frontiers in Marine Science

PERSPECTIVE
published: 20 January 2022
doi: 10.3389/fmars.2021.778452

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

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Specialty section:
This article was submitted to Ocean Observation, a section of the journal Frontiers in Marine Science

Received: 16 September 2021
Accepted: 30 December 2021
Published: 20 January 2022

Citation:
Silveira TM, Carapuço MM and Miranda JM (2022) The Ever-Changing and Challenging Role of Ocean Observation: From Local Initiatives to an Oceanwide Collaborative Effort. Front. Mar. Sci. 8:778452. doi: 10.3389/fmars.2021.778452

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.

FUNDING

This work was done in the scope of the "Atlantic Observatory – Data and Monitoring Infrastructure" pre-defined project, funded by the "Blue Growth" Program of the EEA Grants Portugal 2014–2021.

ACKNOWLEDGMENTS

The authors would like to acknowledge the financial support of FCT through project UIDB/50019/2020 – IDL.

REFERENCES

Bax, N. J., Appeltans, W., Brainard, R., Duffy, J. E., Dunstan, P., Hanich, Q., et al. (2018). Linking capacity development to GOOS monitoring networks to achieve sustained ocean observation. *Front. Mar. Sci.* 5:346. doi: 10.3389/fmars.2018.00346

Bean, T. P., Greenwood, N., Beckett, R., Biermann, L., Bignell, J. P., Brant, J. L., et al. (2017). A review of the tools used for marine monitoring in the UK: combining historic and contemporary methods with modeling and socioeconomics to fulfill legislative needs and scientific ambitions. *Front. Mar. Sci.* 4:263. doi: 10.3389/fmars.2017.00263

Blythe, J. L., Armitage, D., Bennett, N. J., Silver, J. J., and Song, A. M. (2021). The politics of ocean governance transformations. *Front. Mar. Sci.* 8:634718. doi: 10.3389/fmars.2021.634718

Campbell, L. M., Gray, N. J., Fairbanks, L., Silver, J. J., Gruby, R. L., Dubik, B. A., et al. (2016). Global oceans governance: new and emerging issues. *Annu. Rev. Environ. Resour.* 41, 517–543. doi: 10.1146/annurev-environ-102014-021121

Copernicus Marine Service (2021). *Copernicus Marine Service Ocean State Report*. Available online at: https://marine.copernicus.eu/access-data/ocean-state-report (accessed November 9, 2021).

Crise, A., Ribera d'Alcalà, M., Mariani, P., Petihakis, G., Robidart, J., Iudicone, D., et al. (2018). A conceptual framework for developing the next generation of Marine OBservatories (MOBs) for science and society. *Front. Mar. Sci.* 5:318. doi: 10.3389/fmars.2018.00318

Dañobeitia, J. J., Pouliquen, S., Johannessen, T., Basset, A., Cannat, M., Pfeil, B. G., et al. (2020). Toward a comprehensive and integrated strategy of the European marine research infrastructures for ocean observations. *Front. Mar. Sci.* 7:180. doi: 10.3389/fmars.2020.00180

deYoung, B., Visbeck, M., de Araujo Filho, M. C., Baringer, M. O., Black, C. A., Buch, E., et al. (2019). An integrated all-atlantic ocean observing system in 2030. *Front. Mar. Sci.* 6:428. doi: 10.3389/fmars.2019.00428

Eikeset, A. M., Mazzarella, A. B., Davíðsdóttir, B., Klinger, D. H., Levin, S. A., Rovenskaya, E., et al. (2018). What is blue growth? The semantics of "Sustainable Development" of marine environments. *Mar. Policy* 87, 177–179. doi: 10.1016/j.marpol.2017.10.019

European Strategy Forum on Research Infrastructures [ESFRI] (2018). *Strategy Report on Research Infrastructures in Europe, Roadmap 2018*. Available online at: http://roadmap2018.esfri.eu (accessed November 21, 2022).

European Commission (2020). *Destination Earth*. Available online at: https://digital-strategy.ec.europa.eu/en/policies/destination-earth (accessed November 9, 2021).

European Marine Board (2021a). *Sustaining in Situ Ocean Observations in the Age of the Digital Ocean. EMB Policy Brief No. 9*. Oostende: European Marine Board.

European Marine Board (2021b). *Proceedings of the 7th EMB Forum–Big Data in Marine Science: Supporting the European Green Deal, the EU Biodiversity Strategy, and the Digital Twin Ocean*. Available online at: https://www.marineboard.eu/sites/marineboard.eu/files/public/7th%20EMB%20Forum/EMB_7thForum_Proceedings_36p_Web%20%281%29.pdf (accessed November 9, 2021).

FOO (2012). *A Framework for Ocean Observing, UNESCO, IOC/INF-1284*. Available online at: http://www.eoos-ocean.eu/download/GOOSFrameworkOceanObserving.pdf (accessed November 21, 2022).

Henson, S. A., Beaulieu, C., and Lampitt, R. (2016). Observing climate change trends in ocean biogeochemistry: when and where. *Glob. Change Biol.* 22, 1561–1571. doi: 10.1111/gcb.13152

Hill, K., Moltmann, T., Proctor, R., and Allen, S. (2010). The Australian integrated marine observing system: delivering data streams to address national and international research priorities. *Mar. Technol. Soc. J.* 44, 65–72. doi: 10.4031/MTSJ.44.6.13

Howe, B. M., Miksis-Olds, J., Rehm, E., Sagen, H., Worcester, P. F., and Haralabus, G. (2019). Observing the oceans acoustically. *Front. Mar. Sci.* 6:426. doi: 10.3389/fmars.2019.00426

Jahanbakht, M., Xiang, W., Hanzo, L. H., and Rahimi Azghadi, M. (2021). Internet of underwater things and big marine data analytics—a comprehensive survey. *IEEE Commun. Surv. Tutor.* 23, 904–956. doi: 10.1109/COMST.2021.3053118

Larkin, K., and Heymans, S. J. J. (2018). *Strategic Foresight Paper on AtlantOS in the European Context*. Oostende: European Marine Board, 48.

Lin, M., and Yang, C. (2020). Ocean observation technologies: a review. *Chin. J. Mech. Eng.* 33:32. doi: 10.1186/s10033-020-00449-z

Lindstrom, E., Gunn, J., Fischer, A., McCurdy, L. K., and Glover, A. (2012). *A Framework for Ocean Observing. IOC Information Document*. Paris: UNESCO. doi: 10.5270/OceanObs09-FOO

Matias, L., Carrilho, F., Sá, V., Omira, R., Niehus, M., Corela, C., et al. (2021). The contribution of submarine optical fiber telecom cables to the monitoring of earthquakes and tsunamis in the NE Atlantic. *Front. Earth Sci.* 9:686296. doi: 10.3389/feart.2021.686296

Miloslavich, P., Bax, N. J., Simmons, S. E., Klein, E., Appeltans, W., Aburto-Oropeza, O., et al. (2018). Essential ocean variables for global sustained observations of biodiversity and ecosystem changes. *Glob. Chang. Biol.* 24, 2416–2433. doi: 10.1111/gcb.14108

Muñiz Piniella, Á, and Heymans, J. J. (2020). *Report on Initiatives, Strategies and Roadmaps that Contribute to Foresight in Ocean Observation. EU EuroSea Project*. Luxembourg: EU EuroSea. doi: 10.5281/zenodo.3956082

Nieuwejaar, P., Mazauric, V., Betzler, C., Carapuço, M., Cattrijsse, A., Coren, F., et al. (2019). Next generation European research vessels: current status and foreseeable evolution. *Paper Presented at the Position Paper 25 of the European Marine Board*, eds J. J. Heymans, P. Kellett, C. Viegas, B. Alexander, and J. Coopman (Ostend: European Marine Board).

OECD (2016). *The Ocean Economy in 2030*. Paris: OECD Publishing. doi: 10.1787/9789264251724-en

OECD (2019). *Rethinking Innovation for a Sustainable Ocean Economy*. Paris: OECD Publishing. doi: 10.1787/9789264311053-en

Paull, L., Seto, M., Saeedi, S., and Leonard, J. J. (2018). "Navigation for Underwater Vehicles," in *Encyclopedia of Robotics*, eds M. Ang, O. Khatib, and B. Siciliano (Berlin: Springer). doi: 10.1007/978-3-642-41610-1_15-1

Pinardi, N., Stander, J., Legler, D. M., O'Brien, K., Boyer, T., Cuff, T., et al. (2019). The joint IOC (of UNESCO) and WMO collaborative effort for met-ocean services. *Front. Mar. Sci.* 6:410. doi: 10.3389/fmars.2019.00410

Rayner, R., Jolly, C., and Gouldman, C. (2019). Ocean observing and the blue economy. *Front. Mar. Sci.* 6:330. doi: 10.3389/fmars.2019.00330

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

Tanhua, T., McCurdy, A., Fischer, A., Appeltans, W., Bax, N. J., Currie, K., et al. (2019). What we have learned from the framework for ocean observing: evolution of the global ocean observing system. *Front. Mar. Sci.* 6:471. doi: 10.3389/fmars.2019.00471

Tomkiewicz, S. M., Fuller, M. R., Kie, J. G., and Bates, K. K. (2010). Global positioning system and associated technologies in animal behaviour and ecological research. *Philos. Trans. R. Soc. B Biol. Sci.* 365, 2163–2176. doi: 10.1098/rstb.2010.0090

Tonani, M., Balmaseda, M., Bertino, L., Blockley, E., Brassington, G., Davidson, F., et al. (2015). Status and future of global and regional ocean prediction systems. *J. Operat. Oceanogr.* 8 (Suppl. 2), s201–s220. doi: 10.1080/1755876X.2015.1049892

Trowbridge, J., Weller, R., Kelley, D., Dever, E., Plueddemann, A., Barth, J. A., et al. (2019). The ocean observatories initiative. *Front. Mar. Sci.* 6:74. doi: 10.3389/fmars.2019.00074

Vance, T. C., Wengren, M., Burger, E., Hernandez, D., Kearns, T., Medina-Lopez, E., et al. (2019). From the oceans to the cloud: opportunities and challenges for data, models, computation and workflows. *Front. Mar. Sci.* 6:211. doi: 10.3389/fmars.2019.00211

Wang, L., Wang, Yj, Song, S., and Li, F. (2021). Overview of fibre optic sensing technology in the field of physical ocean observation. *Front. Phys.* 9:745487. doi: 10.3389/fphy.2021.745487

Whitt, C., Pearlman, J., Polagye, B., Caimi, F., Muller-Karger, F., Copping, A., et al. (2020). Future vision for autonomous ocean observations. *Front. Mar. Sci.* 7:697. doi: 10.3389/fmars.2020.00697

Wilkinson, M. D., Dumontier, M., Appleton, G., Axton, M., Baak, A., Blomberg, N., et al. (2019). Addendum: the FAIR guiding principles for scientific data management and stewardship. *Sci. Data* 6:6. doi: 10.1038/s41597-019-0009-6

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