.5 kts. A multichannel hydrophone streamer with a length of 1.2 km was towed during the GI-gun shootings. Seismic signals from the large-airgun array were also recorded by a two-channel hydrophone streamer with a length of 150 m. In addition to the DAS measurement, pop-up type Ocean Bottom Seismometer (OBSs) were temporally deployed on the profile before the shooting of the airguns and the pop-type OBSs recording airgun signals were recovered after the completion of the shooting. Corresponding to the airgun shooting, the DAS measurements were conducted at the landing station of the Sanriku cable system. Because the cable system has six spare fibers, we made observations with two identical systems of DAS measurement (N5200A, AP Sensing GmbH) concurrently. Each system used a dedicated fiber and recorded the data independently. The continuous recording began on November 4 and was completed on November 8. The data were recorded for 100 or 80 km of the total length with a spatial sampling interval of 5 m and temporal sampling frequency of 500 Hz. The gauge length was set to 40 m. Although one DAS system had a missing data for several hours during the airgun shooting due to a recording issue, the other system worked throughout the airgun shooting. Data with a total capacity of approximately 8 TB from two DAS systems were obtained.

The DAS measurement senses the exact distance of two scatterers approximately gauge length apart by the interferometry of backscattered light. There are three seismic stations connecting the Sanriku cable system (**Figure 1**). The seismic station has a conventional three-component accelerometer (JA-5; Japan Aviation Electronics Industry, Ltd., Tokyo, Japan). The direction of the X-component of the accelerometer is parallel to that of the seafloor cable. Therefore, the DAS measurement can be compared to X-component of the accelerometer.

The phase data provided by an interrogator were converted to strain:

$$\epsilon_{xx} = \frac{\lambda_l}{4\pi\xi n_C L}\Delta\phi \quad (1)$$

where ϵ_{xx} is the principal strain for the x-direction, λ_l is the wavelength of used laser light in a vacuum, n_c is the refraction index of a fiber, L is the gauge length, ξ is the optical-elastic coefficient for the fiber direction in isotropic media (usually set to 0.78), and $\Delta\phi$ is the phase of a DAS measurement (SEAFOD, 2018). This conversion is a linear operation; therefore, strain is proportional to phase. Strain can be converted to particle velocity under an assumption of a plane wave propagation (Daley et al., 2015; Wang et al., 2018). When a plane wave propagates to the x-direction, we can express displacement as follows:

$$u(x,t) = Ae^{i(kx-\omega t)} \quad (2)$$

where $u(x,t)$ is the displacement for the x-direction, A is the amplitude, k is the wave number, and ω is the angular frequency. Assuming that A is constant, we can calculate

$$\frac{\partial u}{\partial x} = \epsilon_{xx} = \pm\frac{1}{c}\frac{\partial u}{\partial t}\left(c = \frac{\omega}{k}\right) \quad (3)$$

where c is the apparent speed of the plane wave. Consequently, a simple formula is obtained:

$$\frac{\partial u}{\partial t} = c\epsilon_{xx} = \frac{c\lambda_l}{4\pi\xi n_C L}\Delta\phi \quad (4)$$

This means that particle velocity in the media and the phase measured by the DAS have a proportional relationship, and we compared DAS data to the data recorded by a conventional seismometer using the principal of the pendulum.

RECORDS OF EARTHQUAKES

According to the observations carried out in the periods from 2019 to 2021, the records of many earthquakes including deep earthquakes and teleseismic events were obtained through the DAS measurements. First, we inspected the FBE data for local earthquakes to evaluate the performance of the DAS records. The FBE data with a frequency range from 10 to 20 Hz were provided using the software from the supplier of the interrogator and represent the visualization of energy in some frequency band on a time domain. A local earthquake with a magnitude of 3.0 was clearly recognized in the FBE data (Shinohara et al., 2019). Because the earthquake was recorded with a high signal-to- noise (S/N) ratio, we checked the sensitivity of the DAS measurement using the records of earthquakes. The Japan Meteorological Agency (JMA) routinely determines the hypocenters of local earthquakes using land seismic networks. The earthquake catalog from the land seismic network was compared to the DAS records to evaluate the sensitivity of the DAS measurement. We identified all earthquakes with magnitudes greater than 1.8 in the JMA catalog near the cable system in the records from the DAS system (**Figure 2**). All earthquakes with magnitudes greater than 1.8 near the cable system were recorded by the DAS system. The DAS measurement was concluded to have an enough sensitivity for earthquake observation. In addition, a deep earthquake with a depth of 490 km occurring below the Japan Sea in February 2019 was clearly recorded. For other observations, local microearthquakes and deep earthquakes were recorded clearly. The sensitivity of the DAS measurement was examined in previous observations. Sladen et al. (2019) and Ide et al. (2021) reported microearthquakes based on DAS measurements using a seafloor cable in the region of off-Toulon, France and Nankai trough, Japan, respectively. Microseismicity in glaciated terrain has been observed using DAS technology as well (Walter et al., 2020). Because we

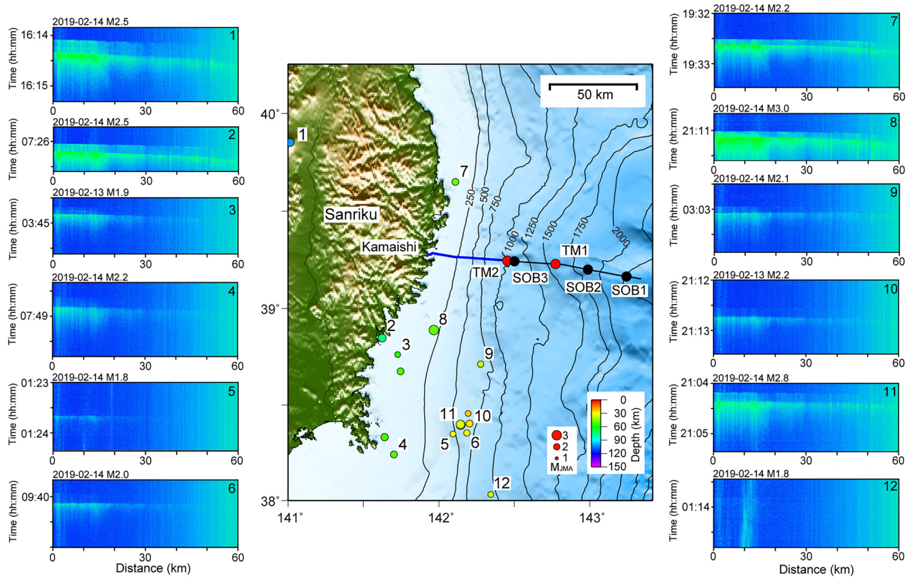

FIGURE 2 | FBE data of local earthquakes recorded by the DAS measurement using the Sanriku cable system. FBE data show the energy of strain rate in a frequency band from 10 to 20 Hz. Position of the seafloor cable for the DAS measurement is indicated by blue and black lines. Event numbers are shown in the FBE data, and epicenters are indicated by numbers on the map.

confirmed that the DAS measurement clearly recorded earthquakes, we made a time–distance profile of earthquake records using phase data (**Figure 3**). The earthquake occurred on February 15, 2019, at a depth of 50 km below the cable system, and the magnitude of the event was 3.0. The phase data of each channel were filtered from 1 to 15 Hz in the frequency to increase the S/N ratio. Although there are 10,000 channels in the distance range from the landing station to 50 km from the coast, we only plotted 100 trace data at an interval of 100 channels. The arrivals of P- and S-waves were clearly seen in the time–distance section. In addition, we recognized seismic arrivals with large amplitudes in distances from 0 to 10 km after the first arrivals before the arrivals of S-waves. The S/N ratio decreases at distances greater than 50 km. The decrease in the S/N ratio is thought to be caused by the attenuation of laser light for the

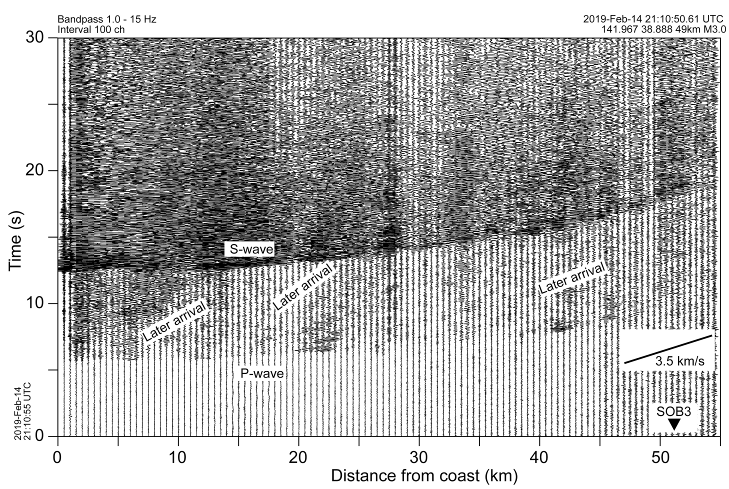

FIGURE 3 | Time–distance profile of phase data for a local earthquake recorded by the DAS system. The phase data of each channel were filtered from 1 to 15 Hz to increase the S/N ratio. Each trace was plotted using the same amplitude scale. The horizontal axis is distance from the coast, and the vertical axis shows time. A position of the seismic station SOB3 in the cable observation system is indicated. There are 10,000 channels in the DAS measurement, and only 100 channels are plotted at an interval of 100 channels. The arrival of P-waves and S-waves are clearly seen. In addition, other seismic arrivals can be recognized. The earthquake corresponds to event No. 8 in **Figure 2**.

interferometry, which travels for a long distance. The teleseismic event was also recorded by the DAS measurement. A large earthquake occurred under the Kamchatsk Peninsula, Russia on March 16, 2021. The depth and magnitude were 13 km and 6.6, respectively, according to the US Geological Survey. The epicentral distance from the cable system was approximately 2,300 km. The earthquake was clearly observed by the DAS measurement (**Figure 4**). Reflecting a long epicentral distance, low frequency was dominant. The DAS records have a high S/N ratio even in the low-frequency band. Within periods ranging from 10 to 5 s, the amplitudes of the seismic signal had large variations depending on the channel positions of the DAS records. We found that the DAS measurement using the seafloor cable off Sanriku could detect teleseismic events with magnitudes greater than 6 and epicentral distances smaller than 2,000 km; however, few teleseismic events were recorded due to the short observation periods and there was no earthquake with a magnitude greater than 7 during the observation periods. To accurately evaluate the performance for recording low-frequency events such as teleseismic events, more observations for longer periods using the DAS measurement are needed.

Because the conventional seismometers are connected to the Sanriku cable system, we can compare the records from the DAS measurement with those from the conventional seismometers. The records of the earthquake that occurred on February 15, 2019 (**Figure 3**) were used for the comparison. First, we searched the DAS data and retrieved the DAS data of close channels to the seismometer SOB3, which is closest to the coast. The DAS data of the adjacent 11 channels were averaged to increase the S/N ratio. After averaging, the phase data were converted to strain data. The SOB3 is positioned at a distance of approximately 50 km from the coast. We read an apparent velocity of 3.5 km/s around a distance of 50 km from the DAS record of the earthquake (**Figure 3**) and obtained particle velocity data using the velocity of 3.5 km/s, which was read from the DAS record. Finally, the velocity data were differentiated to convert to acceleration because the seismometer of the SOB3 is an accelerometer. Because the X-component of the SOB3 is parallel to the cable direction, we compared the acceleration data from the DAS measurement to the X-component of the SOB3 (**Figure 5**). The arrivals of seismic phases on the acceleration data converted from the DAS measurement are consistent with those on the records of the SOB3, and the amplitudes of seismic phases of both records are comparable. Because the converted DAS records to acceleration had similarities with the records of the accelerometer, our results indicate that the DAS measured actual ground movement.

AMBIENT NOISE ANALYSIS

Phase data can be converted to strain data using a simple equation (1) according to the principle of interferometry. We converted phase data to strain data and estimated spectra to investigate the ambient noise obtained by the DAS measurement. First, we evaluated the temporal changes of ambient noise. Because continuous records were obtained through the observation, we calculated spectra at time intervals of 15 min throughout the observation using the DAS data at distances of 10 and 35 km from the coast after the conversion of the data from phase to strain using the appropriate parameters for each observation. The data for the calculation of the spectrum included 262,144 or 131,072 samples, respectively, which correspond to 524.288 s in time length, and the spectra were smoothed on the frequency domain. We calculated the spectra for the observations in February 2019 and March 2021. We obtained a total of 184 and 51 spectra for the observations in 2019 and 2021, respectively. The probability density

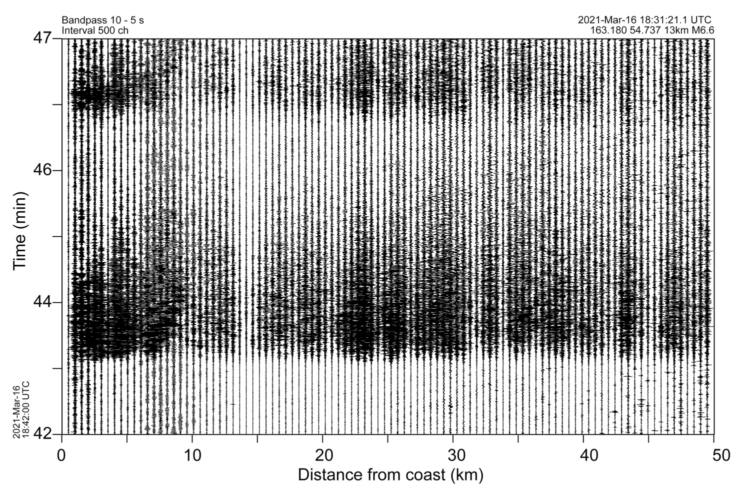

FIGURE 4 | Time–distance profile of phase data for a teleseismic event recorded by the DAS system. The phase data of each channel were band-passed from 10 to 5 s to increase the S/N ratio. The horizontal axis is distance from the coast, and the vertical axis shows time. Each trace is plotted using the same amplitude scale. There are 10,000 channels in the DAS measurement, and only 100 channels are plotted at an interval of 100 channels. An earthquake with a magnitude of 6.6 occurred under Kamchatka Peninsula, Russia on March 16, 2021, and the epicentral distance from the cable system was approximately 2,300 km. Amplitudes of seismic signals had variations depending on the channel positions.

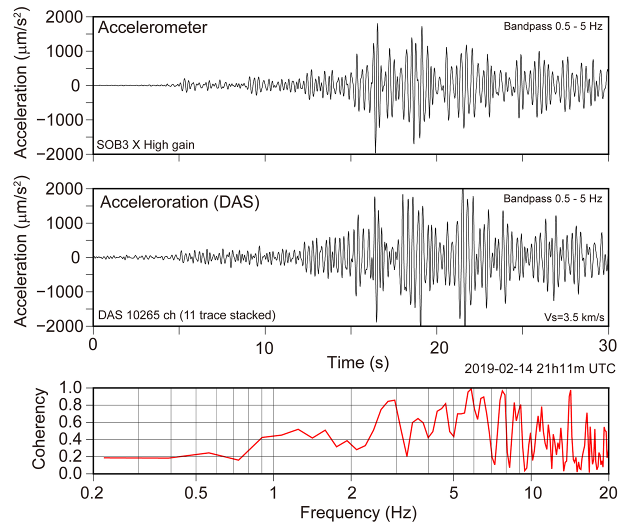

FIGURE 5 | Comparison of the DAS records and records obtained by an accelerometer connected to the cable observation system. The data from the DAS measurement were converted to acceleration to compare the data from the accelerometer (SOB 3). The X-component of the SOB3 is parallel to the seafloor cable. The DAS data for the adjacent 11 channels were averaged and transformed to particle acceleration under an assumption of plane wave propagation with a velocity of 3.5 km. Both the records were filtered from 2 s to 5 Hz. Coherency between the records from the accelerometer and the acceleration data transformed from the DAS records was calculated. The channel of the DAS records to compare the data of the SOB3 was selected using airgun signals.

functions of the power spectra (McNamara and Buland, 2004; McNamara and Boaz, 2006) of the strain were estimated. (**Figure 6**). Although the interrogators for the observations for 2019 and 2021 were different, the noise levels at the same distance were identical. Generally, the larger the noises in the strain, the longer the periods became. On the spectra at a distance of 10 km, large noise peaks were observed at time periods around 15 s for both spectra from the data of 2019 and 2021 (**Figure 6**). Large noises that correspond to microseisms (Webb, 1998) were also recognized at a distance of 35 km. The noise levels of strain-meters installed at the bottom of the borehole in land ranged from -200 to -180 dB (Barbour and Agnew, 2011). Araya et al. (2017) reported the noise levels from a laser strain-meter with a 1,500 m baseline constructed at an underground site of a deep vault in Kamioka, Gifu Prefecture, Japan. The noise levels at the Kamioka site were estimated to be some of the quietest in the world. In comparison with the noises obtained from the strain-meters installed in land, the noise levels from the DAS records were larger at time periods greater than 1 s. The noise levels of the DAS records become larger in longer periods. There is a possibility that this characteristic originates from DAS interrogators. On the other hand, the noise levels of the DAS measurement in the frequency range higher than 1 Hz were comparable to those from strain-meters in land. At a frequency around 10 Hz, the DAS noise levels were close to those of the Kamioka site (Araya et al., 2017).

One advantage of a DAS measurement is obtaining an observation with a spatially high density over a long distance. Taking advantage of a spatially high density for the DAS dataset, the spatial variations of ambient seismic noise along the seafloor cable were revealed. Spectra were calculated using the time window of 524.288 s at every 50 m to estimate the spatial variation of ambient noise (**Figure 7**). We estimated the spatial changes of ambient noise levels for both observations in February 2019 and March 2021 and found that both results from different observations had similar characteristics. The primary seismic noises with a large amplitude in the periods around 15 s close to the coast were recognized. There was a secondary microseismic noise with a period of approximately 1 s from a distance of 10 km. In the vicinity of the coast, large noises with a period of approximately 15 s appeared. These large, low-

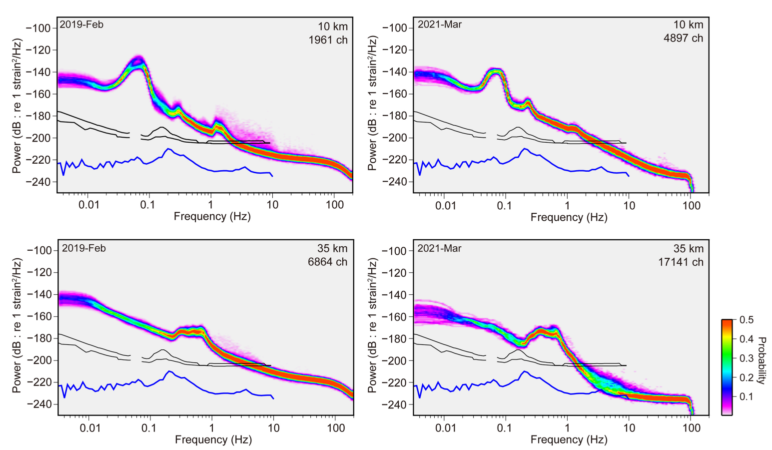

FIGURE 6 | The probability density functions of ambient noise spectra on the seafloor collected by the DAS observation carried out in February 2019 (left) and March 2021 (right). Spectra of the data at distances of 10 and 35 km from the landing station are shown. Phase data of the DAS measurement were converted to strain. Black lines show the spectra of strain-meter on land (Barbour and Agnew, 2011). The blue curve indicates a result of a laser strain-meter in deep vaults in Japan (Araya et al., 2017). The DAS measurement has low noise levels in frequency greater than 1 Hz.

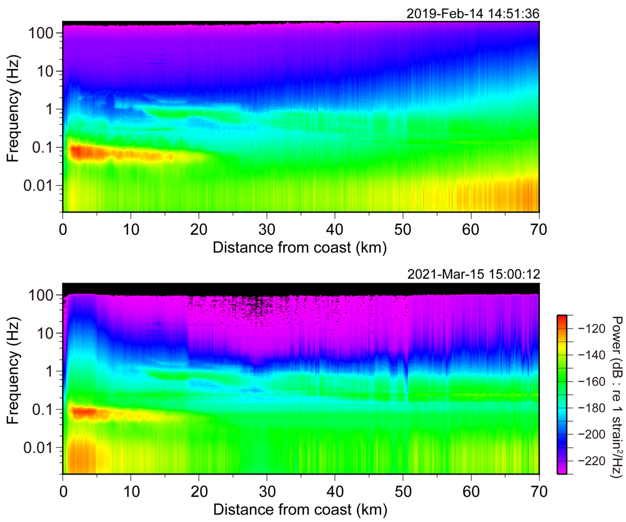

FIGURE 7 | Spatial variation of ambient noise spectra on the seafloor obtained by the DAS measurements in February 2019 (upper) and March 2021 (lower). The horizontal axis is the distance from the coast, and the vertical axis shows frequency. There were large noises around a period of 15 s near the coast.

frequency noise levels were observed by other DAS observations using a seafloor cable (Lior et al., 2021). The frequency of the noise migrates to a lower frequency, and the amplitude becomes small. At a distance of 20 km from the coast, the large noise levels around 15 s disappeared. The peaks of the noise were observed at a frequency of 1 Hz at a distance of 10 km from the coast. The peak frequency of this noise also migrated to a lower frequency, and the amplitude of the noises increases as the distance from the coast increased. These noise levels at large distances from the coast seem to correspond to the microseisms (Webb, 1998), which are commonly observed in the ocean and have a dominant period of 4 s. There is a possibility that this phenomenon is related to the generation of microseisms in the ocean. The observation in February 2019 had slightly larger noise levels in distances greater than 50 km compared to the noise levels at closer distances to the coast. The scattered light travels over a long distance for a large offset attenuate. The small amplitude of scattered light may affect the accuracy of a measurement using interferometry.

The spectra of ambient seismic noises recorded by the DAS system were compared to a noise model after the conversion of the DAS data to particle acceleration. We estimated the spectra of ambient noises using the DAS records. Ambient noises are thought to propagate as surface waves along the seafloor. Spica et al. (2020) obtained an S-wave velocity just below the Sanriku cable system using the DAS data. We adopted an apparent velocity of 500 m/s for the conversion from strain to particle velocity because there was an average velocity of 500–700 m/s for the shallow layers (Spica et al., 2020). We calculated the spectra for the observation in February 2019 at every 1,000 channels, which correspond to a spatial interval of 5 km with a time window of 524.288 s (**Figure 8**). The levels of the ambient noise based on the DAS measurement were close to the high-noise model (HNM) (Peterson, 1993) from the estimated spectra. Large peaks of noises around 15 s were recognized in the spectra estimated from the data collected at distances smaller than 20 km from the coast. These peaks were much larger than the HNM; however, the amplitude of these peaks decreased with the distance from the coast, and there was no peak around 15 s in the spectra calculated using the data at distances greater than 30 km. We also compared the ambient noise spectra obtained by the DAS system

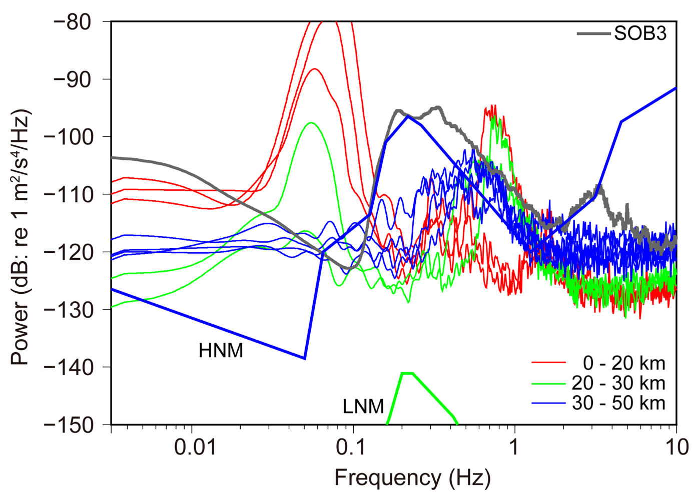

FIGURE 8 | Ambient seismic noise spectra in acceleration on the seafloor estimated using the DAS observation data. The DAS data were converted to particle acceleration under an assumption of plane wave propagation. For the conversion, a wave propagation velocity of 500 m/s was used. The data length for the estimation of the spectra was approximately 524 s. Colors of lines indicate a distance range from the coast. The gray lines denote a typical ambient seismic noise spectrum of the X-component at the SOB3, which is positioned at a distance of approximately 50 km from the coast. The HNM and LNM are also displayed (Peterson, 1993). Noise levels of the DAS measurement are comparable to that of a conventional accelerometer in frequencies greater than 0.5 Hz.

with those of the SOB3, which has a conventional accelerometer and is positioned at a distance of approximately 50 km from the coast. The noise levels obtained from the SOB3 were comparable to those recorded by the DAS system. Although it was inferred that the S/N ratio of the DAS record at a distance of 50 km from the coast becomes lower, the noise levels were similar to that of the conventional accelerometer. At a frequency lower than 0.03 Hz, the noise levels estimated from the DAS records become lower than those from the accelerometer at the SOB3. It can be interpreted that the sensitivity of the DAS measurement is low in this low-frequency range. We concluded that the performance of the seismic observation using the DAS system on the seafloor corresponds to that using a conventional force feedback-type accelerometer in a frequency range higher than 0.03 Hz.

CONTROLLED SOURCE RECORDS

After a few pilot observations using the DAS measurement, we carried out a seismic survey using the DAS measurement and marine-controlled sources in November 2020. The profiles ran along the seafloor cable route of the Sanriku seafloor observation system. The shallowest water depth of the profile was approximately 200 m, and the maximum length of the profile was 213 km (**Figure 1**). In this section, we discuss the data-recording signals from the large-airgun array (four Bolt 1500LL) with a total capacity of 6,000 in^3 due to its large energy. Shooting intervals were 40 s, which correspond to an interval of approximately 100 m at a ship speed of approximately 4.5 knots. Two identical DAS interrogators were used to record the airgun signals. Each interrogator connected separate fibers in the seafloor cable. The temporal sampling frequency was 500 Hz, and the gauge length was set to 40 m. The spatial channel interval was approximately 5 m. The main objective of the recording using two identical interrogators with separate fibers was to make redundant airgun recordings because it was difficult to repeat the shooting in the marine area. There was an additional purpose to confirm the repeatability of the DAS recording, i.e., we tried to check whether identical records using different equipment were obtained. We calculated the coherency between the two records including water wave arrivals, to confirm the repeatability of the DAS records (**Figure 9**). For the estimation of coherency, we applied a bandpass filter from 1,000 s to 25 Hz. As a result, high coherency was generally obtained; however, the coherency at some frequencies had low values. It is known that the airgun source has no broadband spectra. After the calculation of the spectra of an airgun source recorded by the towed hydrophone streamer, the notch frequencies in an airgun source seem to be different from the frequencies where coherency decreases. We concluded that system noises may cause this low coherency. After the records were band-passed with a narrow band filter, which is usually applied for a seismic survey, we obtained similar records. It was confirmed that there is little difference between different interrogators and fibers.

The signals from the airguns were clearly recorded using the DAS measurement (**Figure 10**). The DAS records had a high S/N ratio until the offset distance of 40 km for the seaward side. Water waves were clearly recorded. Before the arrivals of direct water waves, the arrivals of refracted/reflected waves were also recognized. The refracted and reflected waves at offset distances up to 15 km from the seismic sources were observed (**Figure 11**). Because the first arrivals have an apparent velocity of approximately 3.6 km/s, we concluded they were the first arrivals of refracted P-waves. The DAS measurement using a fiber laid down on the seafloor was sensitive to the horizontal direction. The first arrivals had a small amplitude, and then waves with large amplitudes were observed. The later waves with a similar apparent velocity as the first arrivals, which were estimated to be converted to S-waves, had larger amplitudes than the first arrivals. We also compared the time–distance profiles of a common receiver gather from the accelerometer in the SOB3 to a common shot gather and a common receiver gather using the DAS measurement (**Figure 12**). The P-wave arrivals of the DAS records had smaller amplitudes than those of the accelerometer. In the DAS records, S-wave arrivals were more clearly seen on the DAS records compared to the P-wave arrivals. Using the travel times of water waves shooting at various positions, we precisely relocated each channel in the DAS records. The position of the accelerometer of the cable observation system was also redetermined by the travel times of airgun shooting. This information was useful to compare the data obtained by the DAS measurement with the accelerometer.

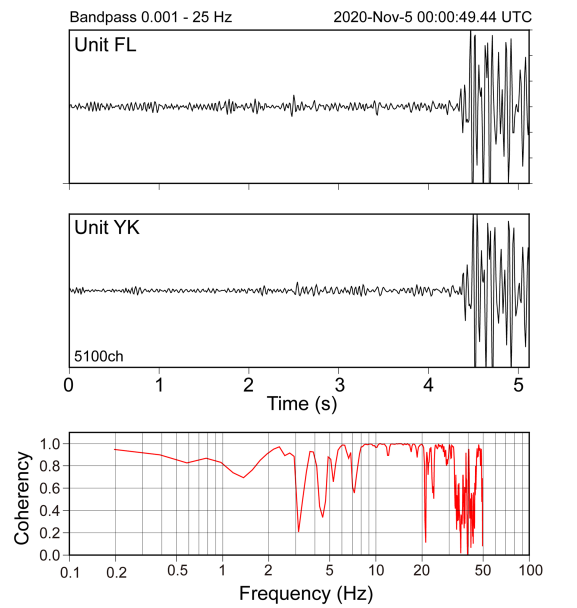

FIGURE 9 | Comparison of the records of airgun signals by two identical interrogators using a different fiber in the same seafloor cable. A bandpass filter from 1,000 s to 25 Hz was applied. The large amplitude of both records indicates arrivals of direct water waves from airguns. Coherency between both the records was calculated (lower). High coherency was generally obtained; however, the coherency at some frequencies was low.

The DAS records and the accelerometer of the SOB3 of the airgun signals were compared to assess the performance of the DAS measurements because the DAS records could be transformed to particle acceleration under the assumption of a plane wave propagation (Daley et al., 2015; SEAFOD, 2018;

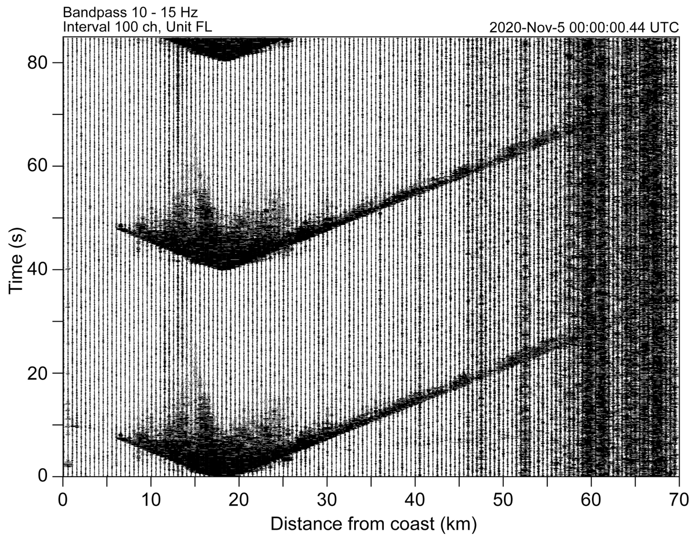

FIGURE 10 | Airgun records by the DAS measurements using the Sanriku cable observation system. The records of every 100 channels are plotted with a bandpass frequency filter. The horizontal axis indicates a distance from the interrogator, and the vertical axis is time. The DAS records have a high S/N ratio up to a distance of 60 km from the coast. Refracted and reflected waves were recognized until approximately 10 km from the seismic source.

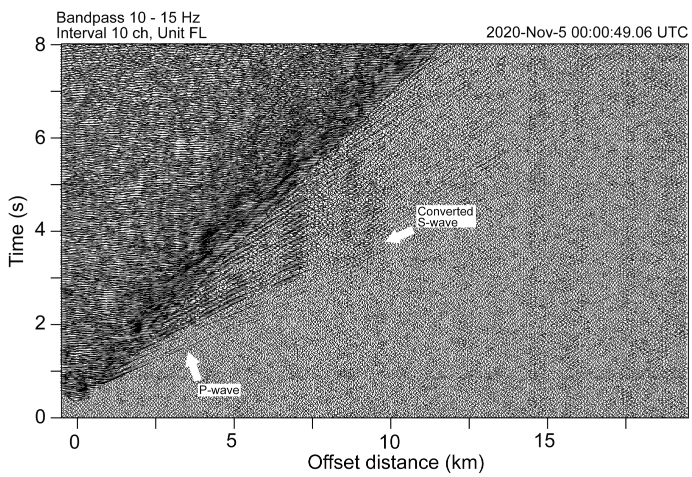

FIGURE 11 | Time–distance profile of the airgun shooting (common shot gather) obtained by a DAS interrogator. To increase the S/N ratio, adjacent 10 traces were averaged, and the bandpass filter was applied. Before the arrivals of the water waves, the arrivals of the refraction waves are clearly seen up to offset distances greater than 10 km. The first arrivals have an apparent velocity of approximately 3.6 km/s. Later arrivals, which were interpreted as converted S-waves, have a larger amplitude than the first arrivals.

Wang et al., 2018). In this case, we adopted an apparent velocity of 2.0 km/s, which is sometimes a representative value for S-waves in the sedimentary layer. To increase the S/N ratio, both records were band-passed with a frequency of 1 to 10 Hz. The transformed DAS records of the channel, which were estimated to be positioned closest to the accelerometer in the SOB3, and the records of the X-component, which were in the parallel direction to the seafloor cable, of the accelerometer in the SOB3 were compared (**Figure 13**). Because the position of the airgun was close to the SOB3 and the DAS records of channel 10265 and records of the accelerometer and DAS were a horizontal component, converted S-wave reflections in the crust were estimated. Both records had similarities, especially in amplitude; however, there were differences. Because the energy of the airgun signal was not large, there is a possibility that the internal noise of the interrogator lessened the similarity. A high dominant frequency of the airgun signal may have affected the similarity as well; however, there is another possibility that

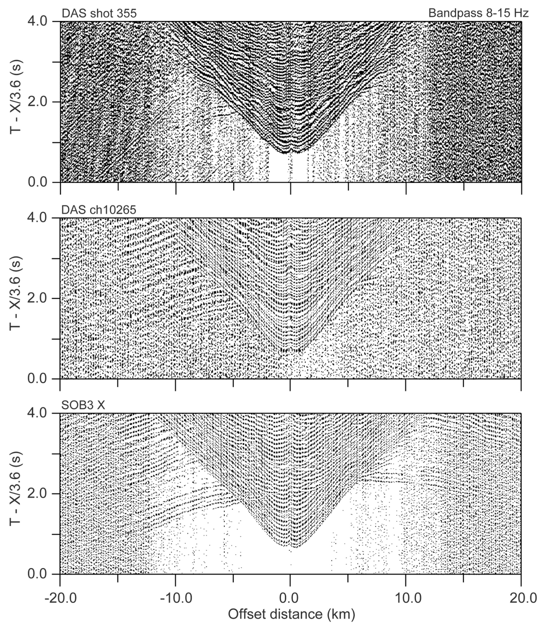

FIGURE 12 | Comparison of time–distance profiles obtained by the accelerometer and DAS. The DAS profiles of both the common shot gather and the common receiver gather are shown. The SOB3 profile is the common receiver gather. The X-component of the records is shown for the accelerometer in the SOB3. The data were bandpass-filtered to increase the S/N ratios. For the DAS profile, the data were displayed every 10 channels, and the adjacent 11 channels were averaged. The positions of the shot number of 355 and a channel of 10265 in the DAS records were estimated to be close to the accelerometer. Although the P-wave arrivals on the DAS records have small amplitudes, both profiles have similar features.

the difference between the records originates from that between the observations of strain and acceleration.

CONCLUSIONS

Distributed acoustic sensing (DAS) measurements that utilize an optical fiber itself as a sensor can be applied for various purposes. An observation of earthquakes using an optical fiber deployed on the seafloor with DAS technology is promising because DAS measurements allow for a dense seismic observation as a long linear array. The spatial resolution of the observation reached a few meters. The length of the array was determined by the measurement range of the DAS interrogator deployed on the optical fiber, and a fine spatial sensor interval was configured. Phase-based DAS measurements with interferometry have become increasingly accurate, and the current state of technology allows for obtaining a high signal quality. Therefore, various sophisticated data analyses can be applied to DAS data; however, we should apply proper data processing because DAS measures strain wave fields, and a DAS measurement is different from conventional seismic measurements using devices based on the pendulum principle. In 1996, a seafloor seismic tsunami observation system using an optical fiber cable was deployed off the coast of Sanriku by the Earthquake Research Institute, the University of Tokyo. The system has six spare (dark) optical fibers that are dispersion-shifted single-mode type and have been incorporated for the future extension of the observation system. We have begun the development of a seafloor seismic observation system utilizing phase-based DAS technology on the Sanriku cable observation system as the next generation of a marine seismic observation system.

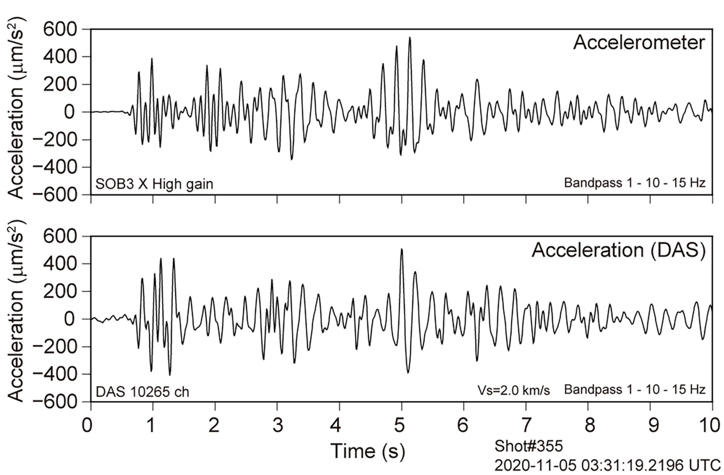

FIGURE 13 | Comparison of the DAS records and SOB3 records for airgun signals (Shot No. 355). The airguns were positioned just above the SOB3. The data from the DAS measurement were converted to acceleration with a wave propagation velocity of 2.0 km/s (lower) to compare the X-component data from the accelerometer (upper). The adjacent 11 channels of the DAS records were averaged. The position of the 10265 channel was estimated to be close to the SOB 3. Both records were filtered from 1 to 10 Hz.

We performed seven DAS measurements using a dark fiber from the Sanriku seafloor observation system for two years beginning in February 2019. A phase-based interrogator was installed in the cable landing station temporarily, and the length of data collection (array aperture) ranged from 5 to 100 km. Different interrogators for the DAS observation were used. Data were recorded with various values of parameters, such as the gauge length, ping rate, and acquisition offset, for the evaluation of the data quality and S/N ratios. The total recording period became approximately 1 month. As a result, many earthquakes including microearthquakes were recorded in each observation period. All earthquakes with magnitudes greater than 1.8 near the cable system were recorded by the DAS system during the first observation. The arrivals of the P- and S-waves of the earthquake with a magnitude of 3 were clearly observed in the time–distance section using the phase data obtained by the DAS measurement. A teleseismic event with an epicentral distance of approximately 2,300 km and a magnitude of 6.6 was clearly captured by the DAS measurement. It seems that the sensitivity and S/N ratio of different interrogators are comparable. Because conventional seismometers are connected to the Sanriku cable system, we compared the records from the DAS measurement and those from the conventional seismometers. The phase data for the DAS measurement can be transformed to particle-acceleration data under the assumption of a plane wave propagation. The acceleration data converted from the phase data from the DAS measurement were consistent with the records of the accelerometer in the cable system. For the evaluation of the noise levels of the DAS measurement, we estimated spectra using the DAS data with distances of 10 and 35 km from the coast after the conversion of the data from phase to strain using the appropriate parameters for each observation. Then, the probability density functions of the power spectra of the strain were estimated. It was found that the noise levels were stable during the observation, and there was little variation in ambient noise. We obtained similar results from the observations using a different interrogator. A DAS measurement can yield observations with a spatially high density over a long range. We also evaluated the spatial variation of ambient seismic noise along the seafloor cable and obtained the spatial variation of ambient noise, which may be related to the generation of microseisms. We compared the spectra estimated from the acceleration data converted from the DAS measurement to that of the accelerometer in the cable system. It was found that the noise levels in acceleration estimated from the records by the phase-based DAS system are comparable to those calculated based on the data from the accelerometer in the cable system.

We carried out a seismic survey using controlled sources and DAS measurements on a seafloor optical fiber cable to determine a structure in November 2020. We shot the controlled seismic sources using a research ship. We used two types of seismic sources: four large airguns with each chamber volume of 1,500 in^3 and two GI-guns with a capacity of 355 in^3. The profiles were laid along the seafloor cable. The profiles had a length of approximately 200 km for the large airgun shooting. The cruising speed was approximately 4.5 knots, and a hydrophone streamer was towed during the shooting. Shot intervals were 40 s for large airguns. During airgun shooting, phase-based DAS measurements were conducted at the landing station of the Sanriku cable system. Because the cable system has six spare fibers, we made observations with two systems of DAS measurements concurrently. Each system used a dedicated fiber and recorded the data independently. The continuous recording was performed with a spatial resolution of 5 m and temporal sampling frequency of 500 Hz. The gauge length was set to 40 m. The total array length was approximately 100 km. The DAS records for the signals from the large-airgun array were evaluated because the large-airgun array released larger energy. The airgun signals were clearly recorded by both DAS systems, including seismic waves penetrating the crust. We obtained equivalent records from both DAS recording systems. It can be concluded that there is little difference between different interrogators and fibers. We compared the time–distance profiles of a common receiver gather from the accelerometer in the SOB3 with a common shot gather and a common receiver gather by the DAS measurement. Although the P-wave arrivals of the DAS records had smaller amplitudes than those of the accelerometer records, both records had the same characteristics, especially for travel times. There was a slight difference between the acceleration records converted from the DAS records and those from the accelerometers. There is a possibility that the observations of strain for a DAS and acceleration for a seismometer caused the difference.

DATA AVAILABILITY STATEMENT

The raw data supporting the conclusions of this article will be made available by the authors, without undue reservation.

AUTHOR CONTRIBUTIONS

MS played a leading role in this study, including the organization of this study, observation, data processing and analysis, and completion of the manuscript. TY, TA, KM, and SS contributed to planning the observation, performing the observation, and interpreting the analyzed results. All authors read and approved the final manuscript.

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ORIGINAL RESEARCH
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InSEA Project: Initiatives in Supporting the Consolidation and Enhancement of the EMSO Infrastructure and Related Activities

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The InSEA project ("Initiatives in Supporting the consolidation and enhancement of the EMSO research infrastructure consortium (ERIC) and related Activities") has the objective, as the full name of the project indicates, to consolidate and strengthen the infrastructures concerning the EMSO ("European Multidisciplinary Seafloor and water column Observatory") ERIC (European Research Infrastructure Consortium) and all those technical-scientific activities related to it. In particular, the project is upgrading localized and distributed marine infrastructures, laboratories, observatories and spatial measurement activities in Southern Italian seas to support those activities of surveys in fixed time series points of observation of EMSO ERIC. The project is developing according to six implementation Objectives of Research (OR) that involve four National research Institutions: INGV, ISPRA, OGS and Anton Dohrn Zoological Station of Naples. The paper illustrates with more details the relevant objectives of the InSEA project and its most significant implementation phases.

Keywords: seafloor observatory, deep sea, smart cable, OBS (ocean bottom seismometer), ocean bottom magnetometer

INTRODUCTION

In the past, the natural phenomena observation on our planet was based primarily on terrestrial monitoring, with both temporal and spatial approaches, i.e. with fixed ground points of observation or spatial temporary networks, or mixed. Until a few years ago, monitoring on the oceans was carried out through discrete measurement campaigns in time and space, largely limited to the sea surface with sporadic exploration of the seabed (Bates et al., 1982). This implied the disadvantage of not having information on the variability of interesting processes in the oceans. Only more recently, since the 90's, technology has allowed the installation of multidisciplinary systems for long periods (years) on the seabed, even at great depths (thousands of meters) (Momma et al., 1996; Butler et al., 2000; Petitt et al., 2002). From the circumscribed campaigns in space and time, we then moved on to the installation of observatories on the seabed, to record in a continuous way the physical, chemical and biological parameters of the seas, of the seabed and rock-water interaction, in order to know the state of the oceans around the planet (Kopf et al., 2012). This kind of seafloor installation is distinct from other temporary marine observational systems. Seafloor observatories intend to preserve most of the characteristics of observatories on land in terms of comparable high standard in resolution and accuracy of the measurements, providing objective and continuous observations of the seabed environment and the corresponding water column (Favali et al., 2015). This extends the observations to the oceans, not only because they are the previously less known and more extensive part of the planet (in fact, the oceans cover seven tenths of the Earth's surface), but also because they represent a fundamental element in the processes that underlie the climate of the Earth, whose knowledge on large time scales allows us to understand their future evolution. The possibilities provided by new technologies have allowed the creation of global and almost contemporary multi-year programs whose aims are the permanent installation and management of multidisciplinary and interdisciplinary systems on the seabed and along the water column. These systems are capable of producing data in real time, being wired through electro-optical cables able to feed and receive data on the ground, *via* optical fibers and, at the same time, command the submarine systems (e.g. Favali et al., 2011). These programs involve many countries: United States of America (OOI-Ocean Observatories Initiative; http://oceanobservatories.org), Canada (ONC-Ocean Networks Canada; http://oceannetworks.ca), Japan (DONET-Dense Oceanfloor Network System for Earthquakes and Tsunamis; http://jamstec.go.jp/donet), China (ECSSOS-East China Sea Seafloor Observation System), Australia (IMOS-Integrated Marine Observation System; http://imos.org.au), Taiwan (MACHO-Marine Cable Hosted Observatory; http://scweb.cwb.gov.tw/macho-web). EMSO (http://www.emso.eu) is the European response to these initiatives, which is in close collaboration also through joint projects. The common motto to all these programs is: "Observing the Ocean to Save the Earth", to underline the importance of studying the oceans using time series of data and to understand more and more the fundamental role in regulating the terrestrial processes that determine the current state and the future of the planet.

In the following sections, we will describe the European context in which InSEA ("Initiatives in Supporting the consolidation and enhancement of the EMSO research infrastructure consortium (ERIC) and related Activities") Project has been undertaking, together with the details of its main objectives and the planned activities. Then, we will conclude with the post-project scenario, the expected results, in terms of innovation and internationality, a final discussion and some conclusions.

EUROPEAN MULTIDISCIPLINARY SEAFLOOR AND WATER COLUMN OBSERVATORY

EMSO is a European Research Infrastructure (RI) that aims to explore the oceans, to better understand the phenomena occurring within and below them and to explain the fundamental role that these phenomena play in the wider and more complex terrestrial systems. EMSO is an infrastructure distributed in the seas around Europe and consists of a system of nodes, located in key marine areas in order to understand the phenomena occurring at sea from the Arctic to the Atlantic, through the Mediterranean, up to the Black Sea (**Figure 1**). The Observatories are multidisciplinary platforms positioned along the water column and on the seabed. They constantly measure multiple biogeochemical and physical parameters in long time series for the study of climate changes, marine ecosystems and natural hazards and their mitigation. EMSO ERIC coordinates the access to the facilities of its interconnected network of seafloor observations and supports the management of data streams from EMSO observatories.

EMSO has solid historical bases on previous scientific and technological enterprises, such as GEOSTAR (e.g. Beranzoli et al., 2000; Favali et al., 2002; De Santis et al., 2006; Gasparoni et al., 2015) and ORION – Ocean Research by Integrated Observatory Networks- (e.g. Beranzoli et al., 2009; Favali et al., 2011) European Projects and the national project MABEL (e.g. Calcara et al., 2001). Important results have been obtained during the developments of these mentioned projects, such as the monitoring and study of the Marsili seamount (e.g. Favali et al., 2011; Italiano et al., 2014; Giovanetti et al., 2016), understanding the geolectrical conductivity under some exploring sites of Southern Tyrrhenian Sea (Di Mauro et al., 2006; Vitale et al., 2009), designing an original tsunami early warning system (Chierici et al., 2012), showing the importance of a multiparameteric geophysical, environmental and oceanographic monitoring (e.g. Monna et al., 2014), to mention just some of the found results.

EMSO offers data and services to a broad and diverse user group, from scientists and industries, to institutions and policy makers. It is a fundamental infrastructure to provide relevant information about the definition of environmental policies based on scientific data. EMSO shares scientific structures (data, tools, computing and archiving capacity) in a common European strategic framework. EMSO directly participates in European projects, and research networks, where it shares its available facilities and gained experience: e.g. DOORS ('Developing Optimal and Open Research Support'), led by GeoEcoMar from Romania, MINKE, coordinated by the Institut de Ciències del Mar (ICM) in Barcelona, and other initiatives, such as ENVRI-FAIR, EurofleetsPlus, ERIC Forum, ENRIITC (http://emso.eu/projects/). Many other European past and present initiatives (e.g. Jerico – Towards a Joint European research infrastructure network for coastal observatories; Fix03 (Fixed point Open Ocean Observatory) enlarge EMSO cooperation to include the Eurosites/Oceansites mooring lines and the networks established to measure carbon dioxide at sea from the ICOS (Integrated Carbon Observation System) programme.

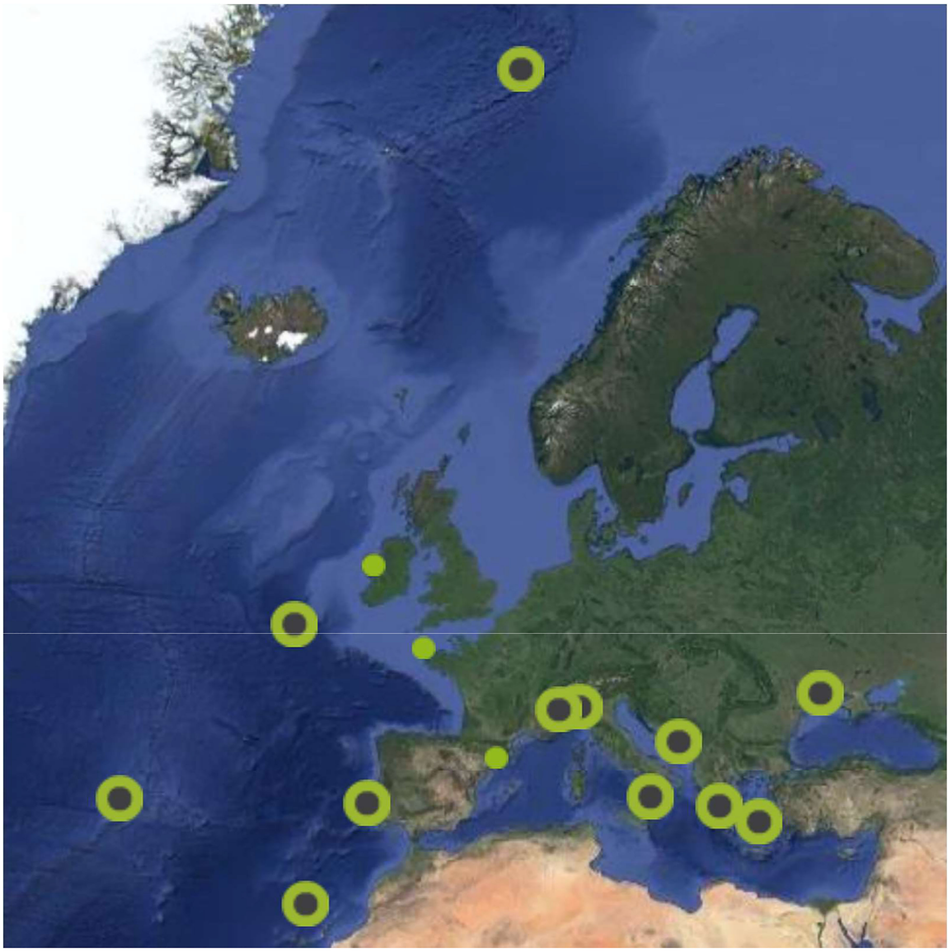

FIGURE 1 | EMSO includes 15 Regional Facilities, among which 3 (the smaller circles) are test sites.

EMSO is an infrastructure declared Landmark (i.e. it has been included among the pan-European research infrastructures considered successful) in the latest Roadmap of ESFRI (European Strategy Forum on Research Infrastructures), published in March 2016. In addition, EMSO has become an ERIC (European Research Infrastructure Consortium) since October 2016, i.e. an international legal entity, a legal framework created for pan-European research infrastructures. EMSO ERIC is currently supported by 9 countries (Italy, France, United Kingdom, Spain, Portugal, Ireland, Greece, Romania and Norway) with Italy hosting the registered office. Each country is represented by one or more Representing Entities, and the Istituto Nazionale di Geofisica e Vulcanologia (INGV) plays this role for Italy. In addition, INGV is the coordinator of the Joint Research Unit (JRU) EMSO-Italy, where is also participating all the research bodies (CNR, INFN, OGS, SZN, ENEA, ISPRA, Istituto Idrografico) and universities, through the CONISMA consortium (35 universities involved in marine science), interested in the scientific purposes of EMSO. The JRU aims to aggregate and enhance the Italian community and its role within the pan-European research infrastructure. Finally, EMSO is usefully inserted in the PNIR (National Plan of Research Infrastructures) within the European research infrastructures of interest for Italy, with all the necessary characteristics for its inclusion: scientific, technological and managerial quality; added value at European level; high level connected services; free transnational access on a competitive basis (peer review); results available in open form (open access).

In the seas surrounding Italy, EMSO has three permanent observing sites: one in the Western Ionian Sea (eastern Sicily), one in Adriatic Sea and the other one in the Ligurian Sea. The site in the Western Ionian Sea holds two privileged points of submarine measurement and observation, the first one offshore Catania and the second one offshore of Capo Passero, on the site of Portopalo. Other points have been indicated in the Tyrrhenian (Campania) and Adriatic (Puglia) as pilot sites for multiparametric monitoring. All sites within the Program areas, i.e. those MS (" *Meno Sviluppate* – Less Developed) and in transition (TR) are being consolidated and enhanced by the current InSEA project.

INSEA PROJECT

The InSEA project has been funded by the Italian Ministry of University and Research for the years 2019-2022 as part of the Research and Innovation PON ("Programma Operativo Nazionale" - National Operational Program). The project involves four National research Institutions, i.e. INGV, ISPRA, OGS and Anton Dohrn Zoological Station of Naples.

According to the extended title of the InSEA project, its main goal is to launch initiatives to support the consolidation and enhancement of EMSO's infrastructures and its activities, which are positioned in the Italian territory and surrounding seas, with particular interest in the MS (from the Italian "*Meno Sviluppate*" meaning "Less Developed") regions (Campania, Calabria, Puglia and Sicily) or in transition TR (Abruzzo and Molise).

The final scientific objective of the project is to improve the ability of the RI to record the geophysical and environmental processes of the marine environment in the seas of the MS/TR areas of the national territory, in order to monitor the state of the seas due to climatic changes or anthropogenic effects and natural hazards.

The project is developed according to six Objectives of Realization/Research (OR) that contribute to the achievement of the final objective (**Figure 2**). They consist in the upgrading of localized (OR1, OR2, OR6) and distributed (OR3, OR4) marine infrastructures, laboratories and observatories (OR4) and spatial measurement activities to support those activities of surveys in fixed time series points (OR7). INGV, OGS, ISPRA and SZN, partners in the JRU of EMSO-ERIC, participate in these activities. At the proposal stage, seven ORs were proposed, but six were finally accepted and funded (the OR5-Integrated Laboratories initially included in the proposal was not finally included in the project). However, we preferred to maintain the original numeration of the ORs.

The whole project, because of its complexity, requires both scientific and administrative coordinations (**Figure 2**), that act in synergy for solving all scientific (e.g., selection of the best equipment for each specific scientific goal) and administrative (e.g. purchase tenders, link with the funding Ministry, etc.) questions.

The close interconnection of the various OR and their products will represent a leap forward in the capabilities of the entire RI to acquire important scientific data to take advantage of advanced and excellence research in the fields of geophysics, geology, geochemistry, volcanology, oceanography and biology. Each OR covers an important aspect of the EMSO RI to be improved and extended (**Figure 3**).

AIM OF THE PROJECT

The InSEA project aims to increase at national level the network of marine observation and monitoring systems in accordance with EMSO-ERIC. The project will be aimed to reinforce already existing nodes of infrastructures integrated to a highly specialized and multidisciplinary laboratory network, dedicated to the study of a wide range of disciplines for the understanding of phenomena in the marine environment. The project may provide services (e.g. monitoring of sites of industrial interest in the marine environment, studies of human activities on marine biodiversity commissioned by public administrations) and propose highly specialized products (e.g. data from integrated sensor networks, or new sensors for specific applications).

InSEA is structured in different components with technological features that define the products that can be obtained and the services that can be delivered. In fact, it is composed of:

- *Fixed observational infrastructures:* a series of permanent structures that include measuring instruments distributed

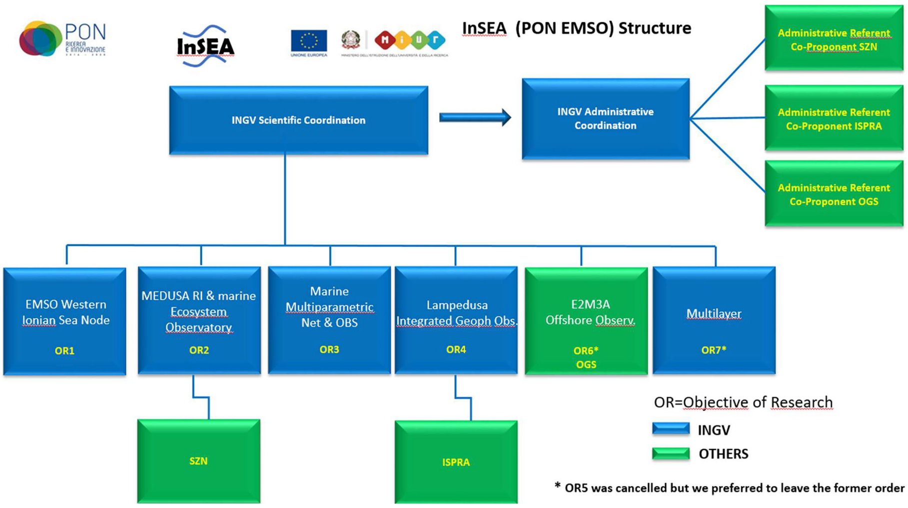

FIGURE 2 | InSEA Project structure and Institutions' roles. The Project for its complexity requires scientific and administrative coordination.

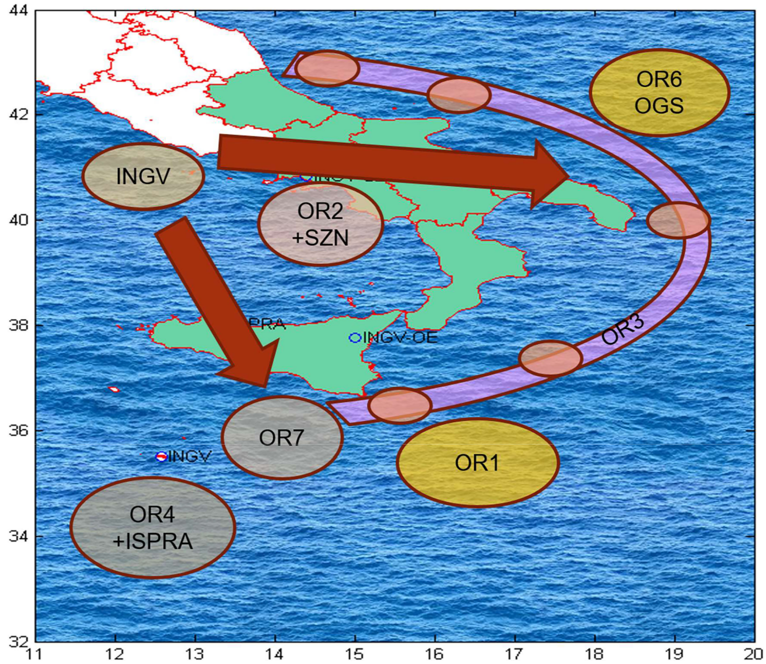

FIGURE 3 | Scheme of the ORs with their main locations and interactions.

on the seabed and along the water column that continuously acquire time series of geophysical and oceanographic data; using electro-optical cables that extend on the bottom, the instruments are powered from the ground and send the acquired measurements in real time.

- *Relocable systems:* they are mobile structures composed of marine monitoring modules, mono- and multi-disciplinary, repositionable, to be used for specific experiments in areas of interest, boats with tools for periodic monitoring, mobile laboratories hosted in containers.
- *Support infrastructures:* they include equipment and instruments placed in ground laboratories and observatories to support marine operations and are necessary for the optimal management and maintenance of the wired network, as well as the management and use of relocatable infrastructures, and for the execution of research and specific services.

The project involves the enhancement of the infrastructures for research in the marine environment located in the MS Regions of Sicily, Calabria, Campania and Puglia and in the TR Regions of Abruzzo and Molise, for which the sea is a primary resource that creates development opportunities. The InSEA project is the Italian contribution to the consolidation in the above-mentioned regions of the European research infrastructure EMSO ERIC coordinated by Italy, which goes in synergy with other ERIC research infrastructures or in any case included in the latest Roadmap ESFRI published (2016).

The planned actions will be performed according to the following objectives:

1) to enhance the marine infrastructures and scientific and technological installations also on the ground to consolidate and expand the network for multidisciplinary monitoring of the coastal and deep marine environment and of the water column;

2) to establish of a mobile intervention system to be used for monitoring surveys in sites of strategic interest or in case of environmental emergencies;

3) to network all existing infrastructures and upgrade for real-time/near-real-time transmission, integrating the measurements of fixed and relocatable observing systems.

The number of researchers that are involved in the project was determined based on the number of researchers and technologists present in the various operating units involved in the project, including the co-proponents as well as the main proponent. Furthermore, the upgrading involves all the technical-scientific impact of the widespread infrastructure. In fact, given the relevance and excellence of the initiative, it is reasonable to expect that specialists from at least the member countries of ERIC, if not extra-European, require sharing infrastructure resources for new studies on an international scale.

The total space where the Project is established corresponds to the sum of the surfaces of the centers, laboratories and places used to host the equipment to be upgraded. The marine and submarine areas affected by the deployment of the infrastructure are not easy to estimate, however they include: South Adriatic, Gulfs of Naples and Pozzuoli, Lampedusa Island and surrounding sea, Portopalo, Catania Harbour, marine area of Eastern Sicily, off-shore Molise, offshore Puglia, offshore Calabria, offshore Southern Sicily (Sicily Channel).

Next, the most relevant resources for OR and how these will affect the existing RI are presented.

OR1 WESTERN IONIAN EMSO NODE

This OR intends to strengthen the EMSO infrastructure in order to guarantee scientific services or the continuous production of high-quality multidisciplinary data and access to them. Within InSEA, for the consolidation and reinforcing of the EMSO sites in Catania and Portopalo in Sicily, the OR1 is performing the following actions:

- Four new multidisciplinary platforms named CALIPSO, DIONE, TETI and DORIDE are being developed to be deployed at the two sites of Western Ionian Sea Facility. The platforms will host geophysical, oceanographical and environmental instruments and data acquisition will be acquired real time at the shore facilities at Catania and Capo Passero where a new EMSO Data Center will be installed. Typical data will be pressure, temperature and conductivity, together with seismic, magnetic and gravity signal variations. As the other acquired data within InSEA project, the data will be available through the EMSO data portal. The observatories will be connected to INGV Junction Boxes *via* ROV-operable connectors to the main electro-optical submarine cables already in place in Catania and Portopalo. All sensors follow the philosophy based on the use of EMSO Generic Instrument Modules (EGIMs). EGIM provides accurate, consistent, comparable, long-terms measurements of ocean parameters, which are key to addressing interoperability of EMSO nodes and the common collection of ocean essential variable time series (for more details, see emsodev.eu). Data from the two sites will be made available to the science community and automatically analysed for geophysical event detection. Seismological and tsunami data will be also available to the National Earthquakes Monitoring Observatory at INGV headquarter in Rome.
- At the Catania Junction Box the InSEA SMART (Scientific Monitoring And Reliable Telecommunications) cable will also be connected. In 2012 a Joint Task Force was established between the International Telecommunication Union (ITU), the Intergovernmental Oceanographic Commission of the United Nations Educational, the Scientific and Cultural Organization (UNESCO/IOC) and the World Meteorological Organization (WMO) to address the technical, commercial and legal aspects in adding scientific instrumentation to commercial telecommunications cable systems (Howe et al., 2019). The project involves the integration of a minimum set of sensors (temperature, pressure, accelerometer) in commercial telecommunications cables using the same type of repeater housing. The Western Ionian Sea Facility will host the first wet demo SMART cable consisting of about 19 km longtelecommunication cable with sensors integrated into the housing of three commercial standard repeaters. The housings will include a temperature sensor, an absolute pressure gauge, a force balance accelerometer and a broadband seismometer (**Figure 4**). *In situ* pressure and seismic measurements are needed to generate reliable tsunami height forecasts in Ionian Sea and data coming from SMART cable could improve tsunami warnings based on land seismic data.

OR2- MEDUSA AND MARINE ECOSYSTEM OBSERVATORY RI

Campi Flegrei is a volcanic caldera located west of Naples in the South of Italy that is continuously monitored by the INGV. The complex contains numerous phreatic tuff rings and pyroclastic cones and has been active for the past 39,000 years. This area is known for repeated cycles of significant slow uplift followed by subsidence. Although long-term changes in deformation do not necessarily culminate in eruption, the most recent eruption in 1538 was preceded by rapid uplift, demonstrating the importance of surface deformation as a monitoring tool. Since 1969 the caldera has had significant episodes of uplift with more than 3 m of cumulative uplift measured in the city of Pozzuoli in the period 1970–1984. After 1984 the area subsided but was interrupted by small episodes with uplift on the order of a few centimeters. The subsidence phase stopped in 2005 when a new general uplift phase began. In 2011, Campi Flegrei was subject to

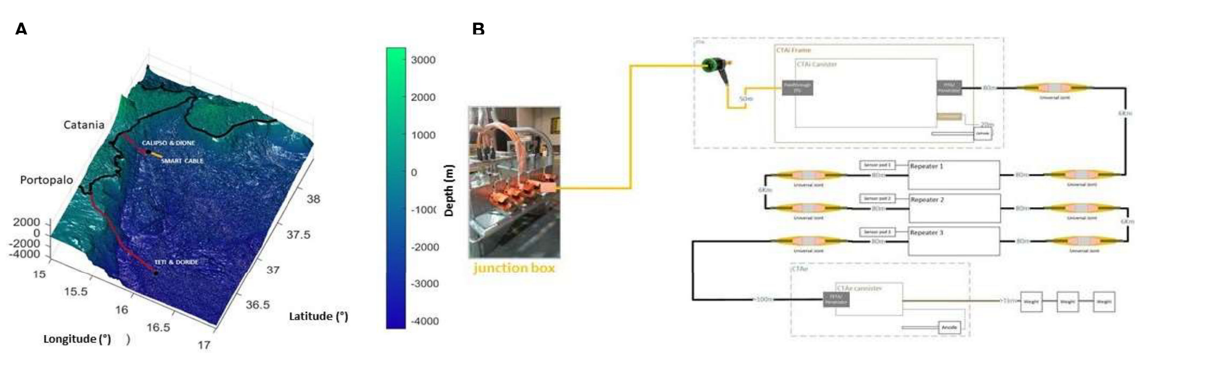

FIGURE 4 | **(A)** Western Ionian Sea map where the new four seafloor platforms and the SMART cable are indicated; **(B)** Scheme of the SMART cable connected to the junction box offshore Catania site.

an acceleration of the uplift trend that was recorded by the on-land geodetic network with a maximum value of approximately 4 cm, as measured at Pozzuoli GPS station over the whole year. At the time of submission of this paper, the uplift has reached a cumulative vertical displacement of about 36 cm. However, the center of the caldera (and presumably the area of maximum uplift) is located offshore.

For all these reasons and with the aim to fill the information gap, previously based only on observations made through the dense multi-parametric network located on the mainland, in 2016 the MEDUSA infrastructure was born in order to monitor, in real time and in shallow water environment, the deformation of the submerged part of the Campi Flegrei's caldera.

This OR will improve the capability of the geodetic/acoustic/oceanographic monitoring of the Pozzuoli – Campi Flegrei and Naples Gulfs.

For the site in the Gulf of Pozzuoli – Campi Flegrei (INGV):

- Assets for upgrading the MEDUSA (Multi-parametric Elastic-beacon Devices and Underwater Sensors Acquisition system) out of water infrastructure (EMERGED-Top)
- Resources for expansion and upgrading of the CUMAS multi-parametric submarine module, (EMERGED-Bottom).

MEDUSA is a multi-parametric permanent marine monitoring and research infrastructure based on instrumented geodetic buoys operating in the Gulf of Pozzuoli (close to Naples, Italy) within the local surveillance system of the Campi Flegrei volcanic caldera (**Figure 5**).

MEDUSA is a complex research infrastructure consisting of four buoys equipped with multi-parametric submarine observatories (wired with as many surface buoys), consisting of geophysical and oceanographic instrumentation, and continuous real time data acquisition/transmission to the Monitoring Center of INGV in Naples (Vesuvius Observatory), where data are integrated to those acquired by the land networks.

The four buoys, of the elastic-beacon type, are positioned on variable depths less than 100m at a distance of about one mile from the coastline. The submarine modules are laid on the sea-bottom and equipped with scientific and control instruments. A geodetic GPS receiver is installed on each turret to measure ground movements at the seabed (Chierici et al., 2016).

MEDUSA is a sophisticated infrastructure for monitoring at sea the volcanic activity of Campi Flegrei, realized as completion of the geophysical instrumentation networks existing on the mainland and managed by the INGV, Vesuvius Observatory (De Martino et al., 2020; Iannaccone et al., 2018). With the economic resources deriving from the InSEA project, the external mechanical parts of each buoy were redesigned, and the external instrumental park and the submarine observatory of one of them were upgraded (**Figures 6**, **7**).

MEDUSA mainly monitors the local seismicity and the seafloor ground movements in the volcanic area of Campi Flegrei's caldera with geophysical and oceanographic sensors.

The MEDUSA infrastructure extends the geophysical monitoring system of Campi Flegrei, in the Gulf of Pozzuoli. Through the use of this infrastructure it is possible to improve the definition of the area of deformation of the area by means of continuous measurements of ground movements on the seafloor (geodetic measurements at sea by analyzing the vertical and horizontal components of the GPS receiver, in conjunction with data analysis of precision pressure sensors installed on the seafloor). More information about MEDUSA infrastructure can be found on the web portal http://portale.ov.ingv./medusa.

For the site in the Gulf of Naples (SZN) (**Figure 8**):

- Mooring not wired in stand-alone mode
- Infrastructure at the bottom (seabed platform) connected to a surface buoy

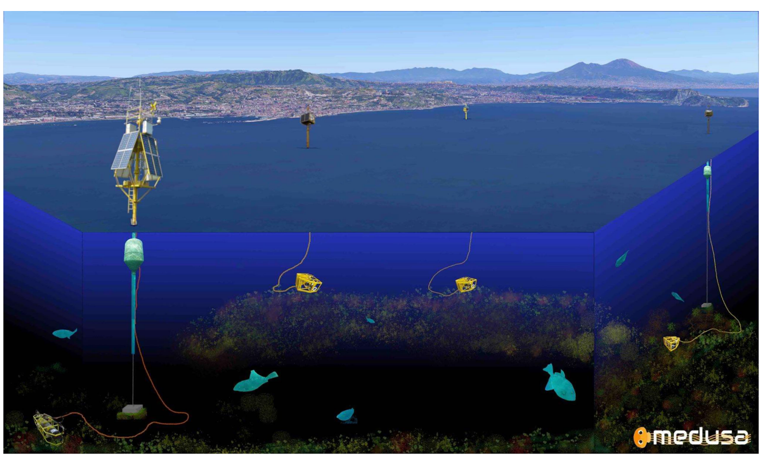

FIGURE 5 | A mixed image-representation view of the MEDUSA's marine research and monitoring infrastructure (Campi Flegrei volcanic area).

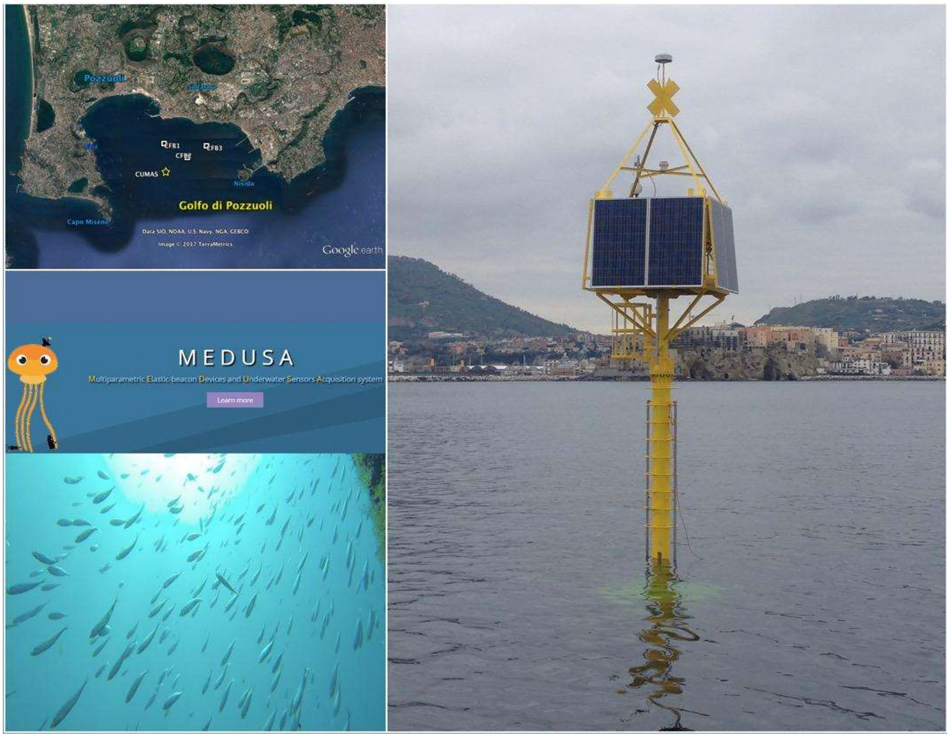

FIGURE 6 | From top-left: the geographical volcanic area where MEDUSA lives; the emerging part of a buoy; an image provided by a submerged HD-camera.

The infrastructure will have the purpose of monitoring geophysical and oceanographic processes in the Gulf of Naples that affect biodiversity near the bottom and in the water column.

The Gulf of Naples is a particularly interesting area from the volcanological (Campi Flegrei), oceanographic and bio-ecological points of view, due to the presence of the Dohrn Canyon, site of upwelling processes.

OR3- MARINE MULTIPARAMETER NETWORK AND OBS

This OR intends to i) increase the equipment for seafloor seismic monitoring (Ocean–Bottom seismometers: OBS) and ii) extend the seismic and geophysical network to the Adriatic and Ionian Sea, by deploying new monitoring nodes within the safety areas

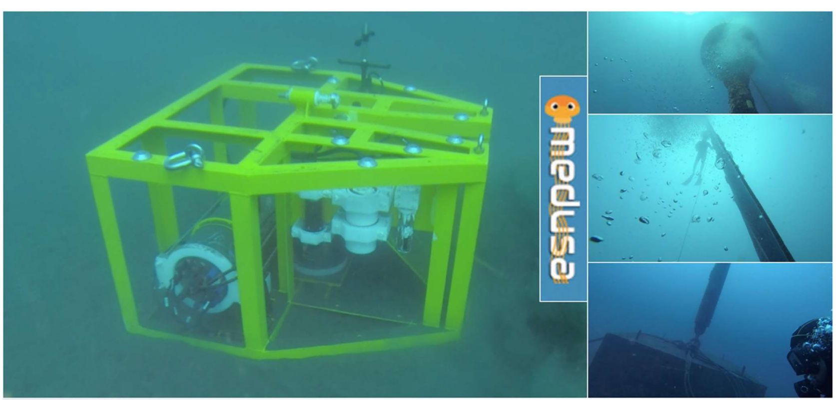

FIGURE 7 | From left to right, top to down: the seafloor multi-instrumented observatory; the underwater view of the floating from the bottom by an UHD submerged camera; a diving operator who performs an inspection on the electro-mechanical cable that ensures the connection of the seafloor observatory to the top of buoy (for the power-supply, Ethernet link and the GPS communication for the time-marking of the data acquired); the buoy ballast on the seabed (see also Xie et al., 2019).

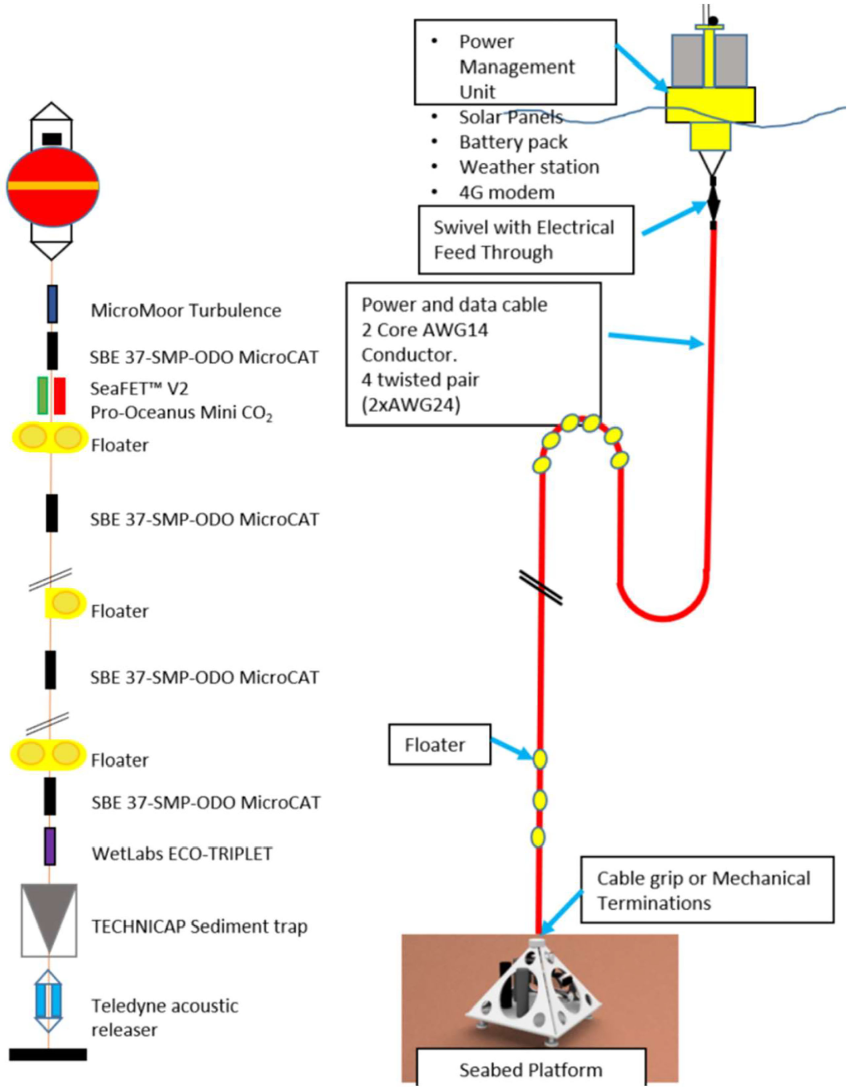

FIGURE 8 | Left: Naples Ecological Research-Fixed seabed Observatory (NEREA-Fix); Right: Seabed platform connected with a surface buoy.

of 5 oil platforms. The final aim will be to extend EMSO multi-parameter monitoring activities in MS and TR areas, with relocatable (BB-OBS) and fixed systems. The following resources and pieces of equipment will be acquired:

- 7 submarine multi-parameter modules (MSM) with trawl resistant shape, 5 of which will be installed and 2 will be used as spare units; the latter will allow to replace the operating ones at scheduled deadlines, for cleaning and calibrating the sensors, in order to guarantee continuity of operation and data flow
- 8 Broad Band Ocean Bottom Seismometers (BB-OBS/BB-OBS TR) with trawl resistant shape
- Laboratory equipment for maintenance and remote control of the marine equipment

Each MSM includes a submarine module (deployed on the seafloor about 200-300 m away from the platform) connected by an electromechanical cable to a surface module on the platform (**Figure 9**); the latter monitors the marine instruments and transfers the data collected from the seafloor to the monitoring centres at INGV.

The submarine module will have the following multi-parameter instrumentation:

- VBB Ocean Bottom Seismometer (120 sec - 100 Hz)
- Multiparameter Probe (O2 and Turbidity)
- Paroscientific Absolute pressure sensor
- Hydrophone
- CTD
- ADCP

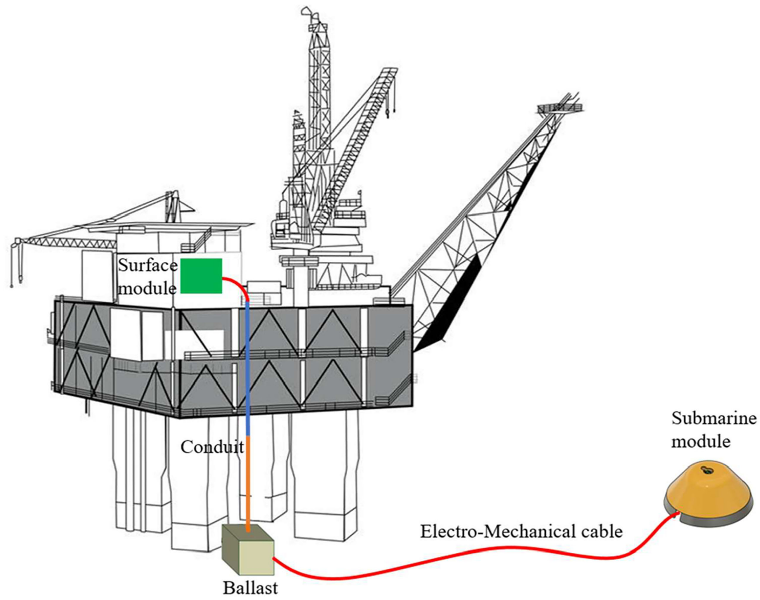

FIGURE 9 | Schematic of an oil platform instrumented with MSM.

The total weight of the submarine module in seawater will be about 160 kgf, sufficient to make the module penetrate several centimetres in the seabed to obtain a good coupling of the seismic sensor with the bottom and to guarantee a good resistance to trawling.

The Electro-Mechanical cable coming from the platform will have the following functions:

- Connect the submarine module to the 48 VDC power supply on the surface;
- Provide data links to the surface for all submarine instruments by means of an Ethernet extender device
- Carry the GNSS data for the digitizer *via* RS422 serial link;
- Act as a recovery element for the maintenance phases of the submarine module

The surface module on the platform includes a fanless PC with two Ethernet ports: one connected to the platform network and the other one connected to the submarine module, by means of a couple of Ethernet extenders and the electromechanical cable. Acquired data travel across a radio link up to a land station, run by the oil company. Finally, data reach INGV monitoring centers thanks to a Virtual Private Network (VPN).

OR4 - LAMPEDUSA INTEGRATED GEOPHYSICAL OBSERVATORY

This OR will perform the following activities: i) Enhancement of the instruments in use at Lampedusa Island Observatory (INGV; **Figure 10**); ii) and acquisition of equipment for improving the instrumentation of M/V Lighea and Perseo ROV (ISPRA; **Figure 11**). In particular, OR4 will acquire the following equipment:

- Magnetometers, solar compass and magnetotelluric station for the geomagnetic station
- No. 3 complete systems of Ocean Bottom Magnetometer (OBM)
- instrumentation for oceanographic boat and ROV Perseo (ISPRA)
- n.1 Kongsberg EM 2040 Compact Multibeam Echosounder Systems (ISPRA)
- n.1 Kongsberg PAP 200 series USBL systems (ISPRA)
- n.1 complete Digisonde

Therefore, this OR will enhance the Integrated Geophysical Observatory of Lampedusa for the improvement of the calibrations of marine magnetic measurements in the sites offshore Catania and Portopalo, and the use of ionospheric radio transmissions for both ship and buoy operations. The completed and integrated stations will also be the key points of integrated geophysical observation at the southernmost part of Europe (Di Mauro et al., 2021). It will then also reinforce the instrumental equipment of the M/V Lighea and the ROV Perseo (ISPRA).

OR6-E2M3A OFFSHORE OBSERVATORY

The main objective of this OR is the strengthening and development of the E2M3A offshore observatory, (Eastern Mediterranean 2 Multidisciplinary Mooring Array) as a contribution to the EMSO-ERIC infrastructure (**Figure 12**).

FIGURE 10 | Lampedusa Island Geophysical Observatory. The stone hut, due to its non-magnetic properties, is dedicated to absolute magnetic measurements, while the two fences protect the buried geophysical sensors.

The E2M3A observatory is part of the Southern Adriatic Regional facility of EMSO-ERIC (Cardin et al., 2016). Oceanographically, it is positioned in the centre of the cyclonic gyre where deep convection processes take place, involving both the atmosphere and the ocean dynamics forming new dense and oxygenated waters. The Southern Adriatic Interdisciplinary Laboratory for Oceanographic Research is particularly devoted towards studies for characterizing the long-term changes of the Adriatic Sea in response to local climatic forcing (Querin et al., 2016).

By implementing sensors, the OR will improve the quality and efficiency of transmission and display in near real-time and delayed observations of key (essential) variables relevant for monitoring environmental processes, natural hazards, climate change, and offshore marine ecosystems. All the information will be useful for navigation, fishing, and tourism information on water quality, with great contributions for monitoring climate change.

In particular, it will acquire the following equipment:

- Buoy hull and acoustic releases for structural purposes of E2M3A and safety
- Meteorological station
- Instrumentation for the increase and diversification of biogeochemical measurements

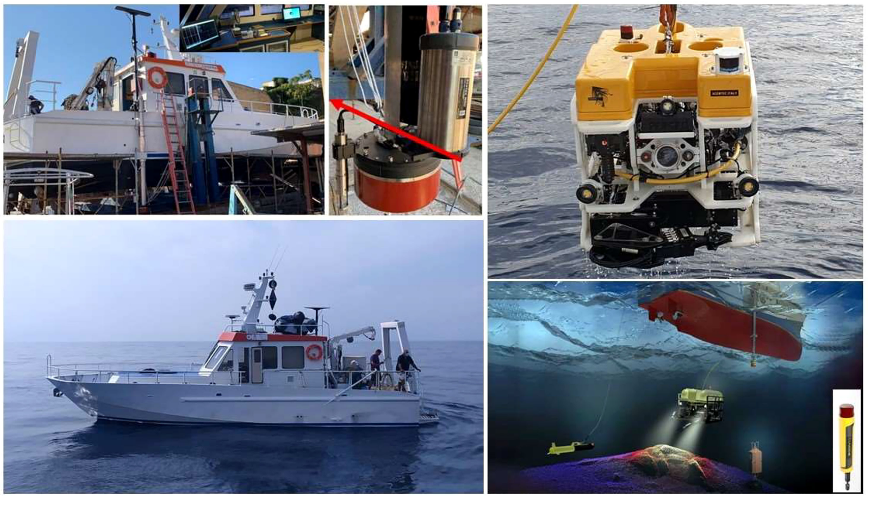

FIGURE 11 | M/V Lighea equipped with Kongsberg EM 2040 Compact Multibeam Echosounder Systems (MBES). ROV Perseo equipped with Kongsberg PAP 200 series USBL systems.

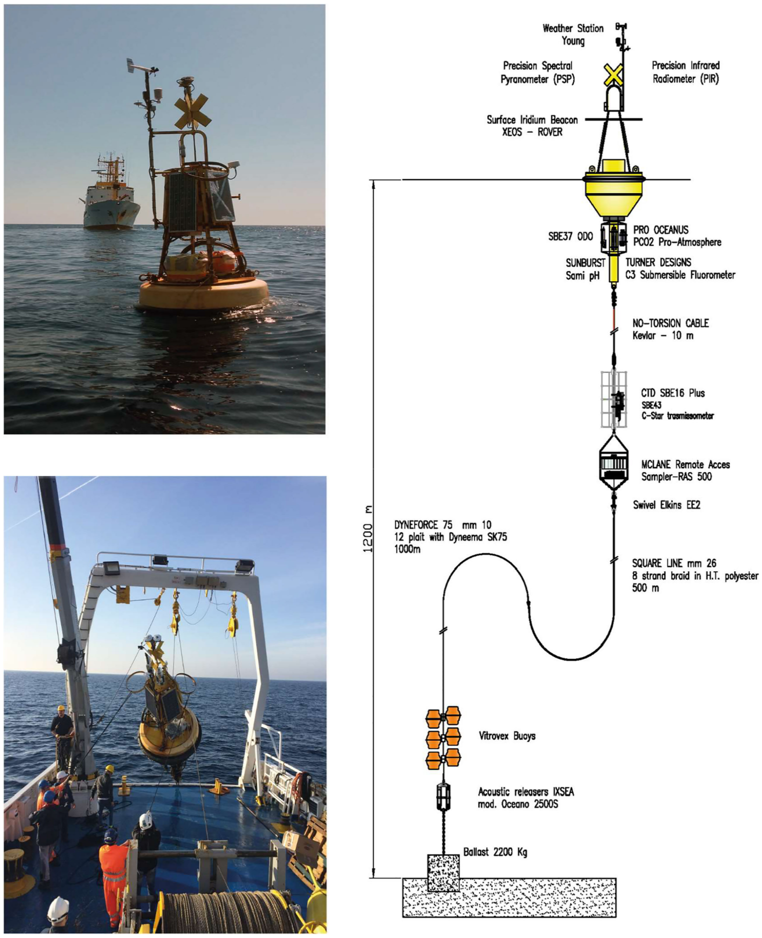

FIGURE 12 | Air-Sea Interaction, water column physics and biogeochemistry measurements carried out by the main mooring hosting the surface buoy at the E2M3A observatory.

- Acoustic profilers for spot current measurements along the water column

OR7 MULTILAYER

This OR will perform a distributed enhancement of the whole southern Italy infrastructure at different observational levels (from bottom to up, i.e. from submarine AUV to aerial vehicles). It will give particular attention to potential (magnetic and gravity) field observations. Therefore, in short words, it will enhance the RI in the sites offshore Catania and Portopalo (Sicily) from aircraft and marine AUV.

Equipment that will be acquired is (see also **Figure 13**):

- Innovative systems for the observation of geophysical/ environmental parameters airborne applications
- Completion/integration provision for the AUV

The implementation scenarios are diversified but integrated with each other. Tenders and acquisitions will be carried out for the acquisition of assets, their validation and implementation. Many of the assets will be installed at the location sites, that is, on seabed or in laboratories functional to the EMSO research activities.

Particular attention in modulating the tenders and purchases will be essential to better match the various subsequent activities, giving priority to those at sea, due to the obvious difficulties of these operations. The experience and skills of the involved operational units, however, put the possible level of criticality to the minimum.

POST-PROJECT SCENARIO

At the end of the InSEA three-year project, the RI EMSO will enrich through the OR1, the instrumental equipment of the submarine infrastructures in Catania and Portopalo sites, together with the deposition of a SMART cable, as a single pilot test for the monitoring of the climatic parameters and of possible tsunamic events. The MEDUSA network for the research in marine environment in the Gulf of Pozzuoli will be enhanced by

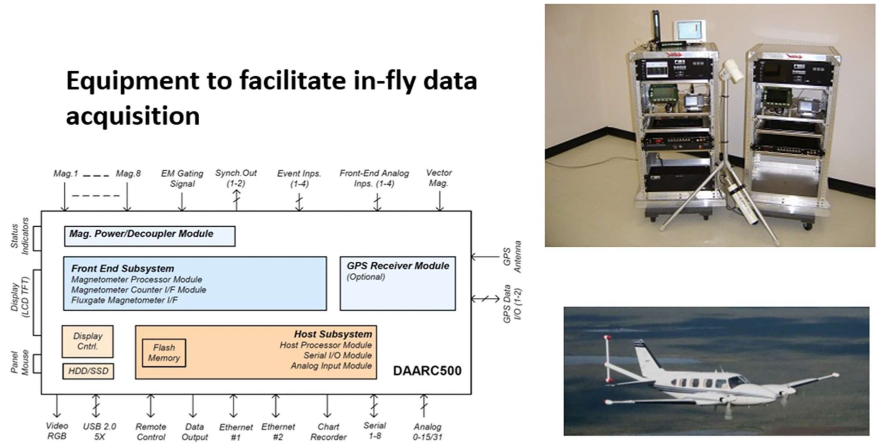

FIGURE 13 | Equipment to facilitate in-fly data acquisition for potential field studies: on the left, the scheme of the various component of the system (DAARC 500); on the right top, the system under calibration in the laboratory; on the right bottom, the airplane used for the scientific survey in operational configuration.

updating the surface area and renewing one of the seabed sites (CUMAS) according to the provisions of OR2. In the same context, the monitoring area of the geophysical and oceanographic processes that affect the biodiversity of the megafauna near the bottom and in the water column in the Gulf of Naples will also be extended. The OR3 will allow the installation of a multiparameter observation network at the hydrocarbon extraction platforms located in the MS and TR areas, expanding and extending at sea the effectiveness of the ground network, geophysics in general, and seismic in particular. The same OR will increase the number of releasable broadband OBS systems useful for geophysical research surveys in Italian seas, in particular at Western Ionian. Another important aspect, produced by OR4, will be linked to the upgrading of the Lampedusa integrated geophysical Observatory, in its geomagnetic and ionospheric functions, with an expansion of the repositionable OBM modules set that will extend the knowledge of the relations of magnetic, ionospheric and marine chemical-physical parameters with natural phenomena such as earthquakes and volcanic activity. Consequently, the magnetic research capacity on seabeds of precursors of tsunamis and seismic events increases. The same OR will enrich the instruments of the M/V Lighea and the ISPRA ROV. The OR6 enhances the site on the seabed in the southern Adriatic with innovative equipment, multiplying the quality of the observational characteristics. The OR7 will make available instrumental equipment for aircraft and AUV, very useful to expand the observational possibilities of submarine sites by extending the knowledge of the physical-chemical parameters of the marine environment into the spatial domain.

EXPECTED RESULTS, INNOVATION AND INTERNATIONALITY

The consolidation and enhancement of RI EMSO on the basis of the activities guaranteed with the purchase of assets within InSEA will make the observational submarine network more efficient, placing it at the cutting-edge level in the European scenario. Furthermore, it will improve the geophysical, oceanographic and climate knowledge of the planet, thanks to continuous and timely observation over long time series at submarine observatories and others. EMSO pursues the long-term objective to be part of the upcoming European Ocean Observing System (EOOS). The latter is expected to integrate multiple platforms and data systems, comprising other ERICs, to achieve the first sustained, standardized and permanent marine observatory network of Europe. InSEA, together with other initiatives of EMSO, i.e. EMSO-Link (http://emso.eu/emso-link/) will facilitate the coordination of EMSO infrastructure as well as reinforce and expand the EMSO ERIC membership to optimize the inclusion of the whole European Marine technology and research institutions. The synergy between INGV and the other research institutes of InSEA (specifically, ISPRA, OGS and SZN) will enable us to achieve excellence in the field of marine observations, by diversifying its effects into new application domains, such as the mitigation of natural and climatic risks, safety in the seas, the interoperability of different instruments placed in sites of scientific and productive interest. The band of multidisciplinary skills and the integration of geophysical, geological, volcanological, oceanographic, climatological and biological knowledge are aspects that ensure the full technical/scientific ability to achieve borderline knowledge.

Important efforts will be given to the offered data and services. Data and metadata will be in accordance with those of INGV and other public research institutes (e.g. seismic data as EIDA-European Integrated Data Archive- format, magnetic data as INTERMAGNET standard). There will be complete possibility to virtual access to some validated data and metadata (e.g. seismic data from marine platforms and smart cable; magnetic data from Lampedusa Geophysical Observatory; geophysical and environmental data from Naples, Pozzuoli and E2M3A) with complete integration with the MOIST (Multidisciplinary Oceanic Information System) platform which is a data management system for multi-paramteric observatories focused on standards, open accessibility and web services (www.moist.it). During the time of the project development and its consequential time of RI maintenance, some possible experiments could be developed under request. Young personnel (operators and scientists) dedicated to parts of the RI will be trained with specific practical and theoretical courses provided by professionally mature scientists.

The InSEA infrustructure, being fully included in EMSO ERIC RI, would take advantage of the support of JRU e/o of EMSO ERIC in the following areas:

- Greater availability of data on the web (data retrieval and communications);
- Technical Support to have data more adherent to FAIR guiding principles (Find-ability, Accessibility, Interoperability, and Reusability);
- Support for logistics in the maintenance;
- Training Courses organization.

The expected reinforcement in the InSEA project of the infrastructures that constitute integral parts of EMSO ERIC, represents a unique opportunity to create the conditions to attract international scientific excellence in laboratories and distributed nodes. The adoption of an Open Access policy, adopted at European level, implies open access to the international scientific community, and to a wider representation of the public and private sectors.

This will produce a multiplier effect that will reward the investment from different points of view. The return is in fact potentially on scientific knowledge, on the economy, on the ability to protect the environment and to mitigate the effects of environmental disasters. Furthermore, the project contributes to the goals of EMSO ERIC, such as the promotion of a sustainable use of the seas and the conservation of marine ecosystems. These objectives are in line with the indications of the European Commission, which in turn are implemented by ESFRI for research infrastructures, e.g. the Marine Strategy Framework Directive, the Maritime Spatial Planning Directive, the Blue Growth Strategy and the G7 Future of the Sea and Ocean Initiative.

In summary, InSEA has a strategic relevance because:

- It will contribute to attracting high quality human capital.
- It will help to create a new market for local companies, producing high level jobs.
- It will be the first step towards the creation of an instrument (to be used by local authorities) to control the marine environment, having the potential to monitor the quality of water, marine flora and fauna.
- It will provide a tool to support the understanding of disastrous natural phenomena in sensitive areas: InSEA will be able to check new and more effective methods to develop early warning instruments of environmental risk, such as that caused by tsunamis, or biological phenomena, such as the proliferation of toxic algae.

DISCUSSION AND CONCLUSIONS

The InSEA project intends to consolidate and enhance the definitive sites at Western Ionian Sea Facility of the EMSO infrastructure or the test-sites, the latter developed in the PON EMSO-MedIT project, as part of similar initiatives on European scale carried out by the other European EMSO-ERIC partners for the purpose of reinforcing of the EMSO sites of which they are responsible. These activities are based on regional, national and European financial support (infrastructural funds). Therefore, the InSEA project will place the Italian country aligned with the other European participants in EMSO ERIC.

As already underlined, EMSO ERIC is usefully included in the ESFRI Landmark (Womersley et al., 2016), that is to say, EMSO is among the RI considered successful for ESFRI. Regarding our country, the launch of the JRU EMSO-Italia is certainly the vehicle to reinforce the Italian presence and its excellence, highlighting the scientific and technological skills of our marine community compared to other countries.

All this reinforces the presence and the Italian role in the field of scientific research and industrial development, with well-established or emerging rapidly possibilities growing in recent years.

Next, we define a classification of potential users of services and technologies:

- national and international scientific community;
- industrial sectors directly related to the use of the sea as a resource, in particular:
  - oil & gas
  - renewable energy;
- public administrations dedicated to monitoring the marine environment and related risks,
- international organizations dedicated to the analysis and monitoring of climate and environmental risks (for example UNEP, etc.)
- port authorities, as regards the part related to coastal monitoring;
- tourism, which is highly dependent on the quality of coastal waters.

The reinforcement given by the InSEA project of the infrastructures present in the national territory makes the participation of our community unique compared to the other countries participating in the EMSO ERIC infrastructure. This also presents characteristics of excellence throughout the national territory, because it supposes a strong driving force for the development of both highly professional figures and industrial-related ones, increasing the competitiveness of our companies (SMI or large companies).

Once the potential users have been defined, we can classify a series of services that the InSEA project can deliver using the enhanced infrastructures, in particular:

- integrated monitoring of the marine environment in real time;

- consultancy for environmental analysis at sea and feasibility studies;
- studies of the effects on biodiversity of productive activities that require the exploitation of the sea;
- development of specific sensors for marine applications;
- development of data acquisition and processing systems.

For example, these elements may refer to relevant research activities that could be initiated thanks to the proposed enhancement. Otherwise, this scientific knowledge could not be obtained and the development of cutting-edge technologies could be impeded/delayed.

To conclude, InSEA project will firmly establish the basis for a better knowledge of the Mediterranean Sea and its whole complex system, contributing to a deeper knowledge of the central role of oceans and how the entire world is working and developing, with the intriguing interconnection among all its parts (Lenton, 2016).

DATA AVAILABILITY STATEMENT

Publicly available datasets were analyzed in this study. This data can be found here: https://www.emsoitalia.it/.

AUTHOR CONTRIBUTIONS

AS: Planning of the manuscript and its organization; AS and MC: Draft of the paper and supervision. All other authors contributed for a chapter and check over all the manuscript. All authors contributed to the article and approved the submitted version.

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Low-Cost, Deep-Sea Imaging and Analysis Tools for Deep-Sea Exploration: A Collaborative Design Study

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A minuscule fraction of the deep sea has been scientifically explored and characterized due to several constraints, including expense, inefficiency, exclusion, and the resulting inequitable access to tools and resources around the world. To meet the demand for understanding the largest biosphere on our planet, we must accelerate the pace and broaden the scope of exploration by adding low-cost, scalable tools to the traditional suite of research assets. Exploration strategies should increasingly employ collaborative, inclusive, and innovative research methods to promote inclusion, accessibility, and equity to ocean discovery globally. Here, we present an important step toward this new paradigm: a collaborative design study on technical capacity needs for equitable deep-sea exploration. The study focuses on opportunities and challenges related to low-cost, scalable tools for deep-sea data collection and artificial intelligence-driven data analysis. It was conducted in partnership with twenty marine professionals worldwide, covering a broad representation of geography, demographics, and domain knowledge within the ocean space. The results of the study include a set of technical requirements for low-cost deep-sea imaging and sensing systems and automated image and data analysis systems. As a result of the study, a camera system called Maka Niu was prototyped and is being field-tested by thirteen interviewees and an online AI-driven video analysis platform is in development. We also identified six categories of open design and implementation questions highlighting participant concerns and potential trade-offs that have not yet been addressed within the scope of the current projects but are identified as important considerations for future work. Finally, we offer recommendations for collaborative design projects related to the deep sea and outline our future work in this space.

Keywords: ocean exploration, marine science, technology, capacity development, artificial intelligence, machine learning, co-design, participatory design

1 INTRODUCTION

The deep seafloor (>200 m) represents 92.6% of the global seabed (**Figure 1**; Eakins & Sharman, 2012) but only a tiny fraction of this percentage has been scientifically explored and characterized[1,2]. Yet, the deep sea provides regulating, provisioning, and cultural services, including many that support life on our planet, such as the cycling of ocean water and nutrients and the regulation of the Earth's climate by acting as a carbon and heat sink (Thurber et al., 2014; Le et al., 2017). The deep sea is also a growing source of living and non-living resources, including fisheries, conventional and non-conventional energy resources, and genetic resources (Ramirez-Llodra et al., 2010; Ramirez-Llodra et al., 2011; Armstrong et al., 2012; Jouffray et al., 2020). In addition, it has the potential to be a source of minerals, although there are significant questions about the sustainability and responsibility of deep-sea mining (Rogers et al., 2014; Levin et al., 2020; Amon et al., 2022b; Amon et al., 2022c). While it is clear that deep-sea exploration is vital to our understanding of planetary biodiversity and function and how to mitigate impacts on them, studying these remote environments has thus far been limited by insufficient technological development, inequitable global access to available resources, and the concentration of expertise in only a few regions.

A critical component of characterizing and understanding the deep seafloor is imaging (Katija et al., 2021), a non-invasive method for observing habitats, identifying organisms, and understanding interactions between organisms and their environment (Huvenne, 2022). Imaging also provides a way to connect humans with remote and inaccessible environments which are therefore "out of sight, out of mind" to most people (Fundis & Bell, 2014; Katija et al., 2021; Genda et al., 2022). Despite the importance of imaging for understanding the deep sea, the tools necessary to undertake this research, as well as the collection of basic parameters such as salinity, temperature, and depth (CTD) to understand environmental conditions, are not available to many researchers around the world (IOC-UNESCO, 2020; Amon et al., 2022d; Bell et al., in prep). For example, preliminary analysis of data from the 2022 Global Deep-Sea Capacity Assessment shows that 19-48% of survey respondents for Africa, Oceania, Latin America, and the Caribbean have access to imaging tools and CTDs, while 48-90% of respondents for Asia, Europe, and Northern America have access to the same tools (Bell et al., in prep). Similar trends are exhibited in access to deployment methods, such as ROVs, AUVs, benthic landers, drifters, towsleds, and HOVs, showing large disparities in access to these deep submergence systems between different regions of the world (Bell et al., in prep).

Our limited understanding of the deep sea is primarily a consequence of not prioritizing the development of affordable, efficient, and equitable approaches to deep-sea exploration and characterization. Many sensors, vessels, and deployment systems can cost tens of thousands to millions of dollars to develop, purchase, and/or operate. Because of their high expense and low availability, the technologies that exist today are more accessible to scientists in wealthy nations, biasing regions explored and motivations for exploration, and creating massive knowledge gaps (IOC-UNESCO, 2020; Amon et al., 2022d; Bell et al., in prep). These tools are still relatively slow at exploring and characterizing the deep sea, especially given the urgent need for robust science to inform management decisions related to increasing exploitation pressures. Furthermore, existing data lack

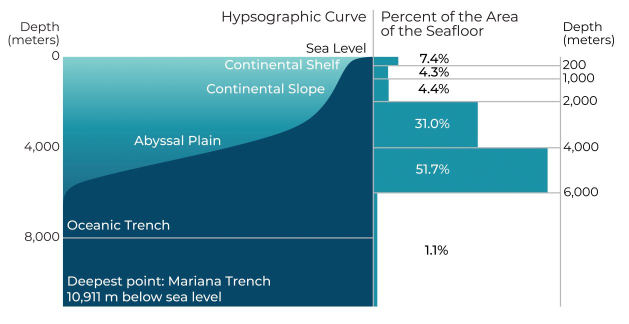

FIGURE 1 | The deep seafloor greater than 200 meters below sea level (mbsl) covers 92.6% of the seabed, 82.7% of which lies between 2,000 to 6,000 mbsl (Eakins & Sharman, 2012).

[1]*We use the following definitions from OSTS, 2020: Ocean exploration provides a multidisciplinary first look at an unknown or poorly understood area of the seafloor, sub-bottom, and/or water column and an initial assessment of an area's physical, chemical, and biological characteristics. Ocean characterization provides comprehensive data and interpretations for a specific area of interest of the seafloor, sub-bottom, and/or water column in direct support of specific research, resource management, policymaking, or applied mission objectives.*

[2]*Developing Economies and SIDS are identified by the UN Statistics Division M49 Standard (https://unstats.un.org/unsd/methodology/m49/).*

sufficient standardization, formatting, aggregation, and access (Brett et al., 2020; Katija et al., 2021), rendering global synthesis and understanding extremely difficult, if not impossible. Finally, even within nations with the tools necessary to conduct deep-sea exploration and characterization, the field has historically been overwhelmingly white and male (Orcutt & Cetinić, 2014; NSF, 2018; Bell, 2019), potentially resulting in biases and gaps due to homogeneity and/or homophily.

Today, humankind is sitting at an inflection point. New technologies, research methods, and communities of people have the potential to transform what it means to explore and characterize the ocean in the 21st century. It is now possible and necessary to accelerate the pace and broaden the scope of exploration by adding low-cost, scalable tools for data collection and AI-driven methods for data analysis to the traditional suite of research assets. Exploration strategies should increasingly employ collaborative research methods to promote inclusion, accessibility, and equity to ocean discovery globally.

Here, we present one step toward this new paradigm: a participatory and collaborative design study on technical capacity needs for deep-sea exploration and characterization. This work was conducted in partnership with twenty marine professionals from around the world representing very different domains, including educators, divers, navigators, scientists, engineers, indigenous peoples, and conservation practitioners. The study focused on opportunities and challenges related to deep-sea exploration and research in developed and developing areas worldwide.

These findings informed our development of a low-cost, deep-sea imaging and sensing system called Maka Niu and a forthcoming artificial intelligence (AI) video analysis tool. We report on the broader collaborative design process and our early steps towards technology prototypes that are currently being tested in nine countries. We close with lessons learned and recommendations for future participatory and collaborative design work in ocean exploration and characterization and outline plans for the Maka Niu and automated video analysis development process. We hope, by presenting our process and learnings, to (1) inform the research and design agendas of others working toward advancing equity in deep-sea exploration; (2) provide insight on the design needs for low-cost sensing and imaging systems and AI-driven image and data analysis; (3) encourage others to utilize collaborative design methods to build low-cost, accessible tools that enable their fields to become more inclusive and equitable; and, (4) increase familiarity and exposure to the deep sea for local communities to encourage literacy, advocacy, sustainable economic opportunities, and effective stewardship.

2 BACKGROUND

In this section, we explain the history and emerging role of participatory design (PD), the current status of low-cost, deep-sea technology development, and share the process that facilitated this collaborative research.

2.1 Participatory and Collaborative Design Approaches

The field of Participatory Design (PD) emerged alongside workplace democracy movements led by Scandinavian trade unions in the 1970s. As workplaces modernized with new technologies, early practitioners of PD argued that workers ought to have a say in the design and management of their changing working conditions (Simonsen & Robertson, 2013). PD (also called *co-operative design* or *co-design*) argues for direct participation by stakeholders in design activities—from setting the initial terms for collaboration to scoping and framing design challenges to making decisions about proposed solutions.

Over the past fifty years, technology designers have begun to embrace and apply participatory and collaborative approaches around the world to contexts well beyond the workplace (Simonsen & Robertson, 2013; Vines et al., 2013; Emilson et al., 2014; Bannon et al., 2018). Researchers in the field of Information and Computing Technology for Development commonly leverage participatory and collaborative approaches to design digital technologies that can lead to socio-economic development for marginalized communities in low- and middle-income countries (Kendall & Dearden, 2020). The growth of participatory methods in this field responds to a history of failed initiatives, including power dynamics in development projects whereby control of funding and decision-making rests in the hands of those in wealthier, so-called "developed" regions and not those with lived experience of problems to be solved (Brown & Mickelson, 2019). As Irani et al. (2010) argue, many "well-intentioned efforts to 'migrate' technologies from industrialized contexts to other parts of the world have foundered either on infrastructural differences or on social, cultural, political, or economic assumptions that do not hold."

Many technology development efforts seek "universal" design solutions that are uniform and scalable across cultures and contexts, often with the laudable goal of making interfaces accessible to all people no matter their ability level (Shneiderman & Plaisant, 2009). However, Bardzell (2010) suggests that a universal approach to design can also "quietly and usually unintentionally impose—without transparent or rational justification—Western technological norms and practices."

In contrast with universalist approaches that flatten difference and encourage conformity, Bardzell suggests using pluralist design approaches. Unlike universalist design approaches, pluralist approaches to design "foreground questions of cultural difference, encourage a constructive engagement with diversity, and embrace the margins both to be more inclusive and to benefit from the marginal as resources for design solutions" (Bardzell, 2010). In other words, pluralist approaches are not intended to be "one size fits all," and are thus more likely to produce culturally-relevant and sustainable solutions.

Participatory design approaches embrace the philosophy of pluralism and are offered as a way forward for intercultural collaborations with diverse stakeholders. Such approaches involve building relationships of trust and mutual benefit, respecting and building on local knowledge, and challenging power dynamics often present in top-down collaborations where groups with more funding and power direct priorities, often at the expense of local partners.

In ocean science, participatory approaches have also been applied to the practice of natural resource management. Co-management—an approach where governments and stakeholders work together to manage natural resources by incorporating local knowledge of resources and different stakeholder priorities—was proposed in response to "increasing criticism of the traditional model of top-down management as a method of governance" (Smith, 2012). According to Smith, co-management requires stakeholders (e.g., scientists, researchers, industry representatives, conservation organizations, community members, and more) to be involved in "making decisions about the resources in question in some capacity, and thus involves significant sustained participation."

Community-driven capacity development work aligns with a new global effort—the UN Decade of Ocean Science for Sustainable Development, which launched in 2021 (United Nations, 2018; IOC-UNESCO, 2021). The Ocean Decade aims to transform ocean science by providing a collaborative framework that can account for different disciplines, sectors, and stakeholder communities. This framework supports the co-creation of knowledge about science and capacity needs. In addition to defining globally-set objectives and priorities among research and development areas, a series of regional consultation workshops helped establish Ocean Decade's strategies based on locally- and regionally-defined objectives, priorities, and needs promoting the use of bottom-up processes from its conception (IOC-UNESCO, 2021).

2.2 Toward Low-Cost in the Deep Sea

Until recently, the most sophisticated and reliable equipment for deep-sea environments have been ROVs, AUVs, and HOVs that cost ~$100k-10M USD to purchase, develop, and/or operate from comparably expensive vessels (Kohnen, 2013; Teague et al., 2018). Increasingly, emerging technologies for ocean exploration and research cost ~$10k-100k USD and are more portable, easier to operate, and offer a variety of capabilities, accuracy levels, and robustness (Sheehan et al., 2016; Dominguez-Carrió et al., 2021; Giddens et al., 2021). For the past few years, "do-it-yourself" and open-sourced shallower tools (<300 m) have been developed using microcontrollers, single-board computers, and commercially available components to create camera and/or sensor systems within ~$100-$1000 USD (Simoncelli et al., 2019; Greene et al., 2020; Lertvilai, 2020; Mouy et al., 2020; Bilodeau et al., 2022; Butler and Pagniello, 2022). Two low-cost camera systems are designed for depths of 5,500-6,000 m (Phillips et al., 2019; Purser et al., 2020), and commercially available cameras such as GoPros can be after-market housed to ~3,000 m; none of these options, however, include sensors such as depth or temperature, which are critical for scientific understanding of the environment.

There is room for innovation in this space, and the collaborative design approach introduced in this paper is an example of how to build upon this movement. By aligning the earliest development stages of ocean technology to the requirements of a diversity of users–for example, the intersection of imaging, sensing, affordability, and ease of use we–can establish a collaborative process and design community to create a new system that meets the community's needs.

2.3 Our Approach

The Open Ocean Initiative incubated the work presented here at the MIT Media Lab in collaboration with individuals and organizations around the world, several of whom are interviewees, test users, and co-authors of this research. Co-development and co-production of knowledge were essential to this study, allowing us to surface interconnected challenges related to ocean exploration across various domains, emphasized as an important approach in the recent work of Woodall et al. (2021). Several other recent publications about capacity building also call for more knowledge sharing in deep-ocean science (Markus et al., 2018; Miloslavich et al., 2018; Howell et al., 2020b).

In 2018, Open Ocean facilitated and participated in the launch of two pilot projects: My Deep Sea, My Backyard, which aimed to grow deep-sea capacity in two Small Island Developing States (SIDS) (Amon et al., 2022d), and FathomNet, an open-source image database that AI algorithms can use to help us understand our ocean and its inhabitants (Katija et al., 2021). Nascent at the time, both efforts have since become critical components of making deep-sea exploration and research less expensive, more efficient, and more equitable (Márquez, 2018). Parallel to these initiatives, a network of researchers and stakeholders was coalescing, building a community of research and practice *via* two events held at the MIT Media Lab: *Here Be Dragons* (Bell et al., 2021) and the *2018 National Ocean Exploration Forum: All Hands on Deck* (Bell et al., 2019; Bell et al., 2020a). These events and projects provide context for building diverse communities from which collaborative, transdisciplinary research and design projects have emerged organically, including this participatory design study to further Maka Niu and AI tool development. In 2021, Open Ocean spun out of MIT as the non-profit Ocean Discovery League (ODL), aiming to accelerate deep-sea exploration by developing accessible systems to broaden the community of those who explore and understand the deep sea.

2.3.1 Maka Niu

Maka Niu, loosely translated as "coconut eye" in Hawaiian, was conceived in February 2020 as an educational tool in collaboration between Open Ocean/ODL, the Polynesian Voyaging Society (PVS), and the MIT Future Ocean Lab (now Oceanic Labs). Maka Niu was envisioned to be a tool that could go deep in the water column to illuminate what is underneath the wa'a (canoe), allowing the community to see and safeguard what extends beyond the loko i'a (fishponds) of the ahupua'a (watershed). Due to COVID-19, the design process took longer than anticipated. However, the delay allowed the Design Research and Engineering Teams to incorporate learnings from the summer 2020 interviews into the design and implementation of the camera systems. While initially conceived as a system for educational use, a broader range of marine users and applications became apparent throughout the interview and engineering design process. Today, Maka Niu is 'a low-cost, modular imaging and sensor platform that leverages off-the-shelf commodity hardware along with the efficiencies of mass production to decrease the price per unit and allow more global communities to explore previously unseen regions of the ocean' (Novy, Kawasumi et al., in prep).

2.3.2 Automated Artificial Intelligence Video Analysis Tools

Our automated ocean video analysis product strategy builds on four years of work on FathomNet, an open-source, expertly annotated database of underwater imagery (Katija et al., 2021). A new effort will take this work further by creating an easy-to-use platform that enables users to analyze their video data with AI algorithms without prior computer programming experience.

The platform aims to create an accessible online tool for holistically analyzing deep-sea video and environmental data using machine learning. Algorithms will rapidly analyze visual ocean data, observations, and associated environmental metadata to automatically localize and classify marine species and features. By dramatically accelerating the ability to analyze ocean video and creating a collaborative environment for open data sharing of discoveries, we will dramatically expand our understanding of global ocean biodiversity and habitats.

3 METHODS

Since July 2020, the Design Research Team has conducted a collaborative design study with our growing global network of colleagues. Our overarching goals are to (1) collect feedback on feature and capability requirements from potential users of the new technologies before and while they were developed; and (2) assemble interested users from the study to test prototypes of the tools created in an interactive, collaborative way.

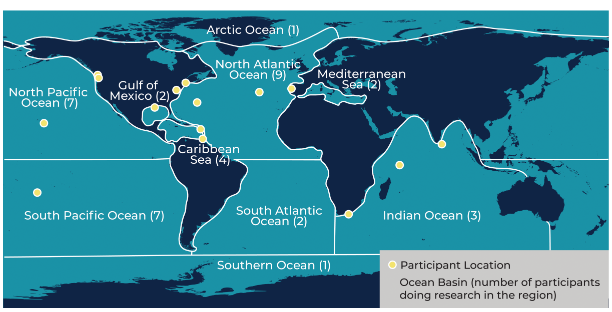

FIGURE 2 | Nineteen out of twenty interviewees self-reported their location of residence (yellow dot) and fieldwork location(s) (ocean basins). Locations of residence include Bermuda (2), Canada, Cook Islands, Montserrat, Portugal (2), Seychelles, South Africa, Sri Lanka, Trinidad and Tobago, and the United States (8). Many participants conduct fieldwork in different ocean basins from their home location.

3.1 Interview Goals and Participants

We used qualitative methods to conduct the interview phase of the collaborative design study from 27 July to 7 August 2020. Interview invitations were extended to project collaborators and network colleagues. A total of twenty people were interviewed during nineteen semi-structured virtual sessions; two participants were interviewed in the same session. Nineteen of the twenty interviewees are co-authors of this manuscript. The purpose of the interviews was to seek feedback on Maka Niu and AI analysis tools. Interview input was reviewed, coded, and analyzed by the interview team. Its synthesis was reviewed and edited by the interview participants in a shared online document such that our findings were collaboratively established. This follows established practices in participatory-collaborative design processes where lead researchers assume the role of facilitators of knowledge production rather than acting as translators between interview subjects and designers (Scariot et al., 2012).

The twenty interview participants were marine professionals representing a broad cross-section of domain expertise such as education, diving, traditional navigation, science, engineering, indigenous knowledge, and conservation. Interviewees were located in ten countries and conducted fieldwork in every ocean basin (**Figure 2**). One-third of the interviewees live in countries or territories with developing economies[3], including 21% who live in SIDS. Of the nineteen interviewees who self-reported their demographic backgrounds, 63% are female, and 37% are male (**Figure 3A**). At the time of the interviews, 37% were between the ages of 30-39 years old, 58% were 40-49, and 5% were 50-59 (**Figure 3B**); and 16% had completed a bachelor's degree, while 37% had a master's degree, and 47% had a doctoral degree (**Figure 3C**). In terms of ethnic/racial origin, seven (37%) of the nineteen interviewees identified as White or Caucasian, two (11%) as Black/African-American, and one each as Native Hawaiian/Pacific Islander, Asian, Afro Caribbean/Latina/White, Asian/Native Hawaiian/White, Black Caribbean, Indian Ocean Islander/African, Mixed, and Jewish/White. One each selected 'A race/ethnicity not listed here' and 'Prefer not to answer' (**Figure 3D**).

3.2 Interview Set Up

Before the interview, interviewers acquainted themselves with the work of each interviewee, and interviewees were provided with background materials on Maka Niu and AI analysis tools and the Open Ocean value-guided design principles (Hope et al., 2019).

3.3 Interview Protocol

All interviews were conducted over two weeks in English *via* video teleconference calls, recorded with permission from each interviewee. The typical interview duration was one hour. Interviewers worked in pairs, with an interviewer and a rapporteur, both among the authors of this paper. A universal set of eighteen questions were asked of each interviewee

[3] *Developing Economies and SIDS are identified by the UN Statistics Division M49 Standard (https://unstats.un.org/unsd/methodology/m49/).*

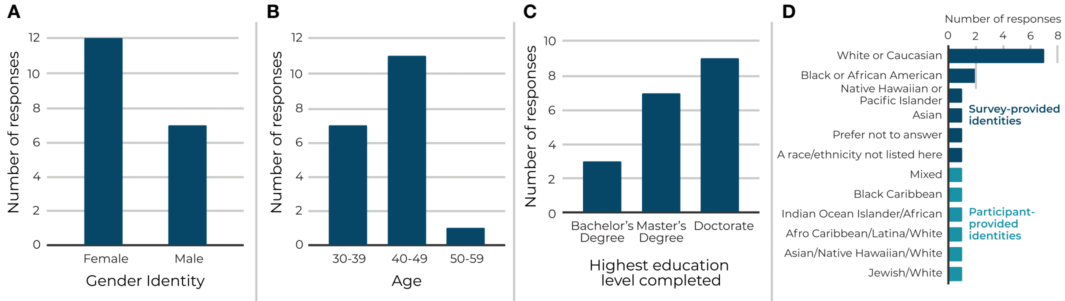

FIGURE 3 | Nineteen out of twenty interviewees self-reported their: **(A)** gender identity, **(B)** age, **(C)** highest level of education completed, and **(D)** race/ethnicity/origin identity.

(see **Supplementary Material**), allowing for qualitative data analysis that yielded comprehensive input to the Maka Niu and AI design teams. The interviews covered four main topics: (1) the interviewee's ocean-related background, interests, and community; (2) low-cost deep-sea imaging tools, with a focus on the capabilities of Maka Niu; (3) AI-driven data analysis, with a focus on capabilities of AI tools; and, (4) the interest and availability for user testing of Maka Niu and/or future AI tools.

Because of its exploratory nature, a semi-structured interview methodology (e.g., Blandford, 2013) was used to conduct this collaborative design study. This approach allowed for emergent data and the identification of broadly-shared challenges in deep-sea exploration and individual mission-critical requirements for each interviewee. Instrumental to developing the interview questionnaire and protocols was having one member of the interview team with experience working in participatory and collaborative design projects in other domains to train and orient the other interview team members.

Each interview began with introductions, followed by a brief description of Maka Niu and the AI tools. The interviewer mainly engaged with the interviewee, guided by the questions while adaptively tuning the conversation flow to listen, acknowledge, and interact responsively to the interviewee's input. The questionnaire was designed to situate the interviewee and their network in the global marine community and determine their interest and needs to explore the deep sea with Maka Niu and automated video analysis tools. At the conclusion of the interview, the interview team provided the interviewees with additional information as requested.

3.4 Data Analysis

Using the Background Materials, the research team created a preliminary *a priori* codebook (Glaser & Strauss, 1999). The team then followed an open coding process, adding emergent codes to the *a priori* codebook. At least two researchers independently coded each interview to increase researchers' exposure to data, prompting new connections and discoveries and supporting team discussion of emergent codes. Emergent codes were discussed as a group. Themes were then generated from codes, and connections were noted between themes. After the themes were generated, the team drafted an initial "Interview Synthesis" document (Bell et al., 2020b) and shared it with all interview participants for their feedback on how their needs and ideas were represented in our dataset. In some cases, the analysis was modified to reflect clarifications provided by interviewees to move toward a collaborative model of developing the study.

4 RESULTS

4.1 Interviewee Archetypes

As part of our data analysis process, we identified different archetypes to represent the interviewees' professional domains, experiences, motivations, and requirements (**Table 1**). Archetypes can be a valuable tool to synthesize concerns and identify differences between stakeholder priorities and requirements. We shared these archetypes with the interviewees to solicit their feedback on how well they reflected their motivations and requirements and made modifications as needed. Archetypes are not meant to be conclusive or dogmatic but rather are offered as a starting point for talking about different perspectives and needs.

Eighteen out of twenty interviewees self-identified up to three archetypes they consider to represent themselves (**Figure 4**). The most frequently represented archetypes were Scientist/Researcher and Formal or Informal Educator (78% each). These were followed by: Policy Maker or Manager (28%), person in Aquatics/Recreation (22%), Engineer (17%), and Traditional Knowledge Holder (17%). Individuals identified as different combinations of these archetypes (**Figure 4**), resulting in specific motivations and requirements that guided ideation and decision-making processes (**Table 1**).

Furthermore, 42% of the interviewees live and/or work in countries or territories with developing economies, highlighting the need for low-cost, low-logistics tools for deep-sea exploration and research. Motivations of those who live and/or work in these areas include: enabling locally-led science while dissolving "parachute science"; sharing local ocean knowledge with people to encourage them to conserve and protect it; engaging populations not usually engaged in scientific research (e.g., fishers, youth, tourists); and, preparing local people for marine jobs. These motivations resulted in specific requirements for deep-sea tools, including:

- low-cost, easy-to-use, and robust;
- no dependence on big boats or internet access;

TABLE 1 | Interviewee archetypes, motivations, and requirements, listed in order of frequency.

Archetype	Motivations	Requirements
Scientist or Researcher	• Getting more eyes on the seafloor, and more data everywhere, especially in deep water (>200 m) • Ensuring data quality and making analysis easier • Being able to make more global conclusions vs hyper-localized ones • Collaborating with other researchers	• Low-cost, easy-to-use and to deploy • No dependence on research vessels • Standardization of data • Accurate AI tools • More specific toolsets (e.g. additional modules) • Ability to reach depths to thousands of meters
Formal or Informal Educator	• Broadening access to ocean-linked tools, skills, and knowledge • Sharing local ocean knowledge with people to encourage them to conserve and protect it • Making learning engaging • Preparing people for marine jobs	• Low-cost, easy-to-use, and error-proof • Integrated with software, works on multiple mobile platforms • Ability to deal with a variety of internet access conditions
Policy Maker or Manager	• Having more information for better-informed management and policy decisions • Being able to collect and analyze data without relying on outsider expertise (from other countries and companies), particularly for countries/communities that currently don't have deep sea assets or expertise	• High data quality • Data ownership • Data accessibility and comprehensibility
Works in Aquatics/Recreation	• Broadening access to ocean-linked tools, skills, and knowledge • Making learning engaging • Preparing people for marine jobs	• Low-cost, easy-to-use and to deploy
Traditional Knowledge Holder	• Recognition of marine traditional knowledge • Protection of culturally significant regions • Connections between traditional knowledge, cultural values, and scientific research • Storytelling to honor heritage and connections to the marine environment	• Low-cost, easy-to-use and to deploy • Ability for science to be driven by traditional knowledge and local communities • Ability for students and local communities to be involved and leading efforts
Engineer	• Allowing for a long-term presence in the ocean • Minimizing potential losses of material	• Low-cost hardware for testing • Long-duration hardware • Open-source • Made of easily accessible parts • Coordination of multiple assets

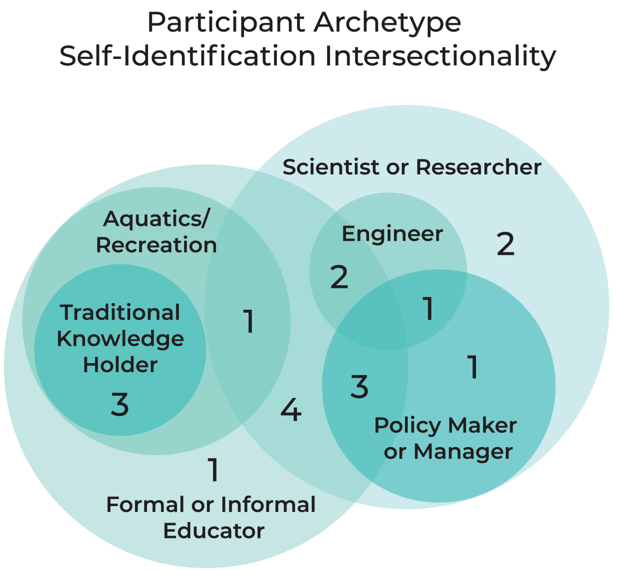

FIGURE 4 | Participant archetype self-identification. Interviewees were asked to identify up to three out of six domains/communities which they represented the most. Eighteen out of twenty interviewees responded.

- ability to deal with maintenance and repair issues locally; and,
- additional language support for software and training.

While we were not able to incorporate all of these requirements into the first iteration of Maka Niu and AI tool development, we took as many into consideration as possible and aim to include others in future work.

4.2 Community Involvement: How Access to This Technology May Differ by Sector

The ocean community includes a wide range of disciplines, levels of expertise, and stakeholder groups such as researchers, engineers, policymakers, indigenous peoples, NGOs, students, fishers, tourists, and offshore industries. Each of these groups uses the ocean for a variety of reasons, including exploration, exploitation, recreation, and conservation. Interviewees are local experts who belong to different combinations of archetypes and regularly interact with different stakeholders in their regions (**Table 2**). They were therefore suited to advise how various communities can play a role in ocean exploration, including testing, improvement, and use of Maka Niu and AI analysis tools, once available. In some cases, financial and other support

TABLE 2 | Communities and areas of potential involvement in low-cost, deep-sea exploration and research.

Community Group	Description of Potential Involvement
Fishing	Fishers were mentioned as key stakeholders in ocean management by 15 of 20 interviewees. Building relationships with the local fishing industry allows for expanding research capabilities. Using Maka Niu and AI analysis tools, fishers can connect with their marine ecosystem and contribute to continued ecosystem monitoring. Interviewees suggested that giving fishers access to data collection methods and the resulting data would allow them to contextualize and value scientific research.
Offshore Industry	The vast majority of data and imagery collected by offshore industries, such as oil and gas, currently tend to be proprietary. Maka Niu provides an opportunity to share deep-sea ecology with this community and encourage future partnerships that prioritize greater transparency and access (e.g., SERPENT).
Tourism	A few interviewees have direct relationships with local tourism. Inviting tourists to form deeper connections with the local ecology and researchers through environmental monitoring and exploration would enhance their experiences and inform them of their impacts while traveling. Partnering with tourism companies that operate in the same regions over long periods would be an opportunity to increase our understanding of regional changes over time.
Policy Making & Management	Data usage may differ between scientists and decision-makers. The versatility of our system should allow data collection and use to be conducted through the lens of different sectors, including management and policy making. Our systems can bridge the gap by using Maka Niu and AI analysis tools to illustrate how deep-sea ecosystems work, how data can be used to inform management, and how they are in turn impacted by policies.
Local Communities	Coastal communities themselves were noted as vital assets for marine research. Suggestions for engagement included local cultural centers like village gathering places and museums. Interviewees proposed strengthening relationships between the local community and their underwater ecosystems to encourage sustainability and marine management. Each community has unique priorities that are driven by its cultural heritage. Accessible, low-cost oceanographic tools provide an educational platform that can enable communities to invest in long-term ecological monitoring and learning opportunities for local people to develop their scientific skills and lead their own projects. Interviewees were also excited by the possibility of building multi-generational community connections around ocean exploration.
Education and Training	All interviewees suggested opportunities for students from K-12 through college to use Maka Niu and AI analysis tools to experience the ocean, learn about marine life, and contribute to a global knowledge base. Younger learners would be able to observe life in the ocean using annotated videos to learn the important species in their area. Middle and high school students would be able to deploy a camera system, collect their own data, begin to contribute to scientific research, and learn valuable technical and scientific skills. Classroom dialogue and partnerships with local college students can identify regional questions which can be explored using these new tools. There is also the opportunity for intergenerational training.
Aquatics and Recreation	Our aquatics and recreation interviewees addressed the role of ocean exploration in inspiring youth to consider future marine careers. Using oceanographic tools that mirror those researchers use allows youth to contribute to scientific knowledge while building interest, enthusiasm, and advocacy for careers in science.
NGOs	Several interviewees lead or are strongly connected to local non-government organizations (NGOs). NGOs offer structured organizations to connect with an important community of volunteers. Interviewees noted that these volunteers would be excited to participate and deploy cameras under the supervision of the NGOs and contribute to the gathering of scientific knowledge.

would be required for involvement. The tailoring of technology and skillshare training to each archetype's research and mission objectives with systems like Maka Niu and AI analysis tools could allow for a more inclusive co-creation of ocean knowledge with different sectors of the community.

4.3 Maka Niu: Data Collection Design Considerations and Implementation

Low-cost imaging and sensing system development is critical for increased efficiency of deep-sea exploration and equitable access to the deep sea. The first technological topic of discussion during the interviews focused on recommendations and requirements for the Maka Niu imaging and sensing system. The interviews pointed to various considerations, including sensor development, features, and capabilities that would ensure the usability of a low-cost system and deployment scenarios to support the interviewees' work. The priority levels in each section below reflect the relative consensus amongst participants about the need for these capabilities.

4.3.1 Sensor Recommendations

The following are the highest priority deep-sea sensing capabilities that interviewees identified as important for their work:

- 1st Priority: Temperature, Imaging, Depth, Salinity
- 2nd Priority: GPS, Oxygen, pH, Acoustic tags, Light attenuation, eDNA
- ● Imaging Recommendations: High definition, Stereo, 360°

Various types of water-quality indicators were also noted, but less consistently than the 1st and 2nd Priority measurements. These included chlorophyll, methane, nitrates, phosphates, alkalinity, and turbidity. Additional work could be done to further refine and prioritize sensing capabilities for the deep sea, similar to the

Essential Ocean Variables defined by Miloslavich et al. (2018) and Exploration Variables identified by the NOAA Office of Ocean Exploration (Egan et al., 2021).

4.3.2 Feature Requests

In addition to specific sensing capabilities, interviewees also discussed other kinds of features that would make the design of Maka Niu easy to use. These included:

- 1st Priority: Easy to access video/database, depth capability of hundreds to thousands of meters
- 2nd Priority: Long duration (days to months), access to live stream
- 3rd Priority: Easy to use and fix, modular, programmable missions

4.3.3 Deployment Scenarios

The Maka Niu system was initially envisioned as a standalone imaging and sensing system that could deploy from various platforms. We discussed some deployment scenarios, listed in order of capacity and interest, and aggregated them into categories:

- On a deployed benthic structure (e.g., lander, elevator)
- Deployed from a small boat (e.g., kayak, fishing vessel, wa`a)
- On a fixed structure (e.g., buoy, mooring)
- By people (e.g., SCUBA diver, snorkeler)
- On a tethered system (e.g., ROV, fishing line)

These deployment scenarios are not mutually exclusive; for example, one might deploy a lander from a small boat. Some additional features of a standalone deployable system could include the ability to: A) deploy/retrieve quickly and easily; B) deploy as a drifting system; C) work without the need for an anchor; D) be baited and, E) deployed as an array of units to simultaneously image/sense larger areas of seafloor.

4.3.4 Maka Niu Prototype Imaging & Sensing System

Following the interviews in the summer of 2020, the Maka Niu Engineering Team designed and built a deep-sea imaging and sensing system over six months (Novy, Kawasumi et al., in prep; see **Supplementary Material**). The Maka Niu Design Research and Engineering Teams considered as many of the design requirements and considerations listed above as possible, particularly the 1st Priority capabilities (**Table 3**). Several 2nd and 3rd Priority items were also incorporated, including GPS, ease of use, and easily programmable missions. Finally, we experimented with the design and prototyping additional modules with different capabilities, such as a light module, through student design projects at MIT and the University of Porto, Portugal, demonstrating the system's modularity. Many of the current Maka Niu system components were designed to be extendible and reusable such that additional Maka Niu modules with different capabilities can be driven by its modular parts, allowing users to address their specific research and exploration needs. Additional details on the design, engineering, and modularity of Maka Niu, including student projects, can be found in Novy, Kawasumi et al. (in prep).

Seventeen Maka Niu deep-sea imaging and sensing systems were built in the spring of 2021 (**Figure 5**). The systems are roughly the size of a large flashlight (**Figures 5A, B**): they are 261 mm long, 64 mm in diameter (76 mm including the button), and weigh 870 g in air (150 g in water). The Delrin housings are rated to 1,500 m water depth and have been designed to increase the operational depth to 6,000 m with aluminum housings. Maka Niu uses a Raspberry Pi single-board computer for controls with an 8-megapixel Pi Camera Module V2 for still, video, and timelapse image recording. The sensing suite includes temperature, depth, GPS, and 9-axis motion tracking. The control collar enables easy switching between six modes: Off, Wi-Fi, Still Capture, Video Capture, Mission 1 (user-programmed video), and Mission 2 (user-programmed time-lapse). The user can modify missions using a graphical programming interface, allowing easy customization of the mission to their operational needs (**Figure 5C**). After retrieval, users can access recorded imagery on any Wi-Fi-enabled device (e.g., smartphone, tablet) while in the field, enabling them to verify their data before returning to shore without internet access. Once data capture is complete, the user can download data directly to their device *via* Wi-Fi or upload it to the online, open-source video annotation web platform, Tator[4] (**Figure 5D**), where they can annotate their images for scientific analysis and/or contribute them to FathomNet[5].

4.3.5 Current and Next Steps

Of the twenty interviewees, thirteen were shipped a Maka Niu system in 2021 to test in eleven locations: Bermuda, Cook Islands, Montserrat, Portugal (2), Seychelles, South Africa, Sri Lanka, Trinidad & Tobago, and the United States (Hawai'i and Louisiana). Systems were provided at no cost to the test user; however, test users assisted with customs fees and logistics in some cases. There were limited systems available; priority was given to interviewees who had time and interest to train and test in winter 2021/2022, had access to seawater, and were geographically distributed worldwide. Members of the Engineering and Design Research Teams also have systems for deployment and testing (see **Supplementary Material** for sample video). Here we highlight key aspects of the testing and iterative technology development phase.

First, the test users were provided with a brief description of our testing goals and an online User Manual, written and continually updated by the Maka Niu Engineering Team. Soon after receiving the systems, virtual training sessions were offered to introduce test users to the hardware and software. Throughout the testing phase thus far, we have maintained technical and administrative support to the test users through various online communication tools.

The collaborative components of the technology development process involve soliciting test user feedback, offering quick and individualized technical support, identifying common issues among test users, and reworking the hardware and software

[4] *Tator Online. https://www.tator.io/*
[5] *FathomNet. http://fathomnet.org/*

TABLE 3 | Implementation of sensing and feature capabilities for Maka Niu identified during interviews, listed by priority.

	Priority	Capability	Implementation
Sensing	1	Temperature	Keller Series 7LD Temperature and Pressure Sensor; Operating range -40-110°C ± 2°C
	1	Depth	Keller Series 7LD Temperature and Pressure Sensor; Operating range 3-200 bar/30-2,000 meters ± 0.15% Full Scale
	1	Salinity	NA
	1	Imaging	1080 high definition video, still, and time lapse imaging
	2	GPS	Sierra Wireless AirPrime XM1110 GNSS GPS receiver with sensitivity of -165 dBm and update rate of 1 Hz.
	2	Oxygen	NA
	2	pH	NA
	2	Acoustic Tag	NA
	2	Light Attenuation	NA
	2	eDNA	NA
Features	1	Easy to access video/database	Post-deployment, video and images can be accessed *via* any Wi-Fi-enabled device using the Tator video annotation platform.
	1	Depth capability	1,500 m depth rating with delrin housing; designed for 6,000 m with aluminum housing
	2	Long duration	Up to 2 days, depending on frequency and quantity of data recording
	2	Access to live stream	NA
	3	Easy to use and fix	With technical support from the Maka Niu Engineering Team, test users have been able to troubleshoot and fix several issues remotely.
	3	Modular	Two student design projects at MIT and the University of Porto demonstrated that the housings and battery control boards could be used to create additional modules such as lights and an anchor release mechanism.
	3	Programmable missions	Users can program custom missions with a user-friendly, block programming-style interface.

to address these issues. The goals of our testing phase include feedback on the user experience; data on the sensor and camera system accuracy; feedback on the camera and sensor system performance at depth and in various environmental situations; establishing a community among the test users for direct technical support with the Maka Niu system and career and personal support while in pursuit of their organizations' mission. In the future, we intend to report on the test users' assessment of the Maka Niu system and the strengths and weaknesses of this iterative technology development process.

4.4 Image & Data Analysis Design Considerations

In parallel with the development of accessible data collection systems, we must also consider the volume of data collected and plan for an easy-to-use way to train and enable efficient and automated video and data analysis. The second technical discussion focused on developing an online platform that would use machine learning and AI to quickly and easily analyze imagery and associated environmental data. Interview questions focused on what features would be helpful for users, what kinds of people might need to use it, accuracy requirements, and technical requirements such as connectivity.

4.4.1 Key Feature and Capability Requirements

The most important feature identified for an image and data-analysis platform is utility: ease of use and accessibility. Interviewees emphasized the simplicity of design as a high priority, keeping in mind that this system will be implemented with users from different cultures, educational backgrounds, and age groups.

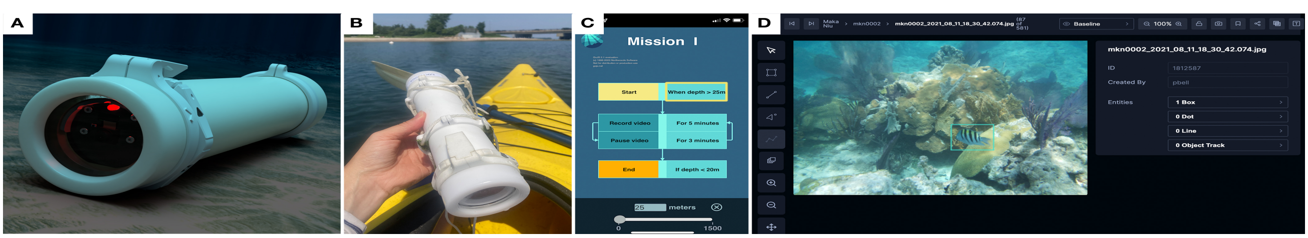

FIGURE 5 | (A, B) Maka Niu is small, lightweight, and easy to deploy. It is roughly the size of a flashlight and weighs 870 g in air (<1 lb). The control collar allows easy switching between modes, and the button triggers actions, for example, starting and stopping video recording. LED flash patterns indicate status information, such as video recording, satellite connection, and battery life. **(C)** The user can modify missions using a graphical programming interface, allowing the user to easily tailor their mission to their operational needs. **(D)** In the online, open-source video annotation platform, Tator, users can localize (green box) and identify the organisms and features observed in their video and still images for analysis and optionally submit them to FathomNet. Image **(B)** by KLC Bell deploying a Maka Niu from a kayak in Narragansett Bay, Rhode Island, USA. Image in **(D)** by T. & K. Noyes using a test Maka Niu system in Bermuda.

The data-analysis experience must be designed with different user groups in mind, and the level of data access and user experience should therefore vary. The interface used by classroom students should look and function differently than the interface for marine researchers. The entire toolset must also be developed for both desktop and mobile devices, internet-limited use, and real-time capabilities.

Interviewees noted that the value of AI is greatly dependent on accuracy; therefore, higher accuracy identification at coarser taxonomic levels (phylum/class) is of greater importance than lower accuracy identification at finer (genus/species) levels. Compatibility with existing databases and collaboration with other image identification efforts may expedite the development of AI-enabled video analysis products and prevent the creation of yet another data silo. Access, storage, and data flow management were also common concerns among interviewees.

Key Features and Requirements include:

- Software must be easy to use; assume no computer programming background.
- Participants desire to combine different data sets (e.g., imaging and environmental sensing).
- Higher accuracy at coarser taxonomic levels is more useful.
- Assume low/no bandwidth situations.
- Consider different user groups, what their experiences are, and what their level of access to data could/should be, including youth, teachers, researchers, and policymakers.
- Governance concerns include data management, access, storage, and ownership.

4.4.2 Current and Next Steps

Maka Niu users can upload their imagery and sensor data wirelessly to the online video annotation platform, Tator. Users can then use Tator to annotate (localize and characterize) their observations directly on the video and still images. The resulting annotations can be used for their own research and/or submitted to FathomNet, an open, online, expertly annotated underwater image database. Each step in this process is optional, and up to the user to decide which are appropriate for their purposes.

The FathomNet database contributes to algorithm development for ocean AI analysis tools. This study's key features and requirements have informed further user interviews in the design and development process of these products.

An online, AI-enabled video analysis prototype is currently in development with numerous partners and organizations, including federal agencies, academic institutions, and non-profit organizations, funded by National Geographic Society/ Microsoft AI for Earth (PI: Author KLCB) and NSF Convergence Accelerator Track E (PI: K. Katija, MBARI).

4.5 Open Design Questions and Considerations

Our interviews revealed several design and implementation questions that highlight participant concerns and potential trade-offs. These questions have not yet been addressed, but doing so will be necessary to ensure that these systems have long-term impact where intended. Six major categories of these open design questions include deployment, sensor development, software, data sharing, funding, and storytelling (**Table 4**).

5 DISCUSSION & RECOMMENDATIONS

The future of scientific deep-sea exploration will require radical and creative solutions to accelerate the pace of discovery. Low-cost tools and smaller, low-logistics technologies for the deep sea are being developed (Hardy et al., 2013; Cazenave et al., 2014; Phillips et al., 2019; Purser et al., 2020; Giddens et al., 2021) and cited as one solution to accelerating deep-sea research and broadening its participation (Amon et al., 2022d; Hand & German, 2018; United Nations, 2018; Bell, 2019; Howell et al., 2020a; Howell et al., 2020b; Pizarro & Pace, 2021). At the same time, the challenge of increasing volumes of underwater video and image data is being addressed with systematic and automated annotation and analysis systems (e.g. Langenkämper et al., 2017; Katija et al., 2021).

Given these technological movements, we sit at an exciting time in oceanographic history—it is now technically possible to lower the cost to these tools and therefore increase access to the deep sea. In doing so, we must also take a participatory and collaborative design approach to ensure that these low-cost data-collection technologies and AI-driven data analysis tools will indeed be transformative and lead to both acceleration of discovery and equitable access to the deep ocean. Below, we share six recommendations for deep-sea collaborative design projects and outline our future work in this space.

5.1 Build Balanced Relationships: Cross-Cultural and Trans-Disciplinary Exchange Is Essential for Conceptualizing and Implementing Innovative, Inclusive Projects

The Maka Niu project was the direct result of long-term engagement and relationship building between Open Ocean/ ODL and PVS. Actions that led to this collaboration experience include: (1) investing time in relationship building and cultural exchange; (2) constraining technology development to that which is feasible and mutually beneficial; and (3) respecting each others' knowledge systems through action, such as conscious effort applied to learning and engaging in multiple perspectives (i.e., knowledge pluralism; Parsons et al., 2016; Bingham et al., 2021). As our organizations' relationship deepened, our ways of knowing expanded, and the quality of project ideas evolved towards those that better intertwined shared goals and had tangible outcomes. Working across intersecting differences—those of culture, gender, geography, institution, and sector—requires time, trust, and respect built through a commitment to a shared set of values and the

TABLE 4 | Open design questions and considerations.

Deployment	*How can we support people in developing deployment plans?* Some participants have significant experience in and around the water but not in deploying tools in the deep sea. Options—including physical hardware and training—for deployment should be developed and shared with users. Duration of deployment was a question that came up a lot, as well as stability of the system in high-current or otherwise difficult environmental conditions. The community around Maka Niu may be able to help provide support and best practices for deployment-related challenges.
Sensor Development	*What additional sensor modules should be prioritized for development?* The environmental sensor modules are a value-add for researchers and educators alike. While our research suggests which sensors may be most useful to work on in the immediate future, there is less consensus about the prioritization of future modules.
Software	*How can we make the software (both camera mission programming and data analysis) easy to use and robust?* We repeatedly heard the need for mobile-friendly, accessible, and simple software solutions. The software needs to be stable and easy to use in multiple environments. UI/UX design is a major area for future research and design efforts. Low/no internet access must be taken into consideration, particularly for situations with unreliable and/or inconsistent bandwidth.
Data Sharing	*How do we balance the desire to share data with concerns about privacy and exploitation?* Our participants indicated concern about exploitation (e.g., who has access to whose data? How will it be used? Will there be a central repository? How will quality be assured?). Some participants also had copyright concerns. Data sharing is critical for global-scale analysis; however, concerns ensuring that it is done equitably and securely are paramount.
Funding	*How can we support local researchers and collaborators to take on the work?* Our interviews pointed to the need for financial support to make the use of these systems possible by people around the world. For Maka Niu and AI analysis tools to have the biggest impact, we will need to determine how to value and support local researchers and collaborators to take on the work and make it their own.
Storytelling	*How can storytelling be integrated into the use and deployment of these tools?* Information from research programs shared with the public is too often limited to the final output of an entire process of scientific and tool development, data gathering, and analyzing. How can we catalyze mutual understanding among the different communities and scientists and demonstrate a long process of learning that allows us to place the gathered information in its context and render it more concrete and impactful for everyone?

principle of mutual learning (Bratteteig, 1997; Lang et al., 2012; Parsons et al., 2016; Bingham et al., 2021; Trisos et al., 2021; Woodall et al., 2021).

5.2 Expect to Pivot Your Priorities: Viewing Expectations as a Complex Path as Opposed to a Firm Resolution Allows for Flexibility and Promotes Equitable Collaboration

The results of the interview study (Section 4) affected research and design timelines, the allocation of funds, and redirected team responsibilities. For example, less technical staff time was spent on developing additional sampling system modules for Maka Niu, while more time was devoted to technical training and support. In addition, the detailed feedback on what criteria an AI video analysis platform must satisfy to be ultimately adopted by the field of ocean exploration resulted in a pause of research and prototyping, then subsequently a reorganization of the approach (Section 4.4.2), which involves new funding and the collaboration of numerous partners and organizations. To arrive at a locally sustainable project, where all partners feel ownership and gain some benefit, early action should be taken to include individuals having a variety of different perspectives and critically reflect on assumptions that underlie your priorities. Open dialogue around individuals' or groups' priorities and expectations can facilitate project planning that aptly addresses social equity, feasibility, necessary compromise, accountability, and resilience to unexpected and unanticipated course corrections (Tebes, 2018).

5.3 Consider the Accessibility of Low-Cost Tools : The Low Financial Risk and Ease of Deploying Low-Cost, Low-Logistics Oceanographic Tools Make Them a Powerful Driver for Capacity Development, Technical Training, and Novel Field Deployment Opportunities

Building on the experience of My Deep Sea, My Backyard (Amon et al., 2022d), the priority for Maka Niu was to create a high-fidelity prototype of a deep-sea camera and sensor system, quickly getting the system in its early phase of development into the hands of as many test users as possible for feedback (Novy, Kawasumi, et al., in prep). Unanticipated, the collaborative-design research revealed that the potential impact of such a low-cost system appeared tied to the tools' dollar value. Several interview participants reported that Maka Niu, with a material cost of <$1000 USD, will be in a low-stakes realm where it is seemingly more approachable, experimental, and versatile. For example, the low-logistics design and low-cost build make it easier for test users to view the Maka Niu prototype as an opportunity to take on new hardware and software skills and deploy it in new conditions and locations, without fear of great financial risk. Participants explicitly stated their intention to try deploying Maka Niu in areas they've long been interested in exploring and sampling, but the conditions were not conducive with their existing larger and more expensive equipment.

5.4 Create Opportunities for Capacity Development: Consider the Engineering Design Process and Open Hardware as Opportunities for Capacity Development

To accomplish the Ocean Decade's challenge of "skills, knowledge, and technology for all" (IOC-UNESCO, 2020; IOC-UNESCO, 2021), the transfer of marine technology—including data collection, analysis, and management tools—and the skills necessary for development, operation, and maintenance of those tools are required. Currently, Maka Niu test users participate in the engineering design cycle—lab and field testing, collecting data, identifying issues, and iterating to improve the system. Through this exposure, test users new to engineering may build valuable hardware and software skills that could translate to the in-country maintenance of these tools, a need identified by multiple interviewees. In addition, our goal is to make these designs open source so that anyone can use them to build–and modify–their own systems. By including partners in the engineering process and making designs and data openly available, we hope that a new model of technology capacity building will emerge, leading to locally-led community of practice that eliminates the dependency on outsider expertise or technical support and development (de Vos, 2020; Stefanoudis et al., 2021; Asase et al., 2022; de Vos, 2022; Harden-Davies et al., 2022; Johnson et al., 2022). These efforts go beyond collaboration and help avoid "parachute science" by responding to the realities on the ground and to what skills people would like to acquire (Genda et al., 2022; Asase et al., 2022).

5.5 Dedicate Sufficient Resources: Ensure Appropriate Time, Funding, and Other Resources Are Allocated to All Steps Above and for the Long-Term, as Needed and Desired by Collaborators

While pressures from research and funding timelines can accelerate the pace of design and development work, we have learned that a slow and thoughtful approach results in increased trust between partners and allows for pivoting in response to what is learned along the way. This shift in mindset also requires funders' understanding that the co-design process takes time and does not always proceed linearly. Unfortunately, much funding is short-term and project-based versus long-term and visionary, forcing work to be completed within an arbitrary timetable that may not be appropriate, particularly for those projects that require long-term relationship-building. It is also critical to compensate people for their time and expertise in the participatory design process. While some design projects expect people to participate simply because they care about the challenge, not compensating participants is unrealistic about the demands on human time and attention and can lead to exploitation. Finally, time spent on the personal growth and development of researchers and organizations is well spent on cross-cultural collaboration. All organizations should consider taking additional time to educate themselves on issues related to exploitation, marginalization, and colonization, as well as positions of privilege, power, and access (Bennett et al., 2021; Trisos et al., 2021; Amon et al., 2022a).

5.6 Follow Through on Commitments: Focusing on the Ideal, Far-Future Outcomes of Co-Design, Co-Development, and Co-Management Projects Will Demand Accountability Among Partners and Operational Planning for a Long-Term Thriving That Grows and Evolves Under the Leadership of Local Ocean Experts

Common causes of failure in collaborative design projects are the lack of sustainable funding, mismatch in stakeholder priorities and benefits gained from the work, and competing demands of other commitments (IOC-UNESCO, 2021). Relationship building helps create a culture of long-term collaboration. However, establishing a code of conduct or a framework to assess the fairness and sustainability of the project's time and resource demands on each partner is essential for overcoming challenges to its success. This framework may take the form of measuring impacts and progress toward capacity development and the transparent documentation of success and failures, as well as conscientious monitoring of ongoing funding, staffing time, needs being met, and project milestones (Bennett et al., 2021; Harden-Davies et al., in review). Ultimately, an inclusive plan should be developed for the project to become financially sustainable, and entirely locally run as it evolves per the needs of local ocean heroes and communities (WWF, 2015; de Vos, 2020; de Vos, 2022; WWF, 2020).

6 CONCLUSION

Historically, deep-sea technologies have been inefficient, expensive, and inequitably distributed around the globe. Deep-sea data are siloed, controlled, unstandardized, and fragmented (Brett et al., 2020). Now, it is not only possible, but critical, to create powerful, low-cost, robust deep-sea sensing systems and share, aggregate, and analyze data on a massive scale. Tremendous changes to the system are not only possible but are on the near horizon.

We are at a critical moment in time. The emergence and expected proliferation of low-cost sensors and systems, combined with the power of cloud computing and AI-driven analysis, could widen the gap between those who have access to the deep sea and those who do not, thus exacerbating the existing inequities in deep-sea exploration and research. Or, if undertaken with an intentional and collaborative design approach, these technological changes could usher in an inclusive and equitable future for deep-sea exploration and research. By building balanced relationships with each other and remaining open and flexible to the perspectives and requirements of others, we can successfully design and deploy new systems–both technological and human–to enable new opportunities for exploration, research, collaboration, and discovery.

We challenge the deep-sea community to address the issues with access to the field of deep-ocean exploration by breaking down the barriers, both technical and human. Only by making the tools and systems significantly more accessible, efficient, and inexpensive will we make meaningful progress toward exploring the deep sea, thereby better understanding this critical biosphere and our impact on it. The data and learnings presented here are our first steps along a long-term path of continued co-development of accessible technologies and holistic capacity development activities dedicated to increasing access to and broadening participation in deep-ocean exploration.

DATA AVAILABILITY STATEMENT

The raw data supporting the conclusions of this article, with the exception of identifying information, will be made available by the authors, without undue reservation.

ETHICS STATEMENT

Ethical review and approval was not required for the study on human participants in accordance with the local legislation and institutional requirements. Written informed consent for participation was not required for this study in accordance with the national legislation and the institutional requirements.

AUTHOR CONTRIBUTIONS

KB, JSC, AH, MQ, KC conceived and designed the study. KB, JSC, AH, MQ, KC, DA, RR, LK, AV, ST, JEC, VW, ZF, KN, ML, SB, AK, JS, CB, NL, BK, CM, TN, PG participated in and executed the study. KB, JSC, AH, MQ, KC, DA, RR, LK drafted the article. AV, ST, JC, VW, ZF, KN, ML, SB, AK, NL, PG critically revised the article. All authors gave approval of the submitted version and agree to be accountable for all aspects of the work.

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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.2022.873700/full#supplementary-material

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Transects in the deep: Opportunities with tele-operated resident seafloor robots

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Scientific, industrial and societal needs call urgently for the development and establishment of intelligent, cost-effective and ecologically sustainable monitoring protocols and robotic platforms for the continuous exploration of marine ecosystems. Internet Operated Vehicles (IOVs) such as crawlers, provide a versatile alternative to conventional observing and sampling tools, being tele-operated, (semi-) permanent mobile platforms capable of operating on the deep and coastal seafloor. Here we present outstanding observations made by the crawler "Wally" in the last decade at the Barkley Canyon (BC, Canada, NE Pacific) methane hydrates site, as a part of the NEPTUNE cabled observatory. The crawler followed the evolution of microhabitats formed on and around biotic and/or abiotic structural features of the site (e.g., a field of egg towers of buccinid snails, and a colonized boulder). Furthermore, episodic events of fresh biomass input were observed (i.e., the mass transport of large gelatinous particles, the scavenging of a dead jellyfish and the arrival of macroalgae from shallower depths). Moreover, we report numerous faunal behaviors (i.e., sablefish rheo- and phototaxis, the behavioral reactions and swimming or resting patterns of further fish species, encounters with octopuses and various crab intra- and interspecific interactions). We report on the observed animal reactions to both natural and artificial stimuli (i.e., crawler's movement and crawler light systems). These diverse observations showcase different capabilities of the crawler as a modern robotic monitoring platform for marine science and offshore industry. Its long deployments and mobility enable its efficiency in combining the repeatability of long-term studies with the versatility to opportunistically observe rarely seen incidents when they occur, as highlighted here. Finally, we critically assess the empirically recorded ecological footprint and the potential impacts of crawler operations on the benthic ecosystem of the Barkley Canyon hydrates site, together with potential solutions to mitigate them into the future.

KEYWORDS

internet operated vehicle, crawler, intelligent marine monitoring, (semi-) permanent mobile robotic platforms, remarkable observations, animal behavior, ecological footprint

1 Introduction

Direct and indirect human pressures on marine ecosystems will intensify rapidly during the coming decade. This will result in an even more severe loss of marine biodiversity and ecosystem services (Danovaro et al., 2008; Danovaro et al., 2017). To support conservation efforts for these ecosystems, it is important to adapt and integrate new monitoring guidelines, data acquisition protocols and cost-effective technologies (Gann et al., 2019; Aguzzi et al., 2020b; Fanelli et al., 2021). Intelligent (i.e., highly autonomous and robotic-sustained) monitoring, not only on a scientific and logistical level but also from the point of view of operational sustainability, is seen as increasing in necessity within the EU's Marine Strategy Framework Directive (Heiskanen et al., 2016) and the UN's Decade of Ocean Science for Sustainable Development (Ryabinin et al., 2019). The importance of this automated approach is highlighted by entities such as the Intergovernmental Panel on Climate Change - ICCP (Bindoff et al., 2020) and the Intergovernmental Science-Policy Platform on Biodiversity and Ecosystem Services - IPBES (Díaz et al., 2019), rendering the development of automation as one of the grand upcoming challenges for ocean science (Borja et al., 2020).

The increasing interest in spatiotemporally structured monitoring programs has resulted in the rapid and spectacular development of marine robotics in this field during this past decade. Additionally, ecological monitoring has been supported with a plethora of developing platforms designs (Aguzzi et al., 2021). A new CONcept of OPerationS (CONOPS) needs to be developed, allowing the implementation of cost-effective technology solutions which rely to a much lesser degree on expensive ship-time, allowing personnel to remain on shore to remotely monitor and support research missions and monitoring plans (Jones et al., 2019; Howell et al., 2020). In this paradigm shift, semi- or fully resident underwater monitoring vehicles are needed to regularly cover large areas of the seafloor under acceptable operational costs and with a minimum environmental impact (Marini et al., 2020; Smith et al., 2021; Zhang et al., 2021). Following this approach, cabled observatories are becoming the core of *in situ* marine ecological laboratories, defining operational control fields for docked mobile platforms, which can even manipulate the environment (Aguzzi et al., 2019).

Here we provide data and examples of use from one such resident robot; the crawler "Wally", an Internet Operated Vehicle (IOV) in use at the cabled Ocean Networks Canada's (ONC) NEPTUNE observatory (Barkley Canyon, off the west coast of Vancouver Island, Canada, NE Pacific) [1]. Operational since 2010 (Purser et al., 2013), this tele-operated robot has gained interest from both industry and science, with additional deployment sites planned for the Mediterranean, the Atlantic, the Norwegian Sea, China, and along the coastlines of Germany, either cabled or untethered to the hosting platforms. A preliminary use of a coastal prototype is foreseen for European Multidisciplinary Seafloor and water column Observatory (EMSO) testing sites such as the OBSEA (NW Mediterranean) and SmartBay (N Atlantic) (e.g., Falahzadeh et al., in review). In parallel, autonomous versions (i.e., "Rossia" advanced model) have been developed for deployment at LoVe (Lofoten) and the Hausgarten site of AWI off Svalbard, or connected to a surface buoy for the detection of UXO (unexploded ordnance) in the Baltic Sea and North Sea (e.g., Aguzzi et al., 2020a). In the untethered mode, a dragged communications buoy is towed behind the vehicle on the surface, connected by a cable which facilitates allows fast radio-frequency or WiFi communication with an operational center located kilometers away.

Within the first 7 years of deployment, this resident crawler has improved our understanding of biogeochemical, oceanographic and ecological processes at the deep-seafloor of a methane cold seep in a submarine canyon. In particular, we have gained insight on the spatial and temporal variability of methane seepage into bottom waters under varying flow conditions, the importance of benthopelagic coupling in the form of carbon fluxes to the deep sea during winter (i.e., fresh chlorophyll reaching the seep site), the effect of oceanographic conditions on the diel rhythmic activity and seasonality of megafauna, the spatial distribution of fauna in relation to seepage and chemosynthetic food supply, and aspects of benthic animals' reproductive behavior (Thomsen et al., 2012;

1 https://www.oceannetworks.ca/introduction-barkley-canyon

Chatzievangelou et al., 2016; Thomsen et al., 2017; Doya et al., 2017; Chatzievangelou et al., 2020a). In addition, technical crawler performance assessments were carried out in parallel; including the design and integration of imaging and data treatment protocols, scientific bias and ecological footprint assessment (Purser et al., 2013; Doya et al., 2017; Chatzievangelou et al., 2020a; Chatzievangelou et al., 2020b).

Discoveries and observations were made during the 24/7 deployments, by pilots operating the crawler in its environment in Barkley Canyon from diverse locations worldwide. A number of these observations have not been published as part of scientific papers to date. Nevertheless, they can provide important information on animal behavior, distribution and the site's morphology, which should be considered when designing upcoming monitoring projects with the crawler in this and other sites, and in guiding future research endeavors. We will present a selection of these observations, many of which may grow into statistically significant datasets in future years, to serve as an example on how to improve protocols for deep-sea ecosystem monitoring. We also critically evaluate the footprint of such resident robots on the faunal and physical composition of deep-sea sites monitored with crawler platforms. This knowledge can be used to support the development of a new framework for the interpretation of animal behavior, considering the influence of the monitoring platform, to improve monitoring efficiency (e.g., *sensu* Ayma et al., 2016).

2 Methods

2.1 Study site

The Barkley Canyon hydrates site is located on a plateau of the west wall of the canyon, at a depth of approximately 870 m. The monitored surface extends over approximately 400 m^2 and is characterized by soft seabed and the presence of short (i.e., ~ 2 m) mounds with visible hydrate outcrops on the west side. The depth differences across the site are < 10 m from the highest peak to the lowest trough, with recorded observations not spread across a particular bathymetric gradient of significance within these depths. Figure 1 shows a schematic representation of the site, the main morphological features and positions of several selected observation spots for which the exact position may hold an ecological importance.

2.2 Crawler description, capabilities, instruments and data

The "Wally" crawler is an approximately 1 m^3, cubic-shaped IOV, which moves on caterpillar tracks. It is connected to an *in situ* central junction box through a 70 m long tether cable, although a further limitation on operational range is the morphology and characteristics of the seabed, preventing full cable extension due to seafloor elevations, or suitability of seafloor for movement (i.e., not too steep, or too soft). The crawler is occasionally removed for servicing and to swap instrumentation, and sensor payloads have varied by deployments in terms of specific sensor models, but in all cases the payload has included one or two cameras (i.e., a forward facing camera for driving and at times a lateral facing camera of higher quality, for observations during transits), a CTD, an ADCP, and sensors for turbidity and concentration of chlorophyll and methane. As marine camera technologies have advanced throughout the last decade, the quality of the footage has varied from 480 pixels to full HD 1080 pixels between deployments, while different types of lasers (i.e., point-lasers and line-lasers) have been used for sizing and 3D scanning.

The crawler weighs ~ 50 Kg in fresh water, including the cable. In practice, this translates to a 0.35 m^2 footprint on the seafloor, applying a weight of ~ 10 g/cm^2 (Purser et al., 2013). These values are comparable to those reported for the abyssal benthic rover deployed at Station M (Smith et al., 2021). Depending on the number of cameras, illumination is provided by either two or three 33 W LED lamps (i.e., two facing forward for driving and the third one serving as light for the lateral facing camera).

All data (numeric output of the instruments, images and video recordings) are stored on collection in an onshore database, and made publicly available *via* the Ocean Networks Canada Oceans 3.0 Portal[2].

2.3 Missions and transects

The crawler has been deployed to traverse specific paths within its operational radius, primarily along an E-W axis, and also to observe the various aspects of the hydrate mound within the western survey area (Figure 1). As precise odometry and navigation are still in development, numerous numbered markers were deployed across the site to provide positional information of the crawler, distances or the precise location of landmark observations.

A southern path, shorter (i.e., ~ 20 m) and straight, was used for linear imaging transects in the first half of the decade. The northern path was longer and partly winding (following the morphology of the seabed and the presence of features of interest such as the hydrate mounds), and it was mostly used for transects during the later deployments.

Transects were performed at a constant speed of ~ 5 cm/s and the imaging mode varied between missions, depending on the specific objectives of each experimental survey (e.g., continuous, forward-looking video recording or time-lapse

2 https://data.oceannetworks.ca/home

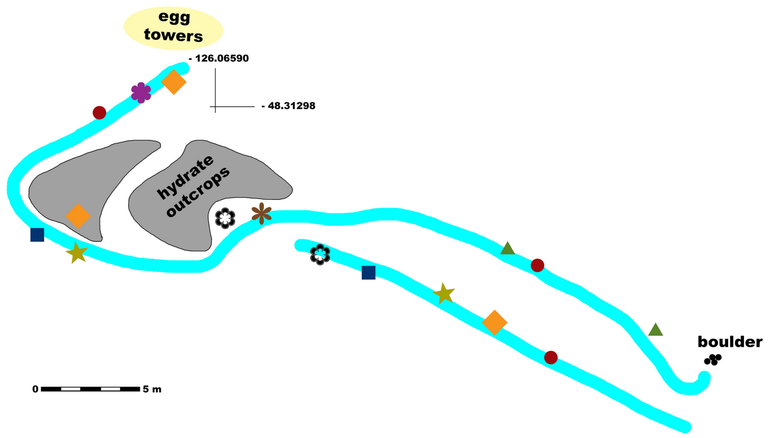

FIGURE 1
Schematic map of the study site (Barkley Canyon hydrates, 870 m depth) with marked locations of several observations. The main transect lines are represented in light cyan. Observations of jellyfish carcasses; decaying macroalgae; sablefish positioning themselves facing against the current; Opisthoteuthidae octopus encounters; aggregations of small crabs; adult crabs with severed limbs; recorded crab aggression; and crab mating behavior are represented by dark red circles; olive-colored stars; green triangles; dark blue squares; orange diamonds; purple, thick flower symbols; brown, thin flower symbols; and black empty flower symbols, respectively.

sideways-looking imaging). As an alternative to transecting, at times the crawler moved to survey spots of interest, where it remained stationary for periods to capture still images or rotating video-scans.

3 Selected observations and monitored events

3.1 Morphological and structural features

As a mobile, resident monitoring vehicle performing transects along marked seafloor stations, the crawler has been able to make spatially geo-referenced observations and record features on the seabed which might have been missed by other mobile, sporadically deployed vehicles (e.g., ROVs, AUVs, towed or drift-cameras) which are vessel-dependent and are not capable of spatiotemporally repetitive and intensive monitoring across the extended temporal scales achievable with the crawler (Bicknell et al., 2016; Dominguez-Carrió et al., 2021). Similarly, fixed platforms (e.g., lander cameras) have a restricted field of view which limits the ecological representation capability of acquired data spatially, though achieving the temporality capable with the crawler platform (Rountree et al., 2020).

3.1.1 Snail towers

Reproductive strategies and phenology in many deep-sea animals are still largely unknown (Danovaro et al., 2014; Danovaro et al., 2020). In gastropods in particular, food availability may trigger specific strategies or aggregations which are otherwise inhibited as too expensive from an energetic point of view (McClain et al., 2014). In April 2014, a dense aggregation of buccinid gastropods was encountered on the western flank of the gas hydrate mound monitored by the crawler (Figure 2A). Close examination showed that these gastropods were in the process of secreting egg towers – defensive nursery structures from which snail juveniles would eventually hatch, also reported in other NE Pacific seeps[3]. In this initial visit, towers were no more than 5 cm in height.

In November 2014 the egg tower site was revisited, and the 5 m^2 area was now abundant with ~ 100 perpendicular, ~ 20 cm tall snail towers (Figure 2B, Supplementary Video 1). Only occasional gastropod shells and fish of the family Sebastidae (i.e., rockfish *Sebastes* and thornyheads *Sebastolobus*) were observed amongst the tower matrix, contrasting with the hundreds of snails observed in April. These egg towers added local structural complexity and habitat niches to the environment (Levin and Dayton, 2009). A subsequent survey in January 2015 showed no observable change in the tower matrix, with occasional adult gastropods and Sebastidae still observed between the towers.

The area was revisited in late summer of 2021, and patches of egg towers were observed and recorded on video (Figure 2C and Supplementary Video 2). Many of the towers were no longer present, and those still present were thickly covered with filter feeding fauna, potentially bryzoans and/or hydroids. Sebastidae

3 https://oceanexplorer.noaa.gov/explorations/20cascadia-seeps/logs/sept27/welcome.html

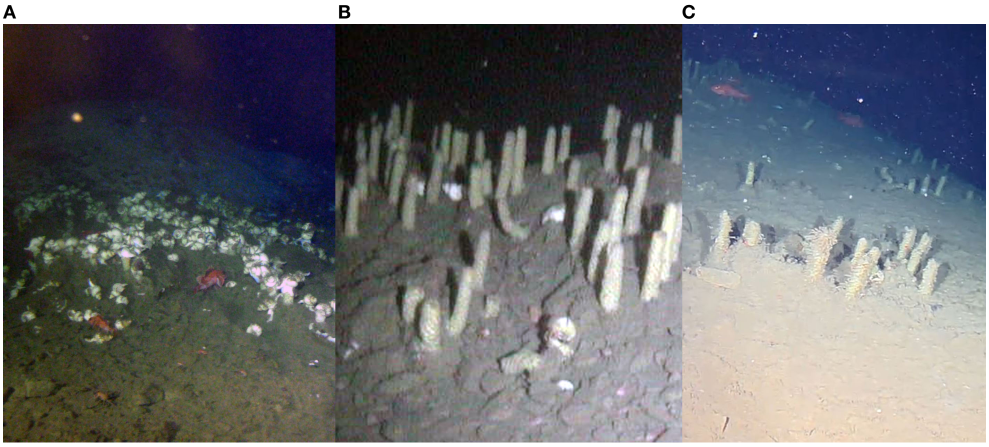

FIGURE 2
Egg towers of buccinid snails, located between two hydrate mounds. **(A)** Snail aggregation covering the seafloor from the point at which bacterial mats were visible on the hydrate mound, and down the flank (image taken on April 22 2014). **(B)** Fully developed and dense egg towers, with only a handful of snails present (image taken on November 06 2014). **(C)** Remnants of the tower field (image taken on August 31 2021). Note the patchy distribution, as well as the varying decaying state of some of the towers.

again dominated the terrain between the towers, with the occasional pacific hagfish *Eptatretus stoutii* and crabs (i.e., grooved tanner crabs *Chionoecetes tanneri* and, more rarely, big scarlet king crab *Lithodes couesi* individuals).

The comparison of footage from the different deployments is expected to shed more light on various aspects of the reproductive behavior of buccinid snails in Barkley Canyon. Observations to date indicate that snails are abundant in the study area. From these initial observations, it would appear that gastropod spawning is occasional across the region, and not repeated on an annual cycle. Continued, long-term observation will allow us to determine the timing of their egg deposition and hatching, and the spatial distribution of the tower fields. Remnant material from the reproductive event increased the habitat complexity of the gas hydrate mound and provided both a habitat for mobile fish and crab fauna, as well as a suitable hard substrate for colonization by filter-feeders. By analyzing the abundance, distribution and overall diversity of other fauna species, we can obtain information on the effect of the presence of the towers on a community level.

3.1.2 Boulder microhabitat as a set for high resolution fauna interactions

Approximately 40 m away from the main hydrate mound, a boulder of approximately 50 cm diameter was first imaged on March 27 2014. A selection of the images from repeated visits made to the boulder over the following months (and years) are given in Figure 3. As a rare example of hard substrate in a site otherwise characterized by soft sediment, the boulder was clearly colonized by numerous encrusting sponges, with the hard, cracked surface providing habitat niches for shrimp and galatheids (Figure 3A). Closer examination showed the boulder to be fringed with unidentified harpacticoid shrimps (Figure 3B).

As a site of interest, the boulder was revisited after 4 days. In Figures 3C, D (images taken 4 days after Figures 3A, B), a nudibranch was also present on the rock encrusting bryozoan/ hydrozoan epifauna, beneath the swaying harpacticoid shrimp individuals. In Figure 3D a chain of eggs has been attached to the bryozoan colony, although it is unclear if it belongs to the nudibranch. Just over a week later (April 08 2014), in Figures 3E, F, the nudibranch has left the bryozoans and moved some cm away. The eggs however were still evident, surrounded by a slightly reduced number of harpacticoids, possibly the result of nudibranch predation. In Figure 3E a rockfish individual was observed utilizing the boulder as refuge or hydrodynamic trap.

From this brief time-series numerous interesting observations were apparent. The harpacticoid species' behavior deep within the canyon was similar to that observed at shallower sub-littoral depths (Caine, 1980). Though caprellid harpacticoid amphipods have been reported within the deep sea, and indeed at methane seep sites, observations have been 'snapshots' rather than time-series behavioral studies (Sibuet et al, 1988). The timing of the egg deposition is also of interest – corresponding with annual surface productivity blooms within the area (Juniper et al., 2013). Reports on interspecific interactions between nudibranchs and caprellids up to now have described mainly antagonistic/competitive relationships (e.g., Caine, 1998; Ros and Guerra-García, 2012), therefore further data are needed in order to determine whether the eggs deposited in the caprellid

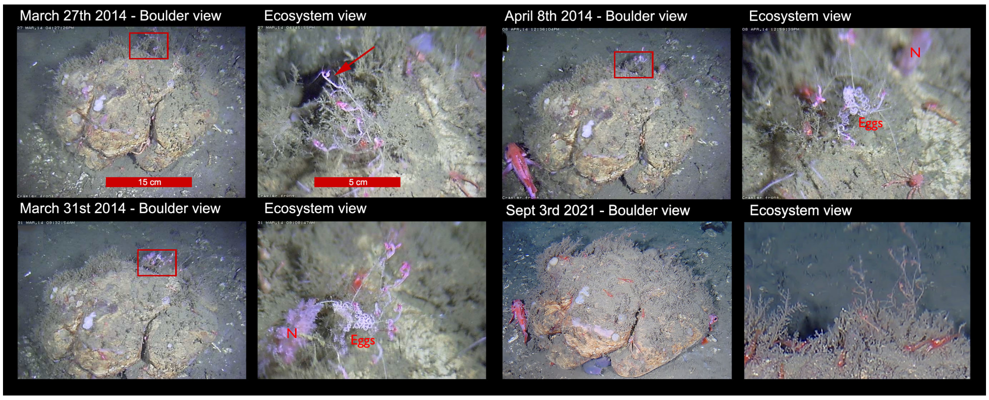

FIGURE 3
Boulder providing several niches colonized by galatheids, rockfish and harpacticoids, and the short (i.e., weeks) and long (i.e., years) term evolution of this small ecosystem. Two images (i.e., a view of the entire boulder -letters a, c, e, and g- and a zoomed part defined by a red rectangle -letters b, d, f, and h-) are provided for each observation. The red arrow points towards a harpacticoid shrimp on top of biogenic (bryozoan) substrate, while the red "N" indicates a nudibranch.

rich bryozoan/hydrozoan branches rather than the unoccupied thickets elsewhere on the boulder were indeed nudibranch eggs.

On a different temporal scale, revisits to the boulder feature in September 2021 indicated the long-term use of the boulder by both rockfish and galatheid squat lobsters, occupying the same spots as individuals of their species in 2014 (Figure 3G). Likewise, the bryzoa/hydrozoa and caprellid relationship was still evident on the fringes of the boulder (Figure 3H). Additional information on sponge growth and longevity may also be gleaned from this time-series data if monitored into the future, with any new settling sponges being observed over time as they develop and grow on the boulder surface.

3.2 Episodic events

The input of fresh biomass in the form of phytodetritus or carrion is an important carbon source that contributes to deep-sea ecosystem functioning (e.g., Van Nugteren et al., 2009; Dunlop et al., 2016; Stratmann et al., 2018). The continuous operations of the crawler allowed for the observation and recording of multiple episodic events (see below) unlikely to have been recorded by any single research cruise. Long-term observations during winter with the crawler revealed the importance of winter storms and downwelling on the export of fresh phytodetritus, showing that winter can be as important for its transfer to deep-sea areas as the period from spring to autumn, despite much lower primary production rates (Thomsen et al., 2017). These phytoplankton pulses disappeared already during and up to the 2 days after bad weather affected the area, and reached the study site at 870 m water depth with a delay of up to two days.

3.2.1 Mass transport of large gelatinous particles

For ~ 20 hours in October 2010, a lateral advection of disintegrated gelatinous particles which resembled shredded jellyfish or salps at 0–2 m height above the seafloor was recorded during a downwelling event (Figure 4). The observations underline the fact that canyons can act as conduits for the transport of organic carbon to the deep sea, either as marine snow, macroalgae (kelp) or carcasses and have been reported elsewhere (e.g., Sweetman and Chapman, 2011; Henschke et al., 2013; Sweetman et al., 2014) but rarely the event itself (e.g., Smith et al., 2014). While turbidity meters can detect such events, the actual shape and size of these particles cannot be determined unless particle cameras (e.g., Nowald et al., 2009) become available in future deployments.

3.2.2 Jellyfish consumption by scavengers

Closer observations of the sedimented seafloor during the October 2010 event revealed that decapod crustaceans were feeding on jelly carcasses in different phases of decomposition. On several occasions, even entire jellyfish were observed laying on the seabed, either in deteriorating state (Supplementary Video 3) or actively being consumed by scavenging decapods such as grooved tanner crabs (Figure 5A). On December 08 2021 another entire jellyfish was observed being transported by currents along the seabed, before settling (Figure 5B). Due to this displacement, the carcass had not yet started to be consumed by benthic scavengers. Future research can reveal the decomposition time of this biomass input, in relation to hydrodynamic conditions (does the carcass settle or gets dragged by currents)?, scavenging by the resident benthic community or transient, opportunistic and possibly attracted

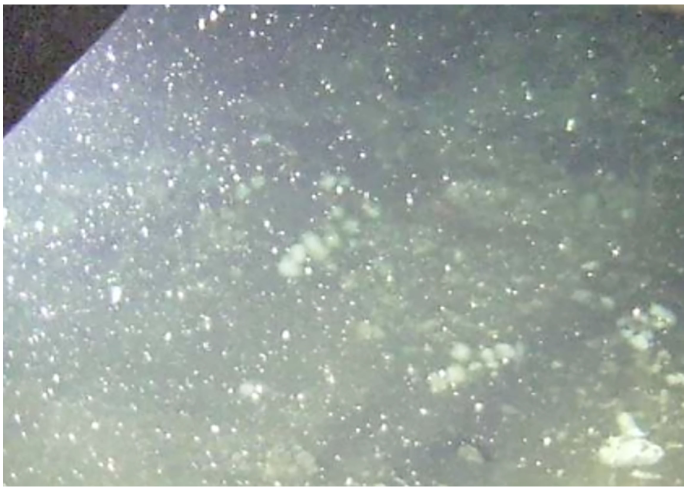

FIGURE 4
Lateral advection of disintegrated gelatinous particles, as an example of a rare biomass input from shallower waters. Note the technical difficulties in determining the depth of view and the shape of the particles, and as a result, the challenging estimation of their size in order to calculate fluxes.

species (e.g., Aguzzi et al., 2012), and finally natural decomposition times.

3.2.3 Shallow algae transport

During a transect on August 28 2021, a vibrant, orange-colored piece of surface-originated macroalgae, was observed on the seabed. The crawler did not approach too close initially, as the mass was relatively bulky and we could not determine whether it consisted of fish eggs or some other biogenic feature. Thus, the pilot followed a policy of minimum disturbance by staying at a safe distance. The algae in contact with the seabed and rippled in response to the movement of bottom waters without being displaced for some minutes, before finally detaching from the seafloor and being transported for a short (i.e., < 1 m) distance by the current (Supplementary Video 4).

Some days later (August 31 2021), close up images were taken from distance nearer proximity and stages of the decaying process were monitored, until the algae disappeared a week after its first appearance (Figure 6). It is reasonable to assume that, following removal of much of its mass, the remains were detached from the seabed and transported out of the monitoring area by the ambient seafloor currents, at a minute-averaged down-canyon velocity of ~ 11 cm/s (maximum > 50 cm/s), as recorded for the period of time between the last sighting of the algae and the next visit of the resting spot, at which point its absence was observed.

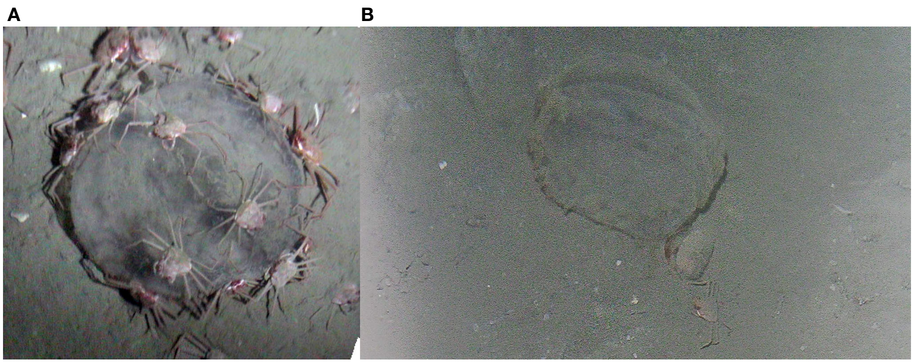

FIGURE 5
Jellyfish laying on the seabed. **(A)** The carcass is being scavenged by numerous small individuals of grooved tanner crab (image taken in October 2010). **(B)** Consumption of the carcass has not started yet, although a tanner crab individual is visible (image taken on December 08 2021).

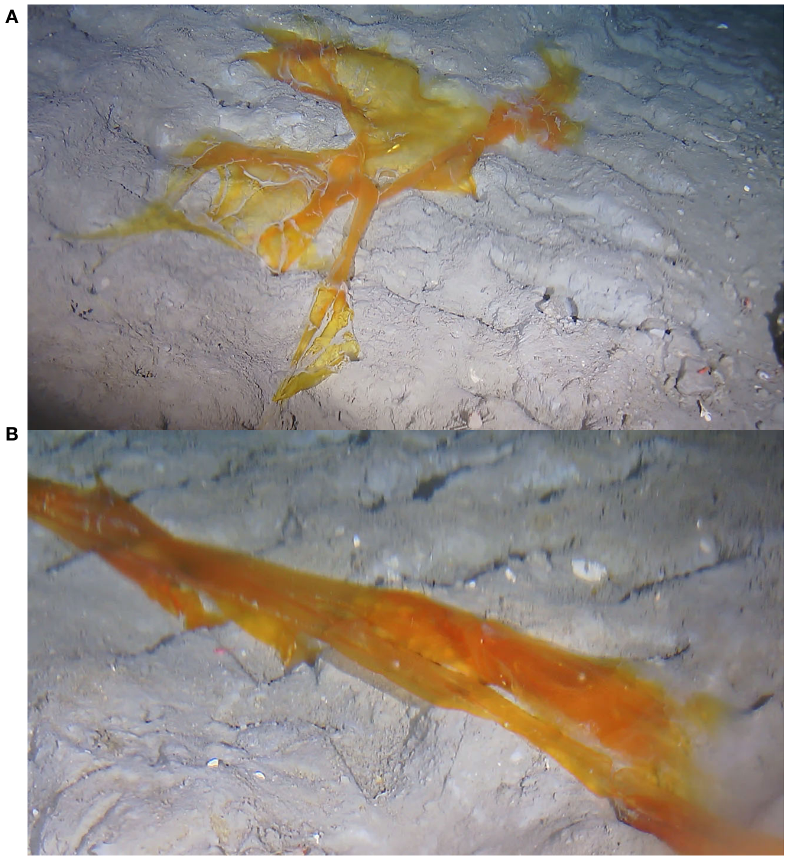

FIGURE 6
Piece of macroalgae, vertically transported to the hydrates site from the surface layers of Barkley Canyon. **(A)** Three days after the first sighting (image taken on August 31 2021). **(B)** Five days after the first sighting on the seabed (image taken on September 02 2021).

Pieces of brown macroalgae have also been observed on various occasions (e.g., Supplementary Figure 1). Opportunistic observations like these, hard to be specifically targeted for studies in deep-sea research, can illuminate questions on the triggers (e.g., surface storms) of vertical transport of fresh plant biomass to deeper waters through canyons during downwelling events (e.g., Zheng et al., 2017), and the role of such material and occasional events in supporting deep ecosystems alongside the regular and/or episodic input of smaller phytodetritus (Baker et al., 2018). Such data are rare; nevertheless, they provide observations of down-canyon transfer of macroalgae which enable discussions on their potential role in carbon sequestration (Pedersen et al., 2021). No direct consumption by fauna was observed with the crawler, underlining the importance of such studies on sequestration. Conventional ROV operations would not allow such observations over extended time, which only resident ROVs would do (McLean et al., 2020).

3.3 Faunal behavior and interactions

Ethological information on displacement rhythms of fauna, bioturbation, feeding rates or predator-prey interactions is of pivotal importance for better understanding the life traits of deep-sea species (Danovaro et al., 2014; Melo-Merino et al., 2020). Unfortunately, this information still eludes standard survey practices (e.g., behavioral interactions beyond the mere time-series of animal counts). Several different behaviors of benthic fauna have been recorded by the crawler throughout the years, including various sorts of interaction between animals and the crawler. These types of observations can increase our knowledge on the impact of a monitoring platform such as the crawler may have on animal behavior. The crawler does not have acoustic imaging or passive acoustic instruments at the moment. Nevertheless, two imaging rotary sonars are deployed further away, outside its operational range (approximately 20 m away towards the east and west extremes). The sonars scan a circular area of 10 m radius (Thomsen et al., 2017). Data from these can be contrasted to, for instance, the fish counts in the crawler's footage, as there is no reason to assume that expected fish densities should differ between the three platforms other than a potential effect of the crawler.

3.3.1 Sablefish

Large groups of sablefish (~ 10 ind.) were observed resting on – or hovering above – the seabed, facing into the current (Figure 7 and Supplementary Video 5). Sablefish utilize odor plumes in their search for food (Løkkeborg et al., 1995; Sigler, 2000; Bailey and Priede, 2002), plumes which are directed by the current regime and circulation within the canyon. More data on their tactic behavior (i.e., response to a stimulus by modifying their orientation and/or locomotion) could be used as an indicator for the origin of food, and also to explain their reported migration patterns across different Barkley Canyon depths (Doya et al., 2014; Chatzievangelou et al., 2016).

Sablefish have been observed interacting with the crawler in different ways. Indicatively, sablefish individuals within the range of the crawler's lights (a few 10s of m, depending on the turbidity of the water, which influences light transmission) have approached the vehicle in a check-and-go act of curiosity. On rare occasions, sablefish approached the crawler at speed and shifted their direction in the last moment to avoid collision, although in one instance, a sablefish swam into the sphere containing the camera. Figure 8 provides evidence that specific sensor lights, e.g., a blinking blue light of a fluorometer, can attract sablefish when pointed at and reflected from the seafloor. Possibly, sablefish attraction to blue light reflects its visual hunting capability to spot and prey upon common bioluminescent organisms, being visual predators (Ryer and

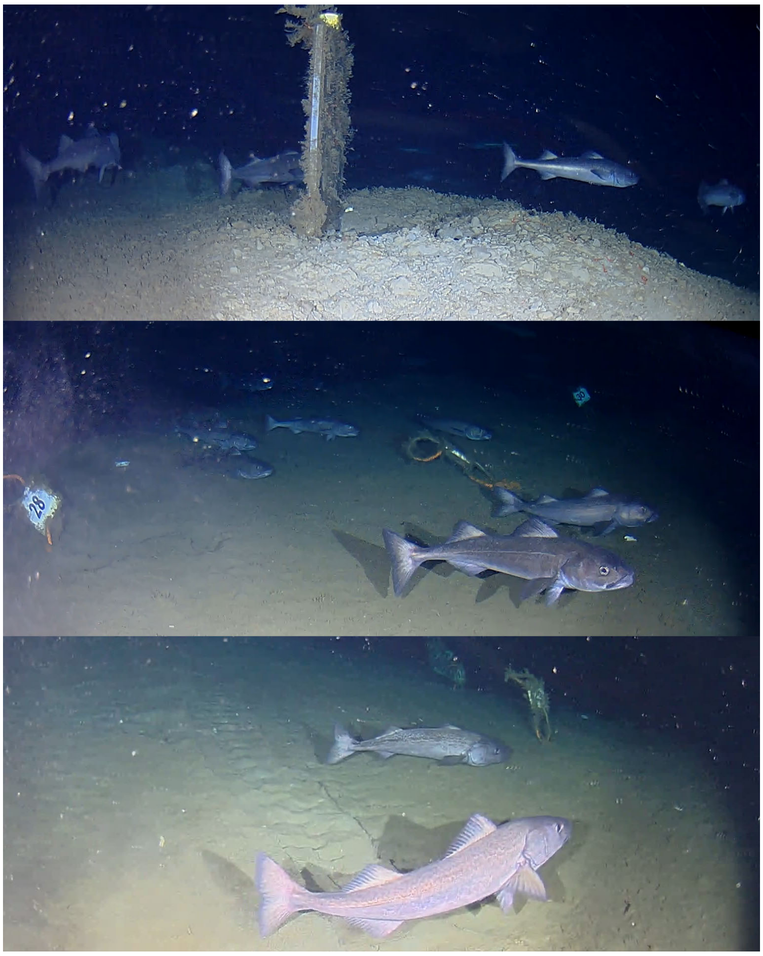

FIGURE 7
Sablefish resting on the seabed or hovering right above it, while all facing against the current (current direction from the right towards the left of the images). Images taken on August 24 2021.

FIGURE 8
Group of sablefish, resting in front of the crawler. Fish are attracted by the blue light of a WetLabs fluorometer, which creates a light stream onto the sediments.

Olla, 1999). In this particular case in 2012, a WetLabs fluorescence sensor was used for redundancy and emitted a light beam into the water column. This may have impacted on the interpretation of turbidity sensor data, as fish are attracted after several hours of recurrent blinking of the sensor's light. During their inspection of the light source they resuspend the sediments, thus sensors of this type should preferably be used only in the water column.

3.3.2 Bottom-dwelling fish

Hagfish were observed primarily prone on the seafloor, flat, coiled or semi-coiled, though they were sometimes observed swimming (parallel or even perpendicular to the seafloor). Interestingly, the angle of the animals' orientation in relation to the crawler (diagonal; Supplementary Video 6), indicated they were (to some degree) aware of the presence of the crawler, even when they did not display an explicit reaction to it. Another common behavior of this species was to swim statically and in a vertical position while maintaining the mouth fixed on the same seabed spot.

Both the deep-sea sole (*Embassichthys bathybius*) and the pacific halibut (*Hippoglossus stenolepis*) seemed barely affected by the presence of the crawler, not moving even when the crawler was at a distance of only a few centimeters, or moving away from them following a period of inactivity. Once though, a deep-sea sole followed the movement of the crawler swimming beside it for a few meters (Supplementary Video 7).

Eelpouts (*Lycenchelis* sp.) were commonly seen crossing the camera's field of view with quick changes of direction, sometimes touching the seafloor during their transit. Commonly they were observed laying on the seafloor and then suddenly burst away when the crawler got too close. At times they were observed drifting vertically, with the head facing towards either the water column above or the seafloor below. In very rare occasions these animals appeared laying on the seafloor flapping their pectoral and caudal fins, independently of their orientation in relation to the crawler.

Rockfish and thornyheads were always observed laying on the seafloor, occasionally moving several centimeters to one meter away if the crawler got too close. Many individuals showed an agonistic behavior towards the crawler (i.e., wide open mouth, flapping their fins).

3.3.3 Octopus

Over the span of 9 years, several encounters with octopus of the family Opisthoteuthidae were made. Given the time span between observations, it is unlikely that all these octopod observations were made of the same individual.

During transect missions in June 2012, the first individual was spotted laying on the seabed right on a previous track depression made by the crawler (Supplementary Video 8). The area was at the time not stable for the crawler to approach, so the pilot circumnavigated the octopus, which showed no sign of stress response.

A second individual was again detected resting in the same position during several days in November 2013 (Supplementary Figure 2). Although the animal's behavior between the periodic transects is unknown, it is possible that the octopus did not move over the intervening days. Time-intensive observations may address questions on the behavior and bioenergetics of Opisthoteuthidae octopods which are otherwise understudied, such as their preying strategies (i.e., are they actively hunting for prey or deploying a waiting strategy)?, or if they are following any circadian, infradian or ultradian activity rhythm.

Later in November 2016, there was a third encounter in similar settings (Figure 9A and Supplementary Video 9). The

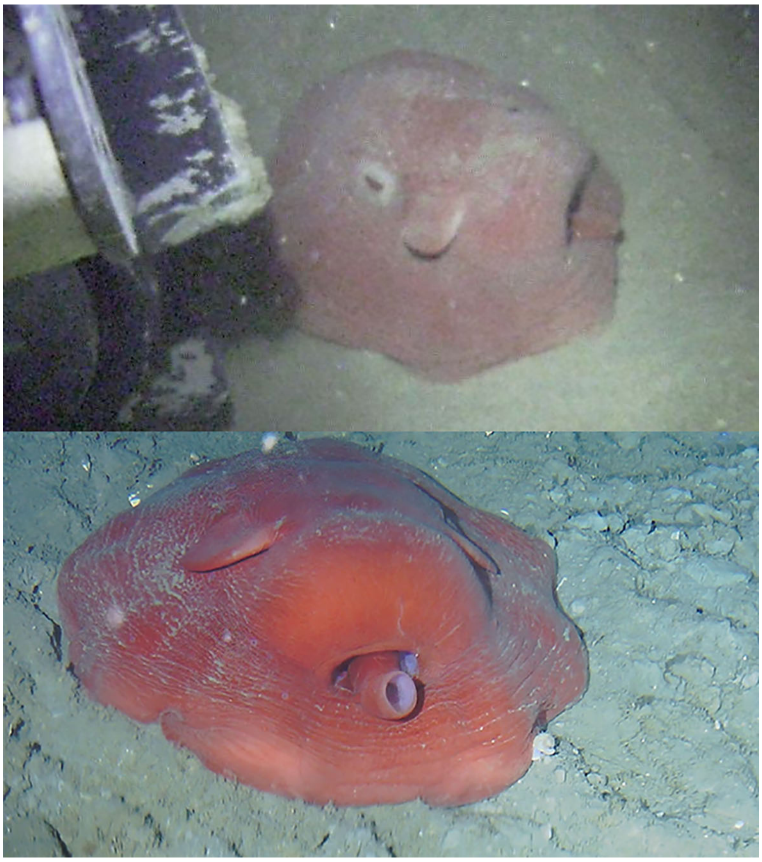

FIGURE 9
Octopus resting on the seabed in a flat-spreading position, on top of the crawler's tracks. **(A)** Note the opened eyes during the octopus' interaction with the crawler's caterpillars (image taken on November 24 2016). **(B)** Note the closed eyes while the crawler remained close to the octopus (image taken on September 13 2021).

crawler approached as close as possible, with minimum speed, and came to touch the octopus with the caterpillar. No avoidance behavior was observed from the side of the animal. On the contrary, when the crawler moved slightly backwards, it actively returned to the vicinity of the caterpillar, possibly identifying the crawler as a potential shelter against predation, rare in soft bottoms (Katsanevakis and Verriopoulos, 2004).

Finally, another specimen was recorded several times in September 2021 (Figure 9B and Supplementary Video 10), and then again on November 24 2021. The octopus did not react to the crawler's approach. On all occasions, the initial posture of the octopus was a non-threatening, flat-spreading position (i.e., horizontally extended on the seabed; Villanueva, 2000).

3.3.4 Crabs

Aggregations of small crabs, presumably small individuals of grooved tanner crab, were observed in several occasions on small elevations of the seabed or on a short hydrate mound (Supplementary Figure 3; Supplementary Video 11). Further studies are needed to understand this behavior, with small decapods previously observed climbing on seabed structures to escape the anoxic first few cm of the BBL (Doya et al., 2016), and generally aggregating as a defense mechanism (Dew, 2010).

Doya et al. (2017) reported an agonistic interaction between a grooved tanner crab and a scarlet king crab over a piece of food. Aggression between various larger crabs was observed in 2021, although the motives were not clear in the video (Supplementary Video 12). Contrary to big burrowing and territorial decapods (e.g., Norway lobster *Nephrops norvegicus*; Sbragaglia et al., 2017), grooved tanner crabs and scarlet king crabs have not been observed defending a particular spot. Overall, many individuals lacked one or several walking legs or claws, while in 2013 a scarlet red leg was observed on the seafloor (Supplementary Figures 4 and 5, respectively). In any case, limb loss can be a common phenomenon within the *Chionoecetes* genus (Edwards, 1972), while it can be a potential sign of aggressive, density-dependent interactions (e.g., dominance hierarchies) leading to autotomy (Fleming et al., 2007).

During a transect in 2021, a couple of grooved tanner crabs were observed displaying the same mating behavior previously described in Doya et al. (2017), with one individual grabbing the other, lifting it and transporting it nearby, farther away from the crawler (Supplementary Video 13). Sometimes an extra conspecific individual can be present nearby during mating, in agonistic posture (Supplementary Video 14).

3.3.5 Shrimps

Small shrimp individuals have been observed being "carried" by the crawler for various meters, laying or walking either on its frame or/and on its floating foam blocks (Figure 10), or feeding from the biofilm on the camera's glass sphere.

3.4 Marine litter

What it looked to be a rusty battery was found over one of the periodic transects of the crawler in 2013 (Supplementary Video 15). During the same deployment period and at a nearby spot, a white plastic object was observed (Supplementary Video 16). The eventual fate of these pieces of debris was not tracked in this case. Canyon circulation dynamics favor the flushing of deep-sea macro-litter (Pierdomenico et al., 2019). This is relevant to the debate of either letting deep-sea litter shelf-bury into the sediment or whether enforcing an active removal is preferable (Madricardo et al., 2020). The crawler can be innovatively used to identify litter debris as is currently done by ROV imaging (e.g., Mecho et al., 2020; Mecho et al., 2021) with the advantage of being able to track the integrity dynamics of the litter and how species interact with it.

A

B

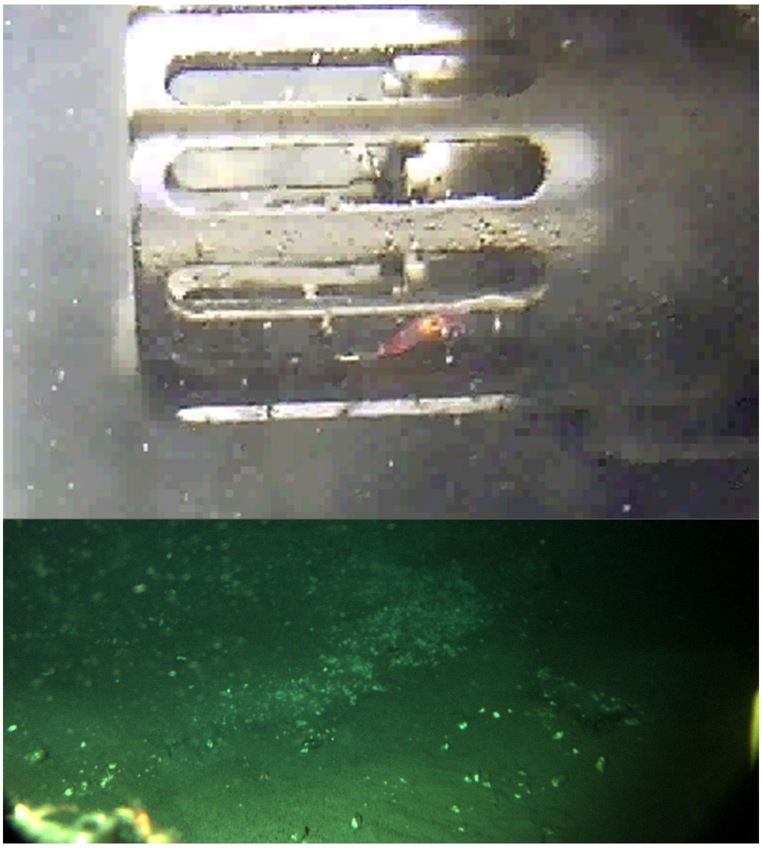

FIGURE 10
(A) Shrimp on the protective frame of an instrument (center). **(B)** Shrimps on the crawler's frame (bottom left), being carried by the crawler during a transect mission (image taken on November 11 2016). Unfortunately, as they were observed *a posteriori* in images, the camera was focusing further away on the mission's objective (i.e., hydrate mound's surface).

TABLE 1 Selected observations made with the crawler during a decade-long period (i.e., 2009–2021), alongside their ecological importance and/or operational impact.

Observations	Ecological importance	Operational impact
Snail egg towers	Snail reproductive behavior	–
	Habitat and community	
Boulder	Microhabitat and community	–
Large gelatinous particles	Transfer of organic carbon	–
Jellyfish carcasses	Deep-sea taphonomy	–
Shallow algae transport	Transfer of organic carbon	–
Sablefish taxis	Feeding strategy	Attraction
Bottom-dwelling fish	–	No reaction unless threatened
Octopus	Preying behavior	Indifference/attraction
	Activity rhythms	
Crabs	Mating behavior	Indifference/avoidance
	Aggression	
Marine litter	Deep-sea pollution	–

[a]Cells with "-" indicate that the respective observations were not relevant or not examined from the point of view of ecological importance or operational impact, respectively.

4 Discussion

Examples of observations such as those presented above are indicative of the potential of crawlers as deep-sea monitoring platforms, capable of encountering events and phenomena that would possibly be missed by short-term surveying or by fixed cabled observatory platforms, or at least highly complementary to their observations. At the same time, these observations provide valuable information useful for critically assessing the monitoring footprint of the presence and operations of such a platform on deep benthic ecosystems (summarized in Table 1 below). In the next sections, we will expand on some of these aspects.

4.1 Impact of operations on the ecosystem

Contrary to more traditional methods (e.g., trawling, dredging, traps and box-corers), imaging transects by crawlers are a non-extractive monitoring methodology (Cappo et al., 2006; Jamieson et al., 2013) which resembles the classic underwater visual censing by SCUBA divers (e.g., Assis et al., 2013). While selectivity of extractive gears has been improving with time (Feekings et al., 2019), imaging is a less invasive alternative capable of providing reliable data on epibenthic megafauna (Ayma et al., 2016; Bicknell et al., 2016) while also representing an overall positive step towards true non-invasive monitoring (Pauli et al., 2010). Nevertheless, some level of physical disturbance has to be assumed, as the crawler leaves tracks on soft sediments which may take from months to years to eradicate, depending on the hydrodynamic conditions and sediment flux to the seafloor (Thomsen and Gust, 2000; Ogston et al., 2008), sediment resuspension by fauna (i.e., bioturbation; Katz et al., 2012; Robert and Juniper, 2012), with artificial heterogeneity potentially affecting beta diversity at small spatial scales (Hewitt et al., 2005). This particular aspect could be tackled with resident ROVs (e.g., Zhang et al., 2021), although potentially compromising the stability during and repeatability among missions.

Differences in the diversity and abundances of the most abundant megafauna species at the site were observed by the crawler, between an area with no previous tracks and an area where crawler missions had taken place before (Chatzievangelou et al., 2020a). In the latter, remnants of the old (i.e., ~ 2 years) tracks were still visible at some spots. The same is true for the tracks left after the late 2016 deployment, with some being visible during an ROV maintenance dive in August 2018. On the other hand, these 2016 tracks were completely covered by a thick layer of soft sediment by the time the area was revisited in summer 2021. In that sense, the crawler can be utilized as a monitoring platform for small-scale ecosystem restoration and recovery experiments with operation terrains revisited at later stages (e.g., after 3 years) and footprint assessed in a similar way as, e.g., in previously trawled areas (Amoroso et al., 2018). Common practice during crawler operations during the last years is to drive the vehicle on the same tracks during transect missions, thus keeping sediment disturbance at a minimum. This approach can be enhanced in the future by the development of increased navigational autonomy and precise repetition of pre-established missions (as, for instance, the more biogeochemistry-orientated abyssal benthic rover; Smith et al., 2021), although this may come at the expense of the ability to avoid slow fauna (see below).

Additionally, some species showed a particular affinity for the crawler's tracks, with the exact reasons currently unclear (e.g., potential shelter from visual predators, grazing in the resuspended sediment or even preferring the distinct micro-circulating patterns). Larger animals (e.g., rockfish, hagfish, halibuts, soles, etc.) very rarely occupied the tracks transversally, but rather along the track axis (i.e., facing forwards or backwards in relation to the crawler). Such species could be incommoded by the bumps of the tracks, or plainly not fit in the width of the tracks due to their length. These are examples of the potential for high local physical heterogeneity originating from crawler actions to influence seafloor community structure and use of space.

Due to the small lag in communications (i.e., ~ 2s, which can increase depending on the ONC system's traffic) between the user and the vehicle, it is possible that animals moving with intermediate-speed can be run over by the caterpillars if they enter the tracks after a move order has been confirmed. This would not be expected to affect fish, as they are quick to burst and swim when they perceive the crawler approaching, nor snails which cannot enter the field of view at high speed and are easy to avoid. The most probable casualties would include medium- to large-sized crabs, which could theoretically move fast enough to appear suddenly on the tracks but not fast enough to avoid the crawler if even an emergency stop is carried out too late. In one case, this lead to an aggregation of a numerous small crabs and buccinid snails that scavenged on the crushed carcass (Supplementary Figure 6). On another occasion, the tip of a scarlet king crab's leg got under the crawler's caterpillar and sank into the muddy seafloor, with this softness preventing the animal from being hurt. The crab reacted by jumping forward at a surprisingly high speed for what is normally observed for this species (Supplementary Video 17). Such rare incidents may result in punctual stress for the animal, but thanks to their generally rapid reactions and the cushioning effect of the muddy seafloor, potential risks remain low. In any case, the percentage of such incidents occurring is minimal in comparison to the total distance covered, the total time of operations and the recorded faunal abundances, while the crawler's speed is maintained low (~ 5 cm/s).

Photic and sound contamination is another aspect of a potential effect of the monitoring platform (Ryer et al., 2009; Lin et al., 2019; Chen et al., 2021). ONC regulations do not allow the lights to be on for more than 2 hours per day, in an attempt to control the effect of artificial light in aphotic depths. Startling, approaching and evasion have all been observed by different species or individuals of a particular species (see section "4.3 Adaptation of fauna" below). Photic contamination can be diminished consistently by using optoacoustic imaging technologies which identify animals without light sources, but based on multi-beam sound frequency emission (e.g., Jones et al., 2019). This solution is especially suited for increasing imaging monitoring penetrability of crawlers of several meters beyond the usual reach of HD camera systems (Aguzzi et al., 2019). Additional solutions may include the use of new, low-light cameras and motors with reduced sound emissions could tackle the issue of light and noise in the future (Phillips et al., 2016; Rountree et al., 2020), though the crawler is already a far quieter system than thruster equipped AUVs or ROVs.

Finally, residual litter can be generated during operations and maintenance (Figure 11). A next generation of crawlers with conventional grippers/robotic arms (Wehde et al., 2019) or based on biomimicking design (e.g., soft robotics) could detect in footage (e.g., Watanabe et al., 2019), collect and store litter items resulting from deployment, in addition to litter reaching the seafloor from the surface (e.g., Pham et al., 2014;

FIGURE 11
Zip tie on the seabed, as an example of marine litter encountered by the crawler during different missions (image taken on September 27 2016).

Pierdomenico et al., 2019) to reduce this effect. However, the main purpose of such manipulators would be to carry out additional experiments and deploy/recover small experimental chambers, microprofilers or to recalibrate/relocate other sensors. This was evidenced in May 2010, when a comparison with data from a temperature probe with the CTD of the crawler was necessary (Supplementary Video 18).

4.2 Ecological representativeness and potential bias

Throughout the various deployments of the crawler since 2009, the spatial range of monitoring operations was ultimately limited by operational autonomy (i.e., the need of an umbilical cable to provide power and communication; Brandt et al., 2016) and, equally importantly, by seabed morphology, such as the steep flanks of one side of the hydrates plateau and the hydrate mounds. In the future, the use of crawlers in unison with faster/more mobile vehicles and crab-like robots (Picardi et al., 2020) may allow the expansion of the spatial representativeness of the results (Aguzzi et al., 2021).

The aforementioned ONC's lighting restrictions may limit the temporal resolution of monitoring plans during the 24h cycle (see previous section "4.1 Impact of operations on the ecosystem" above), with no current capability of multiple transects on a daily basis in the long-term. This issue could be tackled by the development of adequate artificial intelligence, possibly in collaboration with space research scientists, enabling highly automated/pre-programmed missions with optimized duration (Flögel et al., 2018; Aguzzi et al., 2022). Laser-scanning and modelling of 3D point-clouds of the seabed within the crawler field of view may be processed in near real-time, to allow adaptive driving capabilities (Aguzzi et al., 2020a).

The crawler is endowed with a high-resolution camera and even very small animals can be detected from and appropriate distance given suitable illumination. Yet, another potential limitation would be the detection of smaller animal sizes such as macro- and meiofauna, for whom, as well as for endobenthic animals, imaging might underestimate or even completely miss individuals or species (McLean et al., 2020), especially when the crawler is moving and the water is turbid. Thus, a combination of regular imaging, hyperspectral imaging, pin-pointed physical sampling and environmental DNA (eDNA) approaches could be the way to go for comprehensive biodiversity studies (Dumke et al., 2018). Equipping crawlers with eDNA sampling tools may allow the identification of molecular markers for species in a much wider range of sizes in comparison to those targeted by optoacoustic systems (Mirimin et al., 2021, Stefanni et al., submitted).

As mentioned in the previous section, artificial light may attract individuals from outside the current operational range (Widder et al., 2005; Doya et al., 2014) or, on the contrary, repel the ones present, with complex inter- and intraspecific variability making behavioral reactions hard to determine and predict (Geoffroy et al., 2021). Scientists at the French National Centre for Scientific Research (CNRS) who prepare a crawler for long-term deployments at 2500 m water depth in the NW Mediterranean will apply a pulsed, multi-color (i.e., of adjustable wavelength) LED light which can be also dimmed on demand, in an attempt to communicate with deep-sea fauna. The headlights of the crawler are multi-color and can be dimmed on demand (Tamburini et al., pers. comm.). Less is known on the effect of anthropogenic sound on deep-sea fish (Bolgan et al., 2020), however it can disturb their communication and orientation (Hawkins et al., 2015). Raw abundances and densities of fauna may have to be adjusted to account for this type of effect, as shown in the case of strong swimmers such as sablefish, with methodologies similar to the ones applied for the estimation of true densities in baited camera experiments (Priede and Merrett, 1996).

Finally, the platform itself can act as a morphologically complex 3D structure, simulating a small reef as in the case of the octopus and the shrimps, similar to offshore structures industry structures (Gates et al., 2019). This property may affect the counting of animals, and has to be taken into account on a case-by-case basis when estimating faunal abundances.

4.3 Adaptation of fauna to the platform

Generally, differences in the reactions of the benthic fauna of the Barkley Canyon hydrates towards the presence and operations of the crawler have been observed, both among species and individuals of the same species. These included evasive or aggressive behavior, with animals moving away in order to escape as the crawler approached, attraction, with animals approaching the crawler either out of curiosity or for practical reasons, and indifference, with animals not reacting to the crawler on a visible level. Potential physiological reactions due to stress would be very hard to be accounted for with conventional *in situ* methodologies, though potentially the microfluidic detection of hormones with a lab-on-a-chip approach may elucidate such responses (Ozhikandathil et al., 2017). Different reactions reflect a combination of the sensory ecology of the respective species (the way they perceive the world; Burnett, 2011), the level of familiarization with the crawler as a semi-permanent monitoring platform, and other ecological characteristics briefly discussed below.

The use of space may play a role in the level of familiarization reached by each animal. An acceptance/indifference towards biomimetic robots has been observed for many species with increasing coexisting time (Bohlen, 1999; Garnier et al., 2008; Polverino and Porfiri, 2013), which in the case of the crawler can apply to resident individuals/species. Conversely, species known for their territoriality or individuals defending their prey/mate might display agonistic posture (e.g., grooved tanner crabs; Doya et al., 2017).

In general, time spent in the vicinity of the crawler can be expected to reduce reactions, as for instance for sablefish which did not generally avoid it in an active way. For many fish species, as has already been reported for ROV studies, the platform's presence may not represent a meaningful evolutionary signal in the context of their commonly experienced ecological niche (Ayma et al., 2016). On the contrary, Krieger (1997) reported that while sedentary sablefish did not react to the first contact with a submersible, active ones would rapidly turn away (this probably being the first time they encountered an underwater vehicle). The same behavior (rapid avoidance) was observed in simulations of underwater vehicle lighting with sablefish in captivity (Ryer et al., 2009). Behavioral responses of fish towards mobile monitoring platforms can vary in intensity by various external (e.g., vehicle type and operational range, altitude from the seabed etc.), and ecological (e.g., habitat complexity) parameters (Campbell et al., 2021). Nonetheless, risk assessment in animals can vary upon different circumstances and fear can be amplified when, for instance, the crawler's lights trigger curiosity, or when fish in larger schools tolerate more its approach, in ways that a different need can prevail and balance out the predator-induced fear component (Stankowich and Blumstein, 2005; Clinchy et al., 2013). Similarly, many crustaceans reportedly prioritize getting access to more oxygenated water over the instinctive fear of predators that shapes their cryptic behavior (Aguzzi and Sardà, 2008; Haselmair et al., 2010; Riedel et al., 2014; Doya et al., 2016).

For shrimps, the crawler represented an artificial reef that offered the possibility to graze on of bio-fouling layers developed on various parts of its parts, as well as physical protection from potential predators by its structure. This interaction resembles the symbiosis of small parasitic organisms "cleaning" bigger animals and being tolerated by them (Côté, 2000; Bshary and Côté, 2008).

Finally, more motile animals reacted predictably to the presence of the crawler. Long distance swimming predators (e.g., sablefish) could detect the crawler from afar, approach to check the source of the signal and depart, being considerably faster than the crawler. On a larger scale, fishing pressure and the approach of gear may modify fish shoaling tendency and overall collective behavior (Sbragaglia et al., 2021). On the other hand, burst swimmers (e.g., pacific hagfish, soles and rockfish/thornyheads individuals) that normally lay on the seabed, did not react unless the crawler was heading directly towards them and getting too close (e.g., when they were laying on the tracks). Finally, epibenthic animals (e.g., crabs, snails, bivalves, etc.) that could crawl or move slowly were either not reacting, or reacting at speeds not detectable (i.e., minimal in comparison to the already low operating speed of the crawler of ~ 5 cm/s), except for the case of some big crab individuals (i.e., > 20 cm total width – including legs – as calculated by comparing them to the width of the tracks) which would move at relatively fast (e.g., crossing the field of view in a few 10s of s).

5 Conclusions and future outlook

The examples presented here indicate the need to perform measurements at specific stations which should be revisited across different time spans. Such examples should be particularly considered in the light of restoration needs and the quantification of relevant ecological indicators. This is especially relevant as such observations can directly address the attributes that characterize the integrity of an ecosystem (in this case an impacted, recovering or restored deep-sea ecosystem), such as threats, physical conditions, species composition, structural complexity, ecosystem function and external exchanges (Gann et al., 2019).

We list a series of advances which have to occur in order to push intelligent monitoring a level above the current technological and methodological thresholds. In particular:

- Autonomous operational capabilities, in order to disengage specialized personnel from manual operations.
- Increase in intelligent algorithms to enable animal tracking and classification, to increase the percentage of biologically-meaningful information stored on-board.
- Increase in intelligent algorithms for posterior data processing and analysis, to reduce manual human intervention and efficiently translate between crawler-generated data and already available, decades-long datasets derived by long-established methodologies based on physical sampling.
- Minimization of the ecological footprint of crawlers, through continuous assessment and integration of new knowledge into monitoring protocols.

The aforementioned forward steps can advance the characterization of deep-sea species behavior and use of space in small scales, the identification of resident individuals with insights into their life expectancy, as well as community dynamics, biodiversity and habitat quality, in ways that would not be possible with traditional sampling. We believe that the development in crawler technologies can boost deep-sea benthic research and monitoring, in a similar way that mid-water research coevolved with ROVs in previous decades (Robison et al., 2017).

Data availability statement

The datasets presented in this study can be found in online repositories. The names of the repository/repositories and accession number(s) can be found in the article/Supplementary Material. The Supplementary Videos containing the material described in this study can be found in the figshare repository doi: 10.6084/m9.figshare.17162063. All data (numeric output of the instruments, images and video recordings) are stored on collection in an onshore database, and made publicly available via the Ocean Networks Canada Oceans 3.0 Portal.

Author contributions

DC, CD, and AP: conceptualization, methodology, investigation, writing—original draft, writing—review and editing, visualization. LT: conceptualization, methodology, investigation, resources, writing—original draft, writing—review and editing, supervision, project administration, funding acquisition. JA: conceptualization, writing—original draft, writing—review and editing, supervision, project administration, funding acquisition. 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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Supplementary material

The Supplementary Material for this article can be found online at: https://www.frontiersin.org/articles/10.3389/fmars.2022.833617/full#supplementary-material

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Discovery and chemical composition of the eastmost deep-sea anoxic brine pools in the Eastern Mediterranean Sea

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Deep-sea anoxic brine pools are unique and extreme, yet habitable environments. However, their extent and processes of formation are not fully understood. Using geophysical analysis and seafloor surveying, we discovered the eastmost brine pools known in the ultraoligotrophic Eastern Mediterranean Sea, at the Palmahim Disturbance offshore Israel (~1150 m water depth). These brine pools are located directly above a ~1km wide piece of the Messinian evaporites section, which was up thrusted to ~350 m below the seafloor. We sampled brines and short cores to characterize the chemical composition of several small (up to 5m diameter) anoxic, methanic and warm (21.6°C) brine pools and adjacent seafloor sediments porewater. The maximal salinities measured at the pools and adjacent porewater were 63.9 and 72 PSU, respectively. The brines are characterized by enriched Na and Cl concentrations by a factor of ~1.8 and depleted Mg, SO_4, K and Ca contents by factors of circa 6, 3, 2 and ~1.3, respectively, compared to the ambient seawater. Relations of the major element concentrations reveal a mixing curve between seawater and enriched Na/Cl and depleted Mg/Cl, K/Cl and SO_4/Cl end-members, and do not coincide with relics of fossil residual evaporated seawater. We propose their composition reflects: 1) dissolution of Messinian halite (NaCl) by seawater, supported by their low Br/Cl ratios; 2) additional small rise in Na/Cl ratios due to the impact of clay mineral dehydration or/and dissolution of trace (~1% of the Na) amounts of detrital trona ($Na_3H(CO_3)_2{\bullet}2H_20$), coinciding with the enriched alkalinity concentrations; 3) diagenesis processes depleting Mg, K and SO_4, mainly by the formation of authigenic K-rich Mg-smectite, clay mineral dehydration, dolomitization/Mg-calcite precipitation and redox processes. The $\delta^{18}O$ and δD values of the Palmahim brine may reflect the impact of clay mineral dehydration. Comparison to all other East Mediterranean brine lakes shows that the Palmahim brine pool system represents similar provenance of brines as observed for the Eastern Mediterranean Napoli, Nadir and Tyro lakes, while potentially recording additional processes attributed to its proximity to the coastal area.

KEYWORDS

Mediterranean Sea, brine pools, chemical composition, deep-sea, seawater, evaporites, Levant Basin

1 Introduction

Deep-sea brine pools accumulated in seafloor depressions have been discovered in different water bodies, notably in the Gulf of Mexico (Shokes et al., 1977), the Mediterranean (Jongsma et al., 1983; Scientific Staff of Cruise Bannock 1984-12 - Cita et al., 1985) and the Red Seas (Charnock, 1964; Swallow and Crease, 1965; and recently Purkis et al., 2022). The Red Sea occupies the utmost number of brine pools attributed to the dissolution of sub-surface evaporites, which were geochemically categorized into two main types, those situated along the deep axis influenced by seismic/rift spreading and consequent hydrothermal fluid and water/volcanic rock interactions and those tied to sediment alterations (Schmidt et al., 2015; Purkis et al., 2022).

The eastern Mediterranean basin contains several complexes of seafloor brine pools at different sub-basins, in which the Tyro and Bannock were the first brine pools discovered in 1983-4 (Jongsma et al., 1983; Cita et al., 1985; De Lange et al., 1990). The Discovery Basin found in 1993-94 had the highest salinity found in the marine environment (Wallmann et al., 1997b) till the recent discovery of Lake Hephaestus, the youngest athalassohaline deep-sea formation (La Cono et al., 2019). Due to their unique chemical composition, these mostly anoxic brine pools that occupy only a small area of the basin were considered hostile to life. Yet, they were found to host unique macrofauna and microbial biodiversity, being extreme environmental hot spots of productivity (Wallmann et al., 1997a; Aloisi et al., 2002; Van Der Wielen et al., 2005; Daffonchio et al., 2006; Edgcomb et al., 2007; Bernhard et al., 2014; Pachiadaki et al., 2014; Merlino et al., 2018; Steinle et al., 2018).

Brines accumulate at the seabed of collapsed basins in the East Mediterranean, having diverse thicknesses up to a few hundred meters (Cita, 2006). Moreover, high salinity values of interstitial waters (up to 350 g/L) were measured in post-Miocene sediments from different Mediterranean Deep Sea Drilling Project sites (McDuff and Gieskes, 1976; Vengosh and Starinsky, 1993; Vengosh et al., 1994). The creation and variable chemical composition of such deep anoxic brine-filled basins are related to the distribution of Messinian evaporites and suggest the dissolution of different layers or levels of the Messinian suite (Cita, 2006).

The origin of these brines is attributed to two main processes: 1) dissolution of the late Miocene (Messinian) evaporites by seawater; 2) upwards advection of fossil relict brines produced during the Messinian evaporites deposition (Vengosh et al., 1998). The second mechanism was suggested by them to represent relict seawater evaporated to different degrees of concentration and hence different chemical compositions. Several studies infer the brine origin based on the chemical composition of the brines, considering their modification by diagenetic and advection-diffusion processes. Thus, some brine lakes like the Discovery, Kryos and Hephaestus are $MgCl_2$-dominated systems that were attributed to the dissolution of Mg evaporites, mainly bischofite (La Cono et al., 2019). Other brine lakes like, Urania, Bannock and Tyro were related to either the dissolution of different stages of evaporites precipitated in the Messinian or the consequent relics of fossil evaporated seawater entrapped in the sediments and advected upwards (De Lange et al., 1990; Vengosh et al., 1998; Cita, 2006).

The Levant Basin is underlain by Messinian evaporites, reaching a thickness of about 2 kilometers in the center of the basin and pinching out underneath the basin's margins (Gardosh and Druckman, 2006; Roveri et al., 2014; Gvirtzman et al., 2017; Meilijson et al., 2019; Manzi et al., 2021). The salt had undergone extensive and multiphasic deformation from near syn- to post-depositional (Gvirtzman et al., 2013; Feng et al., 2017). The deformation is controlled by both the marginal loading of the sediments as well as the underlying structure (Reiche et al., 2014; Gvirtzman et al., 2015; Ben Zeev and Gvirtzman, 2020). As the salt deforms, it modifies and shapes the seafloor morphology in the region. The Palmahim Disturbance is a significant (c. 50 x 15 km) submarine slide deforming the continental margin of southern Israel, attributed to gravitational slumping above the Messinian evaporites (Garfunkel et al., 1979). Local evocation of Messinian evaporites and extensive faulting at the base of the Palmahim disturbance form potential conduits that allow fluid seepage to the surface (Eruteya et al., 2018).

Following a geophysical study of the area, we conducted in April and November 2021, remotely operated vehicle (ROV) based visual surveys of the ~1150 m deep seabed in the toe domain of Palmahim Disturbance, 60 km offshore the Israeli Mediterranean coast. During this survey, we discovered a complex of several small brine pools, located geographically at the eastmost part of the basin, east of the other deep anoxic brine pools discovered in the Mediterranean Sea. Here, we report on our discovery and aim to characterize the physical and chemical settings of the brines, assessing the brine origin. Our study is based on unique *in-situ* measurements that were performed with a CTD mounted on an ROV arm, as well as measurements of the chemical composition in samples from the brine pool and porewater from a short sediment core at the edge of one pool.

2 Materials and methods

2.1 Geophysical data and bathymetry

Preliminary site evaluation and site selection were carried out based on an analysis of the Oz 3D seismic volume. These commercial 3D seismic data were acquired by Ion-GTX over an area of 400 km^2 using ten 8 km long streamers with a cable separation of 100 m. The data were depth migrated to produce a 25 × 12.5 × 8 m resolution 3D volume. Our geophysical analysis was carried at the University of Haifa Applied Marine Exploration Lab. (AMEL) using the AspenTech Subsurface Science & Engineering software suite.

Initial bathymetric mapping of the study area was carried out using a Kongsberg EM302 and by a Knudsen chirp 3260 Sub-Bottom profiler with 3.5 kHz central frequency mounted in a gondola beneath Israel Oceanographic and Limnological (IOLR) R/V Bat Galim (Kanari et al., 2020). In January 5, 2021, a high-resolution seafloor survey was carried out using the University of Haifa ECA robotics A18D Autonomous Underwater Vehicle (AUV, SNAPIR) deployed from R/V Bat Galim. The SNAPIR AUV surveyed the seafloor with a Kraken MINSAS120 Interferometric Synthetic Aperture Sonar (SAS) at 3cm/pixel resolution, Edgetech 2205 Sub-bottom profiler and a NORBIT 400 kHz central frequency WBMS Multibeam Echo sounder. A preliminary analysis of these data, carried at AMEL, was used for the planning of the ROV survey.

2.2 ROV-based visual surveying and water and sediment sampling

Two ROV surveys, incorporating visual video and *in situ* measurements and sampling, were carried out in the Palmahim Disturbance toe site (Figure 1) using the University of Haifa SAAB Seaeye Leopard Yona ROV, deployed off R/V Bat-Galim. The Yona ROV is equipped with a Schilling Orion 7P Manipulator, SubC 1CAM lite Mk6 (4K) main camera as well as 3 additional SD cameras. An exploratory ROV survey of the site was carried out April 19-29, resulting in the discovery of the brine pools. The main sampling and *in-situ* measurement survey at the site were conducted during 15-17 November 2021.

A Sea-Bird SBE16plusV2 CTD system was mounted on the ROV to collect *in-situ* measurements of pressure, temperature, salinity and dissolved oxygen. To enable a precise controlled *in-situ* measurements of the brine we attached a tigon tube to the arm of the ROV (Figure 1) and connected its other end to the CTD pump. Measurements of the brine pools were performed by introducing the arm alone into the pool (Figure 1). The manufacturer reported precision of the SBE16plusV2 CTD is ±0.004 for salinity (inferred from the ±0.0005 S/m conductivity precision) and ±0.005°C for temperature. The pressure, conductivity and temperature sensors were calibrated by the manufacturer (as described in Ozer et al., 2020). CTD data was processed using the Sea-Bird data processing software following the manufacturer's recommendations. In addition, water samples for dissolved oxygen were sampled and measured onboard immediately upon retrieval following the modified Winkler method (Carpenter–Winkler titration procedure Carpenter, 1965), using an automated Metrohm Titrando 905 titration system to calibrate the dissolved oxygen of the CTD.

A Niskin bottle was mounted horizontally on the front part of the ROV and was triggered using the ROV arm once inserted into the brine pool. Short push-cores (30 cm long Perspex tubes) were collected adjacent to the pool edge using the ROV. Porewaters for major and minor ions were sampled using Rhizons immediately upon retrieval of the ROV onboard from 5 depth horizons and the sediment overlaying water. Sediment samples (~2 ml) for methane concentrations were collected with edge cut syringe from the perspex corer which contains side holes (1 cm in diameter) and immediately transferred into a flushed argon glass bottle containing 5 ml sodium hydroxide (1.5 N) for headspace measurements of methane concentration (after Nusslein et al., 2003). The bottle was sealed with a crimper.

Ambient seawater samples were collected with the R/V Bat-Galim at parallel depths (~1150 m) using Niskin bottles mounted on a Seabird rosette at about 50 km northward to Palmahim Disturbance for the comparison between the chemical composition of the brine pools and porewater to the ambient seawater.

2.3 Chemical analysis

Onboard, water samples were immediately collected directly from the Niskin bottles. The brine salinity (expressed as

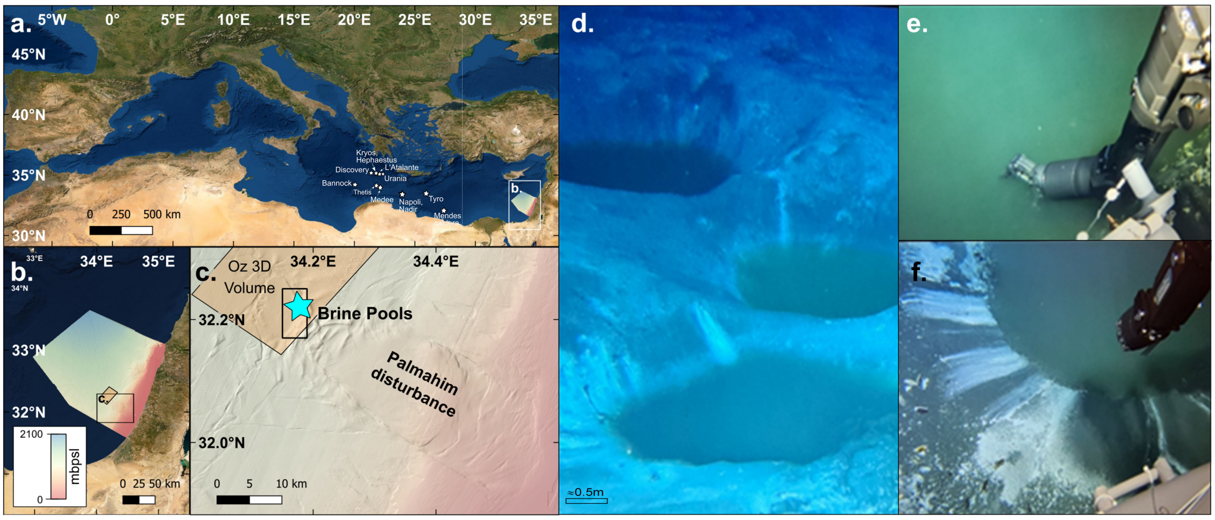

FIGURE 1
Bathymetry and location map of the discovered brine pools at the edge of Palmahim Disturbance, 1100m water depth **(A-C)**. Extracts of video documentation of the brine pools as visualized by the remotely-operated vehicle (ROV) (**D-F**, scale in panel **(D)** is approximated) and *in-situ* CTD measurement of the brine by pumping water *via* a tigon tube attached to the arm of the ROV **(E, F)**.

conductivity), pH, and dissolved oxygen concentrations were measured onboard immediately upon sampling using a WTW Multi 3630 IDS sensor. The pH electrode was calibrated against the standard NBS buffers.

2.3.1 Major and minor ions

Chemical analysis of the brine, porewater and seawater samples was performed by standard spectrometric methods: Na, K, Mg, Ca, and Sr were analyzed by ICP-OES (Inductively Coupled Plasma Optical Emission Spectrometry) Optima 5300 Perkin Elmer. Samples dilution was 1:10, an internal standard of Scandium (Sc) was used (final concentration of 5 ppm) and the analytical precision was estimated within ±0.5%. Cl and Br were analyzed by Dionex ICS-2000 Ion Chromatography. The analytical precision was within ±3%. Ba, Li and Mn were measured by ICP-MS (Inductively coupled Plasma Mass Spectrometry) NexION 300D, Perkin Elmer. The analytical precision was within ±10%. Quality control was performed by the run of 3 Standard Reference Samples (SRSs) of the U.S. Geological Survey (USGS).

2.3.2 Total alkalinity

was measured by potentiometric titration with a Methrom, 848 Titrino plus system using the Gran method to calculate it from acid volumes and corresponding pH measurements between pH 3.3 and 3.8 (Sass and Ben-Yaakov, 1977). The titration acid was 0.05 M HCl, which was verified and adjusted using certified reference seawater supplied by the Certified Reference Materials Laboratory, Scripps Institution of Oceanography, CA (Dickson et al., 2003). Duplicate measurements were made for each sample and the precision error was ±1 μmole·kg^{-1}.

2.3.3 Methane

Was measured from the headspace on a Focus Gas Chromatograph (Thermo) equipped with a flammable ionization detector (FID) at a precision of 2 mmol CH4 L^{-1} (Sela-Adler et al., 2017).

2.3.4 δ^{18}O, δD measurements

For δ^{18}O measurements clean vacuum vessels were flushed with a gas mixture of He (99.6%) and CO_2 (0.4%) for 10 minutes to remove the original atmosphere. After flushing, 0.7 cm of the sampled water was injected to the vessels and left to equilibrate with the CO_2 gas for at least 48 hours at 25°C. Values of δ^{18}O were measured using a Finnigan Gas Bench II extraction system in continuous flow connection with a ThermoFinnigan Delta V mass-spectrometer, following the CO_2 – H_2O equilibration technique (Epstein and Mayeda, 1953). All oxygen isotopic measurements were made in duplicates and are reported relative to Standard Mean Ocean Water (SMOW). Four well-quantified internal laboratory standards were used for calibration. δD measurements were performed using a Thermo Finnigan High-Temperature Conversion Elemental Analyzer (Flush2000-EA) attached to a Delta V mass-spectrometer at a reaction temperature of 1450°C (Nelson, 2000). δD values are reported relative to SMOW. Analytical reproducibility of duplicates was better than 0.1‰ for δ^{18}O and 1.0‰ for δD.

3 Results and discussion

3.1 Geophysical setting at the Palmahim Disturbance brine pools

The study area is located in the northwest part of the Palmahim Disturbance compressional toe domain, as defined by Garfunkel et al. (1979). Our analysis shows that the Messinian to present sedimentary section in this area has undergone complex deformation (Figure 2). This includes folding and combined southeastward up thrusting and left lateral strike-slip displacements along multiple salt-rooted faults. These faults accommodate hundreds of meters of offsets, changing their modes and deformation amplitude along their strike and producing ridges and throughs in the present bathymetry. In particular, an up to ~ 1 km wide and ~3 km long portion of the Messinian evaporites section was up-thrusted by ~1 km, with its top reaching ~350 m below the present seafloor. Directly above the shallowest tip of the up-thrust Messinian sliver, we observe tens of meters wide bathymetric depressions, underlain by high amplitude reflectivity within tens of meters below the seafloor. Similar reflections have been related to active methane seepage farther to the south at the toe domain of Palmahim Disturbance (Rubin-Blum et al., 2014; Eruteya et al., 2018; Tayber et al., 2019). These observations prompted the focused seafloor surveying of this site, leading to the discovery of the Palmahim Disturbance brine pools. We, therefore, suggest that focused seepage of fluids and methane, routed through the subsurface Messinian evaporites sliver, lead to the formation and on-going seepage of the discovered brine pools. The deformation and faulting of the salt have been suggested as a mechanism that may facilitate the migration of fluids to the seafloor in the Levant basin (Eruteya et al., 2018; Tayber et al., 2019; Oppo et al., 2021).

Seafloor surveying of the site discovered a complex of several small (up to 5 m diameter) brine pools (Figure 1) at 1150 m water depth, in the toe domain of Palmahim Disturbance, 60 km off the Israeli Mediterranean southern coastline. At least 5 brine pools were positively identified. The pools are clustered within an area of ~1,500 m^2 and visually seem to be inter-connected (in part) by a system of stream channels. All pools have circular shapes probably owning to their mode of development and formation.

3.2 Geochemistry of the Palmahim Disturbance small brine pools

We mapped the distribution patterns of salinity, temperature and dissolved oxygen in selected brine pools and their vicinity, based on the *in-situ* CTD measurements, which were segmental, as the CTD pump was not enabled constantly to avoid damage by sediment particles (Figure 3). The maximal recorded salinity and temperature were 63 PSU and 21.6°C, whereas all measurements adjacent and above the pool complex or brine-seawater interface, were higher than the ambient background levels (Figure 3). Our observations suggest that regardless of the sharp interface between the brine and bottom seawater, the latter exhibits minor enrichment of salinity and temperature probably attributed to certain diffusion or advection caused by the bubbling out or upwards of methane bubbles, as

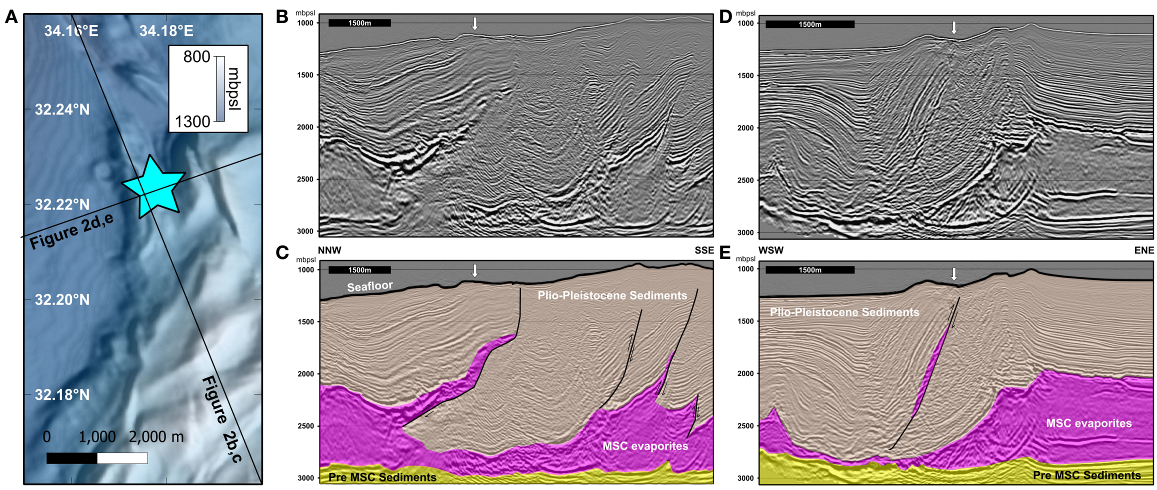

FIGURE 2
Seismic imaging of the subsurface near the brine pools. Two intersecting depth migrated profiles across the location or the brine pools (star in **A**, arrow in **B-E**), one along an NNW-SSE trend **(B, C)** and one along a WSW-ENE **(D, E)** show the Messinian salt being segmented by faults and up thrusted towards the surface, reaching to shallowest levels beneath the discovered brine pools.

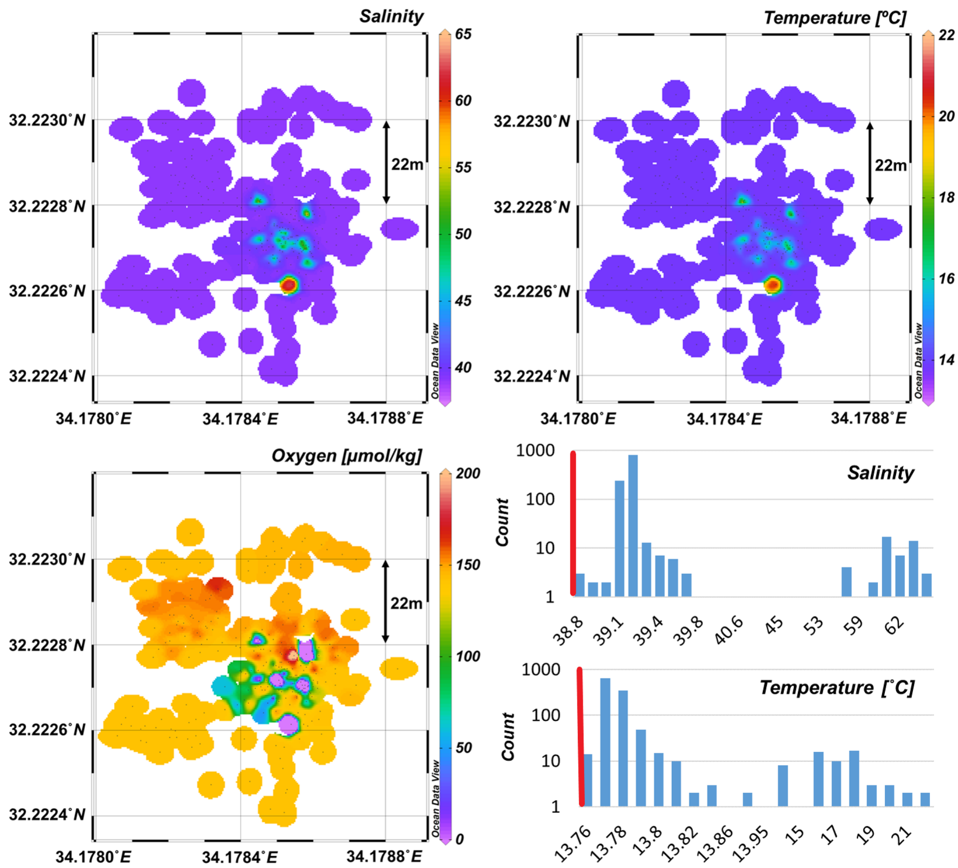

FIGURE 3
Distribution map of salinity, temperature and dissolved oxygen concentrations measured *in-situ* (CTD mounted on the ROV). The column plots represent all the recorded *in-situ* data and the vertical dotted red line the ambient background levels for salinity and temperature (38.767 psu and 13.75°C; recorded at the same depth close to the study area during 2013 (March); 2016 (Sept.); 2017 (Sept)).

visualized by the ROV survey. We also consider disturbance by biota, mainly by the shark *Galeus melastomus*, which occurred in large numbers in the brine pools area, and was often observed swimming next to the brine pools. *In-situ* dissolved oxygen measurements indicate anoxic conditions (<0.1% saturation) within the brine pools. This coincides with the onboard measurements showing values of 0.04-0.7 mg L^{-1} (decreasing), likely representing both the limited mixing with the bottom seawater and the substantial respiration at the interface. We measured high concentrations of dissolved Mn (up to 10.1 µM) in the brine pools and porewater (Figure 4; Tables 1, 2), which are typical below oxic-anoxic interfaces, including anoxic brines (De Lange et al., 1990).

We collected 3 samples from two distinct brine pools with a horizontal Niskin bottle mounted and triggered by the ROV. While it was technically impossible to set the Niskin vertically, the replacement of water *via* the horizontal Niskin was limited in the smaller and shallower brine pool (samples BP3 and BP5, Table 1) and thus the collected water represents the brine and some "contamination" of bottom seawater. Therefore, the chemical composition of those samples represents a mixture between the brine end-member and the ambient seawater. We additionally analyzed the porewater chemical composition of a short (~12 cm) push core collected by the ROV at the edge of one of the pools (Figure 1). The chemical composition of the most saline brine and porewater samples at Palmahim Disturbance, ambient seawater and other brine lakes in the Eastern Mediterranean Sea were compared to assess their origin (Table 2). In the Palmahim Disturbance brine, Na, Cl, Li and Sr are enriched, while Mg, K, SO_4, Br are depleted compared to the ambient seawater (Figure 4). Compared to other Mediterranean brine pools, our results exhibited the lowest Mg concentrations and similar Na/Cl and Mg/Cl ratios as Napoli, Nadir and Tyro brine pools (Table 2).

The chemical composition of all the samples collected here, 3 brine pools and 6 porewater samples, are presented in Table 1, and were used to assess their provenance (end-members) by comparison to the expected seawater evaporation composition,

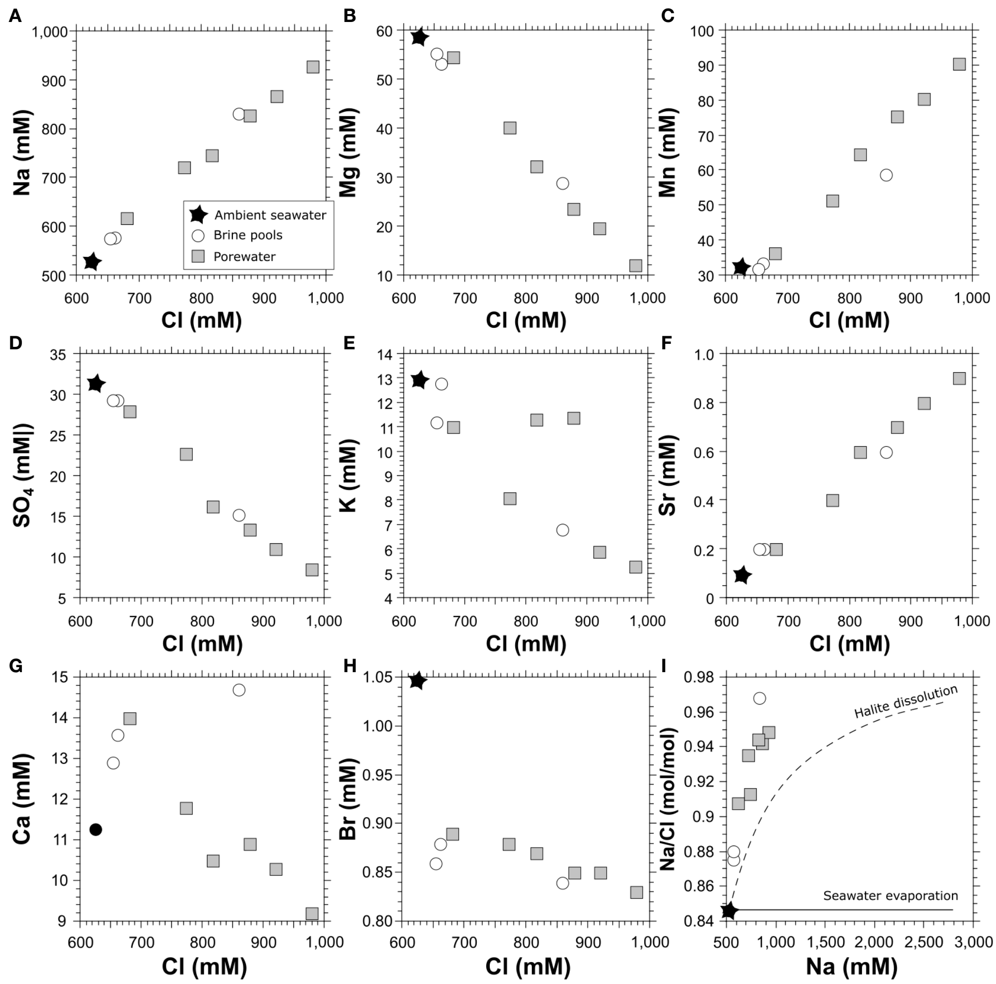

FIGURE 4
Ion concentrations variations vs. chloride concentrations of brine water and porewater from Palmahim site, and of ambient seawater. The lower plot includes the evaporation of seawater curve and the mixing curve between seawater and dissolution of halite.

dissolution of Messinian evaporites and potential diagenetic processes.

Cross-plotting relationships of the major element concentrations reveal a mixing curve between seawater and enriched Na or Cl and depleted Mg, K, SO_4 end-member (Figure 4). The linear increasing trend line for Na, Li and Sr vs. Cl, and the linear decreasing trend line for Mg and SO_4 vs. Cl (Figure 4) suggests an enriched NaCl and depleted Mg and SO_4 end member impacting the brine pool and top porewater composition. The potential enrichment of Na and Cl *via* the dissolution of subsurface evaporitic halite attributed to the Late Miocene (Messinian) crisis by seawater cannot explain the observed relatively high Na/Cl ratios to the full extent (Figure 4). These ratios are much higher than the expected ratios attributed to relics of seawater evaporation path or modified/residual brines after the precipitation of evaporites, starting with halite at a degree of evaporation >10 or Na concentration of ~5500 mM (McCaffrey et al., 1987; Shalev et al., 2018).

A recent study suggests that porewater from the Napoli mud volcano may be affected by clay mineral dehydration hence a decreasing chlorinity and thus increasing Na/Cl ratios (Behrendt et al., 2022). Such a process may explain an enriched Na/Cl end-member which consists of halite dissolution by seawater and additional diagenetic removal of Cl. The relatively low Br/Cl ratios also support the dissolution of early-stage halite evaporites containing low crystalized Br (Shalev et al., 2018).

Considering the linear decreasing relationships between Mg and SO_4 vs. Na or Cl (Figure 4) and assuming a Na end-member at complete removal of Mg and SO_4, a value of 1034-1056 mM Na is calculated. This range represents a contribution of approximately 35% additional Na due to halite dissolution and removal of ~8% of Cl by dehydration. An alternative process that may explain Na/Cl ratios higher than expected by seawater

TABLE 1 Chemical composition of the Palmahim Disturbance brine pools and porewater.

Parameter Water Type	Na mM	K mM	Ca mM	Mg mM	Sr mM	Cl mM	SO4 mM	Br mM	Li µM	Ba µM	Mn µM	$\delta^{18}O$ ‰	δD ‰	pH
Ambient seawater* 1100m	528	12.9	11.3	58.6	0.094	624	31.3	1.047	32.41	0.09	0.01	1.5	7.0	8.01
brine pool-3	578	12.8	13.6	53.2	0.196	661	29.3	0.880	33.33	4.15	0.46	1.5	3.9	7.31
brine pool-4	831	6.8	14.7	28.9	0.641	859	15.2	0.838	58.70	4.88	1.91	2.0	-6.5	7.03
brine pool-5	575	11.2	12.9	55.2	0.170	653	29.3	0.864	31.88	3.28	10.11	1.5	4.8	7.26
porewater-1	857	5.9	10.3	19.7	0.803	920	11.0	0.849	80.43	45.16	4.28	na	na	na
porewater-2	928	5.3	9.2	12.1	0.884	978	8.5	0.831	90.58	63.73	1.28	na	na	na
porewater-3	828	11.4	10.9	23.6	0.700	877	13.4	0.853	75.36	10.71	3.19	na	na	na
porewater-4	746	11.3	10.5	32.3	0.554	817	16.2	0.868	64.49	9.47	2.82	na	na	na
porewater-2T	722	8.1	11.8	40.1	0.440	772	22.7	0.878	51.45	10.92	3.90	na	na	na
porewater-4T	617	11.0	14.0	54.6	0.215	680	28.0	0.895	36.23	4.73	0.73	na	na	na

na, not analysed.
*the ambient seawater isotopic composition from Sisma-Ventura et al. (2016).

dissolution of halite is the addition of Na *via* dissolution of trace amounts (~1% Na) of detrital trona ($Na_3H(CO_3)_2•2H_20$) and/or thenardite (Na_2SO_4), which were observed in sediment cores off the Nile delta (Stanley and Sheng, 1979). The most dominant alkalinity-producing reactions are anaerobic oxidation of methane and carbonate dissolution, followed by sulfate reduction and denitrification processes (Aloisi et al., 2002; Brenner et al., 2016). While the anaerobic oxidation of methane results in a very alkaline environment which promotes carbonate precipitation, sulfide oxidation results in a highly corrosive environment due to the production of sulfuric acid. In addition, at the brine-seawater interface the organic matter mineralization and release of CO_2 may also have a small corrosive impact (Sisma-Ventura et al., 2021). The increased alkalinity in the anoxic brine pools, may thus reflect the latter reactions. However, given that the change in alkalinity is not

TABLE 2 Chemical composition of the Palmahim brine pool (Pal 4) and porewater (Pal PC), ambient seawater and brine pools in the Eastern Mediterranean seafloor.

	Ambient seawater	Pal 4	Pal PC	Discovery	Urania	L'Atalante	Bannock	Tyro	Medee	Thetis	Kryos	Hephaestus	Napoli	Nadir
Reference	This study			Benhard et al., 2014				*De Lange et al., 1990	Yakimov et al., 2013	La Cono et al., 2011	#La Cono et al., 2019		&Charlou et al., 2003	
	mM	mM	mM	mM	mM	mM	mM	mM	mM	mM	mmol/kg	mmol/kg	mM	mM
Na	528	799	928	68	3503	4674	4235	5300	4178	4760	125	93	1347	1884
Mg	58.6	27.9	12.12	4995	316	410	650	71.1	788	604	4380	4720	33.9	27.9
Ca	11.3	14.2	9.22	2.6	32	7.3	17	35.4	2.8	9	1	2	8.4	22.2
K	12.92	6.59	5.30	19.6	122	369	127	19.2	471	230	80	28	8.1	7.2
Cl	624	829	978	9491	3729	5289	5360	5350	5269	5300	9043	9120	1380	1979
SO_4	31.3	15.2	8.46	96	107	397	137	52.7	201	265	320	203	28.4	37.8
Br	1.05	0.81	0.83	110#			9.02*	1.28	65.3	6	70	78	0.69	0.44
Li	0.032	0.057	0.091				0.28*	0.075	0.163	0.09			0.057	0.04
Sr	0.09	0.62	0.88				0.17*	0.33					0.04	0.17
CH4	nd	0.9	13	0.031	5.56	0.52	0.45		0.07		4**		0.06	5.94
Na/Cl	0.85	0.96	0.95	0.01	0.94	0.88	0.79	0.99	0.79	0.90	0.01	0.01	0.98	0.95
Mg/Cl	0.094	0.034	0.012	0.526	0.085	0.078	0.121	0.013	0.150	0.114	0.484	0.518	0.025	0.014
K/Cl	0.021	0.008	0.005	0.002	0.033	0.070	0.024	0.004	0.089	0.043	0.009	0.003	0.006	0.004
SO_4/Cl	0.050	0.018	0.009	0.010	0.029	0.075	0.026	0.010	0.038	0.050	0.035	0.022	0.021	0.019
$\delta^{18}O$	1.5	2.0	na	-2.39#	2.54&							-3.06	2.23	2.06
δD	7.0	-6.5	na	-17.9#								-16.5		

**Steinle et al., 2018 - µmol/kg; na, not analysed.

conservative, and that it does not correlate to a change in Ca concentration, another mechanism may also contribute. This might be the dissolution of trona which would contribute bicarbonate. Indeed, the enriched alkalinity concentrations in the 3 pool samples (Table 1; up to 15,363 μmol kg^{-1}) show much higher values than ~ 2610 μM of the ambient seawater (Sisma-Ventura et al., 2016), similar to the corresponding dissolution of trona, assuming an addition of approximately 1% Na.

The lower Mg, K and SO_4 contents support interaction with sediments during early-to-late diagenesis (Boschetti et al., 2011) and redox processes (Van Der Weijden, 1992). A depletion of SO_4 is attributed to sulfate reduction and the anaerobic oxidation of methane. The Palmahim Disturbance porewater show clear methane enrichment ranging from 4 to 13.8 mmol CH_4 L^{-1}. Methane emission may be related to compressed sediments or gas hydrate destabilization, which may occur at mud volcanoes, seeps and vents related to fault systems (Charlou et al., 2003). We note that considering the anoxic conditions in the brine pools and porewater, it is likely that a certain portion was originally presented as H_2S and thus the SO_4 versus Cl would have been different.

The depletion of K and Mg from porewater may be attributed to the formation of authigenic K-rich Mg-smectite in marine evaporative environments (Hover, 1999) and dolomitization. In addition, subsurface processes of burial diagenesis of the transformation of smectite to illite clay mineral fixes K from porewater even under relatively low temperatures (Hover et al., 2002; Ijiri et al., 2018)

The $\delta^{18}O$ and δD values of the most saline brine pool at Palmahim Disturbance are 2.0‰ and -6.5‰, respectively. Slightly enriched in ^{18}O but heavily depleted in ^{2}H (D) compared to mean values of 1.5‰ and 7.0 ‰ of the EMS deep water (Sisma-Ventura et al., 2016), respectively (Figure 5). Messinian halite fluid inclusions may carry depleted or enriched, positively correlated $\delta^{18}O$ and δD values (Rigaudier et al., 2011; Evans et al., 2015), yet counting for only ~0.2% wt, their dissolution results with minimal isotopic impact during mixing with the seawater end-member. The $\delta^{18}O$ and δD values of the most saline brine pool may therefore reflect the impact of clay mineral dehydration (Dählmann and de Lange, 2003) as for the isotopic composition of pore and fluid water from sediment cores at the Napoli and Milano mud volcanoes dome sites, yet slightly depleted in the $\delta^{18}O$. They indicate a deep end-member typified by enriched $\delta^{18}O$ and depleted δD values related mainly to the smectite-illite transformation process and estimated that this reaction efficiently removes Cl. The latter may explain both, the isotopic composition and the excessively high Na/Cl ratios in the Palmahim Disturbance brines. In addition, the $\delta^{18}O$ values in Palmahim Disturbance are somewhat lower than the expected levels of evaporated seawater to the salinity of 63 PSU, reinforcing that its brine isotopic composition is not solely sourced from evaporated seawater. Yet, the slightly enriched $\delta^{18}O$ but much depleted in δD compared to the EMS deep water indicates that clay mineral dehydration is likely affecting the brine pool isotopic composition.

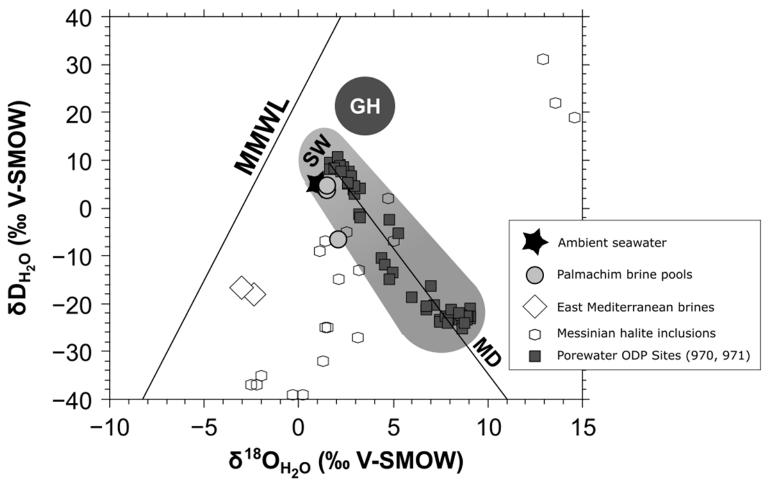

FIGURE 5
$\delta^{18}O$ and δD values of Palmahim Disturbance brine samples (circles), ambient seawater (star) and the Discovery and Hephaestus brine lakes (diamonds). From Dählmann and de Lange (2003): the distribution range of pore fluids from 2 ODP sites (970 and 971) at Milano and Napoli mud volcanoes (gray squares and mixing line); GH - gas hydrate ($\delta^{18}O$ +3‰, δD +20‰); MD - clay mineral dehydration (trend leading towards $\delta^{18}O$ +20‰, δD -70‰). MMWL - Mediterranean meteoric water line (δD =8 $\delta^{18}O$ +22‰) with meteoric water that corresponds to the SW value. Messinian halite inclusions fall on the line (δD =3.82 $\delta^{18}O$ -26.41‰) (Rigaudier et al., 2011).

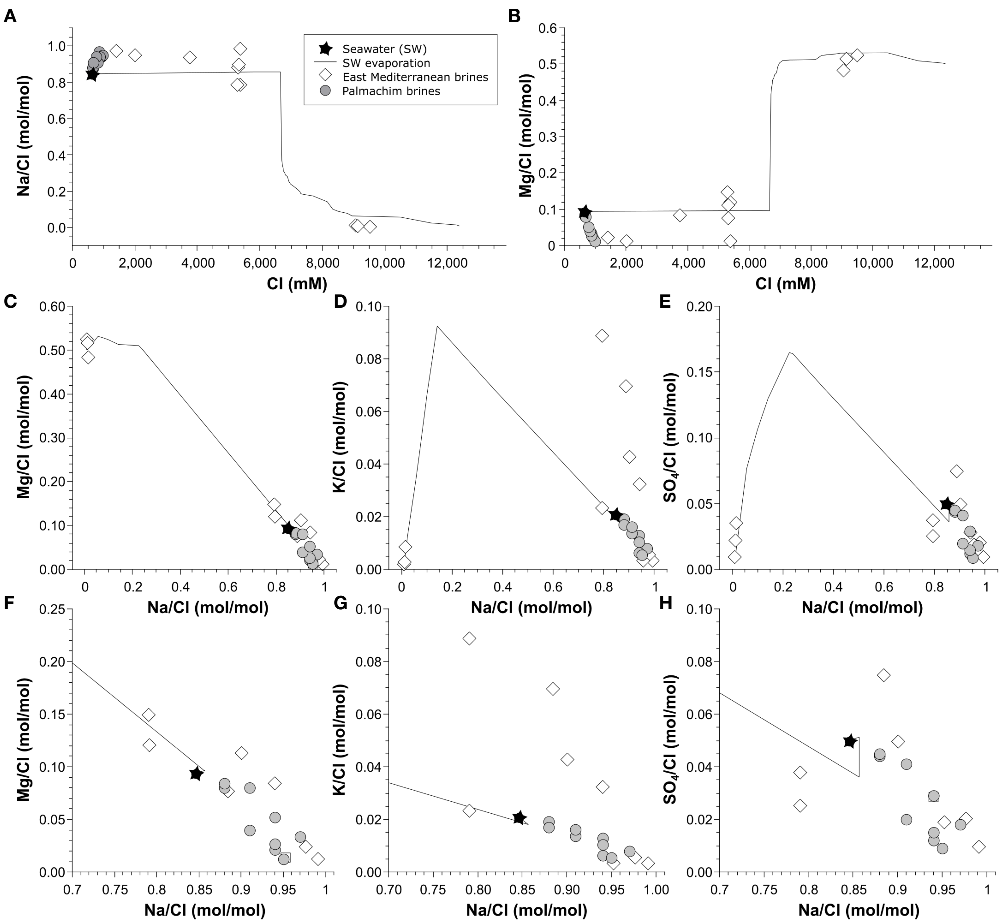

FIGURE 6
Relationships of the ratio between ions and chloride of the Palmahim Disturbance (circles) and other East Mediterranean brine pools (diamonds; based on Table 2). The seawater evaporation path is presented by the black line (based on Shalev et al., 2018).

3.3 Comparison to other Eastern Mediterranean brine pools

The major ion ratios, mainly cross plotting of ion/chloride ratios (Figure 6) assist in revealing the characteristics and origin of the Palmahim Disturbance brine/porewater as compared to other East Mediterranean brines (Table 2 and references therein). Two main mechanisms were suggested as a source of the East Mediterranean brine pools: 1) dissolution of Messinian, mainly late-stage evaporites, precipitated along different degrees of seawater evaporation. The following main minerals were experimentally identified at different degrees of evaporation: gypsum ($CaSO_4.2H_2O$), halite (NaCl), epsomite ($MgSO_4 \bullet 7H_2O$), kainite ($KMgClSO_4 \bullet 3H_2O$), carnallite ($MgKCl_3 \bullet 6H_2O$), kieserite ($MgSO_4 \bullet H_2O$) and bischofite ($MgCl_2 \bullet 6H_2O$) (McCaffrey et al., 1980; Shalev et al., 2018); 2) relics of fossil residual evaporated seawater representing different degrees of evaporation/salinity. During the evaporation path of seawater, the composition or ions ratios of the relict brine change and they become relatively enriched in Li, Br and B (Vengosh et al., 1998; Vengosh et al., 2000; Shalev et al., 2018) attributed to salts precipitation (McCaffrey et al., 1980; Shalev et al., 2018). The latter two processes may interact and are followed by diagenetic processes mainly water-rock interactions, which further changes their composition, mainly regarding Mg, Ca, K and SO_4.

The Na/Cl and Mg/Cl ratios vs. Cl (Figure 6) show brine pools attributed to halite dissolution (e.g. Lakes Napoli, Tyro), dissolution of Mg salts under late-stage evaporation, mainly bischofite, for example, lakes Hephaestus, Discovery and Kryos (La Cono et al., 2019) and of relics evaporated brines, such as Urania and Bannock (Vengosh et al., 1998; Charlou et al., 2003). The Palmahim Disturbance brine represents the lowest Mg/Cl ratios and a Na/Cl ratio beyond the maximum that can be attributed to the dissolution of halite based on its Na or Cl enrichments from the ambient seawater concentration. Nonetheless, the Palmahim Disturbance brine show Na/Cl, Mg/Cl and K/Cl ratios similar to the Napoli and Nadir lakes, as well as to Tyro lake, except Mg/Cl (Figure 6).

The Palmahim Disturbance brine/porewater represents separate characteristics from other East Mediterranean brines in terms of its relatively high and low Na/Cl and Mg/Cl ratios, respectively. While most other brine lakes are located at the deep basin (bathyal depths), the Palmichim Disturbance site is at the toe of the continental slope (relatively close to the coastline), potentially exposed to coastal shelf sabkhas in the past (Lugli et al., 2013). These coastal features would also be connected to the base of the slope through an extensive canyon system that excavated the Levant margin prior and during the salt emplacement (Buchbinder and Zilberman, 1997; Reolid et al., 2022).

4 Summary

We report here for the first time the chemical characteristics of the eastmost brine pools discovered in the eastern Mediterranean basin. Based on their chemical composition it is suggested that this small brine pools system represent similar provenance of brines as observed in the Napoli lake while recording additional process attributed to water-rock interactions, redox processes and potential impacts of its proximity to the past coast and evaporative sabkhas. Its physical-chemical characteristics and methane-degassing environment create a unique biological oasis in contrast to its barren, ultra-oligotrophic surroundings.

Data availability statement

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

Author contributions

Conceptualization: MY, R-BM and HB; Data acquiring: HB, S-VG, OT, KM, AG, GA, JY, BO, MY, R-BM; Formal analysis: HB, S-VG, BO, LM, MY; Project administration: R-BM, MY; Writing original draft: HB, S-VG, BO, R-BM, MY with the help of authors. All authors 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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Maka Niu: A low-cost, modular imaging and sensor platform to increase observation capabilities of the deep ocean

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The deep sea (>200 m) is vast, covering 92.6% of the seafloor and largely unexplored. Imaging and sensor platforms capable of surviving the immense pressures at these depths are expensive and often engineered by individuals and institutions in affluent countries as unique, monolithic vehicles that require significant expertise and investment to build, operate, and maintain. Maka Niu was co-designed with a global community of deep-sea researchers. It is a low-cost, modular imaging and sensor platform that leverages off-the-shelf commodity hardware along with the efficiencies of mass production to decrease the price per unit and allow more communities to explore previously unseen regions of the deep ocean. Maka Niu combines a Raspberry Pi single-board computer, a Pi Camera Module V2, and a novel pressure housing and viewport combination capable of withstanding 1,500 m water depth. Other modules, including high-lumen LEDs, can be engineered to use the same battery charging and control system and form factor, allowing for an ever-increasing number of capabilities to be added to the system. After deployment, imagery and sensor data are wirelessly uploaded to Tator, an integrated media management and machine learning backend for automated analysis and classification. Maka Niu's mobile mission programming and data management systems are designed to be user-friendly. Here, Maka Niu is described in detail along with data and imagery recorded from deployments around the world.

KEYWORDS

deep sea, exploration, technology, user-centered design, machine learning, participatory design, co-design

1 Introduction

The deep sea, which lies below 200 m and covers 92.6% of the seafloor (Eakins and Sharman, 2012), is vast and largely unexplored. This makes imaging and sensor platforms that can withstand the incredible pressures at these depths ubiquitous and mandatory elements of deep-ocean exploration, including human occupied vehicles (HOVs), tow sleds, remotely operated vehicles (ROVs), autonomous underwater vehicles (AUVs), and benthic landers (Phillips et al., 2019; Sun et al., 2021). Pressure housings for these platforms, traditionally made from aluminum or titanium, are often custom-fabricated for a single vehicle or instrument. Exotic materials, specialized subsystems, and one-off fabrication keep the cost of deep-ocean imaging and sensing extremely high. These cost restrictions limit accessibility and restrict deployment opportunities to those with enough operating capital to bear the cost of building and maintaining these deep-sea platforms. However, a growing community of ocean scientists, particularly in regions of the world that have been historically ignored or undervalued, need the exploration capabilities that a low-cost and mass-producible imaging system would provide (Bell, Chow, et al., 2022).

While recent attention has been paid to lowering the cost of deep sea exploration and research systems, there is much room for further improvement (Hardy et al., 2013; Cazenave et al., 2014; Phillips et al., 2019; Giddens et al., 2021). Current advances in the mass production of inexpensive but powerful single-board computers, open-source operating systems, 3D printing, and digital design and fabrication offer opportunities to increase the overall capacity for deep-ocean imaging and data acquisition (Jolles, 2021). At the same time, mission programming and sensor data management have traditionally been the purview of control systems specialists and dedicated data scientists. However, a growing field of open-source operating systems, lightweight web servers, commodity Wi-Fi capabilities, and programming frameworks enables the creation of simplified user interfaces and data handling workflows, which can be used by non-experts and thereby increase the overall capacity of deep-ocean exploration and observation (Amon et al., 2022).

But data acquisition, by itself, only partially completes the goal of scientific observation. Once deep-ocean imagery is recorded, current workflows involve human observation and annotation, which require unsustainable investments of time or restrict inspection to only select data samples. Tools currently under development integrate machine learning to automate the ingestion and inspection of the collected imagery and eventually the visualization of the collected data.

In this paper, we detail and provide open source access to the mechanical, electrical, and digital control design for the Maka Niu system, including the internal 3D-printed dry chassis; the battery management and sealed inductive charging system; and the Raspberry Pi camera and control subsystems. While the use of a Raspberry Pi camera for low-cost underwater imaging is not unique, few of these systems are designed for nor capable of reaching 1,500 m depth or more. (Almero et al., 2021; Bergshoeff et al., 2016; Marini et al., 2013; Marini et al., 2018; Marini et al., 2022). We also describe additional modules that are currently being engineered and suggest the construction of future modules to expand overall system capabilities. This work has the potential to lower the cost of deep-ocean exploration by orders of magnitude, across many sectors and communities of ocean scientists and enthusiasts.

2 Methods

Maka Niu was conceived in February 2020 as an educational tool in collaboration with Nainoa Thompson, Lehua Kamalu, Chris Blake, Sonja Swenson Rogers, and Noelani Kamalu of the Polynesian Voyaging Society. The system was named Maka Niu, or "coconut eye" in Hawaiian, in tribute to the initial concept of using coconuts as flotation devices to deploy the low-cost imaging systems with students from Kamehameha Schools in Honolulu, Hawai'i. Due to COVID-19, the engineering design process took longer than anticipated, allowing us to incorporate learnings from a series of co-design interviews that were carried out with twenty marine professionals from ten countries in July–August 2020 (Bell, Chow, et al., 2022). While originally envisioned as an imaging and sensing system for educational use, the utility of the system for a broader range of marine users quickly became apparent throughout the interview and engineering design process.

The co-design interviews provided requirements and recommendations for sensors and capabilities, as well as considerations for deployment scenarios that would make the system more useful and accessible for a wider range of users (Supplementary Material A). In the design and engineering process, we took into account as many of the design requirements and considerations as possible to incorporate into the Maka Niu system, particularly temperature, depth, imaging, and easy access to video and data, as well as GPS, ease of use, and easily programmable missions (Bell, Chow, et al., 2022). Once the systems were built, thirteen were shipped to be tested by interviewees in eleven locations around the world. A full description of the participatory design study that informed this work can be found in Bell, Chow, et al., 2022.

The research, design, development, and initial deployment of the Maka Niu platform happened entirely during the COVID-19 pandemic. Access to the usual tools, facilities, and resources was at times nonexistent. However, those limitations also prove the value of a system such as the Maka Niu, as it was developed largely in the homes of the distributed team. Using off-the-shelf parts wherever possible, 3D printing both at home and outsourced, and working with fast and low-cost circuit fabricators—all make it possible to build tools with far-reaching impact, while minimizing cost and the requirement for specialty equipment.

All mechanical, electrical, and software components of the Maka Niu design are made available, and maintained, through github repositories linked in the appendix.

3 Results

3.1 Mechanical design

The main mechanical components of the Maka Niu system are the pressure-rated housing, the dry chassis, exterior controls, deployment hardware, and the wireless charging cradle (Figure 1).

Housing: The pressure rated housing of the Maka Niu consists of several machined Delrin components. While this is admittedly an expensive manufacturing process, tight tolerances and resilient material are necessary to achieve the system's 1,500 m depth capability. To reduce costs as much as possible, the design has been minimized to just five machined components: a stock tube with externally threaded ends, a rear endcap, a small cap for the wireless power coil that fits into the endcap, and two hold-downs. The optical port is a simple acrylic disk, 12 mm thick. The optical port and the rear endcap are sealed at the ends of the tube with face seal o-rings, and are held firmly in place by the two hold-downs. The internal space is 40 mm in diameter and 220 mm long. The components are not complex, and none require internal undercuts, which makes it possible to reproduce them using reasonably accessible machining tools.

The housing maintains atmospheric pressure inside with no need to pull a vacuum. The 1,500 m depth-rated housing has been pressure tested in a lab setting at the Woods Hole Oceanographic Institution in Woods Hole, Massachusetts. Test details are discussed in section 3.6.

Dry chassis: The internal 3D-printed dry chassis is a modular design that accommodates a variety of power, computational, and/or sensing needs. It has been designed with quick-locking mated interfaces for fast assembly or reconfiguration. The current standard camera configuration consists of three connecting subsystems: the battery subsystem, the compute subsystem, and the camera subsystem (Figure 2). As user needs change, new subsystems can be designed and swapped in to use other components. For instance, as less-expensive, higher-quality cameras become available, the camera subsystem can be revised to take advantage of these upgraded cameras, while keeping the current battery and compute subsystems.

Exterior Controls: The exterior of the camera has a 3D-printed control interface that consists of a six-position rotating control ring and a levered push button. As with wireless charging, the controls have been designed to function without penetrators to minimize risk to housing integrity. The push button and the control ring each hold a neodymium magnet, the position of which is tracked by hall-effect sensors inside the housing. See section *3.2 Control Interface Sensing* for details regarding the electrical design. The six positions of the control ring correspond to one power OFF state, and five ON state modes (Wi-Fi, still capture, video capture, Mission 1, and Mission 2). The push button enables user input in the ON

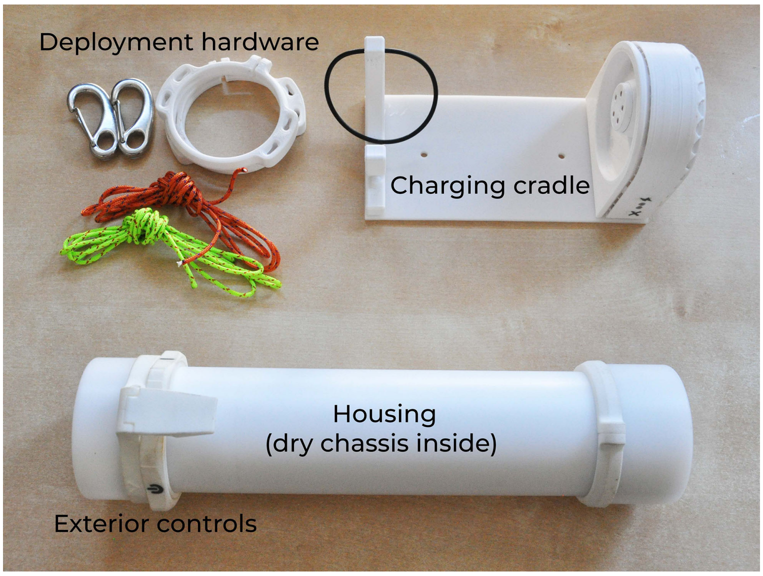

FIGURE 1
The mechanical components of the Maka Niu system include the pressure-rated housing, the dry chassis, the exterior controls, the deployment hardware, and the wireless charging cradle.

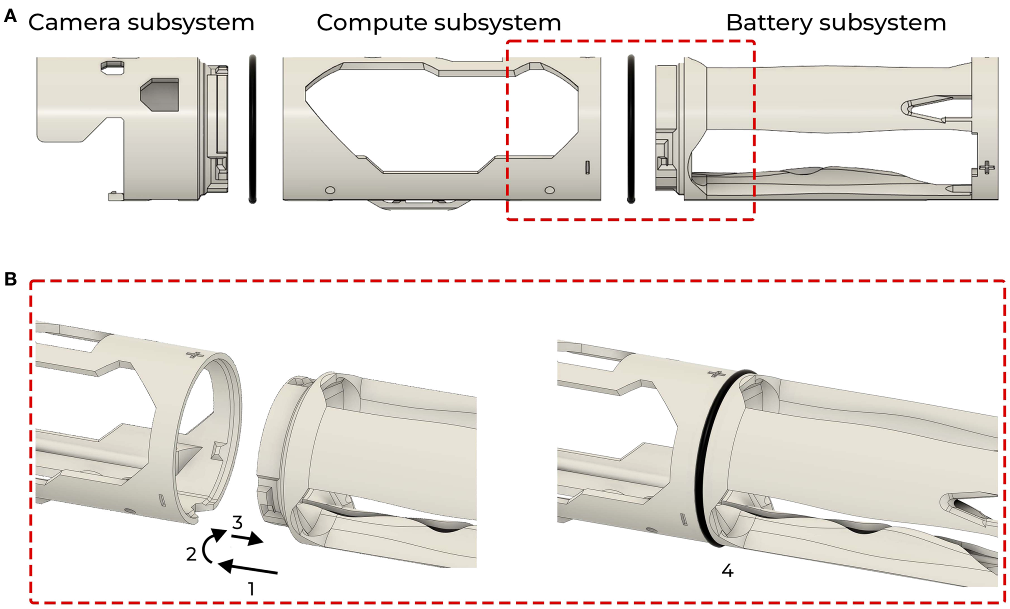

FIGURE 2
(A) The dry chassis consists of three modules with distinct functions. **(B)** Modules connect through a quick four step process: insert one module into another, twist, pull away, and finally place an O-ring in the gap. The O-ring prevents reversal of the described motion, while also functioning as a bumper between the chassis and the housing.

states, such as beginning and ending video capture. To facilitate use as a dive camera, the interface is friendly to one-handed use (Figure 3).

Deployment Hardware: A pair of clamps with quick grip slots, a pair of 1.8 mm Spyderline Micro Dyneema Braid lines, and a pair of stainless steel carabiners are provided to users to facilitate deployment of Maka Niu, whether just below the water surface or just above the sea floor. Users are encouraged to source weights and flotation locally, but the hardware necessary to connect those components to the camera is provided (Figure 4). When not under tension, the lines can slide through the quick-grip slots, so the deployment angle is easy to adjust. Once the preferred angle is set, pulling on the lines locks them in place, and during deployment, tension in the lines from the float and the weight ensures that the lines don't slip. While the angle is set by the upper line, the weight hanging on the lower line slides freely. Regardless of the set angle, the pull of the weight is evenly distributed to both ends of the camera. This reduces bobbing and jerking of the camera in the dynamic underwater environment, and leads to steadier video capture.

Charging Cradle: The body of the cradle consists of a hard plastic mounting plate and 3D-printed housing for the charger circuitry. The design of the cradle takes into account motion during at-sea deployments, as well as the need to manage heat generated by the wireless charging system. The cradle has mounting holes to enable installation to a wall or counter, and a strap is provided to lock the camera into the charger during high seas.

3.2 Electrical design

The electrical components of Maka Niu include the wireless power system, battery pack, computer, camera, sensors, control interface sensing, and feedback interface (Figure 5).

Wireless Power: Maka Niu is charged wirelessly using inductive charging. While use of this technology is unusual in marine research, and increases charging time, it has a key benefit; robustness in non-expert hands. By avoiding wet connectors, exposed metal, and sealed screw caps, inductive charging eliminates concerns that users will forget to replace a cap, damage threads over time, or compromise seals with debris. Charging a Maka Niu camera is akin to charging an electric toothbrush.

Inside the rear endcap of Maka Niu are an inductive coil and a custom printed circuit board, which primarily functions as a wireless power receiver. The design is based on the 15 W wireless power development kit 760308MP2, by Würth Elektronik and Renesas Electronics. The kit provides the groundwork for selecting transmitter and receiver coil pairs, and tuning circuitry to achieve inductive power transmission. The Endcap PCB also has a number of additional features; beyond the

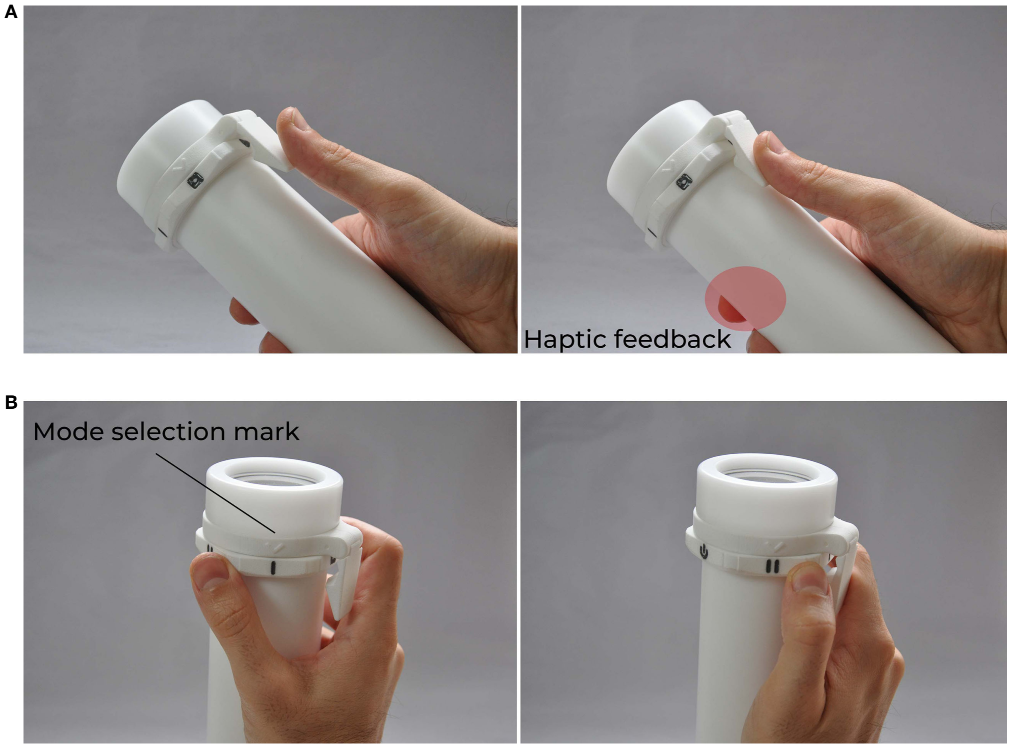

FIGURE 3
(A) The push button is used for specific operations, such as starting and stopping video capture, or taking a still image. These actions also initiate haptic feedback which can be felt by a user holding the unit. **(B)** The control ring can be operated with one hand to select modes. Current mode is indicated by the mode selection mark.

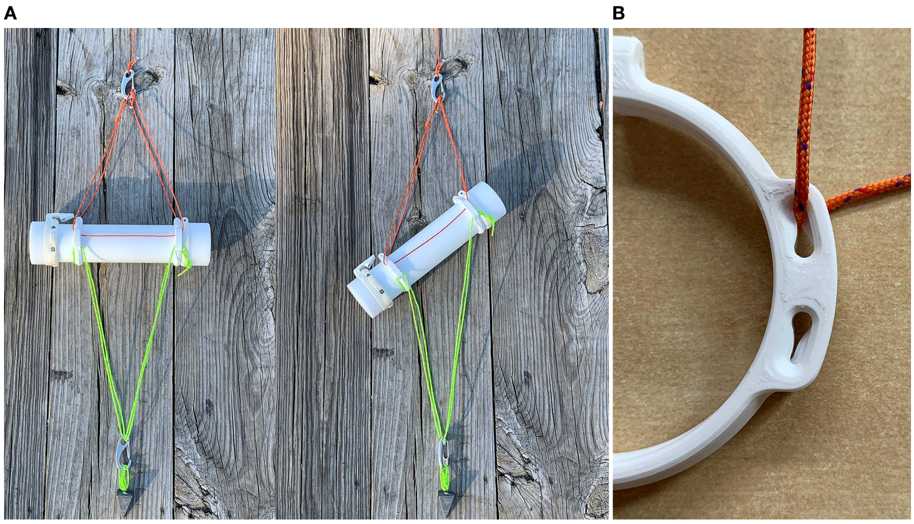

FIGURE 4
(A) The deployment angle of the camera can be adjusted by slipping cords to the desired position. **(B)** Quick-grip slots lock cords in place when they are under tension.

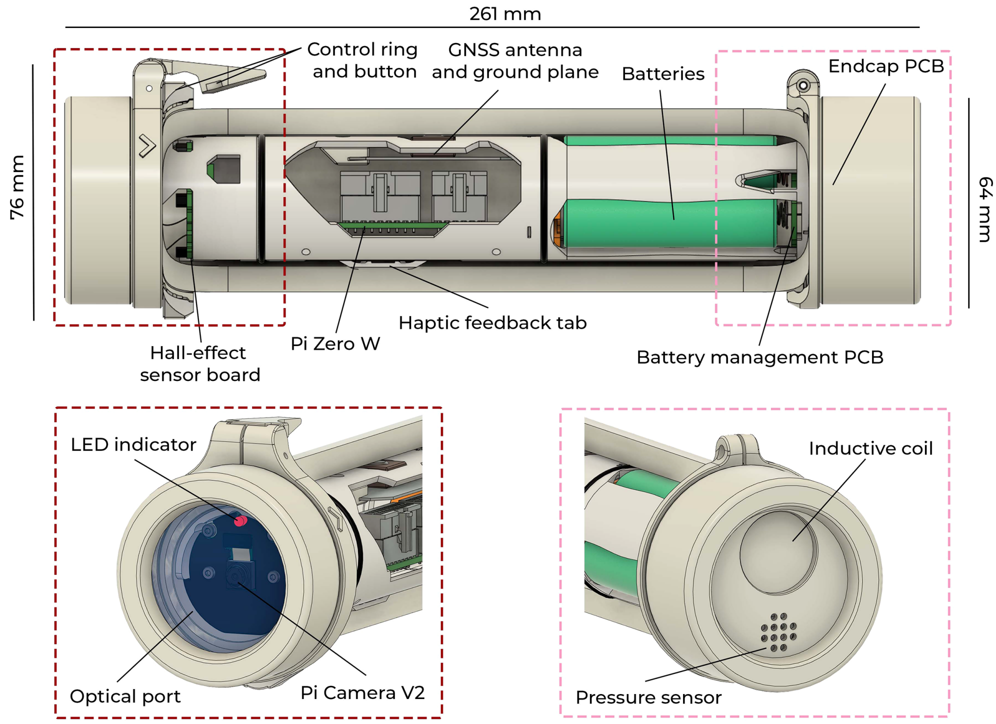

FIGURE 5
A partial cutaway of the housing exposes the dry chassis and the electrical components within. At the front are the optical port, the Raspberry Pi Camera Module and an LED indicator. At the rear are the charging port and the pressure sensor.

inductive charge controller, it contains chips for global position and 9-axis motion sensing.

The charging cradle employs a custom wireless power transmitter circuit, also based on the 15 W development kit. To manage heat generated in the coils, charge rate is limited and a cooling fan blows air over a heatsink behind the transmitter coil. The approximate time to fully charge a depleted Maka Niu battery system is eight to nine hours, making it effectively an overnight process. LED indicators on the charger display its current status, such as charging, charged, and fault.

Battery Pack: The battery pack consists of three 18650 size batteries and a custom battery management system (BMS). The particular batteries used are LG-MJ1, Li-ion batteries with 3500 mAh capacity. They are wired in series for a nominal voltage of 11.1 V, and a maximum possible charge voltage of 12.6 V. In the current design, the charging hardware typically charges the batteries up to 12 V, and the Maka Niu software initiates system shutdown when the voltage drops below 9 V. The current hardware, and software design are not yet optimized for extended battery life, but on a full charge, Maka Niu can record approximately eighteen hours of continuous video. Details of battery testing are discussed in section 3.6, and methods of optimizing for longer deployments are discussed in section 4.3.

Computer: For computation, Maka Niu uses the Pi Zero W by the Raspberry Pi Foundation. It is a low-cost, single-board computer with built-in Wi-Fi and Bluetooth. It is also equipped with a connector to interface directly with the Pi Camera Module V2. On October 28, 2021, a new version—the Pi Zero 2 W with a multi-core chipset—was released, and development and testing is underway to upgrade to this new board.

Camera: The onboard optical camera is a Pi Camera Module V2. With an 8 megapixel sensor, it allows for 3280x2464 stills and 1080p video at 30 fps with a horizontal field of view of 62.2° and a vertical field of view of 48.8° (https://www.raspberrypi.org/documentation/hardware/camera/). The camera is designed for, and well-supported by, the Raspberry Pi community, enabling quick integration and development. While higher-resolution camera modules are available for the Raspberry Pi platform, the V2 module was chosen for its small physical footprint and low cost, which helps to decrease the total cost per unit.

Sensors: Maka Niu is built with a number of additional sensors to create a powerful standalone platform. The unit is equipped with a global navigation satellite system (GNSS), 9-axis motion tracking, and exterior pressure and temperature sensing. Sensor data is logged every second so that the images and videos captured by the camera have accompanying metadata on global coordinates, orientation, and the depth and temperature of the environment.

Geolocative coordinates of all sampled data, especially imagery, is essential to scientific analysis. To determine coordinates, Maka Niu uses the GNSS receiver XM1110 by Sierra Wireless. This receiver is built into the Endcap PCB, and is coupled with an active ceramic patch antenna. The receiver takes advantage of multiple families of satellites—GPS, SBAS and QZSS—and has a 3 m radius of accuracy with 50% Circular Error Probable, according to the manufacturer's specifications.

With access to an open sky, Maka Niu typically acquires satellite data to determine current coordinates and UTC time within five minutes. Once acquired, the UTC time is maintained locally. The GNSS receiver is therefore used as a real-time clock to set timestamps for all of the camera captures and sensor data. Frame-accurate timestamps and GPS localizations are necessary inputs to the Tator and FathomNet machine learning annotation and classification platforms discussed in Section 3.3. GPS coordinate metadata is used specifically for search, sort, annotation, classification and eventually for output data visualization capabilities.

Understandably, Maka Niu cannot receive updated coordinates while underwater. Therefore, users are instructed to power on the Maka Niu above water before each deployment and wait for it to acquire its location, as indicated by a flashing green light. The location will then update every second until the Maka Niu is submerged. When the camera captures an image or a video underwater, the last known position and time are recorded in the metadata. This allows the system to provide an associated location with each capture, along with a measure of uncertainty.

Centered on the Endcap PCB is a 9-axis motion sensor IC, which tracks acceleration, rotation, and magnetic fields in three axes each. This data can be used to approximate Maka Niu's tilt and orientation at the time of image or video capture. The Endcap PCB also connects to the pressure sensor 7LD by Keller, which has an absolute pressure rating of up to 200 bar (~2,000 m). It provides external pressure and temperature data, allowing the approximation of system depth at any time from the pressure values.

Control Interface Sensing: Maka Niu is controlled with a pair of magnets exterior to the sealed housing, one in the mode control ring and the other in the push button (Figure 3). To sense the position of the ring and button presses, inside the housing is a ring-shaped, Hall-Effect PCB with a total of seven hall-effect sensors facing radially outward. Six of the sensors are oriented to sense the inward-facing south pole of the magnet in the control ring, and one is oriented to sense the inward-facing north pole of the levered push button. This ensures that the control ring and the push button operate independently and do not cross-trigger, despite their close proximity. The control interface components are the only mechanical moving parts of the Maka Niu. Critically, the parts do not penetrate the housing, and so even if they wear or break, there is no risk to the integrity of the housing. They can also be replaced without opening the housing.

Feedback Interface: There are two feedback interfaces available to the user: optical and haptic. The Hall-Effect PCB has a red-green LED indicator that is visible through the front optical port. The LED provides information about the state of the Maka Niu, such as what mode it is in, whether it is capturing video, its remaining battery life, and whether the camera has a satellite connection to establish geospatial position. For widest accessibility, flash patterns are also used so that users can recognize all status information without relying on the color of the LED.

A small vibrating motor is mounted in contact with the interior wall of the housing. Haptic feedback is provided to make it easier to use the Maka Niu as a dive camera, with vibrations used to confirm button presses and control ring mode changes.

3.3 Software design

Python: The central program running on the Maka Niu is a Python daemon that handles all of the communication with the device's peripheral hardware. It controls the camera indirectly using shell commands; a separate program, RPi-Cam-Web-Interface, receives those commands and directly operates the Pi Camera Module.

The Python daemon determines which mode is currently selected by reading the state of the six hall-effect sensors to ascertain which one has been activated by the magnet on the control ring. A degree of software filtering avoids noise in the determination of the set mode, while delays ensure that modes can be skipped over by rotating through them quickly with the dial. In the daemon, different sections of code are run depending on the active mode.

The Python daemon checks all available sensors at a rate of 1 Hz. Every time an image is captured or a video is recorded using the push button of the camera, or whenever the dial is in one of the mission modes, the script creates a sensor log file with the same file name as the capture or the mission, and begins to log sensor data into that file (Figure 6). The current state of the ring is also reported in a separate status file for other programs to monitor and act on. Each line begins with a four-letter code representing the source sensor. This data format was modeled on that used by ROVs *Hercules* and *Argus* and developed by Jon Howland (Martin, 2010). The Maka Niu sensor data format is as follows:

- GNSS: provides both current global coordinates and UTC date and time, which the Python program notes and uses for all other data timestamps.

10.3389/fmars.2022.986237

```
GNSS:59112230801246   20210929   010018.647   33.6903978   -118.8602019
BATT:59112377925946   20210929   010018.794   11.79
IMUN:59112631422984   20210929   010019.048   -0.00   0.99   0.02   -2.6  2.7   -0.6   900.0   -313.3   -3073.3   39.39
KELL:59112882817055   20210929   010019.299   -0.26   -0.0   25.45
```

FIGURE 6
Maka Niu logs metadata for every image and for every second of video or duration of a mission. This particular log reveals that on September 29, 2021, at 1AM UTC time, the camera was in the Santa Monica Basin, it was nearly fully charged, it was oriented horizontally at the surface, and the temperature in its environment was 25C.

- •GNS2: provides last known global coordinates and time since those coordinates were updated
- •BATT: provides battery voltage; if this drops below 9 V, the Maka Niu unit initiates shutdown.
- •IMUN: provides data from the inertial measurement unit: acceleration, rate of rotation, and magnetic field strength in three principal axes. This data can be used to approximate the orientation of the camera
- •KELL: provides pressure, depth, and external temperature from the Keller sensor.

The first number on each line of the sensor log is the Pi's UNIX monotonic clock, which gives the number of microseconds since boot. The second and third numbers are the UTC date and time. The monotonic clock gives absolute time differences between measurement readings and is isolated from any changes to the UTC clock, which is sometimes adjusted by the GNSS receiver. All remaining numbers on each line are data from the sensor indicated by the initial four-letter code.

Note that the Keller sensor itself provides only pressure and temperature values; depth is calculated in the Python script using the pressure and offsets. The sensor is rated by the manufacturer with a total error band of 0.5%, and a noise floor maximum of 0.015% from the full-scale measurement. The direction of the error is fixed. Since the pressure sensor is rated for up to 2000 m, at any depth, a given sensor may have a constant depth error of up to 10 m. This error differs from unit to unit. At shallow depths, such an error makes depth data wholly unuseable. To compensate, whenever Maka Niu has an active GPS signal, indicating that it is out of the water and consequently at local atmospheric pressure, the Python script calculates a running average of the presumed depth based purely on the absolute pressure value from the Keller sensor. This number is saved in flash memory and kept as an offset to determine an adjusted depth value of zero meters at the surface. As soon as Maka Niu is submerged, it loses the GPS signal, so the program stops updating the offset, but continues to use it to estimate adjusted depth. By taking advantage of Maka Niu's GPS capability, each unit is effectively able to auto-calibrate itself for fabrication tolerances of the pressure sensor, as well as for local atmospheric pressure, be that at sea level or at a high altitude lake. The method has reduced the shallow water depth error down to sensor noise which is ±0.3 m.

Coconut: When the control dial is turned to either of the mission modes, the Python script sets a flag that signals the Coconut mission management daemon to operate. Coconut is the programmable mission engine that allows scripted, intelligent, reactive, sensor-based mission planning and execution. It is written in Node.js and runs in the background at boot time. Coconut monitors the ring status file and consumes and parses the sensor log file in real-time and uses the data to step through mission sequences. During one of two mission modes, the Coconut mission engine operates as a state machine, using the sensor log data to determine which state the control system should be in according to a pre-programmed mission file. Mission files are simple text-based JavaScript files that describe a series of sequential actions or loops based on sensor data input.

Maka Niu currently ships with two default mission files. Mission 1 initiates video capture in a user-determined capture interval when the unit descends below a user-determined depth; Mission 2 begins time-lapse capture of still frames at a user-determined rate upon mission start.

Missions can be programmed visually using a procedural, graph-based interface accessed through a browser and served from a Node.js Express-based web app (Figure 7). The mission programming graphical user interface (GUI) is based on GoJS, a framework for rapidly building interactive diagrams. Missions can be laid out as a series of blocks or nodes with input values from sensors in real time, such as time or depth used as triggers to progress the mission engine into its next state. Since Maka Niu can act as an access point for a user's smartphone or laptop, missions can be edited in the field immediately prior to deployment if necessary, using a touchscreen on a mobile device or through a standard laptop. Missions can also be edited through the GUI while the device is in client mode on the user's home network and are automatically saved and stored for deployment. GoJS allows for desired trigger values and conditionals to be directly edited and adjusted for execution by the Coconut mission engine.

A user may also access the mission files *via* SSH over the device's natively served Wi-Fi access point or over its Wi-Fi as a client on the user's home network. Mission files can be written or modified using any text editor available to the Linux operating system. The mission engine has full access to the current state of all sensors and can use this data to make control loop decisions,

FIGURE 7
The Node.js Express web-based mission programming graphical user interface (GUI).

such as waiting for a combination of specific conditions to be met and then capturing video or still images.

Being able to program missions through an easy, node-based, drag-and-drop interface is one of the key functionalities that makes Maka Niu so accessible. While a power user can create and edit missions using SSH and the command line interface, graphical programming allows newcomers and non-experts to quickly adjust existing missions, and to easily create custom missions, to suit their operational needs.

Dual Wi-Fi Modes: While out of the water, Maka Niu offers connections to its mission programming environment, media management environment, and all sensor and recorded data communications through a dual-mode configuration that provides network access directly to the device through its native Wi-Fi. In access point (AP) mode, the device offers an access point for device-to-device communication. The main purpose of AP mode is to offer an easy-to-use setup tool to configure the device to operate in client mode on a more robust Wi-Fi network. After connecting a smartphone or laptop to Maka Niu as an access point, a simple configuration page allows a user to input the SSID and password combination of a station mode network. These credentials are maintained from session to session and only need to be entered once while in access point mode. Unless the user intends to create or edit missions or sort and delete media while in the field, the access point mode need not be used again except for diagnostic purposes. In client mode, as a device on a user's main Wi-Fi network, the device gains full access to the internet to upload data for storage, analysis, and visualization. This dual-mode configuration allows for robust and redundant communication, ensuring at least one channel of communication with, and control of, the device is available at all times. During missions, while the unit is submerged, the Wi-Fi system is disabled to increase battery life and mission duration.

VPN and Rover: In addition to accessing the device locally, Maka Niu is also configured to maintain a VPN connection back to a central server. Using OpenVPN clients on the devices and the OpenVPN server on a central machine, units can be monitored, debugged, and upgraded wherever they have an internet connection. Once connected, devices can be logged into *via* SSH and the Coconut web interface can be accessed. Software fixes and updates can be pulled down using the Git software configuration management system, and system log files and mission data files can be examined and downloaded. This capability has enabled the engineering team in Cambridge, Massachusetts, to remotely update the software of several of the thirteen Maka Niu cameras around the world.

Rover is an easy-to-use web dashboard written in Node.js and Express that lists all currently internet-connected Maka Niu systems on a central server. Connecting to a remote system in the field can be done with only a few clicks. Access to the Rover interface and the connected Maka Niu devices is enabled by separate OpenVPN client keys issued to each authorized user. The keys are used to establish a VPN connection back to the central server granting access to the web interface and to the Maka Niu devices. Individual keys can be revoked at any time when access is no longer necessary.

Imaging system: The imaging pipeline aboard Maka Niu allows for video capture at any resolution and frame rate, up to and including 1920x1080 at 30 fps. Still images can be taken at a maximum of 3280x2464, individually or as part of a sequential time lapse. Time-lapse stills can then be uploaded and converted for viewing and analysis as a video. Due to system memory limitations, time-lapse images at full resolution should currently be converted using a different device after upload so as not to overload the system. Lower resolution image sequences can be converted to video on Maka Niu, depending on the number of images.

The imaging pipeline incorporates the open-source RPi Cam Web Interface (RPiCWI) community project. RPiCWI is a highly configurable and extendable interface to the Raspberry Pi Camera Module. It is accessible on any browser and operates on a combination of PHP and Linux system-level shell scripting. It allows complete command line configuration and control of the entire imaging system, and also provides a browser accessible webpage for viewing, sorting, converting, deleting, and uploading all imagery taken during deployment.

At its most basic, RPiCWI offers a FIFO-named pipe for inter-process communication. Changes to configuration or operational commands are sent to the named pipe as simple text strings in a predetermined format. These commands can be activated *via* the lever-button press while the Maka Niu is in manual mode or issued by the JavaScript-based Coconut mission engine when in either of the pre-programmed mission modes. Simple bash or other shell scripts and macros can also be used to extend the capabilities of the device within the RPiCWI environment. Commands from the Coconut daemon can be sent to execute missions or alter camera configuration based on sensor or other conditional input.

One of the strengths of the Raspberry Pi Zero W is a full-featured Linux operating system that lets it function as a powerful single-board computer. This allows for rapid development and the use of a myriad of open source tools and community projects, again lowering the barrier to entry and increasing access to field scientists and development engineers.

Once a video has been captured, it can be processed in multiple ways. Video content is captured to a file in the raw H.264 video format and can be stored or uploaded as such once the device has joined a Wi-Fi network with internet access. However, to be viewed in a browser on the device's internal media management page, raw H.264 files must be containerized or "boxed" to a media player-viewable format, such as MP4. RPiCWI can automatically box H.264 files immediately after capture, in a batch mode triggered manually, or automatically upon device boot.

Due to the single-core nature of the Raspberry Pi Zero W, it is inadvisable to attempt capture and boxing simultaneously. If extended capture is desired, the mission engine will split continuous video into smaller, more memory-friendly "chunks" and delay boxing until no capture is scheduled. Code within the mission engine can detect when a period of non-capture is equal to or longer than half of the length of the previously captured video and use the quiescent period to box the H.264 files.

With the recent introduction of the Raspberry Pi Zero 2 W, featuring a multi-core processor, boxing one video while capturing another becomes less burdensome on the system and boxed videos can be ready for review before or within minutes of the device returning to the surface. All videos and still images can be immediately viewed in a browser connected *via* the device's access point and, should the video contain nothing of value, deleted manually if desired to make room for the next mission.

Once the device has returned to a network with internet access, all materials can be uploaded en masse for viewing and analysis. A single button allows the user to initiate this file transfer to Tator. Once uploaded to the cloud or downloaded to another device on the network, all content can be deleted through the media management page to free up the storage system in anticipation of the next deployment. The media management solution based on the original RPiCWI and extended by the Maka Niu software development team is intended to make the media process extremely streamlined and easy to use.

Tator[1] and FathomNet Another element of Maka Niu designed to ease its use and broaden its impact is the inclusion of a video analytics backend to which all media is uploaded after deployment. Tator, short for "annotator," is an open source, secure, reliable, and feature-rich platform built by CVision AI that offers collaborative analysis and annotation features on top of seamless media management and video playback capabilities. After uploading to Tator, videos are automatically ingested and organized by project, instantly available to collaborators across the world. Media and collected metadata are uploaded to a project, which has a composable ingestion pipeline. Custom parsers are created to parse log and sensor files, and convert them into metadata that is associated with media objects (Figure 8). These metadata can then be visualized and queried as part of any analysis task. Tator also supports running custom machine learning algorithms for automated or semi-automated analysis. Many of the available algorithms were trained using FathomNet, an open source image database for understanding our ocean and its inhabitants. FathomNet is "a novel baseline image training set, optimized to accelerate development of modern, intelligent, and automated analysis of underwater imagery. Our seed data set consists of an expertly annotated and continuously maintained database with more than 26,000 hours of videotape, 6.8 million annotations, and 4,349 terms in the knowledge base. FathomNet leverages this data set by providing imagery, localizations, and class labels of underwater concepts in order to enable machine learning algorithm development" (Boulais et al., 2020). In addition to benefiting from algorithms trained on data in FathomNet, uploaded data can be annotated and contributed to FathomNet as well, using Tator's integrated dashboard for export to the FathomNet API.

1 https://www.tator.io/

2 https://fathomnet.org/

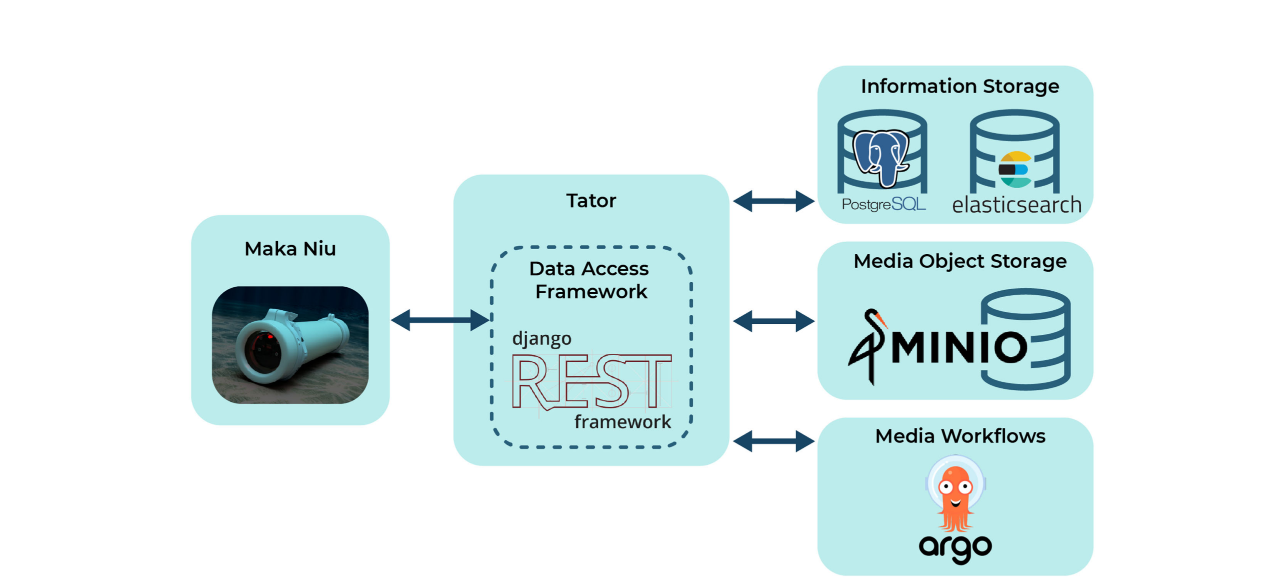

FIGURE 8
The Tator data ingestion pipeline and media management workflow.

3.4 User support

All test users for the initial deployment of thirteen Maka Niu units were given the opportunity to attend remote training sessions *via* teleconferencing with the Maka Niu engineering and software development teams. Links to an online user manual and training videos were shared during the training sessions as well as *via* direct email. Several additional training sessions, singly and in groups, have been offered subsequently for those who could not attend the initial sessions.

3.5 Deployments

Thirteen Maka Niu units were distributed to test users in eleven locations in 2021: Sri Lanka, Trinidad and Tobago, Cook Islands, Portugal (2), Bermuda, Seychelles, South Africa, Montserrat, and the United States (Louisiana and Hawai'i). These units are currently being tested by a subset of the twenty interviewees who provided initial input on requirements and desired capabilities for the design of Maka Niu.

Four of the units are with the development team. In September 2021, unit MakaNiu0001 was deployed on a number of dives from E/V *Nautilus* during an expedition in the Santa Monica Basin, off Southern California, USA. Maka Niu was strapped to the AUV *Mesobot* as a backup camera and recorded temperature, depth, and videos during dives (Figure 9). In total, MakaNiu0001 went on six separate dives with *Mesobot* to depths between 125 and 500 m. Mesobot's missions were for the most part carried out in total darkness, but during a brief lit period, Maka Niu did capture video of flashing marine life at 100 m. The *Mesobot* dives provided an opportunity to compare GPS and depth data collected by MakaNiu0001 with independent coordinate information from the ship and independent pressure data collected by *Mesobot*, confirming the in-the-field functionality and effectiveness of the low-cost sensors built into Maka Niu. Unit 0001's self-determined coordinates during one of the launches were only 6 m off from coordinates provided by the navigator of the ship, and at a depth of 500 m during one of the *Mesobot*'s deeper dives, their respective depth estimations differed by only 2 m, or 0.4%.

The Maka Niu system has been popular with test users for increasing the range of their Baited Remote Underwater Video (BRUV) systems. Test user Sheena Talma deployed unit MakaNiu0008 in the Maldives in September 2022 as part of a BRUV deployment to the seafloor. Maka Niu recorded extensive footage of shrimp, eels, and a bluntnose sixgill shark (Figure 10). The depth of the seafloor was approximately 900 m, and Maka Niu estimated its depth at 894.5 m and local temperature at 5.65 C.

3.6 Testing

Housing: The 1,500 m housing rating was confirmed with two tests at a pressure testing tank at Woods Hole Oceanographic Institute (Table 1). In a destructive test, the pressure in the test tank was increased until the Maka Niu housing collapsed at 3,127 psi, equivalent to roughly 2,148 m in saltwater. In a second test, a Maka Niu was pressurized to 2,235 psi, equivalent to 1,535 m, and held there for one hour. Maka Niu was on for the duration

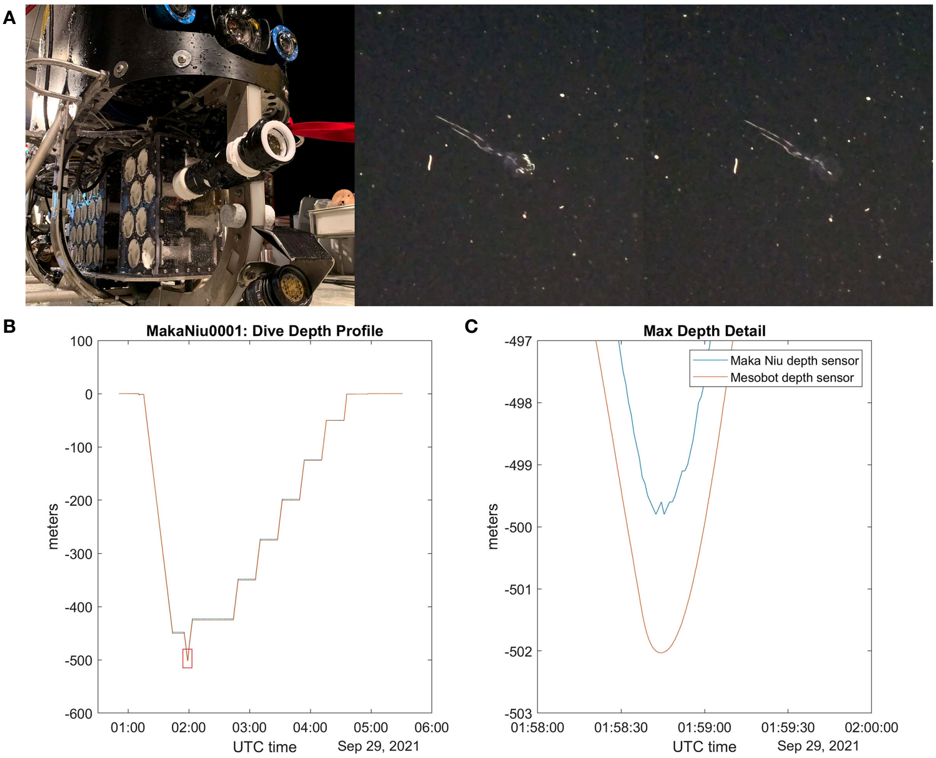

FIGURE 9
(A) Maka Niu was mounted to *Mesobot* below and in parallel to its main camera system. **(B)** Stills from a video recorded by Maka Niu of a flashing marine animal. **(C)** The depth profile for one of the dives, using independent data from Maka Niu and from Mesobot, shows the relative agreement between their measurements.

of the second test, and remained fully functional throughout and after the test.

Keller Pressure Sensor: The raw pressure data recorded by the Maka Niu during the pressure test of the housing can be compared to the pressure profile inside the testing tank (Figure 11). This comparison shows that the Maka Niu's pressure sensor remained functional throughout the test, and that at maximum pressure, which was held for an hour at approximately 2,235 psi, the Keller recorded about 2 psi less, which is equivalent to an error of 0.09%. The uncertainty in pressure data from the testing facility is stated to be ±0.01%, and the uncertainty of the Keller sensor data from the manufacturer is 0.5% of full-scale measurement, which for the keller is 1 bar or 14.5 psi. As expected, at 1,500 m, the percent difference between the Keller sensor data and the tank pressure data falls well within the sum of the two uncertainties.

Battery Runtime: To determine worst-case battery performance, four Maka Niu units—0004. 0005, 0007, and 0008—each performed three runtimes of continuous video recording and three runtimes of one-second timelapse image captures. The units were chilled to approximate underwater temperatures. The testing has shown that during continuous video, the units averaged 18.4 hours, and during timelapse, they averaged 20 hours. (Figure 12).

The nominally 11.1 V battery pack has up to 3,500 mAh charge. This translates to approximately 190 mA or 2.1 W when recording video, and an average 175 mA or 1.94 W with the one-second timelapse. This indicates that the power consumption difference between the camera actively recording and idling between image captures is fairly minimal. In separate measurements, it was observed that when the camera is disabled, current consumption drops almost 50 mA. If timelapses have significantly longer gaps, the camera can be powered down and battery life in timelapse mode can be expected to be increased up to 40% in the extreme limit. Further methods to increase deployment time are discussed in section 4.3.

Image Quality Evaluation: In order to perform a qualitative evaluation of the image quality captured by Maka Niu, a GoPro7 was mounted directly on a Maka Niu. The two devices were then used to take a series of images at shallow depth off the coast of Maui in Hawai'i. The images have not been post-processed. The GoPro camera has a larger sensor resolution and wider field of view, but a comparison of the matched and cropped area of

FIGURE 10
Video stills from a BRUV deployment to 900 m.

coverage from each system shows that, in a well-lit environment, images from Maka Niu are well-matched with those from the GoPro (Figure 13). While 4K imagery would be advantageous, using a GoPro as the imaging sensor in the Maka Niu would add excessive additional costs to each system, and the GoPro also lacks the open source development tools available for the Raspberry Pi camera currently in use.

4 Discussion

The Maka Niu imaging and sensor platform is a 261 mm-long, 66 mm-diameter cylinder, currently depth tolerant to 1,500 m and designed to be the main “control” node of a network of configurable modules controlled over wave-guided wireless communications provided by the Raspberry Pi Zero W or Zero 2 W. The camera is capable of HD video resolution at 30 fps, 8 megapixel still images, and time-lapse sequences. The camera and control computer are integrated into a single unit and can be mounted in any number of configurations according to deployment needs, making it a flexible and agile addition to other ocean observation vehicles or equipment that may lack the capabilities Maka Niu provides.

Maka Niu is conceived, designed, and engineered first and foremost to be as low-cost and user-friendly in operation as possible, while still meeting the stringent and rigorous needs of deep-ocean exploration. Maka Niu is operated wirelessly throughout the life of the platform. There are no penetrators in the pressure housing that might wear and fail over time, and all electrical hardware, mechanical hardware, and software interfaces were designed to ensure this fully sealed, wireless

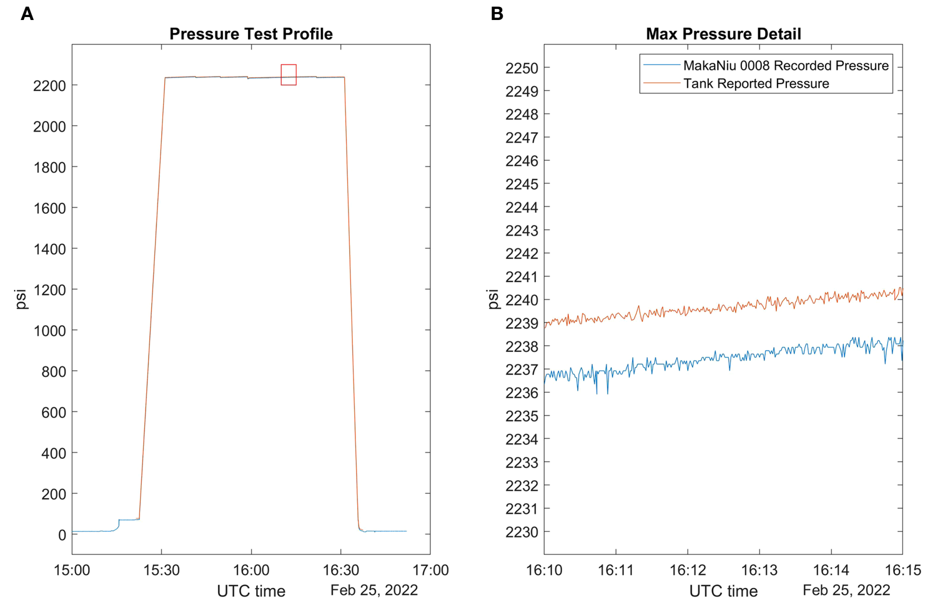

FIGURE 11
(A) Profile of the entire duration of the test, which pressurized the Maka Niu to approximately 2,235 psi. **(B)** A closeup of the pressures reported at the maximum pressure range, showing a difference of approximately 2 psi between the reported and recorded pressures.

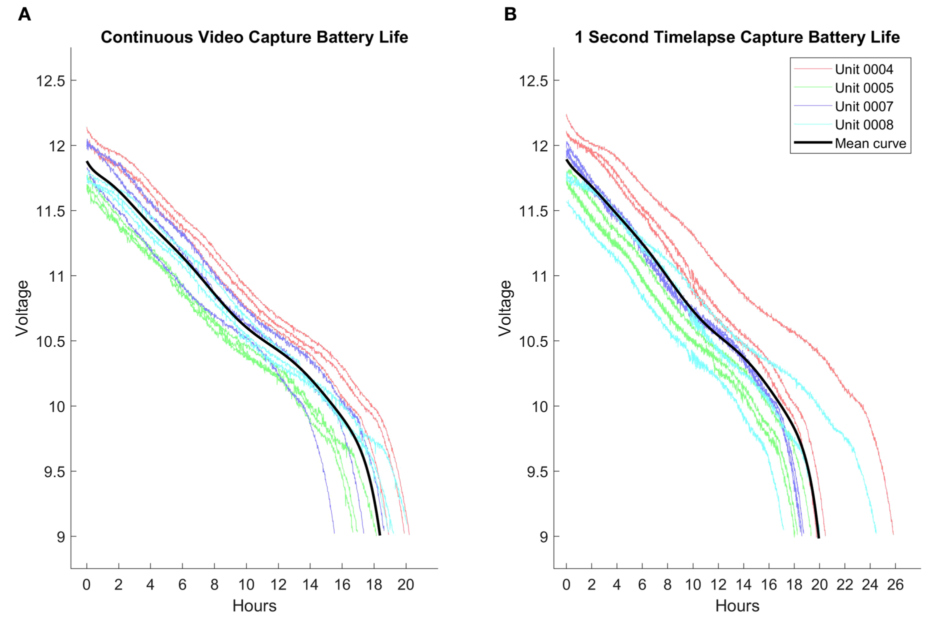

FIGURE 12
(A) Profile of the Maka Niu battery voltage for continuous video recording. Standard deviation for runtime duration is 1.5 hours. **(B)** Profile of the Maka Niu battery voltage for time-lapse imaging at 1-second intervals. Standard deviation for runtime duration is 2.6 hours. Note that the current design of the charging hardware terminates charging when current drops below a certain threshold. Since the cutoff is not based on voltage obtained, the units have inconsistent starting charge, which leads to considerable standard of deviation in the runtime duration. The mean curve in each graph was generated as a 10-degree polynomial estimation of the battery runs stretched or compressed to the average runtime of each set.

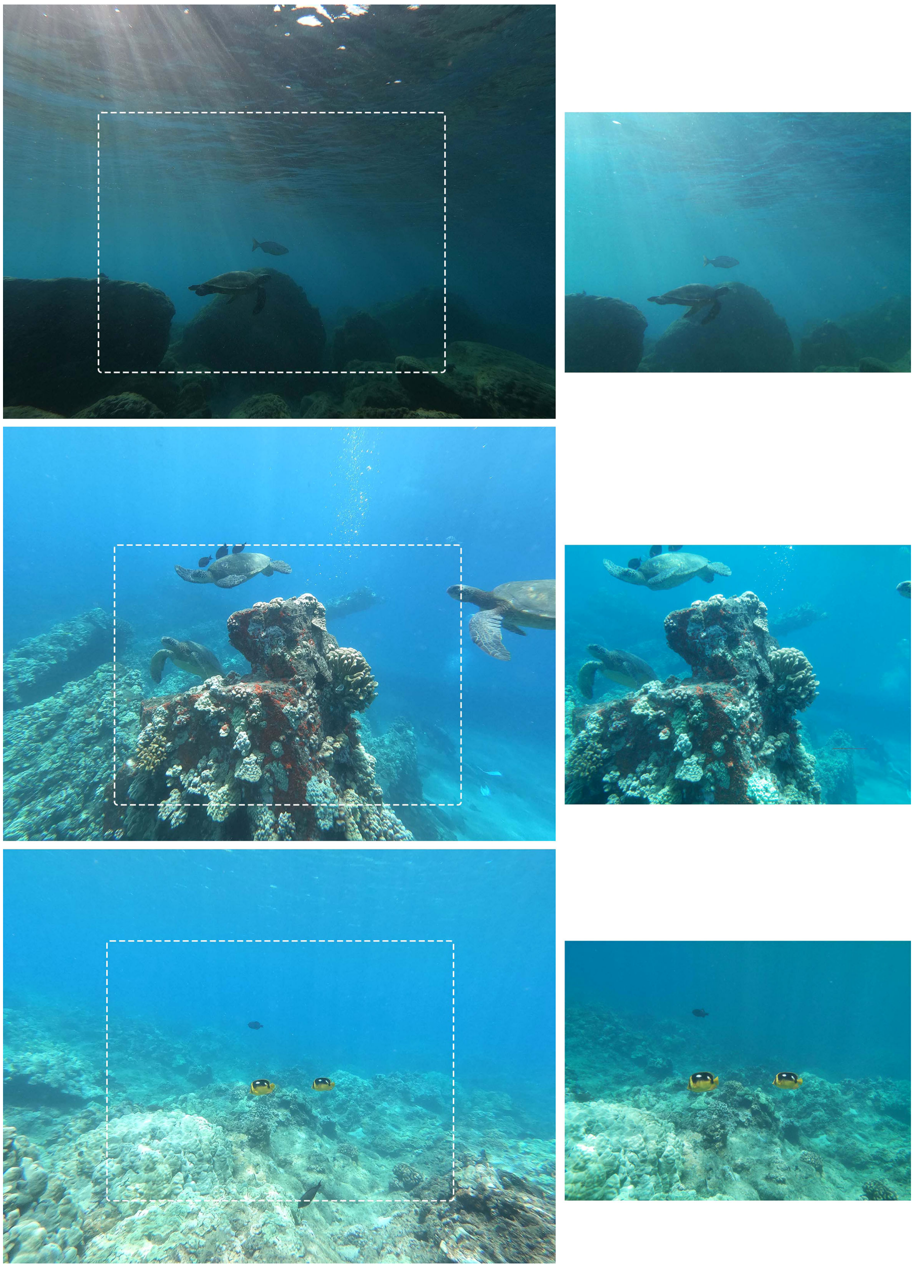

FIGURE 13
Images captured by GoPro7 are on the left; images captured by Maka Niu are on the right. Both devices were set to full automatic control and had post-processing disabled. The GoPro diagonal field of view is 100° and the images are 4000x3000 pixels. The Pi Camera Module V2 diagonal field of view is 62° and the images are 2592x1944 pixels. A white dotted rectangle in the figure marks the approximate cropping of the GoPro images that would result in the equivalent Maka Niu images. Since both the field view and the pixel count of the Maka Niu images are about a third of those of the GoPro, the cropped images would have roughly equivalent pixel count.

use. Charging power is provided using wireless inductive technology; all data communication with the control computer, support modules such as the LED module, and the sensor data/media management system is handled *via* Wi-Fi; and the control computer is operated magnetically from outside the sealed housing.

4.1 Modularity

The current Maka Niu system is the first element of what is intended to be an extendible ecosystem of exploration, monitoring, or sampling devices that can be rapidly built around any combination of the central compute stack, power stack, and housing. While remaining deployment agnostic, multiple Maka Niu devices can be deployed together to achieve the capabilities of a much larger deep-sea platform. Creating a system of reusable modular parts allows new development to focus more readily on the novel capability being explored, without having to reinvent the computation stack, power systems, and pressure housings. To this end, three additional modules were designed and prototyped by students at the Massachusetts Institute of Technology and the University of Porto using the Maka Niu housing, power, and compute components: an LED module, an independent above-water location module, and an underwater release module.

Inter-module communication: While submerged, communication between modules can be accomplished *via* 2.4 Ghz Wi-Fi or Bluetooth, using the native capabilities of the Pi Zero W as long as the modules are within 10 to 15 cm of each other. If longer distances are needed, additional material can be added to the mounting chassis to operate as a waveguide for the RF signals to follow and allow inter-module communication (Jang, 2020). If even longer distances are needed, a Maka Niu acoustic modem module or another well-understood method of underwater communication can be engineered, again developing only the desired novel capability and speeding design through the reuse of pre-existing support modules.

LED module: The module is designed to use the same initial voltage as that provided by the battery subsystem and is controlled by the same compute subsystem. The primary difference between the original Maka Niu system and the LED module is that the camera module has been replaced with a constant-current LED driver circuit board, LEDs, and a heatsink. Using the same battery stack and computer stack allows for easy communication between the original system and the LED module, which increases battery conservation by programming the LEDs to activate only when the camera will be on and recording. Based on interviews with potential users, approximately 8,000 lumens per module should be sufficient for most use cases. Even with LEDs' high efficiency, the power needed to produce sufficient light will draw enough power to create significant heat. To combat this, the LED driver circuit board should be made with an aluminum core, and a heatsink should be incorporated into the housing to conduct heat into the surrounding water. A compatible LED module will expand the types of locations and missions for which the main Maka Niu is appropriate. The combination of camera module and LED module can be mounted or configured according to current mission requirements, lending agility to mission deployments.

Completed prototypes of the LED module are now being tested, along with the feasibility of an RF waveguide armature that would enable an LED module and a Maka Niu camera to coordinate actions underwater (Figure 14). In initial testing, we have demonstrated both Wi-Fi and Bluetooth communication between a camera and a light pair that were held 12 inches apart by a Delrin armature. For the test to succeed, the armature needed to be wrapped in aluminum foil to reflect RF signals back into the Delrin medium. We will be confirming this capability in the field in saltwater environments and designing new armatures that have integrated RF reflective surfaces.

For use as a dive light, the LED module is controlled using the same 6-position control dial and push button interface.

Independent above-water location module: The location module is based on a commercially available personal locator encapsulated in a standard Make Niu housing and equipped with a saltwater switch that triggers it to begin broadcasting the GPS position of the module when it reaches the surface. While submerged, the system remains inactive. When the platform reaches the surface, the location system activates and the GPS coordinates are transmitted *via* SPOT Trace, a satellite communication technology that can transmit its location globally as part of the Globalstar satellite network. The GPS location can be sent as an SMS text message or email, or visualized *via* SPOT Trace's web-based app. The location module uses the standard Maka Niu pressure housing and power subsystem, but exchanges the camera subsystem with an ESP32 and SPOT Trace device.

Underwater release module: The underwater release module allows Maka Niu to be deployed as a benthic lander and is based on a self-contained magnetic mechanism triggered by a control signal sent by the main Maka Niu control module. First, flotation material is added to achieve positive buoyancy ensuring the unit returns to the surface. Next, the release system consists of a weight of ferromagnetic material attached directly to the release module's housing, attracted by the magnet, and acting as an anchor to provide negative buoyancy. Upon mission completion, the release mechanism activates, releasing the weight and consequently causing the Maka Niu to ascend to the surface. The pressure housing and power supply system are duplicates of the base system. The logic of the release system is integrated into the mission engine running aboard the Raspberry Pi in the main control module. The communication between this external module and the Raspberry Pi is achieved *via* Bluetooth. An ESP32 or similar Wi-Fi and Bluetooth-enabled microcontroller platform receives a control signal sent by the Raspberry Pi and releases the weight based on the signal received. The coupling mechanism used in this iteration is based on a permanent magnet housed within the enclosure, which attracts ferromagnetic material to operate as an anchor. When a control signal is received by the ESP32 in the external module, an electromagnetic pulse is sent to a coil surrounding the magnet, temporarily nullifying or "bucking" the force of the magnet, which results in the anchor weight being ejected. As a safety backup, the coupling mechanism is attached to the anchor mass *via* a galvanic time release (GTR) coupler that undergoes timed corrosion in saltwater. Should an error occur in the control system, or insufficient power be provided to the magnet, the GTR mechanism will degrade after a predetermined amount of time, allowing the device to return to the surface.

FIGURE 14
(A) The LED module uses the same housing as the Maka Niu, except the front hold-down is replaced with a copy of the rear hold-down, and water access holes are added for heat-sinking purposes. **(B)** This Delrin armature holds an LED module at an adjustable distance and angle to provide ideal lighting conditions. The armature was also used to test RF-guided Wi-Fi and Bluetooth communication. This did not successfully maintain the connection once submerged until it was wrapped with aluminum foil to act as a waveguide.

4.2 Increasing pressure rating

The current Delrin housing and acrylic port can be swapped, with minimal design changes, to an aluminum housing with a sapphire glass port. We estimate that this change would increase the depth rating to 6,000 m, leading to a version of Maka Niu capable of deployment to the vast majority of the sea floor. The currently used pressure sensor would be swapped for the Series 7LHP, also by Keller.

There are some expected challenges, however. Maka Niu depends a great deal on wireless technologies: global positioning, Wi-Fi, and inductive charging. As a metal housing will likely interfere with these elements, compromises, workarounds, and alternate solutions will need to be explored.

TABLE 1

Test	Procedure	Result
Destructive Housing Test in a Pressure Tank	Progressively increase tank pressure until the Maka Niu housing implodes.	Housing imploded at 3,127 psi, equivalent to a depth of 2,148 m, or 648 m beyond stated rating.
Non-destructive Housing Test in a Pressure Tank	Progressively increase tank pressure to just beyond housing rating to 2,235 psi, equivalent to 1,535 m, hold that pressure for an hour and return to atmospheric pressure.	Housing remained intact, with no visible damage.
Pressure Sensor Test in a Pressure Tank	Compare pressure data recorded by the testing facility with data recorded by Maka Niu during the non-destructive housing test.	The Maka Niu and the pressure testing facility pressure data agreed to within 2 psi at maximum pressure of 2,235 psi.
Battery Runtime Test: Video	Run four Maka Nius recording videos until batteries deplete and units shutdown. Repeat the process three times.	Maka Nius ran for a mean of 18.4 hours.
Battery Runtime Test: Timelapse	Run four Maka Nius, recording time lapses at 1 hz until batteries deplete and units shutdown. Repeat the process three times.	Maka Nius ran for a mean of 20 hours.
Image Quality Evaluation	Attach a GoPro 7 to Maka Niu housing, and capture images in parallel, in daytime, in shallow waters up to 10 m.	In a well-lit environment, the quality of images captured by Maka Niu is satisfactory compared to those captured by the GoPro.

4.3 Improving deployment length

There is a great deal of room for improvement in the power performance of the Maka Niu. The current BMS does not have adequate control over power to individual sensors and chips. For instance, there is no reason to power the GNSS chip when the Maka Niu is under water. It consumes nontrivial current as it searches for satellites, but because it is tied to the same power rail as the Keller pressure sensor, it cannot be fully powered down. Additionally there is no ability to schedule a wakeup of the Pi Zero W if it is put to sleep or powered down. Adding the capability to schedule shutdowns and reboots will drastically increase the variety and potential length of deployments. For instance, a user may be interested in only recording at sunrise and sunset. If at all other times, the BMS can fully power down the Pi Zero W and all sensors other than a clock, Maka Niu could conceivably be deployed for weeks at a time.

4.4 Conclusion

The system we present is realizable by the educational, citizen science, and research communities. Maka Niu is intended as an extensible, open-source framework similar to the Phillips et al. (2019) 5,500 m DEEPi camera system. Maka Niu's small size means it is deployable from almost any size vessel and can be combined with larger research platforms to extend their capabilities, as well.

The use of commercial off-the-shelf components such as the Raspberry Pi Zero W and Zero 2 W decreases cost and increases the number of potential users, thus adding to the overall capacity of ocean observation and monitoring. The Raspberry Pi Zero W systems afford wireless communication with any Wi-Fi capable device, including smartphones and tablets, and allow software development using open-source operating systems and programming frameworks such as Linux, Python, and Node.js to create user interface designs operable by non-experts. Rather than building an all-in-one, multimillion-dollar seagoing platform that attempts to be all things to all researchers, the distributed, modular nature of an extendible ecosystem of capabilities offers flexibility and proportional response to the needs of any deployment.

Often, "affordable" in oceanography describes instruments that cost upwards of tens of thousands of dollars (versus millions). To be sure, this is a significant decrease, but at the same time, tens of thousands of dollars is still unaffordable for many individuals and organizations, particularly in developing areas. The estimated bill of materials for the current design for a single unit of Maka Niu is less than $1,000 USD, excluding labor costs, for the production of fewer than 20 units. Maka Niu is, however, aimed at wide distribution and is designed to take advantage of mass production and economies of scale. We estimate that the bill of materials for an at-scale run of 10,000 Maka Niu systems would be less than $300 USD for each device, again excluding labor costs. The current GoPro Hero 10 Black, equipped with the most robust commercially available housing, can dive to a maximum of 60 m and collect imagery up to a resolution of 5.3K for a total cost of ~$550 USD. It lacks Maka Niu's suite of sensors necessary for deep-ocean scientific research and exploration, many of the basic mission programming options, as well as the ability to develop an extended ecosystem of modules to provide expanded capabilities.

Maka Niu's value as a low-cost data acquisition system is further extended by its integration with Tator, the open-source, online platform that enables seamless image and data upload, management, and analysis. Tator and FathomNet will later be integrated to enable automated localization and classification of imagery collected during deployment (Katija et al., 2022).

Maka Niu's low cost, ease of use, and ever-expanding ecosystem of open source modules provides deep-ocean observation and sampling capabilities for a cross-spectrum of stakeholders—from traditionally funded ocean institutes and trusts, to underfunded research programs in remote island nations, to unfunded citizen science networks, student clubs, and classrooms. These newly accessible deep-ocean capabilities are then amplified and supported by Maka Niu's integration with state-of-the-art machine learning technologies to speed the classification of samples and allow faster and wider dissemination of novel discoveries.

Data availability statement

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

Author contributions

DN, JC, KB, and AA contributed to the conceptualization of the device. DN managed the project and contributed to software and hardware selection, programming, prototyping, and testing, LK contributed to designing, fabrication, mechanical engineering, programming, and testing. JF programmed the mission engine, mission programming app, wireless configuration tool, and data upload tool, and contributed to the UI/UX design. MS contributed to the design of the LED module. PB contributed to the evaluation of open source web servers, the data upload methodology, and mission programming methodology. JS contributed to the development of a weight-release deployment module. KC contributed to the UI/UX design, the user manual, and quick start guide. BW contributed to integration with Tator and FathomNet. KLCB and AA supervised all teams as Principal Investigators. All authors contributed to the article and approved the submitted version.

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Conflict of interest

Author BW was employed by the company CVision AI.

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

The reviewer JJ declared a shared affiliation with the author MS to the handling editor at the time of review.

Publisher's note

Supplementary material

The Supplementary Material for this article can be found online at: https://www.frontiersin.org/articles/10.3389/fmars.2022.986237/full#supplementary-material

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

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

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

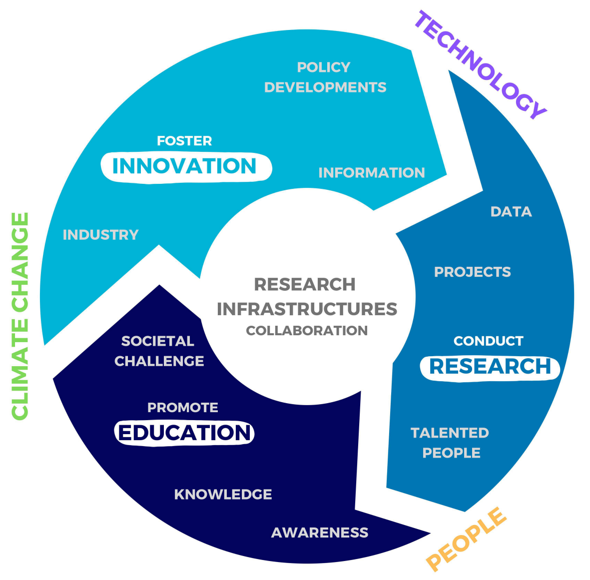

FIGURE 1
The central role of the RIs for conducting research, fostering innovation and promoting education, that are the key drivers of a knowledge-based society.

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.

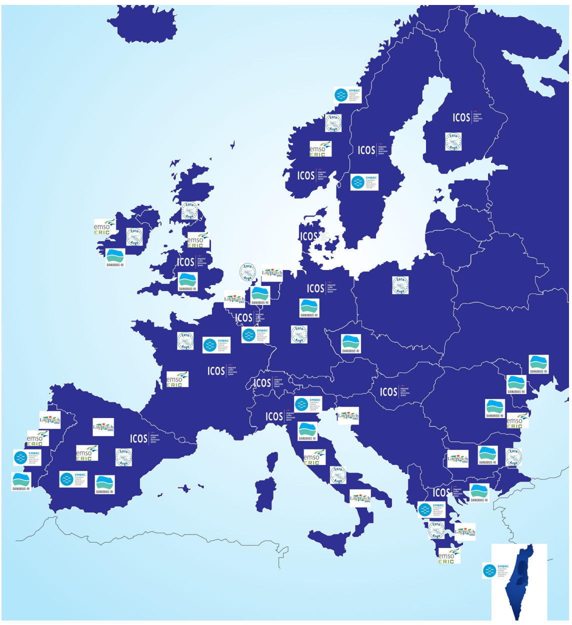

FIGURE 2
The geographical distribution of the Countries involved in the ERICs and in the Research Infrastructure.

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

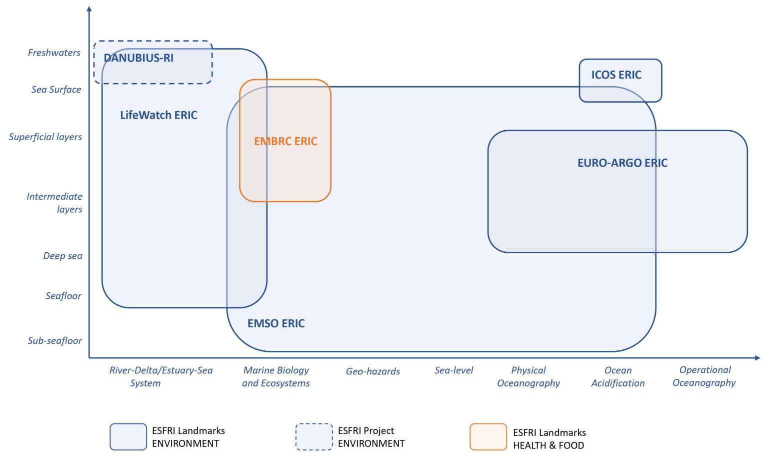

FIGURE 3
The different domains covered by the European marine RIs versus depth from seafloor to sea surface and fresh water (modified from ESFRI, 2018a).

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.

The reviewer [AR] declared a past co-authorship with authors [SP, GP] to the handling Editor.

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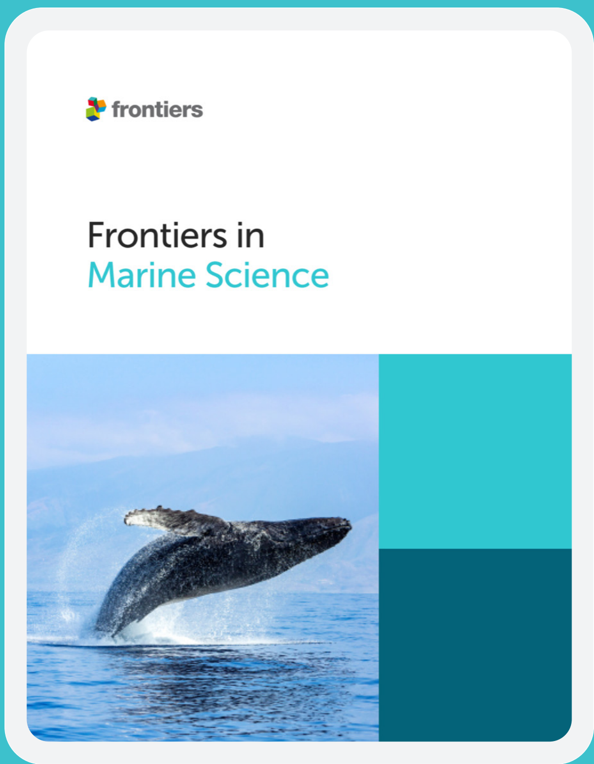

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